From Material Passports to Digital Product Passports

Creating and Validating Linked Data-based Digital Product Passports for the AEC industry

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Preface

Dear reader,

After completing my bachelor's degree in Architecture and Construction Engineering at Avans University of Applied Sciences in Tilburg, followed by a master's degree in Construction Management & Engineering, the completion of this thesis marks the end of my academic journey. Throughout my time at the university, I developed a diverse interest in various aspects of the AEC industry, including sustainability, construction, management, and more. This interest further deepened during my master's studies, particularly through my exposure to data. Recognizing the potential of data utilization, I was eager to expand my knowledge in this area. In addition, I have been interested in sustainability my entire academic career. Therefore, the thesis presented an excellent opportunity to merge these two passions.

I am glad that I was able to conduct research within my fields of interest and gain a lot of new knowledge. Despite my limited knowledge, I learned a lot about applying Linked Data, validating data, and passports in construction. It was, therefore, extra fun to work on a relatively new and unknown topic in construction: Digital Product Passports. Although it was challenging to start this new topic, I can look back at the learning process with great pleasure.

In addition, I would like to thank everyone who assisted me during the writing of this thesis. First, I would like to thank my supervisors at Eindhoven University of Technology. Ekaterina Petrova, Florent Gauvin, and Julia Kaltenegger thank you for inspiring and advising me during the process. I specifically want to thank Julia for helping me during this process and for always being optimistic and thoughtful. With your help, I made more progress than I ever imagined. I would also like to thank my company supervisors Daan Temminghof and Jasper Vissers of the Royal BAM group for their advice and support during the process.

In addition, I would like to thank my friends and family. My friends from Of CoUrsE!, I want to thank you for the cozy coffee mornings and fun activities the last years. And, of course, Thijs for going through the graduation process together. I also want to thank Jelle and my family for listening to my stories about graduation without end, and for their support during the process. All of you together have contributed to making great memories and having fun during graduation!

I hope you will enjoy reading this work!

Janneke Bosma

s-Hertogenbosch, May 2024

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Summary

Material resources are limited and do not possess infinite utility. Moreover, the processing and utilization of these materials result in significant CO_2 emissions. The construction sector contributes with 38% of the total global energy-related CO_2 emissions (United Nations Environment Programme, 2020). Despite the increasing emphasis on recycling, focusing on recycling alone is not enough to successfully transition to a circular economy. Instead of prioritizing recycling, the principles of Refuse, Reduce, and Renew hold greater importance in the 10R hierarchy of Cramer, (2017). The higher the material is situated in the ladder, the more circular it is. This is important to add value and stay within the planetary boundaries (Cramer, 2017a). Unfortunately, most of the construction demolition waste in Europe is situated in the lower rank. The Renew aspect involves the reuse of materials. However, Reuse faces challenges such as aligning supply with demand of products/materials. To address these issues, the concept of a Material Passport (MP) emerges as a potential solution. The MP of buildings and structures contains essential details regarding the materials, including their type, quantity, origin, and installation method. Nevertheless, the absence of a standardized format and consensus among stakeholders regarding the content of the passport poses a challenge. Furthermore, there is a pressing need to verify the data of MPs to ensure its accuracy, thereby enhancing the prospects for reusing and recycling materials.

The Digital Product Passport (DPP) has been proposed as a potential solution to address the existing ambiguity. According to Walden et al. (2021), the DPP is considered as a remedy for the "inconsistent and imprecise flow of information regarding resources, products, and processes." The DPP encompasses all physical goods that are introduced into the market or utilized. Moreover, it encompasses the entire lifespan of an object and can function as a tool for tracking and tracing, while an MP primarily focuses on end-of-life aspects. Nevertheless, the DPP is a relatively new concept and consequently, there is still a lack of clarity regarding the applicable, formats, standards and regulations. Furthermore, similar to the MP, the DPP also necessitates a standard validation process to ensure the quality of the data it contains.

The absence of a standardized format for the DPP raises uncertainty regarding the necessary information that has to be included in the passport. The fact that there is no information is a central motivation in this research. Various formats MPs exist within the literature and practice, while the terms DPP and MP being used interchangeably. To establish a uniform standard, a workshop was conducted to consolidate the outcomes of interviews with experts and existing literature, resulting in a comprehensive list of essential topics (i.e., contents) for a DPP. In addition to the format, ensuring data sharing with stakeholders and traceability of objects throughout their life cycle are crucial aspects when implementing a DPP. Compliance with the EU Battery regulations highlights the significance of an interconnected data space in facilitating these requirements, as well as in upholding the prescribed Findable, Accessible, Interoperable, and Reusable (FAIR) data principles and literature-based DPP criteria.

The exchange and storage of information in the Architecture, Engineering and Construction (AEC) industry rely heavily on Building Information Modelling (BIM) and, more specifically, the Industry Foundation Classes (IFC) open data standard. BIM models serve as centralized repositories for the necessary components, primarily at the element level. Moreover, to

establish a comprehensive passport, the information must also be accessible at the product and material level which can be achieved by integrating manufacturer databases with the data derived when exporting the BIM model to IFC or converting it to other data models. This integration can be facilitated through the utilization of Linked Data, which ensures that the information remains at its source, minimizing the risk of errors caused by communication gaps. Furthermore, this approach guarantees the utilization of the most up-to-date data, with each stakeholder retaining responsibility for their respective portions. To enable the use of Linked Data-bases representations, the the IFC model is converted to Resource Description Framework (RDF), a standardized data model used for describing web resources. Linked Data employs RDF triples to organize the data and its associated relationships, ultimately forming a knowledge graph. Similarly, when a DPP is created, the combination of the IFC data with relevant product and material information can also be represented as a knowledge graph, thereby establishing a Linked Data-based DPP.

Linked Data relies on ontologies, which serve to organize and assign meaning to the information. At present, there is no publicly available version of a DPP or MP ontology that can be utilized. Consequently, this research also proposes a DPP ontology that aligns with specified must-haves identified through the literature review and the workshop with experts.

As previously stated, it is necessary to validate the structure and data of the DPP. In order to validate the Linked Data-based DPP, the rule checking concept developed by Eastman et al. (2009) is utilized. This system comprises four distinct steps: (1) interpretation of rules and logical structuring, (2) preparation of the model for checking, (3) execution of the set rules, and finally (4) generation of the results.

In the initial stage, the guidelines need to be defined. These guidelines are derived from the categorized rule classifications proposed by Lee et al. (2016). The validation tool should ensure the presence and accuracy of essential data, prevent duplication, verify the correctness of data types, and validate the accuracy of data completion. Furthermore, a specific rule is implemented to validate the adherence of data to predetermined boundaries.

In the second step, it is necessary to prepare the IFC model for verification. Within the context of this thesis, the model is transformed into an RDF file. If the Revit model is not instantiated correctly, this could result in the RDF file becoming unusable. Therefore, it is crucial to verify the file prior to its utilization. Along with the IFC model, a material/product passport must be associated. Various passport formats have been assessed, however, none of these formats currently satisfy the specified requirements. Consequently, a database containing material and product information was established in RDF format, which was populated with synthetic data. Subsequently, the RDF representation of the structure is linked to this product and material data.

In order to proceed with the third step, it is necessary to validate the established constraints. Within the realm of Linked Data, there are various languages available for this purpose. In the present investigation, a comparison was made between the Shapes Constraint Language (SHACL) and the Shape Expressions (ShEx) structural schema language or RDF graphs. Ultimately, SHACL was selected as the preferred option for conducting the validation process due to its wider range of capabilities and its endorsement by the World Wide Web Consortium (W3C). The defined constraints were subsequently translated into the SHACL format.

