MSc thesis in Geomatics

Proposal for the integration of a Building Materials part: (ISO 19152-7) within the Land Administration Domain Model

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Abstract

The growing global consumption of non-renewable resources is a significant societal concern. The shortage of primary raw materials and the decreasing availability of space for final waste disposal present an alarming situation. Improperly assigning materials to their recycling potential often results in high-potential materials being downgraded to lower potential uses. Transitioning to a Circular Economy, as proposed by the European Union (EU), offers an effective solution to this problem. A Circular Economy is an economic system designed from societal production and consumption patterns that maximizes the services derived from the linear flow of materials and energy between nature and society. It achieves this by utilizing cyclical material flows, renewable energy sources, and cascading energy flows. To ensure materials remain available and fully utilized over time, they must be documented and registered while in use. The EU has proposed a Materials Passports for buildings which is an electronic set of data and evaluates the recycling potential and environmental impact of materials embedded in buildings.

Land administration is the process of efficient management of land and its associated information, facilitating communication among various stakeholders both within one country and internationally. In this research, land administration is utilized because ownership information from the land administration can be applied to the registration of building materials. It also provides data on location and distance details. The registration methods used in land administration are well-suited to the concept of a materials passports. Hence, this research combines the concepts of Circular Economy and Land Administration. The Land Administration Domain Model, LADM ISO19152–6 edition II contains six parts- Conceptual Model, Land Registration, Marine Georegulation, Valuation Information, Spatial Plan Information and Implementation. Building Materials registration has a lot of links to the Land Administration, like owner, valuation. Introducing the "Building Materials ISO 19152-7" standard can significantly contribute to the Land Administration Domain Model (LADM). It allows building materials registration to be aligned with (inter)national standards, ensuring consistency and improving the overall quality and reliability of land and property management.

The main contribution of this study lies in evaluating the application of Building Materials and establishing a standardized Materials Passports, including its basic requirements and conceptual information model. This research identifies and explores the connections between the Materials Passports and its integration with the core LADM creating a multipurpose harmonized information model.

Acknowledgements

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Acronyms

1 Introduction

This chapter aims to give a better understanding of the thesis research domain and the research objective of this study. The relevance of this research is explained in section 1.1. The research objective is discussed in section 1.2, and the main research question and sub-questions are stated in section 1.3. Finally, in section 1.4 the scope of this research is explained, and the reading guide for navigating the subsequent chapters is presented in section 1.5.

1.1 Motivation

The building and construction sector significantly influences both the economy and the environment, contributing substantially to the Gross Domestic Product (GDP) and representing a major consumer of resources [Norouzi et al., 2021]. According to Global Status Report for Buildings and Construction, a report by the UN Environment Programme (UNEP) and Global Alliance for Buildings and Construction [Environment], 21% of global greenhouse gases were emitted by the building and construction sector. By 2022, buildings accounted for 34% of global energy demand and 37% of energy and process-related carbon dioxide (CO2) emissions. The growing global consumption of non-renewable resources is a major societal concern [Honic et al., 2021]. The building and construction sector is the largest consumer of raw materials, accounting for 60% of the total raw material extraction from the lithosphere [Honic et al., 2019a]. In addition to consumption of resources and energy, Construction and Demolition projects are responsible for the solid wastes. The shortage of primary raw materials and the decreasing availability of space for final waste disposal present an alarming situation. The rapid growth of the world population also leads in a higher demand for raw materials. The primary factor contributing to increased waste is the use of a linear economic model, where raw materials are extracted from the earth, processed, and assembled into buildings. However, at the end of the building's lifecycle, the buildings are demolished, resulting in waste that is often disposed of in landfills without recycling [Korhonen et al., 2018], refer figure 1.1.

Transitioning to a Circular Economy, as proposed by the European Union (EU) [European Commission, 2021], offers a solution to this problem. As shown in figure 1.2, in the Circular Economy models, the end-of-life building materials should be reused and their components and parts deconstructed, to act as material banks for new buildings, keeping the components and materials in a closed loop [Benachio et al., 2020]. Improperly assigning materials to their recycling potential leads to the downgrade of high-potential materials to lower-potential uses. This is due to the inefficient transition from linear to circular economy which requires a systemic approach that considers the entire life cycle of the building and the value chain of the construction [Munaro and Tavares, 2021]. Dutch architect and founder of Madaster, Thomas Rau states that ***Waste is***

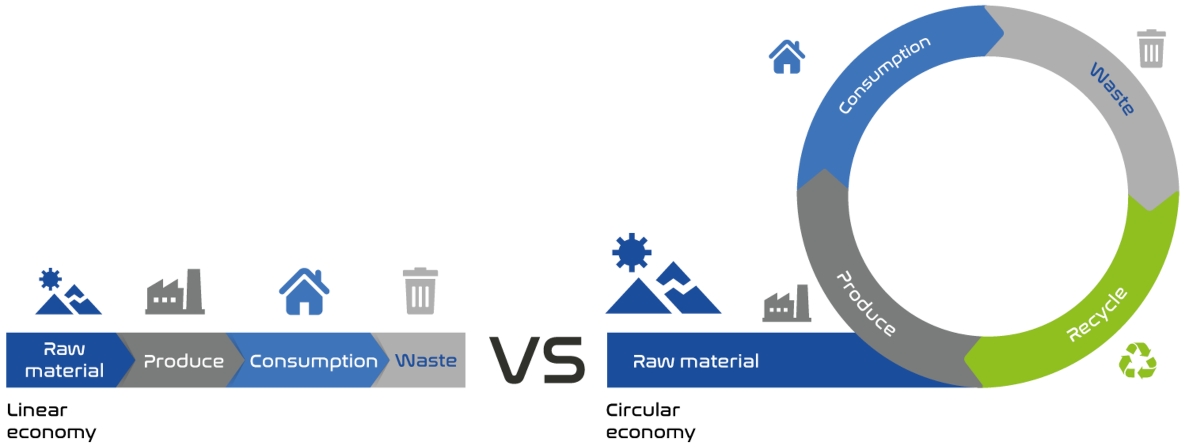


Figure 1.1: Linear and Circular Economy[Martínez, 2024]

material without identity, [Rau and Oberhuber, 2016]. Madaster is a platform with an online library of materials in the built environment, it links the material identity to the location within the building as well as the building's location and records this in a Materials Passports [Madaster, 2022]. When materials lack proper documentation or identity, they often lose their value and are treated as waste. When the materials have an identity, they are recognized for their true potential to be reused thus maintaining their value over time [Rau and Oberhuber, 2016]. Thus having documentation allows materials to be traced, making it easier to recover them from demolition or renovation projects and integrate them into new construction. This helps in the reduction in consumption of raw materials and supports the circular economy.

The Building as Material Banks (BAMB) project of EU's Horizon 2020 involving 16 partners from 8 European countries is an initiative that aims to enhance the value of used building components and materials through circular solutions [Debacker and Manshoven, 2016]. By focusing on design and circular value chains, the project ensures that materials in buildings retain their value, reducing waste and the use of raw resources. Instead of turning into waste, buildings will function as banks for valuable materials, systems, and components, maintaining their functionality and value for reuse, thereby reducing the demand for primary resource extraction. The project led to the development of Materials Passports (MP) and Reversible Building Design, supported by new business models, policy proposals, and management and decision-making frameworks [Debacker and Manshoven, 2016]. Reversible Building designs are building designs that are easily deconstructed, or where parts can be easily removed and added without damaging the building. This approach also supports reversible and transformable designs that can be adapted to changing functional requirements over time [Durmisevic, 2018]. Materials Passports aims to optimize the value retention of materials, products, and components throughout their lifecycle by providing information about their owner, composition, properties, and potential for reuse or recycling. By providing transparency on the legal aspects and traceability of the materials, materials passport can indirectly incentivize suppliers to prioritize the production of healthy, sustainable, and circular materials and building products, which aligns with the goals of Reversible Building Design. These passports simplify the decision-making process for developers, managers, and renovators in selecting healthy, sustainable, and circular building materials. They also facilitate reverse logistics and the return of products, materials and components, promoting a more sustainable lifecycle for building materials [Mulhall et al., 2017].

There are no universally agreed-upon basic requirements for creating a materials passports, which means the content and quality of passports can vary widely [Heinrich and Lang, 2019], [Honic et al., 2021]. A passport might be as simple as an Excel sheet with a few key attributes of the building like the list of the materials/components, or it could be a highly detailed BIM-based digital passport with detailed information about materials and components. This leads to varying quality and completeness, potentially compromising the passport's reliability and usability. Without baseline requirements, the creation of low-quality or incomplete passports remains a significant risk.

1.2 Research Objective

The main research objective of this thesis research is to investigate how the registration of building materials can be implemented following (inter)national standards. The research provides an overview of the literature on relevant topics that focus on the significance of building materials and their registration processes in relation to the circular economy. This review included an examination of ongoing projects related to building materials registration, particularly the concept of the Materials Passports, and an evaluation of its implementation. Simultaneously, consultations with experts using the Madaster platform and the TU Delft Circularity Hub, combined with insights from the literature, highlighted the necessity of establishing a standardized approach.

Based on these findings, the research proposes integrating the Building Material Registration Part (ISO 19152-7) into the Land Administration Domain Model (LADM) to improve data management, interoperability between stakeholders and circularity in the building and construction sector. The Land Administration Domain Model (LADM), an international standard (ISO 19152), offers a conceptual framework for land administration systems [Van Oosterom et al., 2013]. It is a suitable standard as building materials registration is closely related to land administration, which involves aspects like ownership information required for registration of building materials, restrictions related to the building due to heritage or monument status can be obtained from the part 2 of the LADM. The LADM is a geographic based registration system from which the location and distance can be obtained through the Spatial Unit package. The systematic registration approach followed by the LADM is well-suited to the building materials registration as it enables for data gathering through registration of the building materials and the querying of the materials through information provision, while offering precise valuation through a detailed understanding of the materials involved. Valuation supports the circular economy by accurately

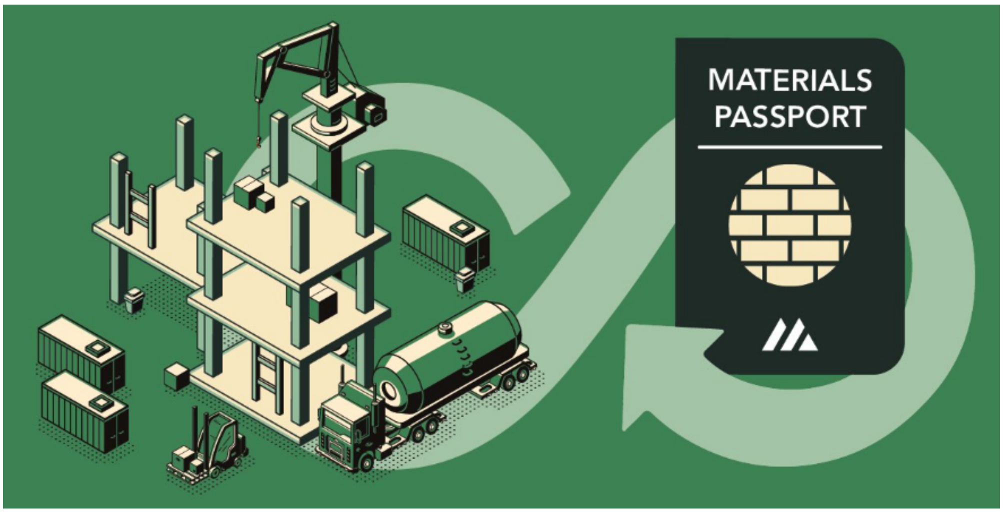


Figure 1.2: Materials Passport for tracking and reusing building materials[Malone, 2023]

determining the value of building materials, enabling their reuse. This contributes to preserving material value, minimizing waste, reducing the need for new resources and fostering sustainable construction practices. The LADM style legislation, governance, and organization are also well suitable for the building materials registration.

1.3 Research Questions

The main research goal of this thesis is to:

How can building materials registration be achieved based on (inter)national standards?

To achieve this, the following sub-questions will be relevant:

1. What are the applications of the building material registration?
2. What criteria are necessary to obtain the Materials Passports?
3. How can the registration and management of the Materials Passports be standardised?
4. How can the Material Passport be created and evaluated?

1.4 Scope

This research aims to propose the integration of a new Building Material Registration Part (ISO 19152-7) to the Land Administration Domain Model (LADM) to improve interoperability, data accessibility and sustainability in the building and construction sectors. Using the LADM framework has multiple benefits, as it is an internationally accepted standard adopted by many countries that have already developed frameworks for their countries [Kalogianni et al., 2021]. Its scalability allows the model to be implemented at different levels, including national and regional levels, which shows the broad applicability of using LADM.

With the integration the existing LADM components such as Party, Administrative unit and Spatial unit which are directly related to the ownership information required for registering building materials can be used. This helps in achieving precise ownership tracking and facilitates the integration of material registration with property records. Restrictions related to heritage or monument status addressed in LADM Part 2, can be systematically documented

The Part 4 valuation is equally relevant. With detailed knowledge of the materials used along with the real estate values, an accurate valuation can be done. The Spatial unit provides the geospatial data which includes the location data and the distance details from the source. This is crucial for identifying the material locations as well as the logistical planning such as transportation and material availability, enhancing operational efficiency.

The structured and systematic registration methodologies used in LADM are well-suited for the Materials Passports. Adding land administration-style legislation, governance frameworks, and organizational principles into building material registration processes would further enhance their standardization and scalability. Effective building material registration requires not only technical solutions but also robust legal, organizational, and institutional frameworks, similar to other functions within land administration. However, this research primarily focuses on technical solutions, while other aspects can be addressed in future work.

1.5 Thesis Outline

This chapter introduces the motivation behind the research, the research objectives, scope, and research questions. It delineates the boundaries of the study. Chapter 2 presents the relevant background information, providing a comprehensive understanding of key concepts such as the circular economy, the Land Administration Domain Model (LADM), Materials Passports, and the Madaster platform. Chapter 3 outlines the research methodology, including a gap analysis of Materials Passports and the subsequent standardization process. This chapter also describes the development of a conceptual harmonized information model.

Chapter 4 transitions the conceptual model from Chapter 3 into a technical implementation using PostgreSQL and PostGIS. It details the creation of the SQL database, including table attributes, relationships, and constraints. Case studies are utilized to validate the database, and challenges encountered during the implementation are also discussed. Finally, Chapter 5 summarizes the research findings by addressing the research questions and proposing avenues for future research.

2 Background

This chapter reviews previous research relevant to the topic of this thesis,gives an overview of Circular Economy in section 2.1. It provides context to Land Administration, section 2.2 and its international standard ISO, the Land Administration Domain Model in section 2.3. It also examines the Materials Passports in section 2.4, concluding with an exploration of Madaster in section 2.5.

2.1 Circular Economy

The linear economic model follows a "take, make, dispose" approach, where raw materials are extracted from the environment, processed into construction materials, and assembled on-site in a manner that prevents deconstruction. As a result, raw building materials become obsolete at the end of their lifecycle, leading to disposal in landfills, along with the waste generated throughout the entire process [Benachio et al., 2020]. The rise in price volatility, supply chain risks, and the increased pressure on resources have led the government to reconsider how resources are used [MacArthur, 2015]. In contrast, the circular economy has been gaining attention because of its emphasis on more efficient resource management [Benachio et al., 2020] where the value of products, materials, and resources is preserved within the economy for as long as possible, while minimizing waste generation [European Commission, 2021].

The circular economy is defined in different ways and [Kirchherr et al., 2017] collected 114 definitions to clarify the current interpretations of the concept. Their analysis shows that the circular economy is most commonly associated with the aspects of reduce, reuse, and recycle. The primary focus of the circular economy is usually on economic prosperity, followed by environmental sustainability. However, the impacts on social equity and future generations are rarely mentioned [Kirchherr et al., 2017]. This, however, does not imply that social value is not an integral part of the circular economy.

The Ellen MacArthur Foundation, a non-profit organization that researches the benefits of a circular economy and its potential to address global challenges such as climate change and biodiversity loss has provided the most widely accepted definition for circular economy. According to [Kirchherr et al., 2017], this definition is also the most frequently cited.

> ***A circular economy is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles [MacArthur, 2015].***

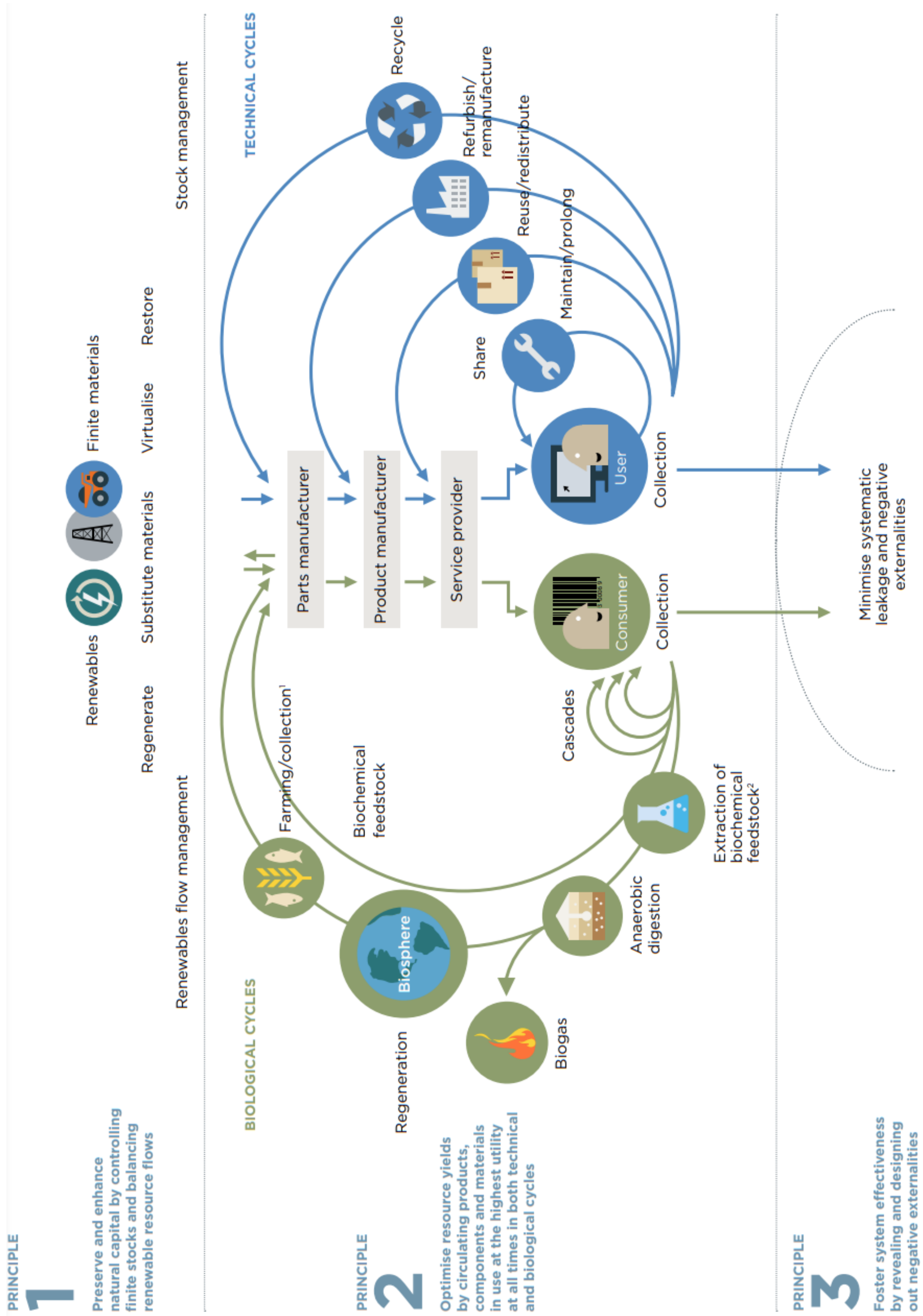


Figure 2.1: Butterfly diagram[MacArthur, 2015]

The butterfly model, shown in Figure 2.1, was developed by the Ellen MacArthur Foundation, illustrates the continuous flow of materials in a circular economy. It highlights how raw materials are retained in a closed-loop system to reduce waste and maximize value. The model consists of two main cycles: the left side illustrates the biological cycle, which deals with biodegradable materials, and the right side shows the technical cycle, which focuses on non-biodegradable materials. The closed loops on either side form a butterfly-like structure, which gives the model its name. In the technical cycle, products and materials remain in circulation through processes like reuse, repair, remanufacturing, and recycling. In the biological cycle, nutrients from biodegradable materials are returned to the Earth, supporting natural regeneration [Skene and Oarga-Mulec, 2024].

2.2 Land Administration

Land in Land Administration can be defined as an area of the surface of the earth together with the water, soil, rocks, minerals and hydrocarbons beneath or upon it and the airspace. It is a combination of both physical, spatial or topographical and thematic attributes like legal status, value, tax data [Henssen, 1995]. Land Administration can be described as the process of efficiently managing the land and information about the land. Its two main aspects are Land Registration and Cadastre. The process of recording legally recognized interests (ownership and/or use) in land is called Land Registration which can be done through deeds or title registration. Cadastre is an official record of information about land parcels, including details of their bounds, tenure, use, and value [Zevenbergen, 2004]. They both complement each other as the land registration answers the questions as to who and how, the cadastre answers the questions as to where how much. Land Administration is important as it supports economic development, environmental management and social stability of the country [Williamson, 2001]. However, the lack of standardization in practice arises from different systems following various standards coupled with the global diversity and complex legal and administrative aspects of land administration. These challenges were addressed by developing an international standard, [Lemmen, 2012].

2.3 LADM

The LADM, is an international standard (ISO 19152: 2012) that provides a conceptual framework for land administration systems, aiming to align their design with societal demands embedded in national and state land policies,[Van Oosterom et al., 2013], [Lemmen et al., 2015]. It is a conceptual model delineating the information content of land administration, designed to be interoperable, extendable and adaptable to specific contexts [Kara et al., 2024]. During revision of ISO 19152:2012, it was decided to make the standard multiparts based on the following packages. The packages of LADM are [Kara et al., 2024], see figure 2.2:

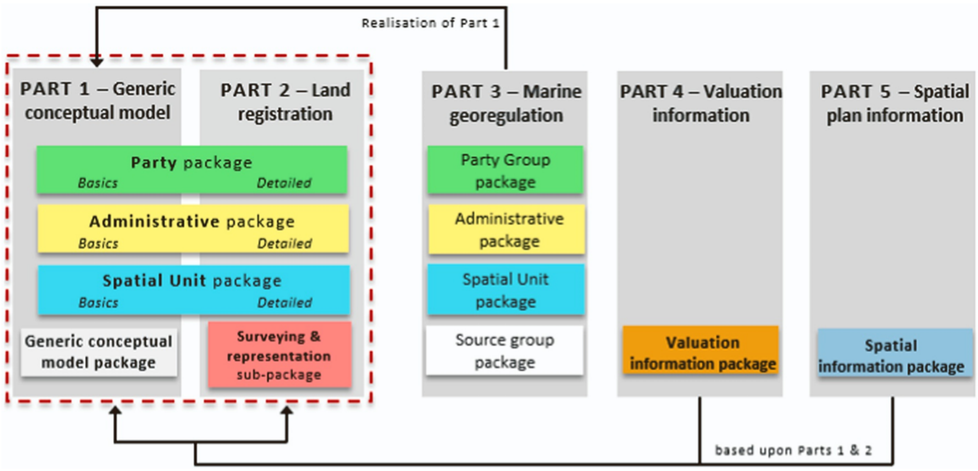


Figure 2.2: Parts and Packages of LADM II[Kara et al., 2024]

- **Party Package** - A party can be individual or organizations like companies, municipalities or a 'group party' comprises multiple parties forming a distinct entity representing legal and natural people.
- **Administrative Package** - It consists of Rights, Restrictions and Responsibilities (RRR) and basic administrative units (BAUnits).
- **Spatial Unit Package** - It can be represented as a point or line, representing a single area or multiple areas of space, defining spatial units along with their geometric and topological characteristics. It contains one subpackage, **Surveying and Representation subpackage** is included in the Part 2 allows the representation of spatial units.
- **Generic Conceptual Model** - It contains the basic requirements that form the basis for each part of Edition II.
- **Source Group Package** - It represents the inclusion and updation of data by integrating both administrative sources and spatial sources.
- **Valuation Information Package** - The Part 4, Valuation Information is organised into a single package.
- **Spatial Plan Information Package** - The Part 5 is organised into a single package based on definitions from Part 1 and 2.

The LADM is multipart, where each part constitute separate standards, with the latest edition comprising six parts. Each part will go through the full standardization process [Kara et al., 2024], See figure 2. The parts are as follows:

Part 1 - *Generic Conceptual Model* - This part provides the scope, definitions, a general overview of the model, its core classes and its individual packages and a more detailed examination.

Part 2 - *Land Registration* - This part introduces the Land Registration Standard incorporating a refined Survey and Representation package featuring various measurement techniques.

Part 3 - *Marine Space Georegulation* - This part provides the structure and concepts for standardisation of georegulation in the marine space.

Part 4 - *Valuation Information* - This part specifies the characteristics and semantics of data in valuation registries maintained by public authorities.

Part 5 - *Spatial Plan Information* - This part includes planned land use (zoning) to be converted into rights, restrictions and responsibilities (RRR).

Part 6 - *Implementations* - This part will address a range of topics needed for implementations of LADM: developing a country profile, modelling processes/ workflows, and encodings.

2.4 Materials Passports

Building as Material Banks, BAMB was part of EU's Horizon 2020 research and innovation funding programme which aims to enable a shift to a circular building sector. As a part of BAMB's objective to enable the transition to a circular building sector, the availability of structured information on materials is crucial for the shifting from the linear economy [Debacker and Manshoven, 2016]. Building materials registration plays an important role in promoting circularirty, improving the valuation of buildings, and minimizing environmental impact. Detailed records of the materials used in the buildings helps in the the identification and recycling of materials, preventing downgrading and reducing the demand for new resources [Benachio et al., 2020]. Proper documentation also allows for more more accurate building valuations by evaluating material quality, durability, and renovation costs [Copeland and Bilec, 2020]. Additionally, building materials registration supports environmental sustainability by tracking embodied energy, carbon emissions, and material toxicity, helping to reduce a building's environmental footprint[Honic et al., 2024]. Moreover, maintaining a detailed inventory of building materials ensures compliance with safety standards and supports hazard identification, improving overall building safety[Heinrich and Lang, 2019]

The MP are digital datasets capture comprehensive information on the materials and components within a building, encompassing their quality, quantity, location, and potential for reuse or recycling [Heinrich and Lang, 2019]. By exceeding the scope of traditional certifications and documentation, Materials Passports provide valuable insights for material recovery assessments, disassembly instructions, and life cycle analysis. They address aspects that are overlooked by other documents or certifications concerning the circularity of building products such as LEED (Leadership in Energy and Environmental Design) which primarily focuses on energy efficiency and environmental impact. This information supports the evaluation and certification by third

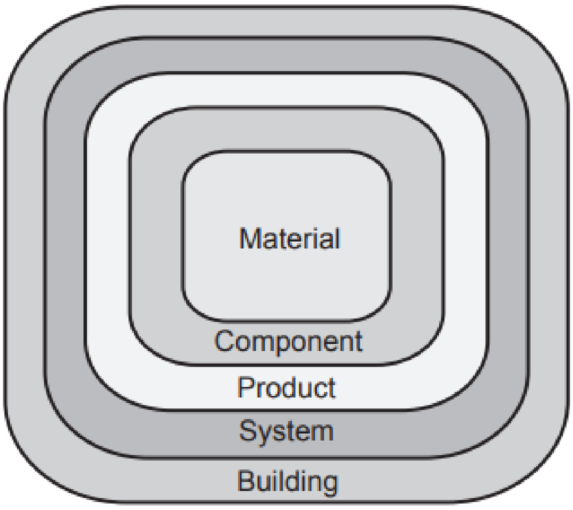


Figure 2.3: Hierarchy level in Materials Passports [Heinrich and Lang, 2019]

parties, while also enabling the inclusion of existing assessments and certifications as source documents.[Copeland and Bilec, 2020]. The Materials passports comprise multiple hierarchical levels as shown in figure 2.3, which include the level of materials, components, products and systems that make up the building [Mulhall et al., 2017]. The hierarchial levels are as follows:

- **Material** is the basic level in the hierarchy represents raw materials such as metals, wood, earth, clay, stones and substances found in products on the market, such as additives, pigments, and polymers. These materials are generic and not regarded as specific products on their own.
- **Component** represents materials that are configured for specific construction such as iron beam, glass panel, concrete beams etc
- **Product** refers to an item that is manufactured or processed for sale. It is made available in the market by an authentic producer and is defined by specific attributes, such as a commercial name, producer identification, and a serial number. A product is not an anonymous material. Examples of products are wall or floor tiles, flooring, gypsum wall panels, wall paint, windows, etc.
- **System** is a complex product made out of multiple components/parts from different manufacturers which could also be used as independent products with their individual passports. For instance, products used in mechanical, electrical, plumbing, facade, and wall systems often consist of a wide range of materials and products.
- **Building** is the highest level in the hierarchy, considers the building as a single unit.

In a building, the process begins with raw materials such as copper and aluminum. These materials are then processed and transformed into specific components, including copper tubes, filters, and boilers. These components are subsequently assembled into a complete system, HVAC (Heating, ventilation, and air conditioning) system. The HVAC system consists of the chiller, boiler, fan, ducts, and other related components, all working together to deliver heating, ventilation, and air conditioning throughout the building [Mulhall et al., 2017].

There are several ambiguities related to materials passports, particularly regarding the data format. These can include Excel spreadsheets, PDF documents, or BIM-based digital passports. Similarly, the source documents used for materials passports can be in various formats, as there is no standardization in place [BV and AB, 2017]. These issues are further explored in the section 3.2.

2.5 Madaster

Madaster is the brand name of the Madaster Foundation, which aims to ensure the availability of materials across all economic cycles. This objective is achieved by registering materials, thus facilitating their accessibility at the highest possible level. Madaster is an online Platform to create Materials passports for building. The platform contains library of materials in the built environment and links the material identity to the location and records this in a Materials Passports [Madaster, 2022]. By creating a comprehensive database of materials through materials passports, Madaster contributes to resource conservation, waste reduction, and the overall circularity of the construction sector. With detailed information on material composition, properties, and quantities readily available, Madaster empowers stakeholders(architects, builders, owner) to make informed decisions about material selection and building design. Madaster also received funding from the EU's Horizon 2020 programme. Currently Madaster operates in Netherlands, Germany, Belgium, Austria, Norway, Switzerland and UK.

To create a materials passports for a new or existing building in Madaster, accurate and comprehensive building data is essential. The more precise and complete the source document, the more reliable and detailed the generated Materials Passports will be. Madaster accepts two primary source file types, refer figure 2.4:

- **IFC files** - derived from a 3D/BIM model.
- **Madaster Excel template** - Used when a 3D/BIM model is unavailable,

While various 3D CAD applications exist, the universal IFC file format enables data exchange. For buildings without detailed 3D models, the Madaster Excel template can be used.

Once the source file is uploaded to the platform, it connects the materials and components to the Madaster database. The geometric data and quantities are directly imported from the IFC model. If any material information is absent, it can be manually added to the platform. All calculations in Madaster are based on the source file, and if the source files contain incomplete or missing information, it can impact the accuracy of the material passport. After identifying all materials, the platform utilizes algorithms to calculate the total amount of materials in the

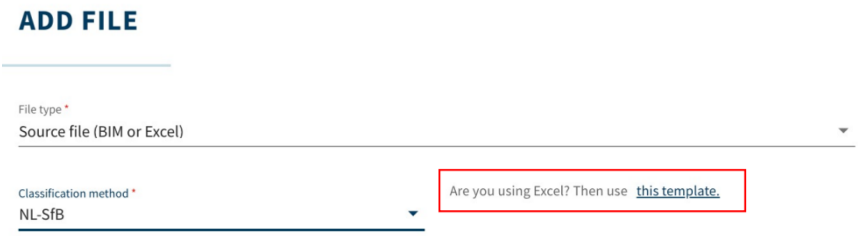


Figure 2.4: Adding source file in Madaster platform

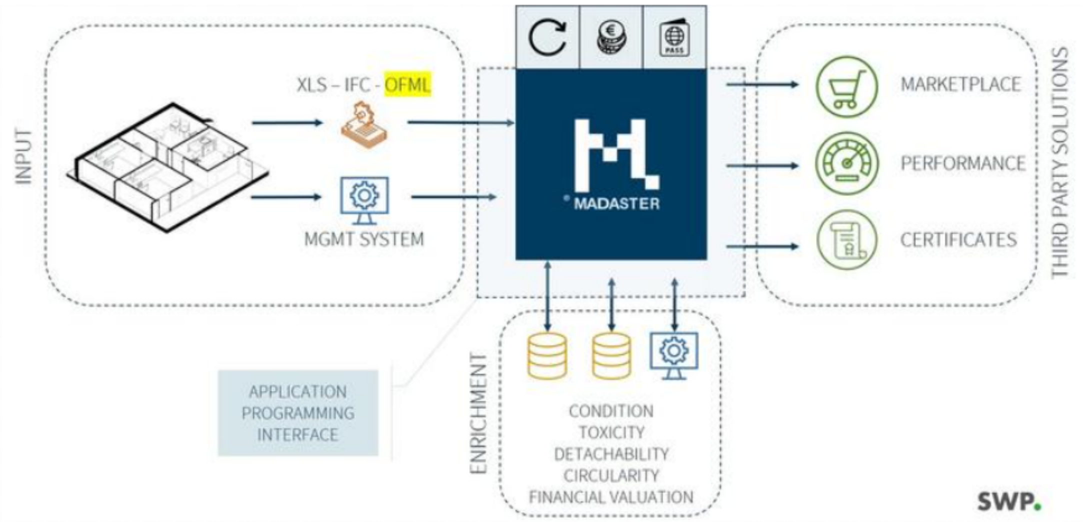


Figure 2.5: Madaster Framework [Madaster, 2022]

building and generate the materials passports. Along with creating the materials passports, the platform enhances the passport by offering insights into circularity, which is calculated through material flow analysis and component detachability. It also conducts a life cycle assessment (LCA) to evaluate the building's global warming potential (GWP) and overall environmental impact. Additionally, it assesses the financial residual value of materials. However, these calculations are based on current trends and may not be entirely accurate, refer figure 2.5.

3 Methodology

While Chapter 1 presented an overview of the research objectives and questions, this chapter aims to provide a detailed explanation of the research methodology and the rationale behind the chosen design. It begins with an overview of the methodology in section 3.1. Section 3.2 narrows down the requirements for creating the Materials Passports through the use of specific use cases, explaining why the LADM is a suitable model for this development. In section 3.3, an initial model is developed and analyzed. Based on the reflection from model 3.3, a refined model is created in section 3.4. And the model was further iterated and explained in section 3.5.

3.1 Overview

The research methods used in this thesis are outlined in Figure 3.1. Multiple methods are applied across different stages of the research. Initially, a literature review was conducted to gather foundational knowledge on relevant topics, which also helped identify gaps within the existing frameworks.

Based on these insights, a conceptual Harmonized Information Model was developed, focusing on scalability and a streamlined registration process. The development process began with a systematic identification of model requirements through use case analysis. The model was then integrated into the Land Administration Domain Model (LADM), leveraging its alignment with the model's requirements and its status as an established ISO standard. Building materials were introduced as a proposed new part within the LADM framework. An initial model was created, which was iteratively refined on the basis of expert feedback and reflection. The final model includes additional classes to enhance its representation of its hierarchical structure.

After developing the Information Model, a database was implemented using PostgreSQL and PostGIS, with SQL scripts. Each feature class was represented by its own table, and separate tables were created for each code list. Functions and triggers were added to maintain data integrity and facilitate querying within the database. Finally, the information model was validated by executing various database queries to assess its functionality and robustness.