In the fourth step, the validation report is produced. To achieve this, the SHACL file is utilized to validate the RDF files. PySHACL is employed for this purpose. The PySHACL code is adjusted to generate a validation report within the Visual Studio Code terminal, where the scripts are developed. Additionally, the PySHACL code is enhanced to generate a PDF report – a document containing crucial details such as missing topics, inaccurately entered topics, and their associated IFC Globally Unique Identifiers (GUIDs). These GUIDs can then be utilized to rectify any errors in the source files, including the Revit file, as well as any material and product databases or passports. As such, this master thesis presents an approach for scaling Material Passports to checkable Linked Data-based Digital Product Passports for the AEC industry.

Samenvatting

Niet alle materialen zijn oneindig bruikbaar. Daarnaast komt er bij het verwerken en gebruiken van de materialen veel CO_2 vrij. De bouw is verantwoordelijk voor 38% van de totale CO_2 emissies wereldwijd (United Nations Environment Programme, 2020). Ondanks dat er steeds meer gereycled wordt is dit niet genoeg om een succesvolle circulaire economy te verwezelijken. In plaats van Recyclen staan er Refuse, Reduce en Renew hoger op de 10R ladder van Cramer, (2017). Hoe hoger het materiaal is geplaatst op de de ladder hoe circulairder het is. Dit is van belang om van waarde te zijn en binnen de planetaire grenzen te blijven (Cramer, 2017a). Echter is momenteel het grootste deel van het bouwafval geplaatst onderaan de ladder. Binnen de Renew trede van deze ladder valt het hergebruik van de materialen. Echter zijn er verschillende uitdagingen gekoppeld aan hergebruik, zoals het koppelelen van vraag en aanbod van producten/materialen. Een Materiaal Paspoort (MP) kan een oplossing bieden voor deze problemen. Een MP bevat onder andere informatie over de type en hoeveelheid materiaal, de oorsprong, en methode van installatie. Echter is er momenteel geen standaard en duidelijkheid onder stakeholders over wat het paspoort precies inhoud of welke informatie het moet bevatten. Daarnaast is er een noodzaak de data van MPs te valideren om de kwaliteit te waarboren en de kans op hergebuik en recycling te vergoten.

Het Digitale Product Paspoort (DPP) is geadresseerd als een oplossing voor de onduidelijkheid. Dit paspoort wordt gezien als dé oplossing voor “het ontbreken van een consistente en nauwkeurige informatiestroom over middelen, producten en processen” (Walden et al., 2021). Dit paspoort omvat alle fysieke goederen die op de markt worden geplaatst of in gebruik worden genomen. Daarnaast omvat het DPP de gehele levenscyclus van een object en kan deze dienen als een track & trace instrument, waar een MP zich voornamelijk focust op de einde levensduur. Echter maakt de DPP pas recent een entree en is hierdoor nog onduidelijkheid over de eventuele standaard en regelgeving. Daarnaast dient dit paspoort, net als het MP, gevalideerd te worden om data kwaliteit te waarborgen.

Doordat het DPP momenteel geen gestandardizeerd format heeft, is het onbekend welke informatie in het paspoort opgenomen dient te worden. De afwezigheid van deze informatie speelt een centrale rol binnen dit onderzoek. In de literatuur en praktijk zijn er verschillende formats en worden de termen DPP en MP door elkaar heen gebruikt. Om uit deze formats een standaard te definiëren is een workshop georganisered met experts. De resultaten van deze workshop zijn met de literatuur gecombineerd tot een lijst van ‘must-have’ onderwerpen voor een DPP. Naast het format is bij de opzet van een DPP het van belang dat de data gedeeld kan worden met de belanghebbende en dat de objecten traceerbaar zijn door de hele levenscyclus. Volgens de EU Battery regulations kan een ‘interconnected data space’ hierbij helpen evenals bij het behalen van de gedefinieerde Findable, Accessible, Interoperable en Reusable (FAIR) data principes en de door literatuur gestelde DPP eisen.

Binnen de Architecture, Engineering en Construction (AEC) industrie wordt veel informatie uitgewisseld en opgeslagen met het gebruik van BIM en IFC. Een BIM model is een locatie waarin (delen van) de benodigde onderwerpen veelal (op elementniveau) worden ondergebracht. Daarnaast dient de informatie beschikbaar te zijn op product en materiaal

niveau om een volledig paspoort te creeëren. Dit kan bijvoorbeeld door de databases van de fabrikant te integreren met de te verkrijgen data van het, naar IFC of andere data modellen, geëxporteerde BIM model Dit kan onder andere door het gebruik van Linked Data waardoor de informatie bij de bron blijft en er minder kans is op fouten door communicatie. Daarnaast is men zeker van de meest up to date data en blijft iedere eigennaar verantwoordelijk voor het eigen onderdeel. Om Linked Data te gebruiken is de data van het IFC omgezet naar RDF. RDF is een standaard data model dat gebruikt kan worden om web resources te beschrijven. Linked Data maakt gebruik van RDF triples om de data te structureren samen met bijbehorende relationships. Meerdere triples vormen gezamenlijk een knowledge graph. Zo ook wanneer een DPP opgesteld wordt. De combinatie van het IFC samen met eventuele product en materiaal informatie kunnen een knowlegde graph vormen. Oftewel een Linked Data gebaseerd DPP. Linked Data bestaat uit ontologieën, welk dienen om informatie te organiseren en toe te wijzen. Momenteel is er geen gepubliseerde ontology voor Mps en DPPs aanwezig. Om dezer reden stelt dit onderzoek een DPP ontology voor welk in lijn is met opgestelde must-haves om een DPP op te zetten.

Om dit mogelijk te maken werkt Linked Data met ontologieën. Deze ontologieën structureren de informatie en geven bijbehorende betekenis. Momenteel is er geen (gepubliceerde) versie van een DPP of MP ontologie die hergebruikt kan worden. Om deze reden is er een DPP ontologie aangedragen gebaseerd op de door literatuur en expert workshop gedefinieerde must-haves.

Zoals eerder benoemd dient de data en structuur van het DPP gevalideerd te worden. Om het Linked Data gebaseerd DPP te valideren wordt de rule checkings system van Eastman et al. (2009) aangehouden. Dit systeem bestaat uit vier stappen, namelijk (1) de interpretatie van regels en logisch structureren, (2) het voorbereiden van het model voor de controle, (3) het uitvoeren van de gestelde regels en als laatst (4) het rapporteren van de resultaten.

Voor stap 1 dienen de regels opgesteld te worden. Deze regels zijn gebaseerd of de classified rule types van Lee et al 2016. De validatietool dient onder andere te controleren of de must-haves aanwezig en ingevuld zijn, niet dubbel voorkomt, het data type correct is en of de invulling van de data correct is. Daarnaast is een regel aangedragen om te valideren of de data valt binnen gestelde limieten.

In stap 2 dient het IFC model voorbereid worden voor de check. In de context van dit rapport wordt dit model omgezet naar een RDF bestand. Wanneer het Revit model niet goed ingeregeld is, kan dit zich doorvertalen in het RDF waardoor deze onbruikbaar is. Hierdoor is het van belang het bestand te controleren alvorens het gebruikt kan worden. Naast het IFC dient er een paspoort gekoppeld te worden. Er zijn verschillende paspoort formats vergeleken echter sloten deze formats momenteel niet aan op de gestelde eisen. Om deze reden is een materiaal en product database aangemaakt in RDF welk ingevuld is met dummy data. Het RDF van het gebouw is vervolgens gekoppeld aan deze product en materiaal informatie.

Voor stap 3 moeten de gestelde constraints uitgevoerd worden. Binnen Linked Data kan dit in verschillende talen. In dit onderzoek zijn de SHapes Constraint Language (SHACL) en de Shape Expressions (ShEx) vergeleken. Uiteindelijk is SHACL gekozen om de validatie uit te voeren, aangezien deze over een breder spectrum van mogelijkheiden beschikt en aangedragen wordt vanuit het World Wide Web Consortium (W3C). De gestelde constraints zijn vervolgens vertaald in SHACL.