3.2 Requirements

The Materials Passports is a generally accepted tool for documenting building materials in EU, yet it presents certain ambiguities [Honic et al., 2019b]. Key areas of uncertainty include the choice of source documents used to generate the passport and the format of the final passport itself [BV and

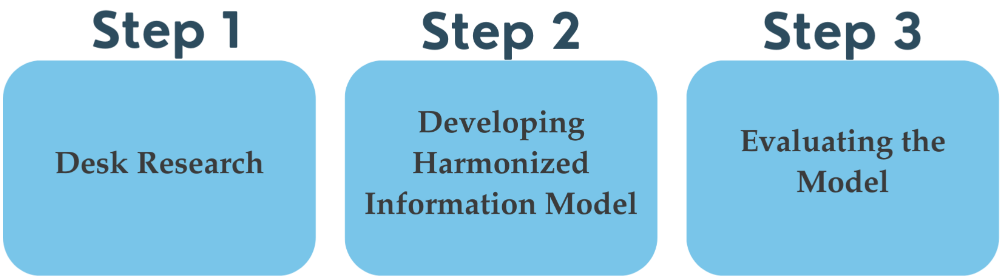


Figure 3.1: Methodology Flowchart

AB, 2017]. One primary drawback is the lack of standardization in data formats. Both the source documents used to generate the passport and the final passport itself can take various forms, such as Excel sheets, PDF documents (with or without original drawings), or BIM-based digital passports [Heinrich and Lang, 2019]. This diversity in formats creates compatibility, interoperability, and data integration challenges. When source files are in different formats, it complicates the creation and maintenance of the passport, especially when data needs to be updated or shared among stakeholders.

The absence of a unified method for collecting information across different sources for creating materials passports leads to fragmented solutions, where each organization or stakeholder develops their version [Heinrich and Lang, 2019], [Honic et al., 2024]. This lack of consistency hinders interoperability between systems, making it difficult to transfer or use data effectively across projects, industries, and regions. Without a standardized framework, the efficiency and potential of materials passports as universal tools for documentation and sustainability are significantly limited.

Another challenge is the high degree of customizability offered by materials passports [Heinrich and Lang, 2019]. While this flexibility allows them to be tailored to the specific needs of stakeholders such as architects, engineers, and property owners, it also results in inconsistencies such as varying prioritization of data. For example, an engineer's passport might focus on structural materials, while a property owner's version might prioritize legal or financial details. These tailored approaches can make it difficult to compare, aggregate, or standardize data across various contexts.

The development of an information model can address these challenges related to the ambiguity of the materials passports. The first step involves defining the core requirements, which are achieved through two use cases: one for querying materials and another for registering materials. By utilizing these use cases the requirements can be refined based on practical considerations, thereby enhancing the clarity and understanding of the necessary specifications. The use case used for the research is given in the following section 3.2.1.

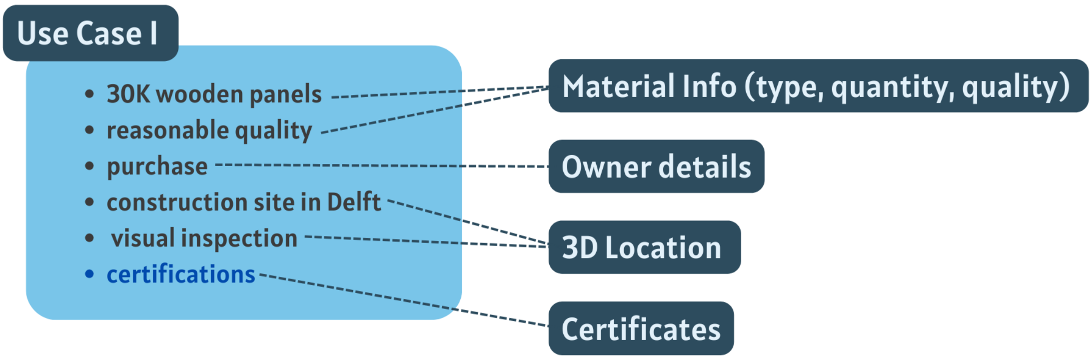


Figure 3.2: Requirements from the use case I

3.2.1 Use Cases

> ***Use Case I- A construction company is looking for 30K wooden panels of reasonable quality for a project in Delft. Before finalizing the purchase, a representative plans to conduct a visual quality inspection to ensure the panels meet their standards. Additionally, the company prefers panels with certifications for sustainability and fire resistance though these are not mandatory. The company specifically aims to source reused materials from an existing building that is about to be demolished, aligning with its commitment to circularity.***

The following keywords were extracted from the above use case: *30K wooden panels, reasonable quality, purchase, construction site in Delft, visual inspection and certifications (not mandatory)*. These keywords form the basis for the development of the requirements. For instance, **30K wooden panels** specifies the quantity and type of building materials required. The **reasonable quality** defines the standard of material quality. For **purchase** of the building materials necessitates the inclusion of details about the owner or seller of the materials. The **construction site in Delft** requires location information on the site from which the materials are sourced. The **visual inspection** requires a detailed 3D model of the site to help locate the materials. The requirements have been refined using keywords and the mapping of these requirements based on the identified keywords is illustrated in the figure 3.3.

> ***Use Case II- A building owner in Delft is constructing a new office complex and wants to register all materials used, including relevant certificates for future maintenance and for circularity aspects.***

To register all materials used in the construction, detailed information is required about each **materials**. This includes type, quantity, quality, and specific attributes such as size and weight. **Owner information** also be documented to verify that the correct person is responsible for registering the building materials and for managing the maintenance. The building's **geographic location**, along with **3D data** detailing the position of each material within the structure, is essential for linking materials to the building. **Certificates** demonstrating energy efficiency and sustainability

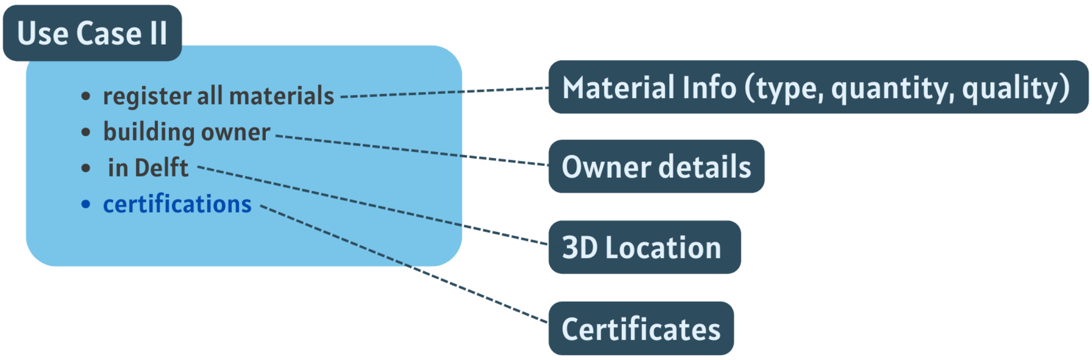


Figure 3.3: Requirements from the use case II

directly influence a building's valuation [European Commission, 2019]. Thus, the fundamental requirements for developing the information model have been identified from the use cases and an optional requirement.

From the above two use cases the main requirements for the materials passports are :

- Materials and components data requirement, provides detailed information about each material or component used in the building, including type, quantity, and quality. This data also includes information regarding the producer or supplier of the materials, ensuring traceability of the materials.
- Information about the current owner of the building prefarably with the link to the legal property documentation. This ensures transparency and traceability, making it easier to manage ownership transitions and access necessary legal information.
- Location is an important requirement, which includes both the geographical location of the building and the precise placement of materials and components within the building. The location data for materials within the building facilitates efficient retrieval and extraction. during deconstruction, minimizing the risk of damage.
- Documentation of any certification standards met by the materials, such as sustainability labels (e.g., FSC for wood), safety certifications, or environmental impacts marks suitable requirement. These certificates validate the quality and sustainability of the materials, ensuring they meet required standards for reuse or recycling.

3.2.2 Why use LADM?

Once the requirements are finalized, the next step is to develop the model. The Land Administration Domain Model (LADM) and the requirements for the model share significant overlap. Ownership details of a building can be retrieved from land administration data stored in the LA_Party package, as the ownership of the building typically includes ownership of its materials. Restrictions outlined in Part 2 address constraints related to the building, such as those associated with

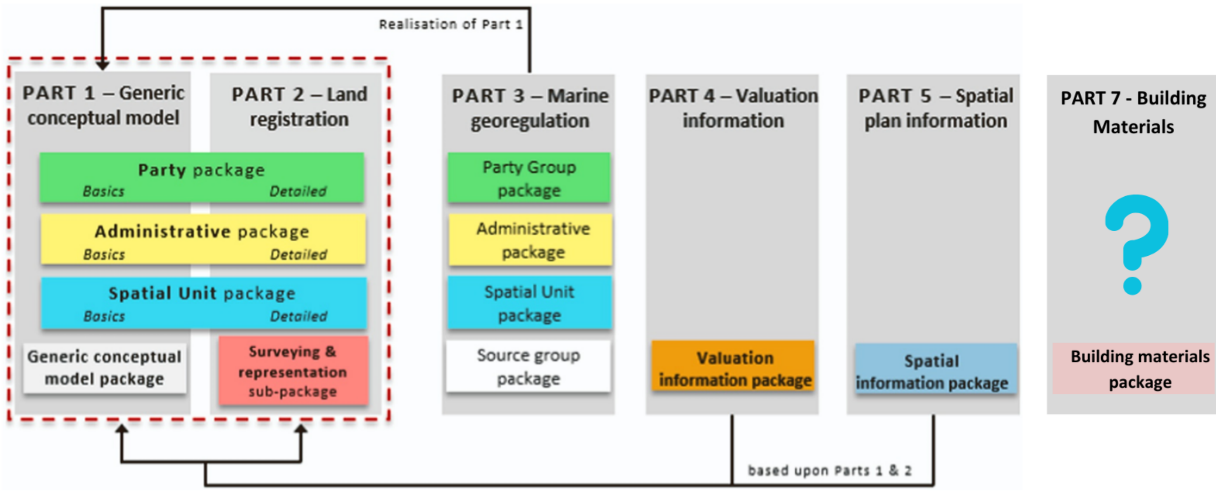


Figure 3.4: Proposed Building Material part: (ISO 19152-7) in LADM

monuments, which are also part of land administration. Part 4 on valuation is relevant for registering building materials. A detailed understanding of the materials enables precise valuation, subsequently informing decisions regarding their suitability and approval.

The LADM is a geographic based registration system that provides spatial information such as location and distance through the Spatial Unit package. The systematic registration approach used in land administration aligns well with the concept of a materials passports. This approach has two key components: registering building materials for data collection and providing searchable information about those materials.

Building materials could be introduced as a new part within the LADM framework, Figure 3.4. The primary challenge will be integrating this new component with the existing key parts of the model. The new part can be developed using the VersionedObject and LA_Source classes as they support the registration of building materials. The new building material part can be integrated into the LADM through the VM_Building class from Part 4, as shown in Figure 3.5. The VM_ValuationUnit is the smallest unit in the process of property valuation, and it is an aggregation unto itself. This can only be i) VM_SpatialUnit - a land parcel, ii) VM_Building - a land parcel with a building, and iii) VM_CondominiumUnit - a land parcel with an apartment complex, which is an aggregate of buildings. The VM_Building class registers a building in the LADM, which is a suitable class to integrate the new part. It consists of attributes of the building - area, volume, energy performance, type of heating source used, type of heating system, type of cooling system, number of floors, date of finished construction, construction material, quality of construction, etc.

The VersionedObject class is an abstract class in the LADM for the management and maintenance of historical data [ISO, BS, 2010]. It was developed because the official data changes over time based on the RRR relation to the party. History requires that both newly inserted and updated data be recorded with a timestamp. This class provides optional beginning and end lifes-

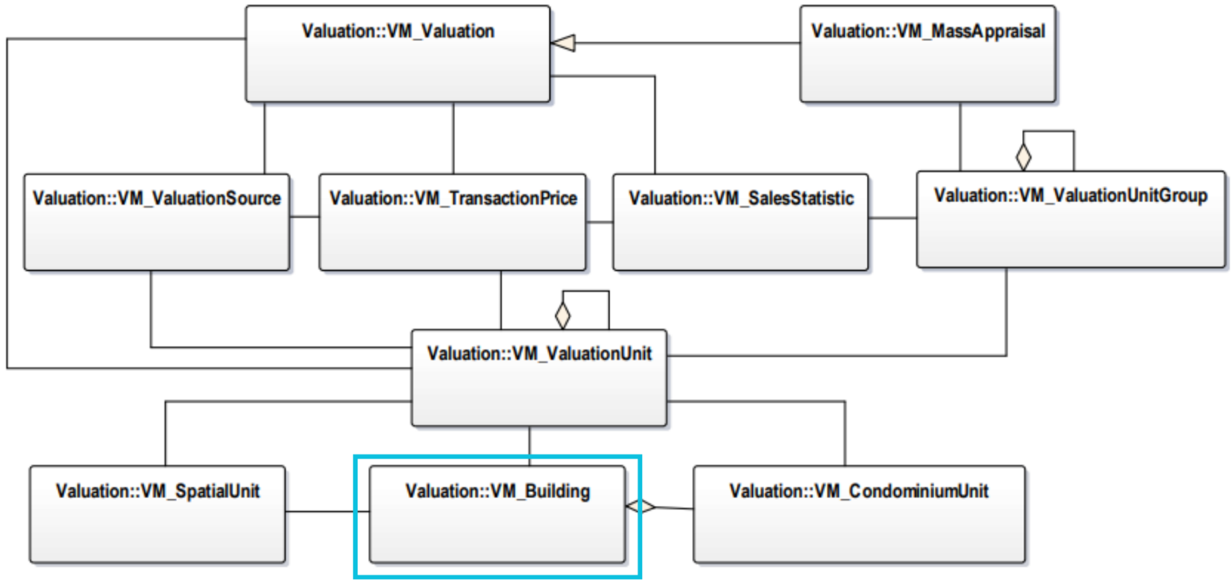


Figure 3.5: Valuation Information Part 4 of LADM

pans, along with real-world timestamps, to the inheriting classes. All LADM classes are directly or indirectly subclasses of VersionedObject, with the exception of LA_Source and its subclass LA_AdministrativeSource. In this way, the contents of the database can be reconstructed as they were at any historical moment [Kara et al., 2024].

The LA_Source class supports various types of sources and represents the events that triggers changes in the registration process. All dates and times associated with this class are recorded as system (or database) time, reflecting the moment when the event was processed and stored. The association between VersionedObject and LA_Source enables the versioning of source instances [ISO, BS, 2010] (see figure). Constraints are implemented to ensure that dates and times in VersionedObject and LA_Source correspond accurately. Both VersionedObject and LA_Source include a second set of optional temporal attributes that represent the relevant valid times in the real world [Kara et al., 2024].

3.3 Initial Model

An initial model was developed for the registration of building materials within the framework of the Land Administration Domain Model (LADM), figure 3.6. All classes in this model inherit properties from the VersionedObject class, signifying that they derive their attributes and behaviors from the parent class. The LA_Party class provides information about individuals involved, typically the owner. The LA_RRR class defines the relationship between the person and the land parcel containing the building.

The 3D location of the building is represented by the LA_SpatialUnit class. For building materials, two new classes were introduced to reflect the hierarchy: BM_ComponentLevel and BM_Material

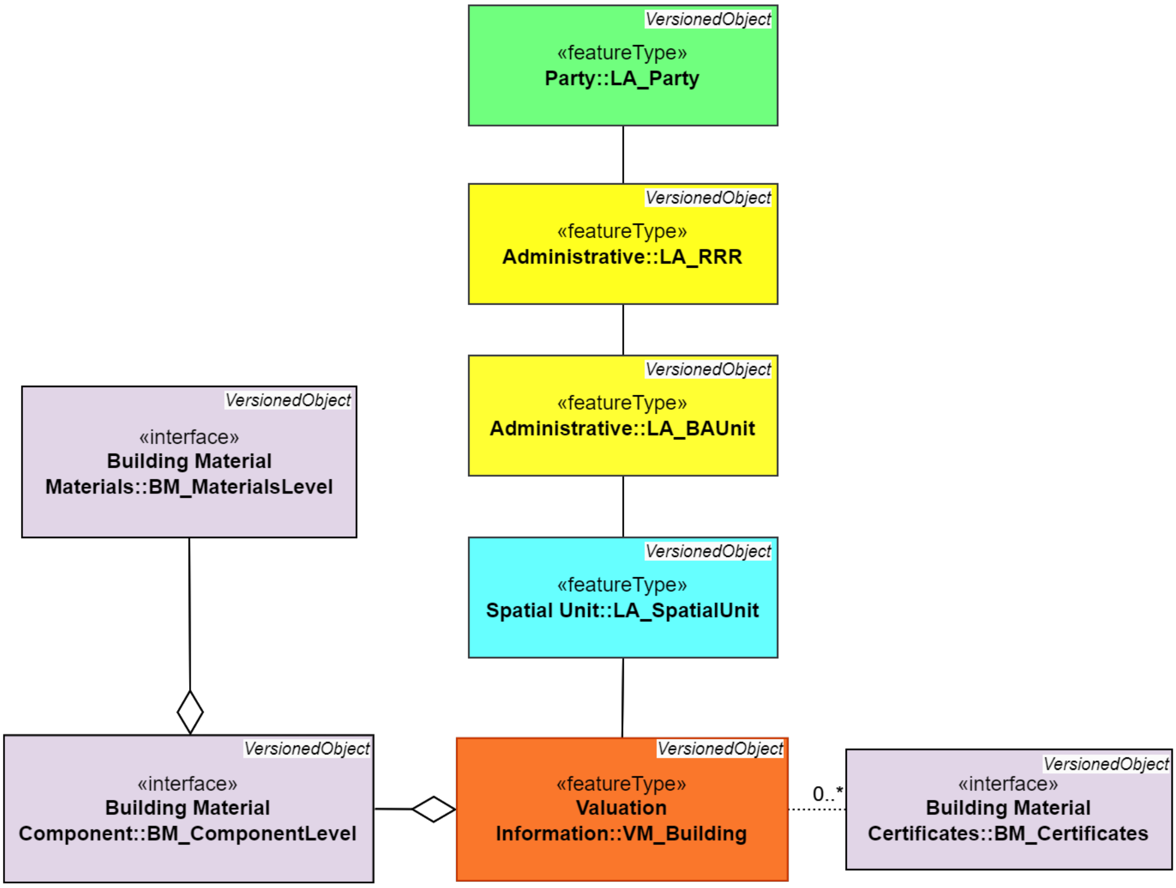


Figure 3.6: Initial Model showing the relationships between the new building classes and classes of the core LADM

Level. These classes are designed to store information about the components and materials used in the building. In aggregation relation, one class contains or is composed of instances of another class, while the parts can exist independently of the whole. For example, the VM_Building class aggregates instances of the BM_ComponentLevel class, illustrating that a building comprises various components, yet each component can exist independently of the building. Similarly, the BM_ComponentLevel class aggregates instances of the BM_MaterialLevel class, indicating that a component consists of multiple materials, which can also exist independently of the components.

The BM_Certificates class is optional for the VM_Building class. The multiplicity of this association is 0..*, implying that no certificates or multiple certificates may be associated with a building. These certificates pertain to the building as a whole, simplifying the model by excluding certificates for individual components or materials. This design choice ensures the model remains focused and avoids unnecessary complexity.

3.3.1 Reflection

The proposed model for building material registration within the LADM framework provides a solid foundation for managing hierarchical relationships between building components and materials. However, the classification of building materials is an extensive domain that spans from low-level raw materials to high-level building structures as stated in section 2.4. This classification is inherently complex, as each level possesses its own distinct properties and characteristics. While the introduction of BM_ComponentLevel and BM_MaterialLevel addresses some of this complexity, additional hierarchical levels are necessary to accommodate for various levels of details. This expansion, while beneficial for granularity, could also increase the model's complexity and needs careful consideration to balance detail with usability.

A significant concern with the proposed model is redundancy in data storage due to the interrelated nature of aggregates within the hierarchical structure. Similar properties, such as material type, quantity, or nature of waste, may recur across multiple levels, leading to inefficiencies. To mitigate this, the implementation of data normalization techniques and version control mechanisms for building materials package is recommended. These strategies would minimize redundancy while ensuring the consistency and integrity of hierarchical relationships.

The current model does not explicitly address renovations or the inclusion of additional building systems, such as fire alarm systems, CCTV, and burglary alarms. To address this limitation, the introduction of a new class for building systems linked to building materails package is proposed, enabling the representation of additional systems and their attributes. Furthermore, temporal tracking of renovations and upgrades should be incorporated to capture the dynamic state of a building over time. In addition, the model would benefit from incorporating life-cycle and maintenance data for components and materials. This includes the ability to track maintenance schedules, document historical renovations, and manage replacement cycles for building systems. Such

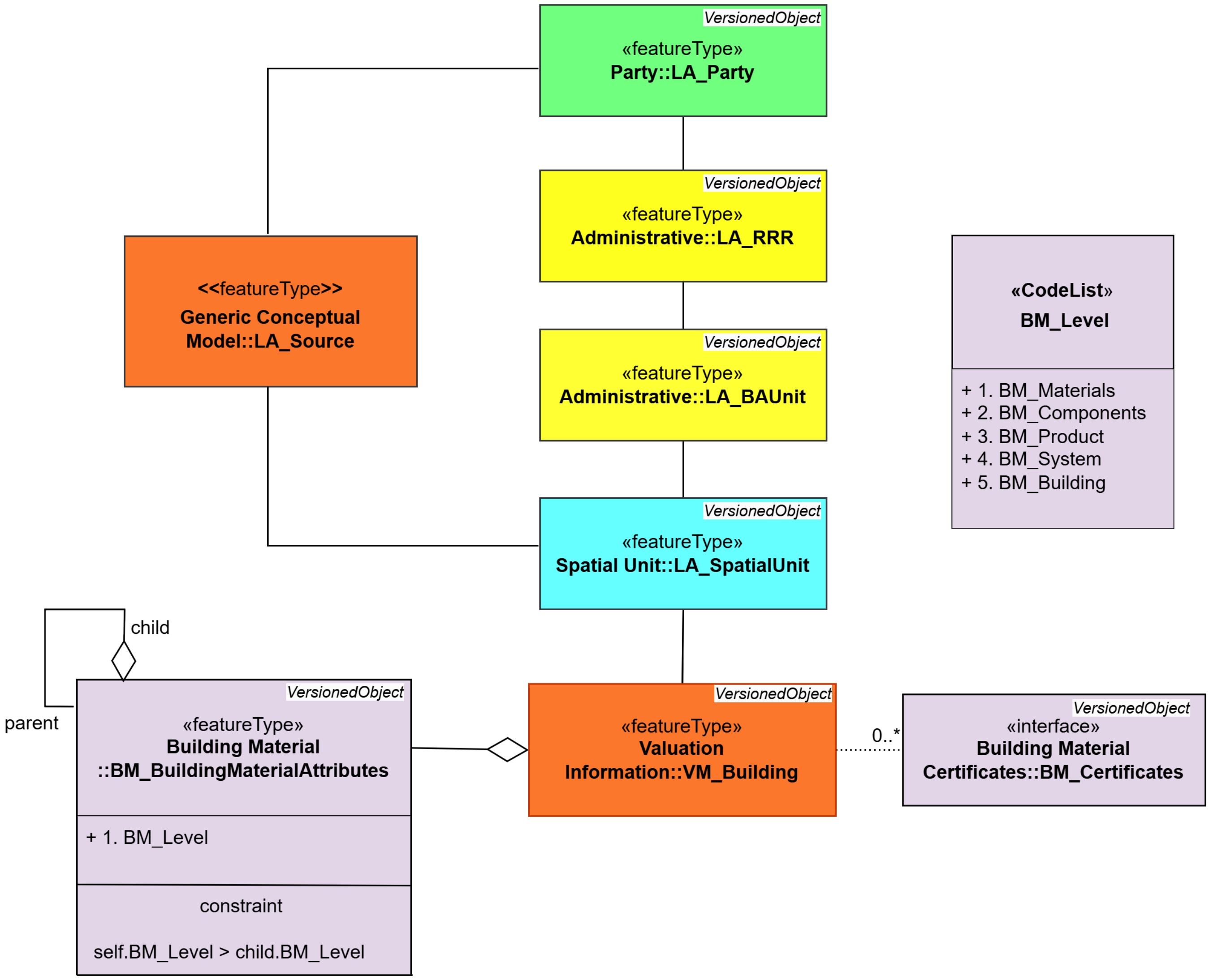


Figure 3.7: First iteration of the model showing the relationships between the new building classes and classes of the core LADM

features would provide a comprehensive view of a building's lifecycle and improve its utility for asset management. The integration of environmental sustainability metrics, such as carbon footprint, recyclability, and energy performance, would align the model with contemporary standards and regulations in sustainable construction.

3.4 Revised Model

The first iteration of the model represents a significant expansion from the initial version, transitioning from a simple structure with only two classes (BM_Materials and BM_Components) to a more detailed classification system as shown in figure 3.7. A notable addition in this iteration is the BM_BuildingMaterialAttributes, which is an early attempt at defining shared characteristics among different material elements to minimize data redundancy. The new class includes a

BM_Level code list. This new code list defines a hierarchical structure for building materials, with values such as BM_Materials, BM_Components, BM_Product, BM_System, and BM_Building, each corresponding to a distinct stage in the materials passports hierarchy as explained in section 2.4. This classification helps to accurately identify and register the materials.

Additionally, the model incorporates self-aggregates within the same class, enforcing a constraint that the BM_Level of any parent entity must always be greater than the BM_Level of its child entities, thereby maintaining the hierarchy.

3.4.1 Reflection

Using a CodeList to define hierarchy limits the model's flexibility since a codeList consists of fixed and predefined values. This rigidity can make the system less adaptable for future requirements. Enforcing a strict parent-child relationship (self.BM_Level > child.BM_Level) requires all elements to follow a fixed progression. If any materials or components do not fit neatly within this structure, it becomes difficult to accurately represent them.

The parent-child structure is designed to maintain a logical flow, ensuring that each level naturally builds upon the previous one. However, in the model it prevents skipping intermediate levels. For instance, if information is available only for materials and the system, but details about the intermediate components and product levels are missing, the model would not effectively accommodate this scenario. This constraint makes it difficult to represent cases where the hierarchy is incomplete.

Despite these shortcomings, the first iteration marks progress compared to the initial model by providing a more comprehensive classification of building materials. However, it still does not fully capture the interdependencies among the classification.

3.5 Final Model

A refined model for building material registration was developed addressing the limitations and gaps identified in the initial version, introducing several key enhancements to improve efficiency, scalability, and comprehensiveness. The updated design integrates feedback to ensure better alignment with real-world requirements and standards. Different classes are developed to represent each hierarchical level of the Materials Passports framework refer section 2.4. These classes are BM_Materials, BM_Components, BM_Product, BM_System and BM_Building. This structure organizes building materials systematically, ensuring that all the classes are classified with clear relationships. Each level of the hierarchy corresponds to a layer of material composition, enabling a more granular and organized representation of building materials. This structured approach also supports more detailed tracking of material properties across different levels.

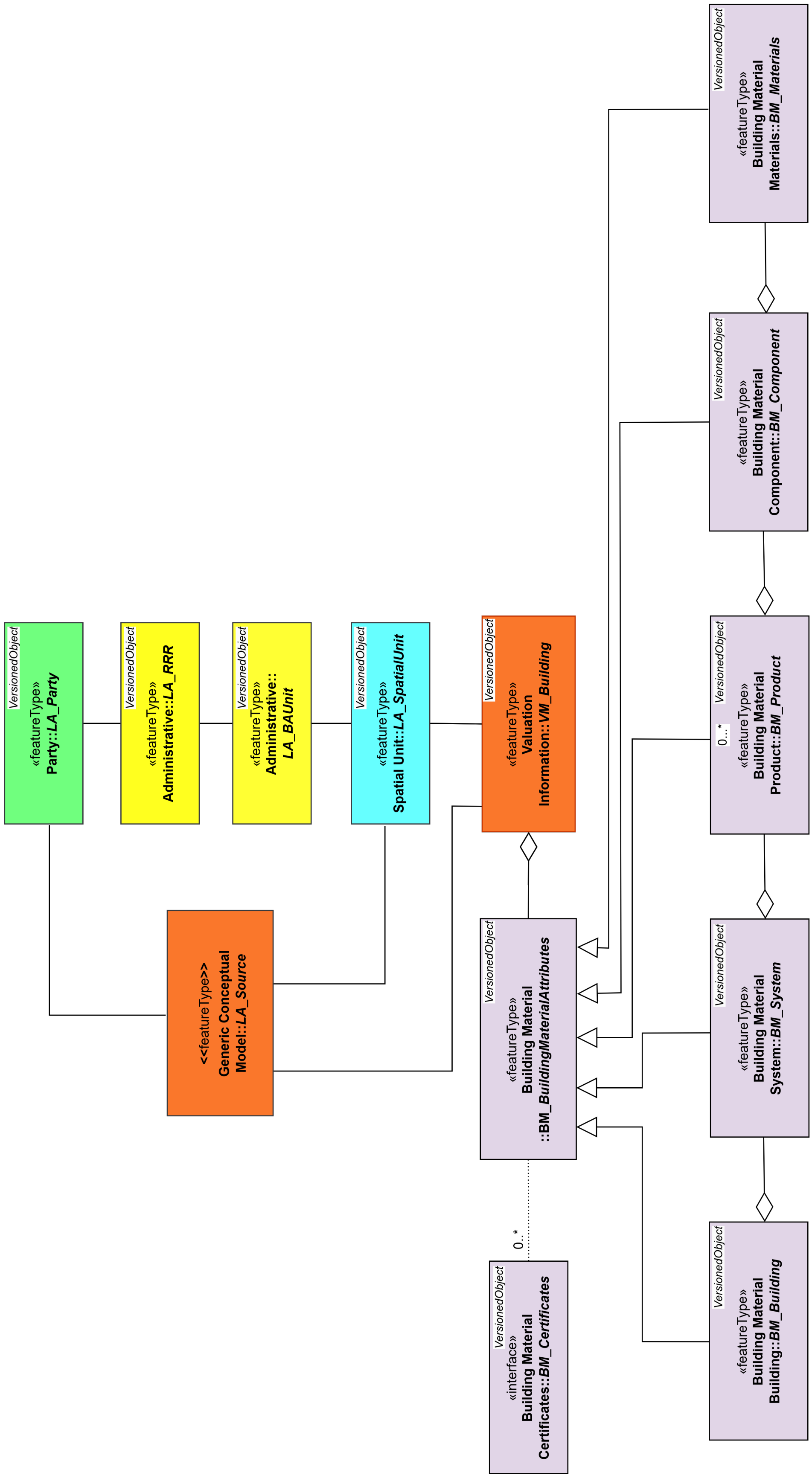


Figure 3.8: Final Model showing the relationships between the new building classes and classes of the core LADM

Higher-level classes in the model act as aggregates of lower-level classes, emphasizing the composition of materials and components. For example, systems are composed of components, and components are composed of materials. This aggregation not only simplifies the representation of complex relationships but also reinforces the idea that individual parts can exist independently of the whole. This structure ensures scalability and simplifies the addition of new elements or layers as needed.

To address the redundancy observed in the initial model, a new superclass BM_Building MaterialAttributes, has been introduced to centralize attributes shared across all classes. All the classes of the building material package inherit the attributes from the superclass except from BM_Certificates class, as shown in Figure 3.8. This superclass contains shared attributes such as the general properties, the dimensional attributes, and also the technical and the life cycle properties shown in Figure 3.9. By centralizing these attributes, the model eliminates redundancy and ensures consistency across different hierarchical levels. This approach also simplifies data updates, as changes to shared attributes need to be made only once in the superclass, rather than across multiple classes.

While most classes share unified attributes, the BM_System class introduces specialized attributes to represent the structural or functional systems of the building. These functionalities can range from plumbing to fire and safety. To represent this an additional attribute constructionMethods is added to the BM_System class. The renovations like fire alarms, CCTV and Burglary alarm system are all part of the BM_System class.

3.5.1 Super Class BM_BuildingMaterialAttributes

The class BM_BuildingMaterialAttributes is introduced as a superclass for the new building material part. The VM_Building class will aggregate instances of the BM_BuildingMaterialAttributes class. The attributes of BM_BuildingMaterialAttributes are shown in Table 3.1. Most of the attributes are based on the excel template from the madaster platform. GTIN is the Global Trade Item Number which is a unique string of characters for the identification of individual products and product packages [Heinrich and Lang, 2019] [ISO/IEC, 2014].

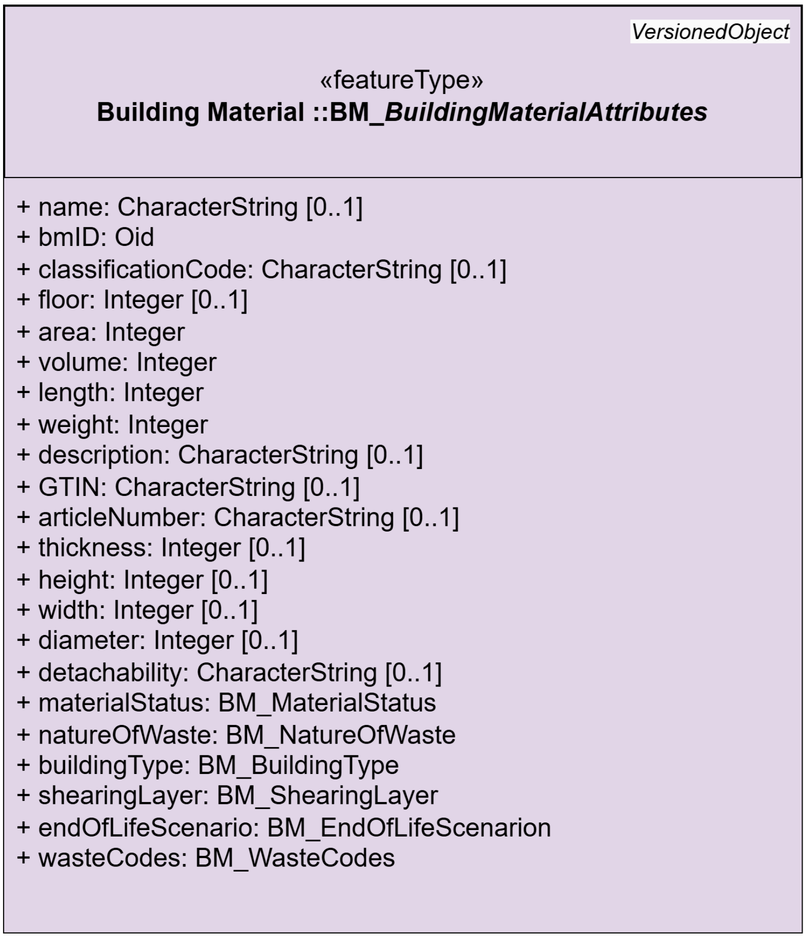


Figure 3.9: Building Material:: BM_BuildingMaterialAttributes

Attribute Name	Type	Cardinality	Description
name	CharacterString	0..1	The name of the object.
bmID	Oid	1	The unique building material identifier.
classificationCode	CharacterString	0..1	The classification code
floor	Integer	0..1	The floors on which the building material is located
area	Integer	0..*	The area of the building material
volume	Integer	0..*	The volume of the building material
length	Integer	1..*	The length of the building material
weight	Integer	1..*	The weight of the building material
description	CharacterString	0..1	The description of the building material
GTIN	CharacterString	0..1	The Global Trade Item Number
articleNumber	CharacterString	0..1	The Manufacturer's article number
thickness	Integer	0..1	The thickness of the building material
height	Integer	0..1	The height of the building material
width	Integer	0..1	The width of the building material
diameter	Integer	0..1	The diameter of the building material
detachability	CharacterString	0..1	The type of detachability
materialStatus	BM_MaterialStatus	0..1	The status of the material used
natureOfWaste	BM_NatureOfWaste	0..*	The nature of waste
shearingLayer	BM_ShearingLayer	1	The shearing layer on which the building material is located
endOfLifeScenario	BM_EndOfLifeScenarion	1..1	The end of life scenario of the building materials
wasteCodes	BM_WasteCodes	0..1	The type of waste code

Table 3.1: Attributes of BM_BuildingMaterialAttributes

3.5.2 BM_Certificates

The building certificates are relevant as it is a tool or rating system to assess the buildings performance. Most certificates address key issues such as energy efficiency, water conservation, and waste management while new issues like the health and well-being of the building's occupants are also addressed. Transparency and traceability are central to the effectiveness of such certifications. As emphasized by the EU regulation on establishing a Union registry for permanent carbon removals, carbon farming, and carbon storage in products [European Parliament and Council of the European Union, 2024], ensuring full traceability of certified units and avoiding fraud or double counting are essential principles. By integrating these principles into building certification frameworks, the model can support robust data integrity and compliance.