In stap 4 dient vervolgens het validatie gerapporteerd gegenereerd te worden. Hiervoor dient de SHACL (het controlebestand) de RDF bestanden te valideren. Dit wordt gedaan door middel van PySHACL. Deze python code genereerd een validatierapportage in een terminal in Studio Visual Code (het programma waarin de scripts worden gemaakt). De PySHACL code is vervolgens aangepast, zodat deze ook een PDF print met de belangrijke informatie , zoals de ontbrekende onderwerpen, de foutief ingevoerde onderwerpen en bijbehorende 'Globally Unique Identifier' (GUID). Deze GUID kan vervolgens gebruikt worden om de fouten te verbeteren in de oorsprong: het Revit bestand en eventuele materiaal en product databasen/ paspoorten. Als zodanig presenteerd deze master thesis een aanpak voor het opschalen van Materiaal Paspoorten naar controleerbare Linked Data-gebaseerde Digitale Product Paspoorten voor de AEC industrie.

Abstract

The use of materials is not indefinite. Producing new materials results in significant CO2 emissions across the entire value chain of the construction industry. To address this, action at the highest level of the 10R ladder is crucial, focusing on "Refusing," "Reducing," and "Renewing" materials, which also encompass the reuse of materials. Material Passports can play an essential role in facilitating this process. However, the absence of a standardized format for these passports and the lack of consensus among stakeholders regarding their content pose challenges. Furthermore, data verification is essential to enhance the likelihood of reuse. A Digital Product Passport (DPP) (expected to become mandatory by 2026) can address these concerns and is regarded as a solution to the issue of inconsistent and unreliable information. Additionally, the DPP can serve as a tool for tracking and tracing. The stakeholder responsible for introducing a product to the market will retain the responsibility of providing the DPP. Consequently, throughout the entire lifecycle of a product, multiple DPPs will need to be exchanged to ensure the data is available and up-to-date. Given the amount and complexity of information and its stakeholders, Linked Data can help prevent the loss of information.

This study introduces a DPP format and validation process using BIM and semantic technologies. It applies this format and process to two case projects (a transformation building and a terraced house) stored in RDF graphs. Additionally to the RDF graphs, a product and material database is established. Based on defined 'must-haves' a DPP ontology is proposed, and validation rules in the Shape Constraint Language (SHACL) are created. The final validation is carried out using a enhanced pySHACL script. This script generates a file with any constraint violations and corresponding IFC GUID. Based on this information the original files can be improved. The proposed process and a prototype mock-up of a dashboard are validated using requirements, competence questions, and user input. This format and validation will contribute to the standardization and correctness of DPP data to increase the chances of object reuse in the future.

Keywords: Building Information Modeling (BIM), Linked Data, Digital Product Passport, Material Passport,

List of Abbreviations

A-Box	Assertion Box
AEC	Architectural, Engineering & Construction
BAMB	Building As Material BANK
BCAO	Building Circularity Assessment Ontology
BEO	Building Element Ontology
BIM	Building Information Modeling
BLC	Building Lifecycle Ontology
BMAT	Building Material Ontology
BMP	Building Material Performance Ontology
BOT	Building Topology Ontology
BPO	Building Product Ontology
CAMO	Circular Materials and Activities Ontology
CDW	Construction and Demolition Waste
CEO	Circular Exchange Ontology
CO_2-eq	Carbon Dioxide Equivalent
CPOV	Core Public Organizaton Vocabulary
CQ	Competency Questions
CTO	Construction Tasks Ontology
CWA	Closed World Assumption
CPR	Construction Products Regulation
CSRD	Corporate Sustainability Reporting Directive
DBL	Digital Building Logbook
DICBM	Digital Construction Building Material Ontology

DPP	Digital Product Passport
EoL	End-of-Life
EPD	Environmental Product Declaration
EPR	Extended Producer Responsibility
ESPR	Eco-design for Sustainable Products Regulation
ESRS E5	European Sustainable Reporting Standard E5
ETL	Extract Transform Load
FAIR	Findable, Accessible, Interoperable and Reusable
FOAF	Friend Of A Friend Ontology
FOG	File Ontology for Geometry
GDPR	General Data Protection Regulation
GHG	Greenhouse Gas
GUID	Globally Unique Identifier
LBD	Linked Building Data
LCA	Life Cycle Analysis
LOCN	Location Core Vocabulary
LOD	Linekd Open Data
IDS	Information Delivery Specifications
IFC	Industry Foundation Classes
IRI	Internationalized Resource Identifier
MoSCoW	Must-haves, Should-haves, Could-haves and Won’t-haves
MP	Material Passport
MPO	Material Passport Ontology

MVD	Model View Definition
OECD	Organization for Economic Co-operation and Development
OMG	Ontology for Managing Geometry
OPM	Ontology for Property Mangement
ORG	Organization Ontology
OWA	Open World Assumption
OWL	Web Ontology Language
PCI	Precast Concrete Insitute
PRISMA	Prevention and Recovery Information System for Monitoring and Analysis
PROV	Provenance Ontology
QUDT	Quantities, Units, Dimensions, and Types Ontology
RBox	Rule Box
RDF	Resource Description Framework
RDFs	Resource Description Framework schema
RFID	Radio Frequency Identification
SPARQL	SPARQL Protocol And RDF Query Language
SPIN	SPARQL Inference Notation
SHACL	Shapes Constraint Language
ShEx	Shape Expressions
SPARQL	SPARQL Protocol and RDF Query Language
SPI	Sustainable Product Initiative
SWRL	Semantic Web Rule Language
T-Box	Terminology Box
UML	Unified Modelling Language

URI	Uniform Resource Identifier
URL	Uniform Resource Locator
W3C	World Wide Web Consortium

Glossary

Area	Spatial area. The complex includes adjacent greenery/land (Platform CB'23, 2019).
Attribute	A feature or characteristic that describes something or someone.
BIM model	Building information modeling (BIM) is the holistic process of creating and managing information for a built asset (Autodesk, n.d.)
Building	Designation of the structure built or to be built that forms a whole and fulfills a specific function (e.g. residential building, transformation building, and railway track) (Platform CB'23, 2019).
Cardinality	The number of elements in a set.
Circular loop	The products/raw materials are reused in numerous life cycles. They remain available within the same loop. As a result, there is hardly any waste.
Class	A class is a template that can be used to create objects that contain both data (attributes) and functions (methods) that can operate on that data.
Closed-loop system	Keeping products/raw materials in the same loop without creating waste. See "circular loop.
Complex	Collection of related (construction) works, where this collection fulfills a specific function, e.g. highway and shopping center (Platform CB'23, 2019).
Economic operator	Stakeholder responsible for the Digital Product Passport information associated with its object (Cobuilder International, 2023).
Element	The (abstract) parts of a (building) work that are distinguished solely based on a desired function (Platform CB'23, 2019).
Environmental footprint	The effect that a person, activity, company, etc. has on the environment based on a life cycle approach.
Instance	A specific object created from a class, where it inherits the attributes and methods of that class and can have its own unique set of attribute values.

Linked Data	A method for publishing structured data in such a way that it can be made available on the Web and therefore more usable. In addition that the information can be uniquely linked relationally (Bizer, Heath, et al., 2009).
Material	The processed raw material used for the manufacture of construction products (Platform CB'23, 2019).
Object	An object is an overarching term, a combination of material, product, element, and building.
Ontology	An ontology is a formal, explicit specification of a shared conceptualization (Pauwels et al., 2022).
Product	Products that are delivered to the construction site and are part of an element after processing. In the case of prefabrication, products are already manufactured into elements before they are delivered to the construction site (Platform CB'23, 2019).
Property	A property is a characteristic or attribute of an object in a class. It contains information about the object and can contain several datatypes.
Raw material	The raw material is an unprocessed fabric. Fossil raw materials are made into materials by an artificial process, which cannot easily be returned to the original raw material (Platform CB'23, 2019).
Recycle	Reusing materials from waste. Products cannot be reused without turning them into a new product (European Commission & Directorate-General for Financial Stability, 2023). E.g. reusing a door as a table.
Reuse	Reusing materials/products while maintaining the original purpose (European Commission & Directorate-General for Financial Stability, 2023). For example, reusing a door in another building.
Revit	BIM software widely used by architects, engineers and contractors .
Semantic Web	A vision and set of technologies that enrich Web pages with structured data, allowing computer systems to better understand and process what is on the Web (W3C, 2024)
UML	UML is a general-purpose, developmental, modelling language that is interlinked to provide a standard way to visualize the design of a system it is used in the field of software engineering (Pauwels et al., 2022).