With the EU Green Deal targeting carbon neutrality by 2050 [European Commission, 2019], obtaining building certifications will likely become mandatory. These certifications are highly beneficial, significantly influencing buildings valuation. It consists of three attributes *name*, *description* and *url* link to the issuing organisation. The attribute *name* is type characterString it is the name of the certificate. The attribute *description* is also CharacterString type which describes the certificate refer Figure 3.10.

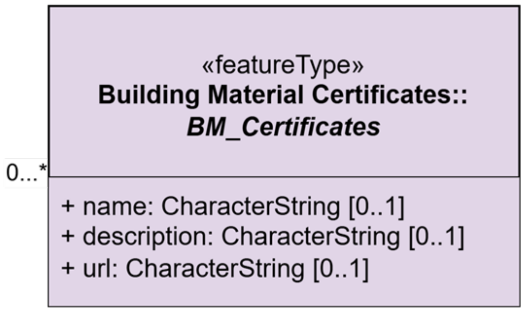


Figure 3.10: Building Material Certificates:: BM_Certificates

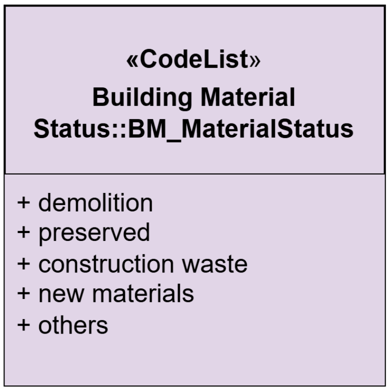


Figure 3.11: Codelist for BM_MaterialStatus

3.5.3 Codelist

A CodeList is a predefined, controlled vocabulary that provides a standardized set of values for specific attributes within a model. It is extensible with new values, and the proposed CodeList values are sourced from Madaster.

1. BM_MaterialStatus

This codelist categorizes the building materials based on their current status. The values are *demolition, preserved, construction waste, new materials* and *others* refer figure 3.11. Demolition is the materials from the deconstruction of buildings. The materials preserved from the original building and used in their original form without any degradation are considered preserved. Construction waste is the solid waste generated during the construction or remodeling of buildings. New materials are freshly manufactured materials. The others include all the materials that do not fall into the categories mentioned above. This provides a structure to track and manage materials during deconstruction and deconstruction of projects.

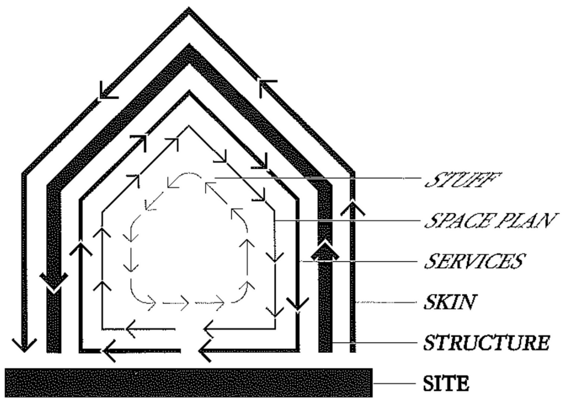


Figure 3.12: Shearing layers of building [Brand, 1995]

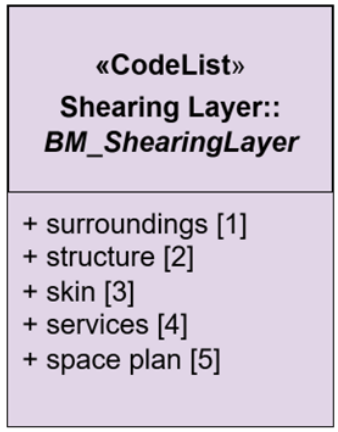


Figure 3.13: Codelist for BM_ShearingLayer

2. BM_ShearingLayer

Buildings are layered by different rates of change due to the different components and these layers are called shearing layers. According to [Brand, 1995] there are six layers, refer figure 3.12. *Surroundings* is the geographical setting, the urban location, and the legally defined lot, on which a building is situated. The boundaries and context of the surroundings often remain unchanged for generations, persisting beyond the lifespan of individual buildings this refers to the boundaries in the BAUnit and SpatialUnit of the LADM. *Structure* is the foundation and load-bearing components of the building, such as beams and columns. Due to their complexity, importance and high cost these elements are usually unaltered. *Skin* is the exterior surfaces of the building, including the facades and windows. It is the visual identity of the building hence this layer is subjected to periodic updates to keep up with new aesthetics. *Services* are the layer responsible for the functioning of the building which includes wiring, and plumbing. *Space Plan* is the interior layout of the building which includes walls, doors and floors. These five elements compose of the values of this codelist. This provides insights on managing and understanding the buildings lifecycle. Figure 3.13 shows the values of the codelist.

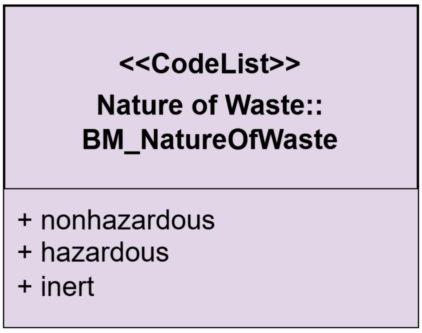


Figure 3.14: Codelist for BM_NatureOfWaste

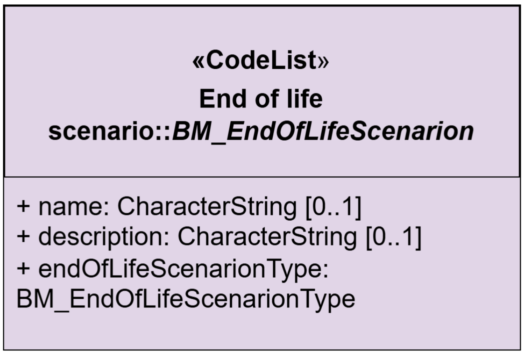


Figure 3.15: Codelist for BM EndOfLifeScenarion

3. BM_NatureOfWaste

Based on the environmental and the health impacts the nature of waste is categorized into *non-hazardous, hazardous and inert* [European Parliament and Council of the European Union, 2008] as shown in figure 3.14. Nonhazardous waste refers to waste materials with minimal risk to health and the environment, such as wood and non-toxic materials. Hazardous wastes are those that contain harmful substances such as asbestos, and chemical wastes. It requires special processing to prevent contamination. In contrast, inert waste consists of materials that are chemically and physically stable, which is no threat to the environment like stones. This helps with the proper identification and handling of wastes produced.

4. BM_EndOfLifeScenarion

This codelist contains three attributes refer figure 3.15. The name provides an identifier label. The description gives the detailed description of the end of life scenario materials. The BM_EndOfLife ScenarionType specifies the type from a predefined codelist.

5. BM_EndOfLifeScenarionType

The codelist provides a range of end of life scenario for the building materials, refer 3.16. It enables better management of the materials after their life. It categorizes various methods based on how the building materials are handled once they reach the end of their usefulness.

6. BM_WasteCodes

This codelist contains three attributes. The name provides an identifier label. The description gives the detailed description of the waste codes. The wasteCodesType specifies the type from a predefined codelist.

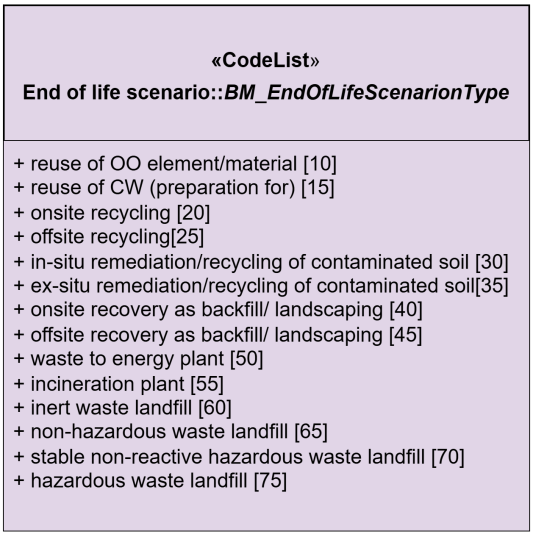


Figure 3.16: Codelist for BM_EndOfLife ScenarionType

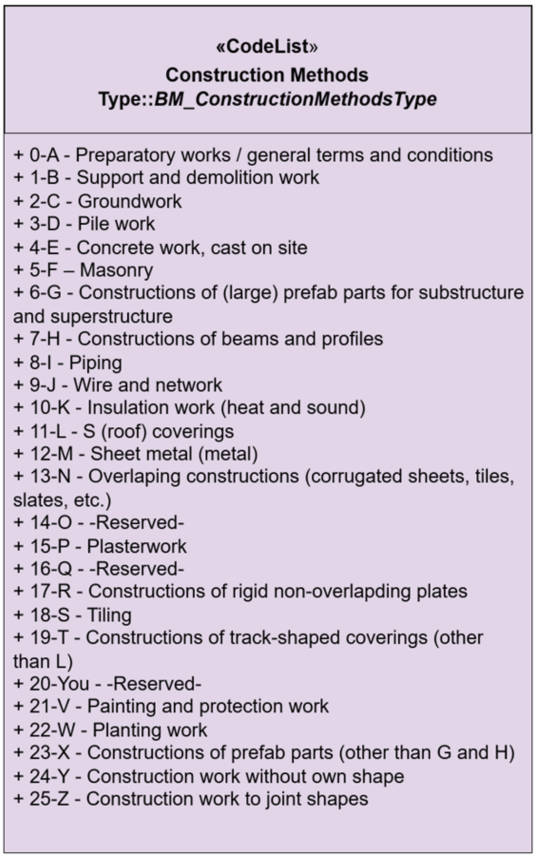


Figure 3.17: Codelist for BM_ConstructionMethodsType

7. BM_WasteCodesType

It defines the various wastes mainly generated from construction, demolition, and electrical equipment. Each value contains specific waste codes that identify materials as shown in 3.18. Due to a lack of standards this codelist is developed with reference to the European Waste Code [European Commission, 2000]. This can be modified in the future.

8. BM_ConstructionMethods

This is a codelist specifically for the BM_System. This contains three attributes. The name provides an identifier label. The description gives a detailed description of the construction methods. The constructionMethodType specifies the type from a predefined codelist BM_ConstructionMethods Type.

«CodeList»
Waste codes::*BM_WasteCodesType*

+ wastes from electrical and electronic equipment [16 02]
+ transformers and capacitors containing PCBs [16 02 09*]
+ discarded equipment with PCBs other than those in 16 02 09 [16 02 10*]
+ discarded equipment containing chlorofluorocarbons, HCFC, HFC [16 02 11*]
+ discarded equipment containing free asbestos [16 02 12*]
+ discarded equip. with haz. components other than 16 02 09 to 16 02 12 [16 02 13*]
+ discarded equipment other than those mentioned in 16 02 09 to 16 02 13 [16 02 14]
+ hazardous components removed from discarded equipment [16 02 15*]
+ components removed from discarded equip. other than those in 16 02 15 [16 02 16]
+ concrete, bricks, tiles and ceramics [17 01]
+ concrete [17 01 01]
+ bricks [17 01 02]
+ tiles and ceramics [17 01 03]
+ mix. or separate fractions of concrete, brick, tile&ceramic cont. dang. Subs [17 01 06*]
+ mix of conc., brick, tile&ceramic other than those mentioned in 17 01 06 [17 01 07]
+ wood, glass and plastic [17 02]
+ wood [17 02 01]
+ glass [17 02 02]
+ plastic [17 02 03]
+ glass, plastic & wood containing or contaminated with dang. Substances [17 02 04*]
+ bituminous mixtures, coal tar and tarred products [17 03]
+ bituminous mixtures containing coal tar [17 03 01*]
+ bituminous mixtures other than those mentioned in 17 03 01 [17 03 02]
+ coal tar and tarred products [17 03 03*]
+ metals (including their alloys) [17 04]
+ copper, bronze, brass [17 04 01]
+ aluminium [17 04 02]
+ lead [17 04 03]
+ zinc [17 04 04]
+ iron and steel [17 04 05]
+ tin [17 04 06]
+ mixed metals [17 04 07]
+ metal waste contaminated with dangerous substances [17 04 09*]
+ cables containing oil, coal tar and other dangerous substances [17 04 10*]
+ cables other than those mentioned in 17 04 10 [17 04 11]
+ soil (incl. exc. soil from cont. sites), stones&dredgings [17 05]
+ soil and stones containing hazardous substances [17 05 03*]
+ soil and stones other than those mentioned in 17 05 03 [17 05 04]
+ dredging spoil containing hazardous substances [17 05 05*]
+ dredging spoil other than those mentioned in 17 05 05 [17 05 06]
+ track ballast containing hazardous substances [17 05 07*]
+ track ballast other than those mentioned in 17 05 07 [17 05 08]
+ insulation materials and asbestos cont. const. materials [17 06]
+ insulation materials containing asbestos [17 06 01*]
+ other insulation materials consisting of/containing dangerous substances [17 06 01*]
+ insulation materials other than those mentioned in 17 06 01 and 17 06 02 [17 06 04]
+ construction materials containing asbestos [17 06 05*]
+ gypsum-based construction material [17 08]
+ gypsum-based const. materials contaminated with dangerous substances [17 08 01*]
+ gypsum-based const. materials other than those mentioned in 17 06 01 [17 08 02]
+ other construction and demolition wastes [17 09]
+ CDW containing mercury [17 09 01*]
+ CDW cont. PCB (e.g sealants, resin-based flooring, sealed glazing units or capacitors) [17 09 02*]
+ other CDW (including mixed wastes) containing dangerous substances [17 09 03*]
+ mixed CDW other than those mentioned in 17 09 01, 17 09 02 & 17 09 03 [17 09 04]
+ separately collected fractions [20 01]
+ fluorescent tubes and other mercury containing waste [20 01 21*]
+ discarded equipment containing chlorofluorocarbons [20 01 23*]
+ discarded EEE other than those in 20 01 21 & 20 01 23 cont. Haz components [20 01 35*]
+ discarded EEE other than those in 20 01 21, 20 01 23 & 20 01 36 [20 01 36]

Figure 3.18: Codelist for BM_WasteCodesType

9. BM_ConstructionMethodsType

This code list outlines various construction methods based on the Netherlands' NL/SfB materials classification system. The NL/SfB classification is referenced as a preliminary model to demonstrate its relevance, but it can later be adapted to align with international standards. The code list categorizes different systems according to their functionality, such as piping and tiling, refer figure 3.17.

4 Evaluation

In the previous chapter 3, a conceptual harmonized information model was developed. This chapter presents the evaluation of the model through the development of a database for the building material registration in section 4.1 and testing the database in section 4.2. Section 4.3 provides the overview of the workshop conducted with the stakeholders.

4.1 Developing the Database

For the development of the database, PostgreSQL and PostGIS tools were selected. Although Enterprise Architect offers built-in functionality for generating SQL tables from UML diagrams, PostgreSQL was chosen because new classes were introduced that are not supported by Enterprise Architect's table generation features. As a result, it was deemed more effective to utilize PostgreSQL for this purpose. The SQL code corresponding to the UML model was created manually to accommodate the specific requirements of the newly introduced classes.

4.1.1 Data Type

The table 4.1 outlines the data types used in the database. The most commonly used data type is 'characterstring', which accommodates both text and numerical values. This is represented as either 'TEXT' or 'VARCHAR' in the database. For example, it is employed for attributes like 'description' and 'name', which predominantly store text, and for attributes like 'GTIN', which may contain numerical data. The 'BOOLEAN' data type is used for attributes such as 'shareCheck' in the 'LA_RRR' class, consistent with its representation in both LADM and the database. Similarly, 'geometry' is used for spatial attributes in the 'LA_SpatialUnit' class, maintaining alignment between LADM and the database. The 'integer' data type is also utilized as needed. The 'dateTime' type in the 'LA_Source' class is represented as 'TIMESTAMPTZ' in the database, ensuring compatibility for timestamped data with timezone information.

LADM Data Type	Database Data Type
CharacterString	TEXT, VARCHAR
Boolean	BOOLEAN
Geometry	GEOMETRY
Integer	INTEGER
DateTime	TIMESTAMPTZ

Table 4.1: LADM Data and Database Data

The Land Administration Domain Model (LADM) includes 'Oid' and 'Fraction' attributes, but these were not utilized when creating the database. Instead, a sequence was implemented as a unique identifier, incrementing by 1 to ensure all values remain distinct.

4.1.2 Class/Codelist to table

All codelists and classes are represented as separate tables. The mapping between UML concepts and SQL structures is outlined in the table 4.2. The class or codelist name in UML corresponds to the name of the SQL table. Similarly, attribute names in UML are directly translated into column names in the SQL table. The attribute type determines the data type of the respective column. If an attribute has a multiplicity of 1, it indicates that null values are not allowed, which is enforced in SQL by adding the constraint 'NOT NULL'.

UML	SQL
Class/Codelist name	Table name
Attribute name	Column name
Attribute type	Data type
Multiplicity: 1	Not Null (Constraint)

Table 4.2: Mapping between UML and SQL concepts

Codelist

For creating the codelist tables, first a sequence is created, for example, for codelist BM_Material status_ID, a sequence BM_Materialstatus_ID_seq is created to generate unique numeric values, starting at 1 and incrementing by 1 for each new entry, without any minimum or maximum value constraints. Then the the codelist table BM_Materialstatus is created with two columns: BM_Materialstatus_ID and type. The BM_Materialstatus_ID is an integer column that doesn't have a null value and is automatically populated using the sequence. It serves as the primary key as shown in figure 4.1. The type is a text column storing descriptions of material statuses. Once the table is created it is populated with values, refer figure 4.2.