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Introduction

1. Introduction

The introduction section provides an overview of the research context and the specific issue that will be addressed in this thesis. Additionally, the research questions are outlined, and the chapter concludes with a roadmap for the remaining sections of this thesis.

1.1 Background

The built environment is one of the biggest contributors to the significant use of natural resources. The International Energy Agency (2022) reports that the combined sectors of buildings and construction account for 30% of global final energy consumption and 27% of total energy sector CO_2 emissions. These numbers are increasing, driven by factors such as developing countries' growing access to energy, and the rapid growth in floor areas of global buildings (International Energy Agency, 2022).

Various materials, such as metals and sand, are utilized in the creation of concrete, frames, glass, and other construction elements. Unfortunately, these materials are depleting rapidly, which poses a significant environmental challenge in terms of planetary boundaries (Anderson et al., 2015);(Rockström et al., 2009);(Steffen et al., 2015) The depletion of these materials causes negative effects on the environment. Additionally, it is important to take into account the high embodied energy required for the transportation and processing of these materials, which results in high CO_2 emissions (Mehra et al., 2022). The building construction industry is responsible for a substantial 38% of the total global energy-related CO_2 emissions (United Nations Environment Programme, 2020).

Circularity in the built environment

In recent years, the Netherlands has made a gradual shift from a linear economic (consumption) model to a circular economic model, as its aim for a sustainable future. In the linear model, commonly referred to as the "take-make-waste" model, an emphasis is placed on virgin materials and inefficient waste streams, which are not sustainable in the long run as the resources are not infinite (Loppies, 2015); (Zhang et al., 2021). Therefore, a transition to a circular economy is essential. Caldas et al (2022) further highlight the increasing relevance of the circular economy in the Architecture, Engineering and Construction (AEC) industry since 2009, as the sector is responsible for 50% of raw material consumption and 35% of all waste (The Swedish National Board of Housing, Building and Planning 2023;European Commission, 2020). Greenhouse gas (GHG) emissions from material extraction, manufacturing of construction products, as well as construction and renovation of buildings are estimated at 5-12% of the total national GHG emissions. According to the European Commission, greater material efficiency could save 80% of those emissions (European Commission, n.d.-a).

In the ideal circular construction, all materials and components will remain in the circular loop (continuous loop), with no waste generated. The output of materials is used as input materials for new products, creating a closed-loop system. The circular economy aims to minimize its environmental footprint by eliminating the use of toxic chemicals and relying on renewable energy (Ellen Macarthur Foundation, 2013) (See Appendix A, Figure 1a). This approach circularity helps to prevent the depletion of natural resources.

Three indicators for circularity on the planetary level are defined by Huesemann & Huesemann, (2011) :

> "1. All energy comes from renewable sources at or below renewable rates.
>
> 2. All materials come from renewable sources at or below renewable rates
>
> 3. Waste (this includes emissions) can only be released at or below assimilation rate, without negative impacts for the ecosystem or biodiversity" (Huesemann & Huesemann, 2011)

When it comes to materials, it is important to follow the 4R principle which stands for Reduce, Reuse, Recycle, and Recover, in that order of priority. The highest priority is to save and reduce the amount of materials needed. Second, is the reuse of material whenever possible. Third, the materials should be recycled as much as possible, and last, the remaining materials should be recovered (Kirchherr et al., 2017). This principle can be further broken down into the 10R principle of Cramer (2017) (See Appendix A, Figure 2a). The higher the material is situated, the more circular it is. Unfortunately, most of the Construction and Demolition Waste (CDW) in Europe is situated in the lower rank. The recovery rate for CDW in the Netherlands has reached 91% since 2001 and (almost) 100% since 2010. In 2018, 100% of CDW was recovered (Statista, 2024) and in 2012, 95% was recycled (Deloitte, 2015). However, recycling alone is not enough to achieve a circular economy. Therefore, the focus needs to be on the top of the ladder, including Refuse, Reduce, and Renew, among others. This is important to add value and stay within the planetary boundaries (Cramer, 2017a).

"Nederland Circulair in 2050" (Ministerie van Infrastructuur en Milieu & Ministerie van Economische zaken, 2016) (sets an ambitious goal for achieving a 50% reduction in primary raw material consumption by 2030 and a fully circular economy in the Netherlands by 2050. The European Union has also developed action plans to promote circularity throughout Europe (European Commission, 2020b). The construction sector is a key player in this movement, transitioning from the linear 'take-make-waste' approach towards a circular economy (Breteler, 2022). While the initial focus has been on recycling building materials, it is not always needed to make the material go back to its original state. Even though there is a shift toward reuse possibilities, reused materials in new constructions are still limited (Caldera et al., 2020; Hart et al., 2019).

To facilitate the reuse of materials in a circular economy, materials and components are extracted from existing buildings. In 2021, the Netherlands had approximately 9.13 million buildings. This includes apartments, which are counted as separate housing units. In 2019, approximately 10800 buildings were designated for housing, and around 5430 utility buildings were demolished (Economisch Instituut voor de Bouw, 2022). In April 2021, the number of buildings ready for demolition was around 1300 (SGS Search, 2021). This release of materials provides dozens of opportunities for potential reuse.

Although the concept of circular construction is promising, there are still several challenges to overcome to achieve a high percentage of material and component reuse. Ideally, all materials and components should remain within the circular loop (Ellen Macarthur Foundation, 2013).

However, policies and regulations governing material research and inspection lack guidelines and standards for assessing the structural integrity of reused components, making reuse difficult. Additionally, there is a lack of information about the quality of components being available in the early stages (Charef et al., 2021;Platform CB'23, 2022). As a result, the risks, uncertainties, and costs of the reuse of materials over the use of new materials are significant. Moreover, it is challenging to match supply and demand for available materials across different parties, considering factors like time, location, availability and quality (Rijkswaterstaat, 2020).

A Material Passport (MP) can provide a solution to the problem mentioned above. Using a MP, materials can get their own ditigal identity and can be traced across life cycles. The passport enables high-quality reuse of materials and the related material data, and contributes to more effective management and maintenance. An MP comprises information about the type and quantity of the material, the method of installation, and the location of the objects. Any changes made during the use phase are also recorded in the passport. Additionally, the information about the quality and (financial) worth is linked to it (Rijkswaterstaat, 2020).

With the Introduction of MPs and similar methods of preserving data required for maintaining a high-quality circular loop (reuse and recycling), a need for data standardization and validation is required. This helps ensure that the appropriate data quality standards are upheld when the need for reuse or recycling arises.

1.2 Problem statement

MPs offer a promising approach to support the circular economy in the construction sector. However, the implementation of MPs faces several challenges in the commercial, political, social, and technical areas that require further research and collaboration among stakeholders to make the process more feasible and accessible. MPs are a relatively new concept and are not widely implemented in the construction sector yet. Even though there is a growing awareness of the circular economy, more steps should be taken and additional research has to be done (Buchholz & Lutzkendorf, 2022; Goswein et al., 2020). One of the main issues is the lack of a standard for this tool leading to interoperability issues, data uncertainty, and misinterpretation of data. Another problem arises when looking at the maintenance of MPs. When considering the lifespan of buildings and the uncertain number and type of building owners over multiple life cycles, storing and updating the data can be a challenge (Goswein et al., 2020).