When creating the table, constraints are defined directly. For example, in the code above, two constraints are applied: the 'ID' column is set to 'NOT NULL', ensuring it cannot have null values, and it is also designated as the primary key. Defining the primary key during table creation, rather than adding it later, ensures more efficient operation and better performance.

Class

The BM_BuildingMaterialAttributes is the superclass of the new building material part. It stores detailed information about building materials, including their physical properties, classifications, and associated metadata. The table includes a primary key, BM_BuildingMaterialAttributes_ID,

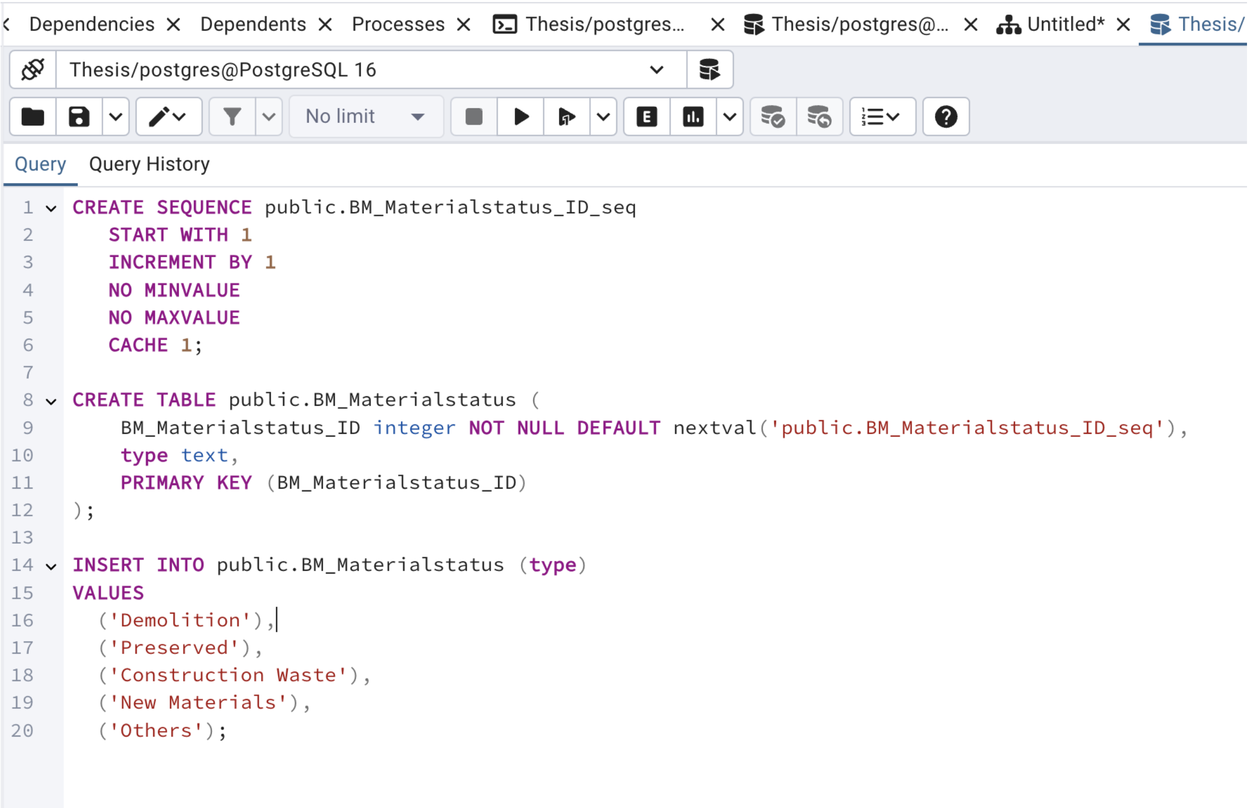
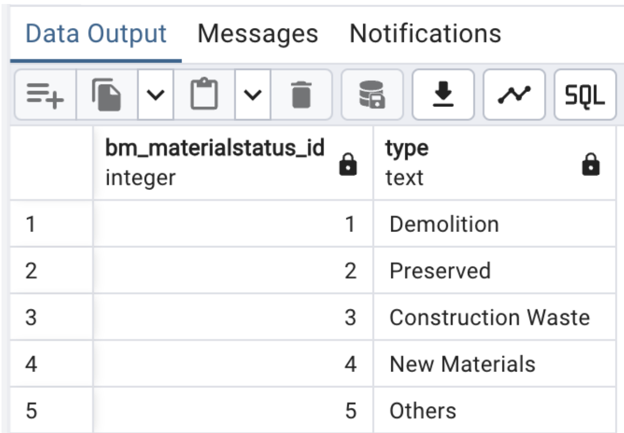


Figure 4.1: BM_MaterialStatus



	bm_materialstatus_id integer	type text
1	1	Demolition
2	2	Preserved
3	3	Construction Waste
4	4	New Materials
5	5	Others

Figure 4.2: BM_MaterialStatus codelist values

Query Query History

```
);

-- Create BM_BuildingMaterialAttributes table with corrected foreign key reference
CREATE TABLE public.BM_BuildingMaterialAttributes (
    BM_BuildingMaterialAttributes_ID integer NOT NULL DEFAULT nextval('public.BM_BuildingMaterialAttributes_ID_seq'),
    name text,
    classificationCode text,
    floor integer,
    area integer,
    volume integer,
    length integer,
    weight integer,
    description text,
    GTIN varchar(255),
    articleNumber text,
    thickness integer,
    height integer,
    width integer,
    diameter integer,
    detachability text,
    materialStatus_ID integer, -- References BM_MaterialStatus
    natureOfWaste_ID integer, -- References BM_NatureOfWaste
    buildingType_ID integer, -- References BM_BuildingType
    shearingLayer_ID integer, -- References BM_ShearingLayer
    endOfLifeScenario_ID integer, -- References BM_EndOfLifeScenarion
    wasteCodes_ID integer, -- References BM_WasteCodes
    PRIMARY KEY (BM_BuildingMaterialAttributes_ID),
    FOREIGN KEY (materialStatus_ID) REFERENCES public.BM_MaterialStatus(BM_MaterialStatus_ID),
    FOREIGN KEY (natureOfWaste_ID) REFERENCES public.BM_NatureOfWaste(BM_NatureOfWaste_ID),
    FOREIGN KEY (buildingType_ID) REFERENCES public.BM_BuildingType(BM_BuildingType_ID),
    FOREIGN KEY (shearingLayer_ID) REFERENCES public.BM_ShearingLayer(BM_ShearingLayer_ID),
    FOREIGN KEY (endOfLifeScenario_ID) REFERENCES public.BM_EndOfLifeScenarion(BM_EndOfLifeScenarion_ID), -- Correct foreign k
    FOREIGN KEY (wasteCodes_ID) REFERENCES public.BM_WasteCodes(BM_WasteCodes_ID)
);
```

Figure 4.3: BM_BuildingMaterialAttributes

which uniquely identifies each record and is automatically populated using a sequence. The table also contains foreign key columns which establishes the association with other tables. For example, the column materialStatus_ID column references to the BM_MaterialStatus table. These relationships maintain data integrity and establish meaningful connections between this table and other tables in the database.

The BM_Materials table is used to store materials information. The table has two columns: BM _Materials_ID and BM_BuildingMaterialAttributes_ID. The BM_Materials_ID column is an integer that serves as the primary key for the table, uniquely identifying each record. The BM_Building MaterialAttributes_ID column is an integer that acts as a foreign key, linking each material to an entry in the BM_Building Material Attributes table. This foreign key relationship ensures that every material inherits specific attributes, such as classification and physical properties, from the BM_BuildingMaterial Attributes table. By using the primary and foreign key constraints the table maintains data integrity, ensuring that each material is properly associated with its corresponding attributes. All the other classes also follows the same as the BM_Materials.

4.1.3 Relation between tables

The tables are structured in a way that reflects their relationships, primarily through inheritance and association. The relationships are defined using foreign keys that link attributes from one table to another, thereby enabling the use of consistent data throughout the schema.

Inheritance

Inheritance allows objects to inherit properties from a parent class. The BM_BuildingMaterial Attributes table serves as the central repository for material data with other tables like BM_Materials, BM_ Components, BM_Product, BM_System and BM_building inheriting these attributes through foreign key associations. Each of these tables represents a specific aspect of a building material, such as its materials, component, product, system, or building-level application, while maintaining consistency through shared attributes in the BM_BuildingMaterial Attributes table.

For example, the BM_Materials table is related to BM_BuildingMaterialAttributes through the following foreign key:

FOREIGN KEY (BM_BuildingMaterialAttributes_ID) REFERENCES public.BM_Building MaterialAttributes(BM_ BuildingMaterialAttributes_ID)

FOREIGN KEY(BM_BuildingMaterialAttributes_ID) defines a foreign key constraint on the column BM_BuildingMaterialAttributes_ID. *REFERENCES public.BM_BuildingMaterialAttributes(BM_ BuildingMaterialAttributes_ID)* this part specifies the referenced table and referenced column. This foreign key ensures that the materials listed in the BM_Materials table will share all the attributes of a material stored in BM_BuildingMaterialAttributes, ensuring consistent data across related entities.

Aggregation

For the hierarchical relationship aggregation relation is suitable. In which the higher class is the aggregation of the lower class. Aggregation is represented by foreign key references where each higher-level class contains references (foreign keys) to lower-level classes, showing that they are composed of or depend on the latter. Below is an example of aggregation of material on components.

FOREIGN KEY (BM_Materials_ID) REFERENCES public.BM_Materials(BM_Materials_ID)

Here *FOREIGN KEY (BM_Materials_ID)* defines the foreign key reference on the BM_Materials_ID column. *REFERENCES public.BM_Materials(BM_Materials_ID)* represents the the referenced table and column. This means that each record in the BM_Component table (which represents a component in the product) can aggregate or be associated with one or more materials in the BM_Materials table.

Association

The association is the relationship between two or more tables that are linked together based on certain attributes or keys. It is linked through foreign key reference. In the database, BM_Building MaterialAttributes has several associations with other metadata tables like BM_MaterialStatus, BM_NatureOfWaste, BM_BuildingType, and BM_ShearingLayer. For the BM_BuildingMaterial Attributes table is linked to the BM_MaterialStatus table using a foreign key

FOREIGN KEY (materialStatus_ID) REFERENCES public.BM_MaterialStatus(BM_Material Status_ID)

4.2 Testing the Database

The datasets utilized for testing the database was provided by **Campus Real Estate & Facility Management (CREFM)** of TU Delft. Two functional buildings from the campus were selected to conduct the analysis. To evaluate the adaptability and robustness of the proposed information model, one older building and one relatively newer building were chosen. This selection aimed to assess how the model performs under varying levels of data availability.

For the older building, the available building material data is incomplete, as comprehensive records of the original building materials are not available due to the building's age. The existing information is primarily limited to maintenance records and data on renovations, which provide only a partial view of the building's material composition. This limitation offers an opportunity to examine the model's ability to operate effectively despite the incomplete input data availability of the building materials known and the effects of it on the building material registration.

4.2.1 Building 45

Building 45 was constructed in 1952, it is located within the campus on Leeghwaterstraat is shown in figure 4.4. The building was built at 1952. For this building, parcel number and kadastral map is available and is shown in figure 4.5. Due to the building's age, no spatial data exists. Instead, the available documentation comprises the original architectural drawings and an Excel file cataloging all renovated and replaced materials.

The Excel file follows the NL/SfB classification system, the Dutch adaptation of the international SfB standard, which is widely employed in the construction industry. This classification system is structured into five tables:

- Table 0 - Spatial Facilities: This table provides codes for defining the spaces to be created within a building.
- Table 1 - Functional Building Elements: This table contains codes representing the functional components of the building facility.
- Table 2 - Construction Methods: This table includes codes specifying the construction methods to be employed.

Figure 4.4: Building 45

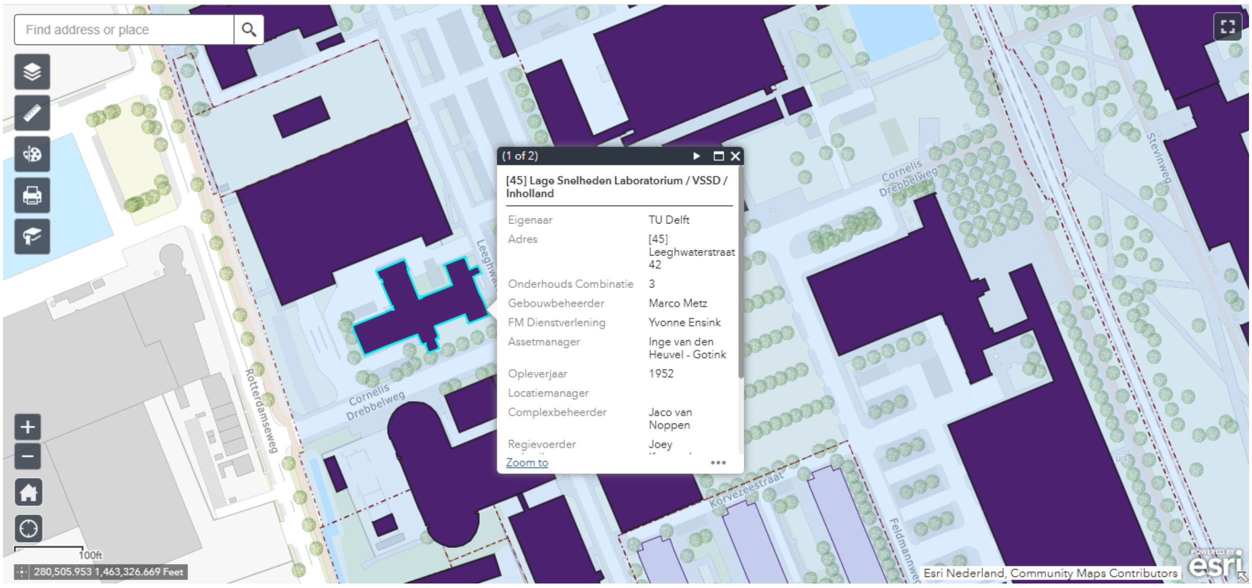


Figure 4.5: Building 45 details[ArcGIS]

- Table 3 - Construction Materials: This table offers codes for identifying the materials to be utilized in construction.
- Table 4 - Activities, Features, and Properties: This table encompasses codes related to the organization of preparation and construction processes, the characteristics and properties of buildings, spaces, and construction materials, as well as the attributes of activities performed by current or future users.

The building materials data in the Excel file primarily represents the functionality of elements, such as fire dampers and frames, refer figure 4.6. Although some information about the material is included such as stairs wood and transparent facade glass. The classification is based on functionality/system level rather than material properties. The excel file data was first cleaned using Python before uploading into the model. From the database, a materials passports was generated, with the function pathway used for this process depicted in figure 4.7. The final materials passports created for the building 45 is presented in figure 4.8. The database was then tested by querying data using the code of bm_constructionmethods. The code '21' represents façade construction, was used to query and retrieve the data from the database. The query is presented in figure 4.9, and the corresponding results are displayed in figure 4.10.

The Madaster platform was used to cross-verify its capability to generate a materials passports. For this process, the address and cadastral details were manually input into the platform. However, since the Madaster Excel template operates at the materials and products level rather than the system level, the platform was unable to generate a materials passports.

Vrije Code	NL/SfB	Conditi	Naam	Tag	NL/SfB	Elemen	Capacitei	Soort	Locatie	QR-code
1040	31		45 Low Speed Wind Laboratory / VSSD / Inholland		31.20	Waterslagen		Waterslag beton	G45 - BD0 - Zuid	
1021	31		45 Low Speed Wind Laboratory / VSSD / Inholland		31.20	Blankglas		Doorzichtig gevelglas	G45 - BD0 - Noord	
1022	31		45 Low Speed Wind Laboratory / VSSD / Inholland		31.20	Blankglas		Doorzichtig gevelglas	G45 - BD0 - Oost	
1023	31		45 Low Speed Wind Laboratory / VSSD / Inholland		31.20	Blankglas		Doorzichtig gevelglas	G45 - BD0 - Zuid	
1024	31		45 Low Speed Wind Laboratory / VSSD / Inholland		31.20	Blankglas		Doorzichtig gevelglas	G45 - BD0 - West	
1041	31		45 Low Speed Wind Laboratory / VSSD / Inholland		31.21	Kozijnen			G45 - BD0 - Noord	45.31.KOZIJNEN
1042	31		45 Low Speed Wind Laboratory / VSSD / Inholland		31.21	Kozijnen			G45 - BD0 - Oost	45.31.KOZIJNEN
1043	31		45 Low Speed Wind Laboratory / VSSD / Inholland		31.21	Kozijnen			G45 - BD0 - Zuid	45.31.KOZIJNEN
1044	31		45 Low Speed Wind Laboratory / VSSD / Inholland		31.21	Kozijnen			G45 - BD0 - West	45.31.KOZIJNEN
1025	31		45 Low Speed Wind Laboratory / VSSD / Inholland		31.21	Kozijnen		Hout	G45 - BD0 - Oost	45.31.KOZIJNEN