Currently, the Digital Product Passport (DPP) as a related concept is also making an entrance, as it also aims to enable the tracking and tracing of objects, including the provenance of materials. The DPP is a more comprehensive version of the MP (Çetin et al., 2023) and is expected to become a legal requirement by 2026. Product passports are generally seen as a solution to "the lack of consistent and precise information flow about resources, products, and processes" (Walden et al., 2021). Nevertheless, there is still a lot of uncertainty about the DPP concept and its implementation in the construction industry. Just like an MP, there is no standardized format (Çetin et al., 2023), and the regulations surrounding it are yet to be established.

1.2.1 Research Gap & Research Objective

To transition to a circular economy, the AEC industry must address its environmental impact and the increasing depletion of materials. Therefore, change is required to highlight the importance of material reuse. DPPs can enable this change. However, progress is still needed to enable a standard format and method for their implementation and validation. In addition, the data needs to follow the Findability, Accessibility, Interoperability and Reusability (FAIR) principles and be stored, updated, and made available in a way that an optimal amount of materials can be reused. This research aims to investigate the implementation of DPPs using Building Information Modelling (BIM) and Semantic Web technologies with the overall purpose of defining a standard DPP format and a method for validating the passport structure and content.

The objective of this research is to enhance the understanding of DPPs in the AEC industry and enable their implementation and reuse using scalable and extensible semantic technologies. The research further seeks to contribute to the use of DPPs in construction companies. As such, the focus is also on validating the data in the passports. This will enable a workflow, in which contractors can control and maintain the quality of the data required for the standard DPPs.

1.2.2 Research Question

The literature study and the problem definition lead to the following main research question:

How can a Digital Product Passport for the AEC industry be created and validated using BIM and semantic technologies?

This main question will be split up into multiple sub-questions. These include:

1. What is the current state-of-the-art of MPs, DPPs, automated data validation tools, BIM-based technologies, and semantic technologies?
2. Which parts of a DPP will need to be validated and which part of the validation process is required by the contractor?
3. How can a proof-of-concept for the DPP validation method be developed and tested in a real-world use case?
4. How can the validation process and output be visualized and feedback - provided to the end user?

1.3 Reading guide

In the text below the structure of this thesis is described.

Literature review

Chapter 2 describes the methods used to perform the literature review. Chapter 3 explores the state of the art of Material Passports in the AEC industry. For this purpose, the context of a Material Passport is determined, as well as, its functions. The different formats are cited and the challenges are named. In Chapter 4, we move from the Material Passport to a Digital Product Passport. It explains what the passport entails, the regulations and standards that (may) be involved, and the challenges. Chapter 5 briefly discusses the state-of-the-art of various data uses in the AEC industry. For example, BIM and IFC are briefly cited and followed up with Linked Data and Semantic Web technologies. The literature concludes with Chapter 6 which will discuss the validation process, rule types, and the different rule-checking language

The expert workshop

Chapter 7 defines the format of the Digital Product Passports. First, the methodology is explained and then the input and elaboration of the questionnaire and workshop are discussed. This concludes by discussing the outcomes in the form of a list of must-have topics.

Prototype design

Chapter 8 discusses the prototype design. it goes through the various steps to arrive at the validation process. This starts with a methodology. Next, requirements and competence questions are drawn up, after which a UML is created. Data is selected to be applied for the validation process, and a DPP ontology is provided. Lastly, the data is prepared, and the validation process is set up.

Prototype evaluation

Chapter 9 discusses the evaluation of the validation process. Here the process is validated with input from company experts. In addition, the databases are checked against the competence questions and the requirements established in Chapter 8 are checked.

The conclusion

Chapter 10 concludes the thesis with a discussion, scientific and societal contributions, recommendations, and conclusion.

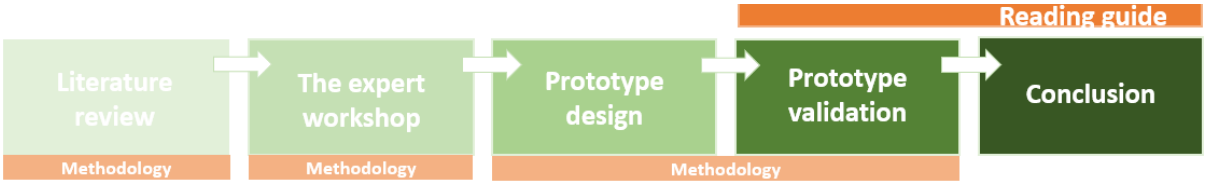


Figure 1: Reading guide

Literature Review

2. Literature review as a research approach

The following chapter will delve into the literature approach, offering a brief overview of the PRISMA method and outlining the various steps involved in conducting the literature review.

2.1 The systematic review methodology

The literature discussed in the following chapters laid the groundwork for the development of the DPP prototype, serving as a precursor to establishing the foundational knowledge. This research employed a systematic review method using the PRISMA method. This review method offers a concise overview of prior studies and knowledge gaps are identified based on the synthesized results. PRISMA consists of a checklist including seven subjects of review, including the studies' title, abstract, introduction, methods, results, discussion, and other information. Each subject is again divided into multiple subtopics (Page et al., 2021). During this research, the PRISMA checklist is translated into a more general checklist, to adjust to this thesis subject, see Table 1.

The subjects have been dealt with in their entirety instead of per subtopic. Furthermore, four extra checks were included. These are the inclusion or exclusion criteria. The inclusion criteria are: (1) the article needs to be in English or Dutch, (2) the method needs to be relevant to the research, (3) the research should be in the context of in the AEC industry, and (4) the articles should be published after 2018. The last two checks are less strict depending on the influence of the article.

Table 1: Literature checklist based on the PRISMA Method

Topic	**Research**
Title	The title of the research
Abstract	The abstract of the research in total
Introduction	Split up in rationale and objectives
Methods	Split up in type of method and type of data being used
Results	The results of the research
Discussion	The limitations of the research and implications of the results
Other information	Key-words, short summary of subject, include or exclude and reasoning behind it, writer, year, and number of citations
Relevant AEC	The relevance of the article towards the AEC
>2018	A recent article, no outdated information
English or Dutch	The article is written in an understandable language to the researcher
Method relevant	The method used in the article is relevant to the context of the research

All articles were sourced through the utilization of the Scopus research engine. Initially, a curation process was initiated by employing specific keywords, namely "Material Passports" and "Built Environment." Another combination consisted of "Material Passports" and AEC Industry", "Digital Product Passports" and "Built Environment", and finally "Digital Product Passport" and "AEC Industry." Next, a screening was executed based on the title, abstract, and keywords of the articles. Subsequently, an extensive analysis and synthesis of the chosen papers was undertaken. Simultaneously, additional articles were identified through the snowballing method. In addition to Scopus, alternative research engines (Google Scholar) were explored. However, no additional information was found. Consequently, no articles retrieved from these alternative engines were incorporated into the study.

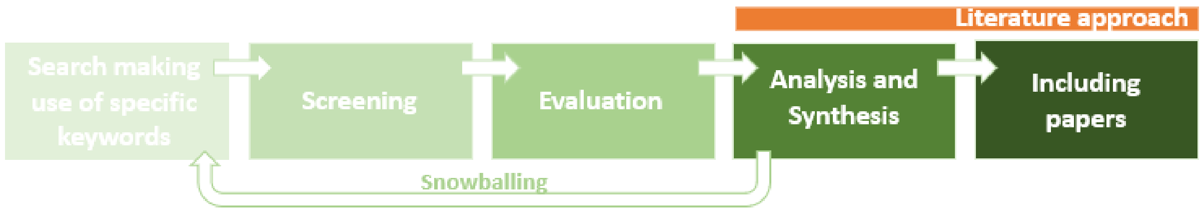


Figure 2: Systematic literature review approach

3. Material Passports in the AEC industry

The current chapter explores the state-of-the-art literature on Material Passports (MPs) within the AEC industry. First, the contextual framework of the MP is explained, followed by an overview of their diverse purposes. Subsequently, the study proceeds by explaining the various formats and alternative approaches associated with MPs.

3.1 Material Passports: context and definition

The MP has emerged to understand and enable the closing of material flows (Heisel & Rau-Oberhuber, 2020). The MP concept does not have a common definition, explanation, and data format. This lack of standardization is evident in the various names used to indicate the same concept, such as resource passport, recycling passport, building passport, etc. This research will utilize the MP convention, since this term is most often used in the existing literature (van Capelleveen et al., 2023). van Capelleveen et al. (2023) investigated the available MPs in the literature and formulated the following overarching definition:

"A material passport (or product passport) is a digital interface composing a certified identity of a single identifiable product by accessing the set of life cycle registrations linked to this object to yield insight into the sustainability and circularity characteristics, the circular value estimation, and the circular opportunities for both that product and its underlying component and materials." (van Capelleveen et al., 2023, p. 14).

3.1.1 The stages of a Material Passport

The MP has various purposes throughout its life cycle of a built facility. Honic et al. (2019a) consider four stages for the MP (see Figure 3). **MPa** is understood as a rough analysis and optimization tool during the conceptual design stage. In this phase, variant studies are conducted to determine the most suitable construction regarding recycling and reuse potential and environmental impact. In other words, this stage has the largest impact in terms of reuse, recycling, waste, and environmental impact. In terms of BIM modeling, unique challenges arise. For example, in the conceptual stage, precise geometry must be accurately modeled while ensuring that each BIM element is correctly classified. When executed accurately, the MPa has the potential to serve as a valuable decision-support tool for conducting variant studies (Honic et al., 2019a).

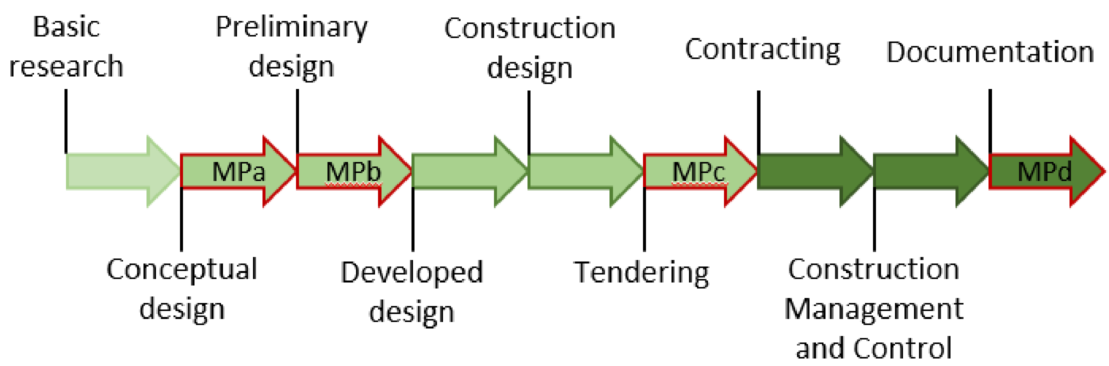


Figure 3: Stages of a Material Passport

The **MPb**, on the other hand, is utilized as an optimization tool during the preliminary design phase where thicknesses and specific layers can be adjusted. During the preliminary design phase, a multi-layered model is created which includes information on the material, volume, and thickness of each layer. It is important to utilize the provided building element template, although minor adjustments such as altering the material of a layer can be made if necessary (Honic et al., 2019a).

The **MPc** is utilized during the tendering stage to assess the exact material composition. Finally, the **MPd** serves as the final document where the material/product inventory of the building can be found. This document will be the basis for a secondary raw materials cadaster (Honic et al., 2019a).

3.2. Existing Material Passport formats and implementations

The strive towards the circular economy has resulted in many cross-sector and sector-specific passports (Jansen et al., 2022). One of the first conceptualizations of the MP was proposed by Hansen et al, (2013) and is called "Nutrition Certificates." These certificates describe the characteristics of materials to encourage their recovery or reuse in continuous loops, instead of becoming waste (Hansen et al., 2013). A MP prototype was also developed as part of the Buildings as Material Banks (BAMB) project. This prototype tracks the residual value of building products along the supply chain (Luscuere, 2017;BAMB, 2019). Çetin et al. (2023) consider the MP for the building industry by Madaster Foundation (a not-for-profit entity) as one of the first commercialized MPs. Madaster is an online platform that provides insights into the products and materials used in buildings, their economic value, and prospective carbon emissions (Madaster, 2023).

In addition, Honic et al. (2019b) developed an MP with various variants to assess environmental impacts. The MP was used in a case study that compared the environmental performance of concrete and timber. Meanwhile, Munaro et al. (2019) created an MP for the wood frame system in the Brazilian industry. The authors found that the lack of reliable input data and the lack of Environmental Product Declarations (EPDs) hinders the creation of MPs. To overcome these obstacles, a consolidated database of MPs can provide a solution to optimize and evaluate the environmental impact and recycling potential of products and materials. However, political, commercial, social, and technical challenges continue to hinder the creation of FAIR MPs (Honic et al., 2019).

A new MP standard is currently under development by CB'23. Various stakeholders are involved during projects in the AEC industry and each has a different perspective on what a MP standard entails (Kovacic et al., 2020; Platform CB'23, 2022; Platform CB'23, 2023). Therefore, the standard proposed ny CB'23 aims to provide a unified format for different passport types currently in circulation, allowing for easy comparison and connection between them. This is necessary due to the lack of agreements between different passport administrators.

3.2.1 BIM-Based Material Passports

BIM models can be used to create MPs. Both the BAMB project and Honic et al. (2019b) proposed methods to generate MPs based on BIM data (Heinrich & Lang, 2019) and enable them to function as a design optimization and inventory tools. Commercial Mp implementations are created by Madaster (Madaster, 2023) and Cirdax (Cirdax, 2023). The web-based Madaster platform enables registering building materials, calculating the level of circularity of buildings, providing an overview of the economic value of materials, and managing material circularity (Madaster, 2023). Furthermore, Honic et al. (2021) also developed a novel method to be able to expand MPs towards existing buildings by incorporating BIM and laser scanning technologies (Honic et al., 2021).

BIM is most often used by architects and engineers in the design process. It enables the creation, storage, sharing and reuse of valuable data on design, building, and material properties, and allows design communication between stakeholders in collaborative environments. As such, BIM can offer a data foundation to generate MPs, support data exchange and contribute to narrowing, slowing down, closing, and regenerating the resource loops. Furthermore, BIM can be used in combination with Radio Frequency Identification (RFID) tags and blockchain to store information about the material. However, it is emphasized that BIM models are hardly used or updated upon project completion (Çetin et al., 2022).

3.3 Alternatives for Material Passports

There are various technologies and naming conventions that can be considered as some form of passports, such as cradle-to-cradle passports, eco-labels, and Digital Twins (Adisorn et al., 2021), smart labeling, Circular Material Passports (Göswein et al., 2022), and DPPs. However, there is a difference in the scope and application of each. For example, the DPP is typically product-level and can be used on cross-industry level.

The Digital Building Logbook (DBL) on the other hand, can also be used in this context. However, the DBL can be used o building level while the scale of MPs can be on area, complex, building, element, product, material, and raw material levels (Çetin et al., 2023).

The DBL is defined as a common repository for all relevant building data; it facilitates transparency, trust, informed decision making and information sharing within the construction sector, among building owners and occupants, financial institutions and public authorities (European Commission, 2020b). The DBL covers several sustainability aspects and is not only limited to circularity.

3.4 Challenges and limitions to material Passport implementation

Although the MP concept has been circulating for several years, there are still challenges to be addressed. One issue is the **differing descriptions** of what the passport aims to accomplish, leading to confusion among stakeholders and limiting the ability to establish consistent semantic and technical standards. The MP could encounter a challenge in **maintaining a continuous stream of material information**. As an illustration, Hoosain et al. (2020), suggest that steel commonly used in construction can be recycled without the need for extensive laboratory tests. However, changes in the characteristics of steel may occur when exposed to fire, underscoring the importance of knowing the usage history of building materials (Hoosain et al. 2020).