Figure 4.6: Excel data of Building 45

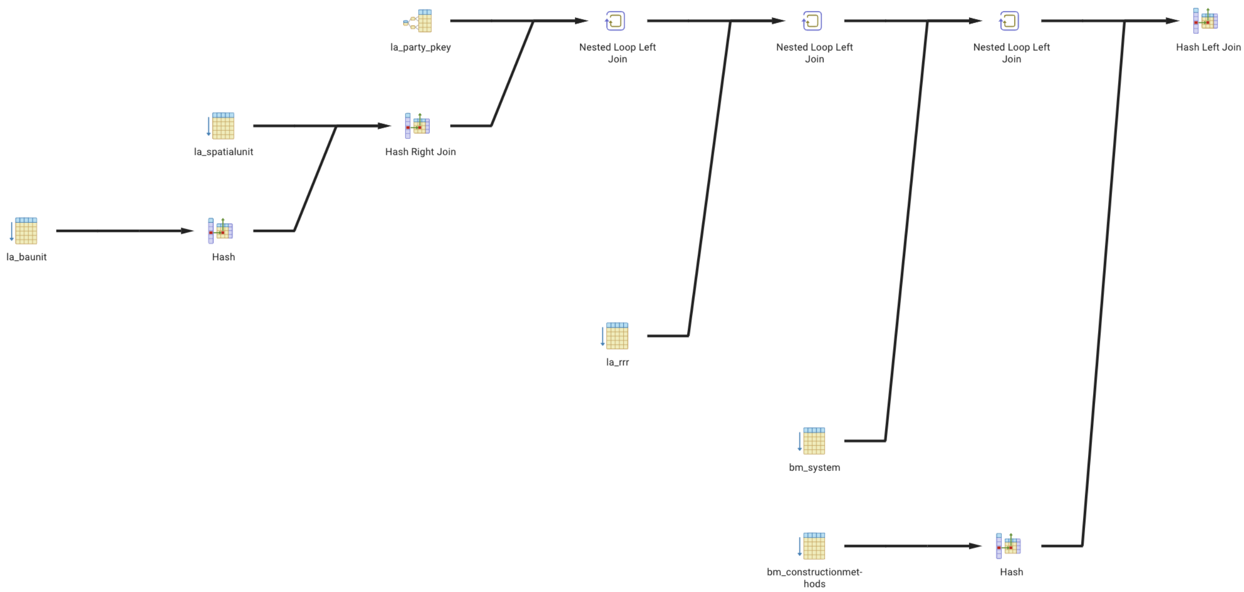


Figure 4.7: Function pathway of generating Materials Passports

Data Output | Explain | Messages | Notifications

	name text	description text	beginlifespanversion timestamp with time zone	beginrealworldlifespanversion timestamp with time zone	nameofthebuilding text	area numeric	code integer	quantity numeric	unit character varying (
1	TU Delft	Owner	2022-12-05 00:00:00+01	1952-06-01 00:00:00+01	45 Low Speed Wind Laboratory / VSSD / Inholland	3156.3	0	1.00	pst
2	TU Delft	Owner	2022-12-05 00:00:00+01	1952-06-01 00:00:00+01	45 Low Speed Wind Laboratory / VSSD / Inholland	3156.3	0	1.00	pst
3	TU Delft	Owner	2022-12-05 00:00:00+01	1952-06-01 00:00:00+01	45 Low Speed Wind Laboratory / VSSD / Inholland	3156.3	21	81.95	m2
4	TU Delft	Owner	2022-12-05 00:00:00+01	1952-06-01 00:00:00+01	45 Low Speed Wind Laboratory / VSSD / Inholland	3156.3	21	531.94	m2
5	TU Delft	Owner	2022-12-05 00:00:00+01	1952-06-01 00:00:00+01	45 Low Speed Wind Laboratory / VSSD / Inholland	3156.3	24	1.00	st
6	TU Delft	Owner	2022-12-05 00:00:00+01	1952-06-01 00:00:00+01	45 Low Speed Wind Laboratory / VSSD / Inholland	3156.3	27	1.00	st
7	TU Delft	Owner	2022-12-05 00:00:00+01	1952-06-01 00:00:00+01	45 Low Speed Wind Laboratory / VSSD / Inholland	3156.3	27	13.55	m2
8	TU Delft	Owner	2022-12-05 00:00:00+01	1952-06-01 00:00:00+01	45 Low Speed Wind Laboratory / VSSD / Inholland	3156.3	28	1.31	m2
9	TU Delft	Owner	2022-12-05 00:00:00+01	1952-06-01 00:00:00+01	45 Low Speed Wind Laboratory / VSSD / Inholland	3156.3	31	372.35	m2
10	TU Delft	Owner	2022-12-05 00:00:00+01	1952-06-01 00:00:00+01	45 Low Speed Wind Laboratory / VSSD / Inholland	3156.3	31	1.00	st
11	TU Delft	Owner	2022-12-05 00:00:00+01	1952-06-01 00:00:00+01	45 Low Speed Wind Laboratory / VSSD / Inholland	3156.3	31	5.00	st
12	TU Delft	Owner	2022-12-05 00:00:00+01	1952-06-01 00:00:00+01	45 Low Speed Wind Laboratory / VSSD / Inholland	3156.3	31	3.00	st
13	TU Delft	Owner	2022-12-05 00:00:00+01	1952-06-01 00:00:00+01	45 Low Speed Wind Laboratory / VSSD / Inholland	3156.3	31	4.00	st
14	TU Delft	Owner	2022-12-05 00:00:00+01	1952-06-01 00:00:00+01	45 Low Speed Wind Laboratory / VSSD / Inholland	3156.3	31	793.41	m2
15	TU Delft	Owner	2022-12-05 00:00:00+01	1952-06-01 00:00:00+01	45 Low Speed Wind Laboratory / VSSD / Inholland	3156.3	31	17.42	m2
16	TU Delft	Owner	2022-12-05 00:00:00+01	1952-06-01 00:00:00+01	45 Low Speed Wind Laboratory / VSSD / Inholland	3156.3	31	9.40	m1
17	TU Delft	Owner	2022-12-05 00:00:00+01	1952-06-01 00:00:00+01	45 Low Speed Wind Laboratory / VSSD / Inholland	3156.3	32	1.00	st
18	TU Delft	Owner	2022-12-05 00:00:00+01	1952-06-01 00:00:00+01	45 Low Speed Wind Laboratory / VSSD / Inholland	3156.3	32	1.00	pst
19	TU Delft	Owner	2022-12-05 00:00:00+01	1952-06-01 00:00:00+01	45 Low Speed Wind Laboratory / VSSD / Inholland	3156.3	32	1.00	st
20	TU Delft	Owner	2022-12-05 00:00:00+01	1952-06-01 00:00:00+01	45 Low Speed Wind Laboratory / VSSD / Inholland	3156.3	37	4.00	st
21	TU Delft	Owner	2022-12-05 00:00:00+01	1952-06-01 00:00:00+01	45 Low Speed Wind Laboratory / VSSD / Inholland	3156.3	41	91.52	m1
22	TU Delft	Owner	2022-12-05 00:00:00+01	1952-06-01 00:00:00+01	45 Low Speed Wind Laboratory / VSSD / Inholland	3156.3	41	659.77	m1
23	TU Delft	Owner	2022-12-05 00:00:00+01	1952-06-01 00:00:00+01	45 Low Speed Wind Laboratory / VSSD / Inholland	3156.3	41	932.47	m2
24	TU Delft	Owner	2022-12-05 00:00:00+01	1952-06-01 00:00:00+01	45 Low Speed Wind Laboratory / VSSD / Inholland	3156.3	42	850.00	st
25	TU Delft	Owner	2022-12-05 00:00:00+01	1952-06-01 00:00:00+01	45 Low Speed Wind Laboratory / VSSD / Inholland	3156.3	43	336.00	m2
26	TU Delft	Owner	2022-12-05 00:00:00+01	1952-06-01 00:00:00+01	45 Low Speed Wind Laboratory / VSSD / Inholland	3156.3	43	1278.00	m2

Total rows: 96 of 96 Query complete 00:00:00.097 Ln 12, Col 44

Figure 4.8: Materials Passports for Building 45

Thesis/postgres@PostgreSQL 16

Query | Query History

```
SELECT
    la_party.name,
    la_rrr.description,
    la_rrr.beginlifespanversion,
    la_rrr.beginrealworldlifespanversion,
    la_baunit.name AS "nameofthebuilding",
    la_spatialunit.area,
    la_spatialunit.geometry,
    --la_spatialunit.referecepoint,

    bm_constructionmethods.code,
    ROUND (bm_constructionmethods.quantity, 2) AS quantity,
    bm_constructionmethods.unit,
    bm_constructionmethods.bm_constructionmethods_id AS "constructionmethod_id"
FROM
    la_party
LEFT JOIN
    la_rrr ON la_party.la_party_id = la_rrr.la_party_id AND la_party.la_party_id = '1'
LEFT JOIN
    la_baunit ON la_party.la_party_id = la_baunit.la_party_id AND la_party.la_party_id = '1'
LEFT JOIN
    la_spatialunit ON la_baunit.la_baunit_id = la_spatialunit.la_baunit_id AND la_baunit.la_baunit_id = '1'
LEFT JOIN
    bm_system ON bm_system.vm_building_id = '1'
LEFT JOIN
    bm_constructionmethods ON bm_constructionmethods.bm_constructionmethods_id = bm_system.bm_constructionmethods_id
WHERE
    la_party.la_party_id = '1'
    AND bm_constructionmethods.code = 21;
```

Figure 4.9: Query for selecting code '21'

Data Output | Messages | Notifications

	description text	beginlifespanversion timestamp with time zone	beginrealworldlifespanversion timestamp with time zone	nameofthebuilding text	area numeric	geometry geometry	code integer	quantity numeric	unit character v
1	Owner	2022-12-05 00:00:00+01	1952-06-01 00:00:00+01	45 Low Speed Wind Laboratory / VSSD / Inholland	3156.3	[null]	21	81.95	m2
2	Owner	2022-12-05 00:00:00+01	1952-06-01 00:00:00+01	45 Low Speed Wind Laboratory / VSSD / Inholland	3156.3	[null]	21	531.94	m2

Figure 4.10: Result of the query

4.2.2 Building 25

The Building 25 located in The Green Village, was constructed in 2015 is shown in figure 4.11. Although it is relatively newer compared to Building 45 the spatial data remains incomplete. The available data includes the cadastral number (figure 4.12), building drawings and 3D spatial data in Revit format refer figure. Revit files are primarily used by architects during the design phase to help with the analysis. The Revit file was visualised in the Revit software and it was observed that the file lacked critical data impacting the quality of the resulting Materials Passports and the registration process, as shown in figure 4.13. In this, all the parameters are absent in the selected component. The quality of the generated model is influenced by the completeness and accuracy of the input data.

The Revit file was converted into a IFC format following the procedures outlined on the Madaster platform [Madaster, 2025]. During the conversion, the file was saved as an "IFC4 Design Transfer View," a format tailored for interoperability. The exported IFC file was subsequently visualized using OpenIFC Viewer, revealing that the deficiencies present in the original Revit file persisted in the converted IFC file and more missing data. Although some material data were present in the file, they were incorrectly assigned. For example, a wooden staircase was labeled as a name rather than being defined as an attribute of the elements, as shown in figure 4.14. These missing or misallocated data have impacted the quality and reliability of the generated Materials Passports. This suggests that the missing data could be a result of incomplete material definitions or incorrect IFC export settings. FME was used to transform the IFC data into a format compatible with the developed database. However, due to data misalignment, FME was unable to extract information from the IFC file, ultimately preventing the model from generating the Materials Passports.

The IFC file was uploaded to the Madaster platform for cross-verification to generate Materials Passports. The 3D visualisation of the building 25 in Madaster platform is shown in figure 4.15. The platform is user friendly and in the 3D visualisation, it is possible to select objects. Due to the inaccuracies in the input IFC file, the generated Materials Passports was incomplete and unreliable illustrated in the figure 4.16. Here the unknown material percentage is high. Although the Madaster platform provides the capability to manually add data to improve the accuracy of the Materials Passports, these modifications are limited to the platform and do not address the deficiencies present in the source file. The Madaster platform generates a Materials Passports irrespective of the completeness of the input data, however, when the input data is insufficient, the reliability and accuracy of the generated Materials Passports are compromised.

Accurate input data is essential for generating reliable Materials Passports. In this research, the source file contained inaccuracies and missing data, rendering it unsuitable for thorough testing. The critical takeaway is the significant impact of source file quality on the reliability of the results. If the source data fails to meet the required standards of quality, the resulting outputs will inevitably be unreliable. Platform-specific data enrichment cannot compensate for insufficient input data, as it fails to ensure outputs that meet the desired standards of quality and reliability.

Figure 4.11: Building 25

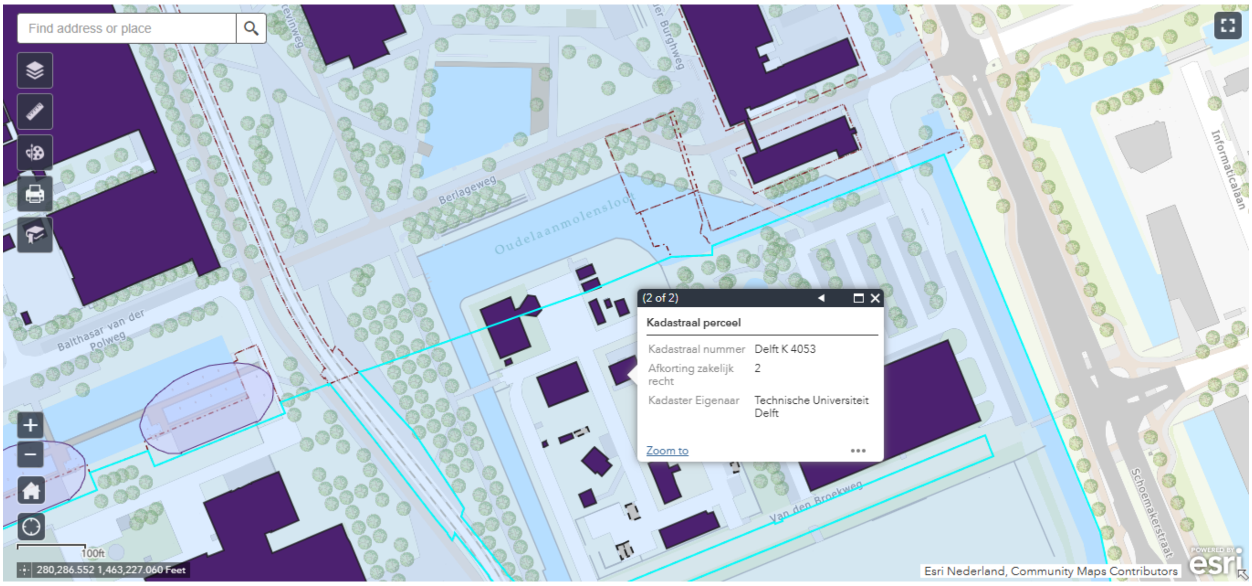


Figure 4.12: Building 25 details[ArcGIS]