Additionally, the **lack of EPDs and reliable input data** hinders the MP creation (Munaro et al., 2019). The use and existence of a consolidated database of MPs can enable a solution to optimize and evaluate the environmental impact and recycling potential (Munaro et al., 2019). However, **challenges in various political, commercial, social, and technical areas** need to be overcome to enable the creation and implementation of MPs (Honic et al., 2019).

4. Scaling Material Passport to Digital Product Passport

The following section explains the Digital Product Passport (DPP) concept. It provides insights into what a DPP entails and what it consists of. Furthermore, it provides insights into the potential requirements and regulations that could affect the wider implementation of DPPs.

4.1 Digital Product Passports: context and definition

The MPs are crucial in the transition from a linear to a circular building industry. Yet, this requires standardization of the tool and sets of common requirements and conventions, which do not exist yet. The DPP was proposed by the European Commission as a more future-proof and timely alternative that serves as a regulatory framework “for setting eco-design requirements for sustainable products” (European Commission, 2022a). The DPP provides information about a product’s durability, composition, origin, reuse, repair, dismantling possibilities, and end-of-life- handling. In addition, it shall be put into service or be applied to any physical good placed on the market (European Commission, 2022d). Product passports are often seen as a solution to the lack of precise and consistent information flow about products, resources, and processes (Walden et al., 2021). Furthermore, a DPP can act as a ‘track and trace’ instrument (using unique identifiers) for life cycle assessments of unique and pooled product information (Adisorn et al., 2021;de Römph & Cramer, 2020). It is seen as a uniquely identified and verified Digital Twin of a product and the economic operator placing this product on the market is responsible for creating a DPP and making it publicly available (Cobuilder International, 2023). The DPP can allow the envisioned exchange of collected product-related life-cycle data. As such, DPPs can become essential to supporting the adoption of a circular economy and realizing the associated resource savings (Adisorn et al., 2021;Walden et al., 2021;Berg et al., 2022;Plociennik, Pourjafarian, Nazeri et al., 2022). Furthermore, Adisorn et al. (2021) performed a stakeholder workshop in which it was argued that a DPP can also function as a substance inventory to keep a view of the valuable secondary raw materials and a capital stock of the future. According to van Capelleveen et al. (2023), the terminologies of a MP and DPP are very similar, and in the literature, the terms and meanings are used interchangeably. Furthermore, there is a wide range of approaches, and companies also make use of their own formats and representations (Çetin et al., 2023). This leads to multiple formats and, ultimately, no uniform format being available (for both MP and DPP). Adisorn et al. (2021) performed a comparison between MPs and DPPs. Table 2 shows the results of the comparison.

Table 2: Comparison of Digital Product Passports and Material Passports, (Adisorn et al., 2021)

Comparison of Digital Product Passport & Material Passport		
	Digital Product Passport	**Material Passport**
Status	Pre-conceptual phase	Demonstration
Product Category	Any physical good that is placed on the market or put into service. This also includes subproducts.	Building materials
Key Information Categories	Composition, origin, repair, and dismantling, handling at the end of its service life	Information on reuse of materials; cross-ref. to data sheets, EPDs
Life-Cycle Phase Targeted	Repair, production, and disposal to complete life-cycle	End-of-Life
Data Tool	Unknown	The MP platform, BIM discussed
Information Providers	Suppliers, manufacturers	Manufacturers
Target Groups	Consumers, market surveillance. Any Industry (including Built Environment)	Architects, builders, and deconstruction companies. Built environment

4.1.1 Structure of the Digital Product Passports

A DPP can consistof different 'sub-DPPs.' For each stage of the supply chain of an object, a DPP can be made. A product can also consist of different subproducts, each with its own DPP (Watson et al., 2023). In addition, each of these DPPs can each contain different information depending on the needs of the responsible stakeholder. Therefore, the information must be clear on all levels and provide the right level of detail as required for every stakeholder (Adisorn et al., 2021). The stakeholder (economic operator) who places the object on the market is responsible for creating the DPP and making it available to the public (Cobuilder International, 2023). Additionally, this means that a lot of information will need to be exchanged during the process to create a full overview of information to be used after the end of the life of the object. To prevent data loss during the exchange, a Linked Data-saving method can bea solution (Watson et al., 2023).

For most manufacturers and suppliers the data flow is unidirectional. However, for the asset administration shell and DPPs a more multidirectional information flow is discussed. Especially during the operational phase, it might be challenging to acquire product information and to keep the DPP up to date (Adisorn et al., 2021;Eppinger et al., 2021). See Figure 4.

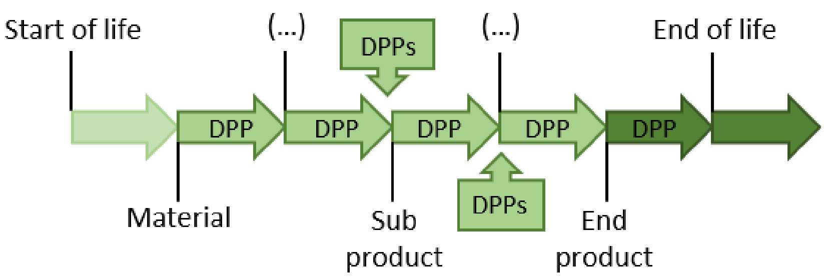


Figure 4: Cumulative DPP addition through the object life cycle (adapted from Watson et al., 2023)

4.1.2 Potential users of Digital Product Passports

Two main groups of users interact with a DPP. The first group consists of the 'suppliers of data', which includes manufacturers, wholesalers, and service providers. The second group is the 'users of data', which includes engineers, asset owners, consultants, and contractors. These users provide data that is utilized for various purposes such as product selection and improved decision-making. To ensure that the data is accurately retrieved and enriched, each piece of information must be assigned a unique identifier. All economic operators are held accountable for the quality of the data they provide throughout the lifecycle of the object (Cobuilder International, 2023).

The data users can also act as data providers for example during the maintenance, renovation, and demolition phases. It is essential to update the information during this period, particularly when an object requires maintenance. Additionally, when an object acquires new functions in the post-use phase, it becomes necessary to update its data. Çetin et al. (2023) provides a diagram of potential users during these phases, highlighting their influence. See Figure 5.

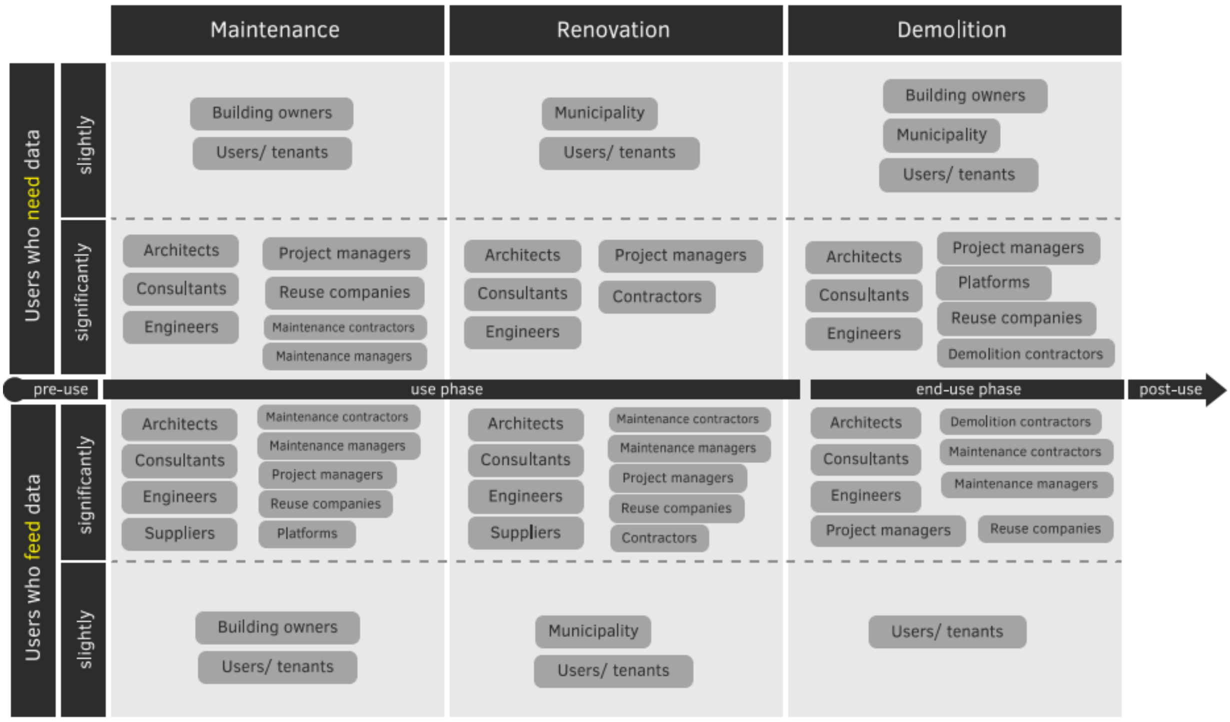


Figure 5: Stakeholder mapping potential users DPP in maintenance, renovation, and demolition phase, (Çetin et al., 2023)