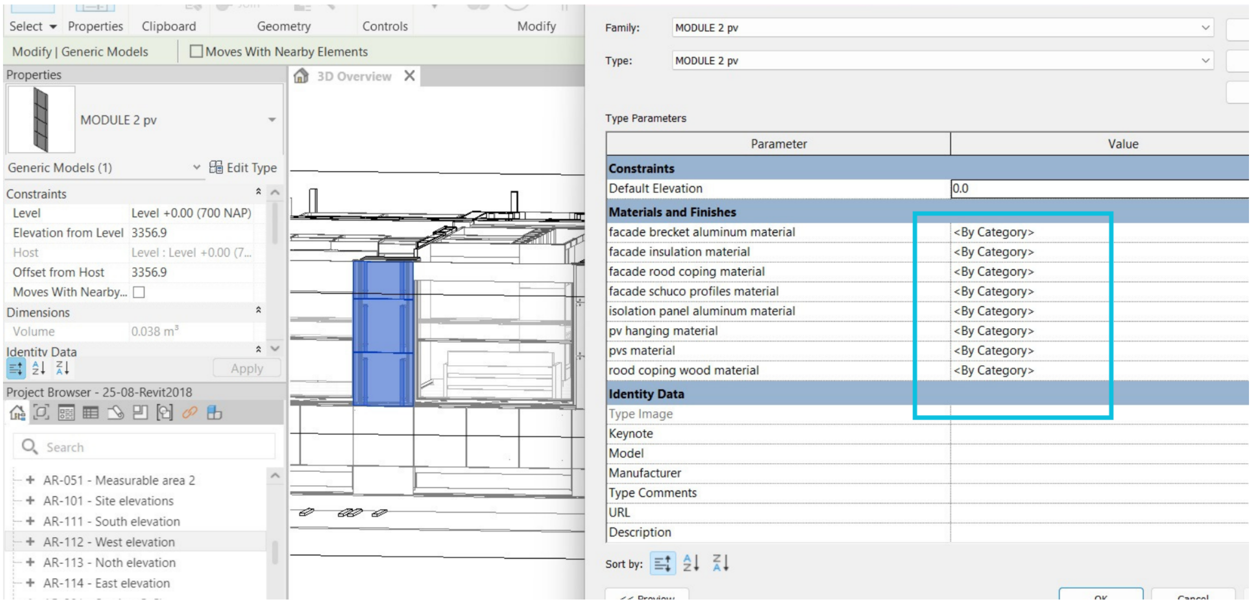


Figure 4.13: Revit file of Building 25

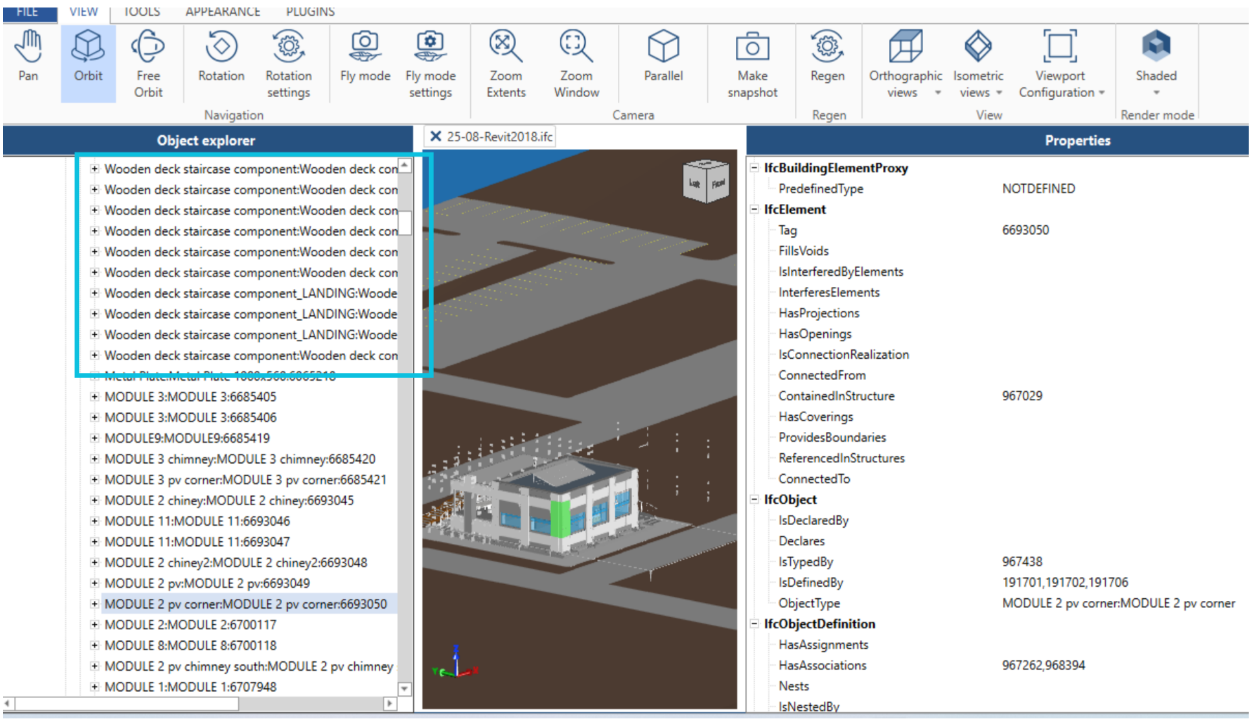


Figure 4.14: IFC file of Building 25

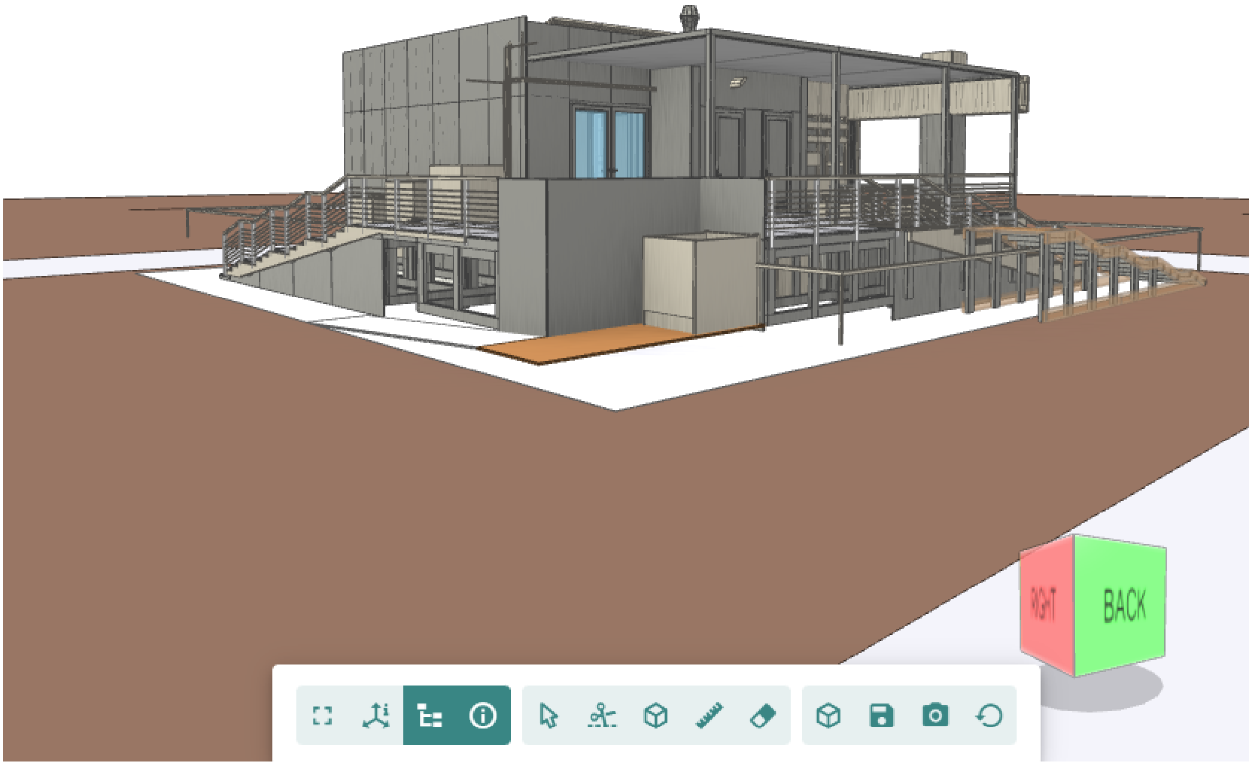


Figure 4.15: 3D visualisation of Building 25 in madaster platform

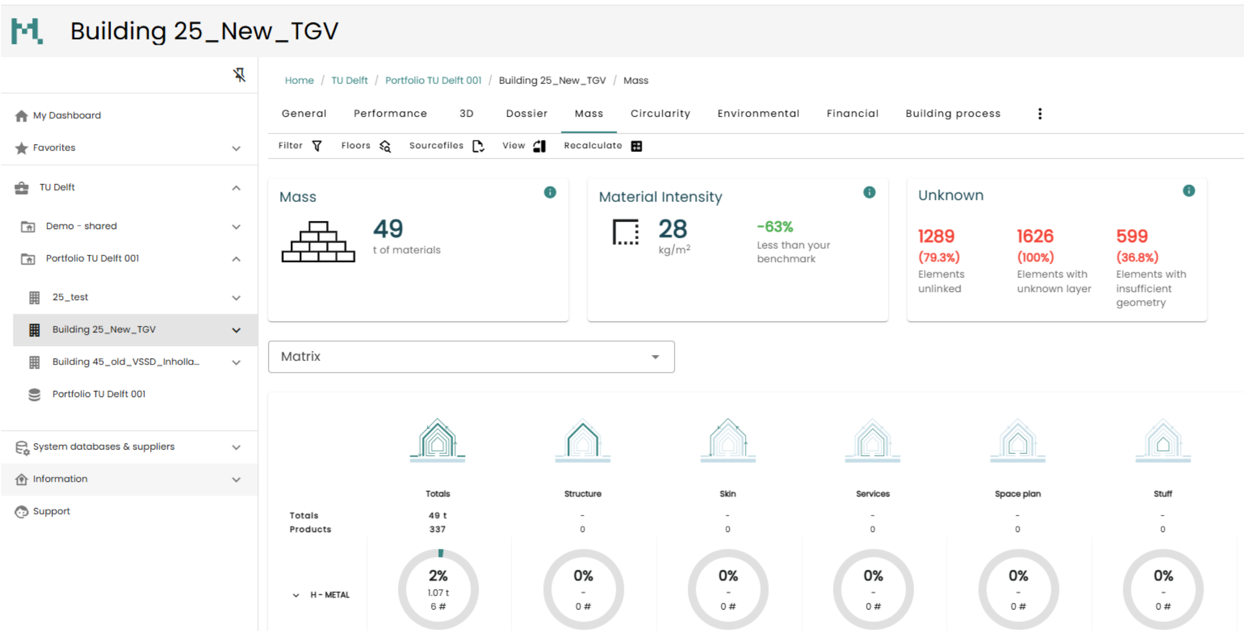


Figure 4.16: Materials Passports of Building 25

4.2.3 Reflection

The datasets used for this research focused on buildings in the Netherlands, utilizing the Dutch construction material classification system, NL/SfB. The model was evaluated using two functional buildings—one older and one relatively new. These buildings differ in multiple aspects, including the type of source data file, the classification levels used in those files and the level of available information. The significant variation between the two buildings enabled a comprehensive assessment of the model's performance across different conditions.

One of the limitations was the availability of complete and accurate data for functional buildings. While newly constructed buildings generally provide comprehensive source data, Building 25 had limited data available. Older buildings often lack detailed material descriptions. For Building 45, only renovation-related data was available, primarily focusing on system level rather than material information. Despite these limitations, the model successfully generated a Materials Passports and enabled database queries, demonstrating its adaptability .

Another issue encountered was data conversion. The source files frequently came in various formats, which leads to potential data loss during the conversion process. For Building 25, the original Revit file was converted to the IFC format. This conversion highlighted existing gaps in material information, with some properties either being incorrectly assigned or not transferred at all. Tackling these conversion-related discrepancies is a critical area that requires further improvement in the material registration processes.

Another obstacle was the incorrect data assignment, which was the primary obstacle preventing the import of the data into the database. Even in the original Revit file, the data was not properly assigned, as highlighted in section 4.2.2. Resolving this problem requires not only correcting the misassignments but also ensuring that the model's structure is properly set up to facilitate a smooth import process into the database system.

4.3 Workshop

A workshop was conducted with stakeholders involved in this research, including personnels from Madaster and the Circular Built Environment Hub at TU Delft. The session provided participants with an overview of the research findings, highlighting the model, its development process, and the final outcomes. The goal was to gather feedback from participants on the model and its practicality.

One of the key pieces of feedback received is that the model is complex due to its hierarchical structure. As a result, not all information may be easily accessible at every level. However, this structure was intentionally designed to ensure no data is overlooked, as all levels are represented and can also function independently. Another concern raised is that the model appears too ambitious, providing a broad, high-level overview rather than focusing on specific priorities. A suggested improvement is to refine or simplify the model by concentrating on essential aspects, such as the registration of steel beams, rather than maintaining a generalized approach. However, it is important to note that the model was initially developed as a foundational standard for building materials registration, with scalability and long-term applicability in mind.

Furthermore, the Madaster team highlighted the importance of GDPR, pointing out that most of their users prioritize the privacy of their personal data, especially when it comes to third parties accessing information about building materials. Owners currently have control over their registered materials, but for future purposes, it was suggested that they be given the option to open their registration in advance, ideally 6–12 months before selling or renovation. This early access could facilitate smoother transactions, provide potential buyers or project stakeholders with necessary material insights, and enhance planning for reuse or recycling of materials. Providing a balance between transparency and privacy in implementing this feature effectively.

Although the model takes material quality into account, obtaining accurate and reliable information on this aspect in practice remains a significant challenge. Factors such as incomplete historical records and variations in material degradation make it difficult to assess quality with certainty.

A key question regarding the model that arises was: What's in it for the owner? Beyond the ability to track materials, there need to be clear incentives for owners to engage with the system actively. Potential benefits could include cost savings through better material reuse, compliance with sustainability regulations, or even financial incentives such as tax benefits or subsidies for maintaining updated material records. Apart from this, it is essential to provide owners with a strong motivation to keep the data updated during renovations, ensuring the system remains relevant and valuable over time.

Another challenge is that much of the feedback received from participants extends beyond the scope of the current research. For example, suggestions to incorporate Customer Relationship Management (CRM) systems, while valuable in a broader business or asset management context, do not align with the primary focus of the study. While these insights may be relevant for future expansions or industry applications, the current research remains centered on material registration and tracking rather than customer engagement strategies.

5 Conclusions and Discussions

This chapter presents the conclusions and key insights derived from the study. This chapter the answers the research question of this thesis in section 5.1. Then in section 5.2 the futureworks are discussed.

The objective of this research was to evaluate the registration of building materials based on international standards. The main challenge encountered was identifying a suitable international standard to integrate with the registration process of building materials. This is due to the lack of standardization within the building materials and construction sector, where ambiguities often arise in material classification. For instance, questions such as ”What constitutes a wall?” or ”How should a partially glass partition be classified—as a wall or something else?” highlight the complexities in categorizing building materials. These ambiguities necessitate a hierarchical classification system within the materials passports to address such issues. Despite this approach, considerable uncertainties persist regarding the definition and classification of building materials. Additionally, there was no uniform way to collect all the information regarding building material registration.

Identifying a compatible standard for material registration was challenging. The Land Administration Domain Model (LADM) was ultimately selected as the most suitable standard due to its comprehensive structure and essential requirements. However, integrating building material classification into an established standard like LADM posed additional challenges. The new components needed to link seamlessly with core LADM classes while ensuring that the new classes adequately addressed the complexities of material classification. Furthermore, these relationships had to be kept straightforward to maintain simplicity and usability.

To address material classification, a superclass was designed, from which other classes inherited properties. These subclasses were associated hierarchically to ensure comprehensive coverage of relationships while maintaining consistency. One of the primary challenges in this process was the development of codelists. The absence of a widely accepted international material classification system complicated this effort, making the task intensive. For demonstration purposes, European standards were adopted as a reference for the functionality of the model. Since this is an initial draft the model focuses on the content, there remains potential for improvement through the addition or refinement of classes and codelists.

The availability of complete and accurate data for existing buildings remains a challenge, regardless of their age. For older structures like Building 45, spatial data is often missing, and the available information primarily pertains to renovations. Meanwhile, in Building 25, data has been incorrectly assigned. Both Buildings lack georeferencing in their datasets. Since most files pertain to individual buildings, they are often not georeferenced, relying on a local reference system (LCS) rather than a coordinate reference system (CRS). To accurately position a model in real-world coordinates, a transformation must be applied and stored within the model.

To address these issues, establishing standardized guidelines for dataset management is essential. While some level of incomplete data is inevitable, the model can still function despite these gaps. However, to achieve higher-quality results, data availability must be improved by identifying gaps and supplementing missing information where possible.

Another critical issue is incorrectly assigned data, which can be mitigated by standardizing data input in accordance with international standards. Ensuring a checklist of required parameters before exporting files further enhances data integrity. Proper georeferencing of files ensures accurate spatial positioning, and incorporating valid geometric and topological features aligned with OGC standards strengthens the overall dataset.

5.1 Research Questions

What are the applications of the Building Material registration?

The registration of building materials has several different applications as mentioned in section 2.4, below are some of the important applications and merits.

- **Circularity -** A detailed understanding of the materials used in buildings is essential for enhancing their recycling potential. Accurate classification of recycling potential is crucial to preventing material downgrading, enabling reuse at the highest possible quality. Also, proper registration allows easy identification and separation of reusable materials. Furthermore, reusing materials significantly reduces the demand for already depleting natural resources.
- **Valuation of Building -** When the materials are well documented, it will be easier to evaluate their quality and durability, which in turn facilitates accurate building valuation. Additionally, knowing the exact location of materials within the building, along with their lifespan information, aids in analyzing renovation costs. This detailed insight allows for accurate assessments of material durability, maintenance needs, and potential replacement timelines, helping to estimate future renovation expenses effectively.
- **Environmental Impact -** The material used in the building have direct impact on the environment. Materials passports contribute to understanding a building's environmental footprint by providing data on embodied energy, carbon emissions throughout its life cycle and material toxicity.
- **Safety and Security -** Maintaining an inventory of all the materials used in the building ensures compliance with safety standards and regulations. This inventory is instrumental

in the identification and removal of hazardous materials within the structure. In emergencies, having a detailed plan of the building and an inventory of materials is essential, as it provides critical information for first responders, facilitating effective and safe interventions.

This means that registration of building materials serves multiple purposes, all of which benefit from the efforts to establish this registration.

What criteria are necessary to obtain the Materials Passports?

Materials Passports is a registration standard for building materials that is designed to maximize their reuse potential and support sustainable practices. It systematically documents the materials used within a building, providing critical information for effective management and lifecycle extension. As mentioned in section 3.2 the key criteria for obtaining a Materials Passports include ownership details or a Kadaster link, which facilitate legal transactions related to the building and its materials. Accurate 3D location information is essential for identifying the building and mapping the spatial distribution of its materials. Detailed data on the materials and components within the structure is crucial for evaluating their reuse potential. Additionally, economic valuation provides insights into the materials' financial worth, aiding decision-making processes. Life Cycle Assessment (LCA) of the materials is necessary to understand their environmental impact and optimize their integration into a circular economy. Finally, the inclusion of certifications enhances the passport's quality by validating the materials' compliance with established standards. Together, these elements make the Materials Passports a vital tool for promoting sustainable construction and material reuse.

How can the registration and management of the Materials Passports be standardised?

The registration and management of materials passports can be streamlined by adopting established standards. The Land Administration Domain Model (LADM) emerges as a suitable standard for materials passports registration and management due to its comprehensive framework that already incorporates most of the fundamental requirements of a materials passports as outlined in section 3.2.2.

The LADM includes dedicated classes for essential data elements, such as ownership details. For instance, the LA_Party class contains information regarding the owner or relevant individuals, while the LA_BAUnit and LA_RRR classes define the relationship between the individual and the property, like ownership relation. Another critical requirement, the representation of 3D spatial data, is effectively addressed within the LA_SpatialUnit class, which stores detailed location information.

While the LADM framework encompasses these essential aspects, the integration of material-specific data would require additional classes or extensions. Nevertheless, the existing valuation information provided in Part 4 of the LADM aligns with the objectives of materials passports, making it highly relevant for this application. Thus, the LADM provides a robust foundation for materials passports registration and management, requiring only minimal adjustments to include materials information. Thus building materials registration can be added as a new part to the existing LADM

How can the Materials Passports be created and evaluated?

Using the information model developed for building materials part in the LADM, this conceptual model can be transformed into a technical model through spatial SQL tables in PostgreSQL and PostGIS as mentioned in chapter 4. Once the technical model is operational, the source files can be incorporated. The model was evaluated through case studies.

Two cases were selected for this purpose: Building 45, an older structure with limited available data primarily related to maintenance and renovations. The Materials passports was created for this building and queried the database. Building 25, is a relatively newer building also had missassigned data, and the available data was in Revit format, which was saved in different formats. Due to the lack of foundational data required for testing, the evaluation could not be carried out.

The source files need to be standardized to ensure they contain sufficient data. Since much of the data is incomplete, there will always be some missing information in the files. Additionally, the available data may not be essential, leading to inaccuracies. Further the model was evaluated by conducting workshop with Madaster staff and the Circularity Hub of TU Delft.

5.2 Futureworks

While the research examined the technical aspects of building materials registration, future research can address the following:

- A more detailed investigation of attributes specific to certain hierarchical levels in material registration, currently uniform attribute structure across all levels.
- Formulating guidelines like georeferencing, geometric and Topological Validity for the source document.
- Future research can explore the legal and organizational aspects of building material registration to develop a detailed framework for material tracking and governance.
- Although the model operates with various data formats, establishing a standardized data format for materials passports can be analyzed in the future research.
- While the materials passports system facilitates material registration, the absence of a platform for selling materials presents an opportunity for future research to investigate the development of a marketplace for these transactions.

- Future research can also address privacy concerns under GDPR, as unauthorized access to building materials could expose owners to risks like burglary or misuse of information.
- Future research could examine how materials passports systems can address cross-border regulations and certification standards for materials in international projects involving multiple countries.

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Colophon

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