4.2 Policy developments

Digitalization gained importance in the European policy landscape, especially for the EU's green transition (European Commission, 2022c). In 2022 the European Commission emphasized the role of Digital technologies in driving circular innovation. DPP usage is recommended together with tags and watermarks for sustainable products. These policy developments are followed by the EU's post-Covid recovery plan, which aims to strenghten sustainability efforts by accelerating investments in the "twin" transitions of digital and green technologies (European Commission, 2021). The DPP is also mentioned in other initiatives and frameworks such as the EU Green Deal (European Commission, 2019), the EU Sustainable Products Initiative (SPI) (European Commission, 2022d), and various industry-specific initiatives. Additionally, the DPP is also recognized by the German Federal Environment Ministry for achieving circularity at scale (UNECE, 2021).

The European Commission released a Circular Economy Package which includes a proposal for an Eco-design for Sustainable Products Regulation (ESPR). A DPP is identified in the ESPR to enhance the traceability of products and their components (Götz et al., 2022). In 2024, this legislation will likely come into force if the trilateral process between the European Parliament, European Council, and the European Commission is concluded. Afterwards, the DPP requirements will be defined for specific product groups as a part of the EU sustainable products initiative (Koppelaar et al., 2023). The EU Battery regulation is one of the most advanced passports and the first example of a DPP mandated by law from January 2026. The contents of this passport will be specified in the EU delegated act by December 2024 (Walden et al., 2021; European Commission, 2020b).

At the EU level, several efforts aim to introduce new passport instruments. An overview of the current DPP initiatives can be found in the Wuppertal Institute working paper (Jansen et al., 2022). The EU-funded CIRPASS project, which lasts from 2022 to 2024, also aims to establish a future overview (European Commission, n.d.-b;Digital Europe, n.d.).

4.3 Digital Product Passport data requirements

The main aim of the DPP is to improve the circularity of products (Walden et al., 2021) (Berg et al., 2022; Plociennik, Pourjafarian, Nazeri, et al., 2022)Plociennik, Pourjafarian, Saleh, et al., 2022). This includes providing stakeholders with relevant information about a product to encourage sustainable development (Adisorn et al., 2021). To accomplish these aims, a DPP would include the following data:

- **Manufacturing data** - includes essential information such as the product's composition, details about the manufacturing process (such as the joining technique used), and the chemical and physical properties of the materials. It also covers any nonhazardous or hazardous impact on the environment or human health (Plociennik, Pourjafarian, Saleh, et al., 2022; Adisorn et al., 2021;Guth-Orlowski, 2021).
- **Usage data** - includes information about replacement, products, parts, and repairs, and is essential for implementing circular solutions. (Plociennik, Pourjafarian, Saleh, et al., 2022; Harrison & Conrad, 2011). To facilitate collaboration among all value and supply chain stakeholders, this data must be presented in a standardized and comparable format. (Adisorn et al., 2021).

- **End-of-life (EoL) data** - includes the documentation on sorting, collecting, and treating objects during the EoL phase (Plociennik, Pourjafarian, Saleh et al., 2022).
- **Life cycle data** – includes, e.g., the products' sales volume and can provide valuable insights into the expected volume of waste at any given time and the potential for recycling resources (Plociennik, Pourjafarian, Saleh et al., 2022; Lell et al., n.d.). This information can be used to assess the environmental and social impact of the product throughout its life cycle, in addition to its origin (European Commission, 2022d). By leveraging full life cycle data, businesses can optimize the design, production, usage, and disposal of their products (Adisorn et al., 2021).

Access to this information can be made possible on the Web or by smart tags such as QR codes that are developed based on printed sensors to enable product or object identification offline (Gligoric et al., 2019).

4.4 Further requirements and regulations related to Digital Product Passports

Jansen et al. (2023) performed a requirement analysis for a DPP. These requirements are adapted and supplemented from ISO/IEC 25010:2011 for system and software quality. Furthermore, Buchholz & Lützkendorf (2022) made a selection of the most relevant data-related requirements addressed in Hartenberger et al. (2021) and (European Commission (2021b) relevant for digital building passports. The requirements are very similar and complement each other to create a more comprehensive list. The requirements stated by Jansen et al. (2023) and Buchholz & Lützkendorf (2022) are as follows:

- **Legal obligations**: It needs to be ensured that the DPP will be compliant with the General Data Protection Regulation (GDPR) (Berg et al., 2022;Jansen et al., 2023), the Extended Producer Responsibility (EPR), the EU government legislation "right to repair", and the new Ecodesign for Sustainable Products Regulation (ESPR) (Jansen et al., 2023).
- **Functional suitability**: Alignment with sector-specific needs is essential, particularly for supporting circular economy objectives and ensuring supply chain transparency. The DPP should not impede existing chain processes, product quality, or safety (Jansen et al., 2023).
- **Security, confidentiality, and IP protection**: The data must guarantee origin, integrity, verifiability, and compliance. Immutability is essential and secure data exchange within the value chain members must be ensured. The data control should remain with the data providers to safeguard intellectual property (Jansen et al., 2023; Buchholz & Lützkendorf, 2022).
- **Accessibility**: Ensure access for assigned parties through an access control mechanism. Furthermore, ensuring participation opportunities for the parties without stable internet connections or advanced IT systems (Jansen et al., 2023). According to Buchholz & Lützkendorf (2022), all required users needs permanent access to the whole life cycle data. Furthermore, the data should be easily understandable for the user.
- **Interoperability**: The DPP information must be exchangeable across different company boundaries. This interoperability within and between systems will be enabled using shared semantics and standardized data schemes (Jansen et al., 2023; Buchholz & Lützkendorf, 2022).

- **Modularity and Modifiability**: The DPP should offer flexibility, allowing users to make additions and modifications. Furthermore, actors, products, or attributes can be removed or adapted as requirements evolve, making it essential for the DPP to accommodate the changes in the value chain (Jansen et al., 2023).
- **Availability and Time behavior**: The information should be accessible when needed, with changeable requirements for real-time data in various use cases. Certain parts may need to be real-time capable (Jansen et al., 2023). The data always needs to be valid and up to date (Buchholz & Lützkendorf, 2022).
- **Portability**: The information should be transferable between software systems to enable decentralized systems. Portable product identifiers are needed to track a product's life cycle. In addition, they should be harmonizable and referenceable across the EU (Jansen et al., 2023). According to Buchholz & Lützkendorf (2022), a chronological timeline of the evolution needs to exist by tracing back the data. Each passport should contain a unique identifier which is linked to the information about the basic characteristics (European Commission, 2020a).
- **Non-Redundancy**: At the passport level the data should not contain excessive information (e.g. redundant or irrelevant information)(Buchholz & Lützkendorf, 2022).

Besides the technical requirements mentioned above, it is also important to enable the DPP to be scalable. Furthermore, the DPP should be sustainable itself (e.g. it should not lead to rebound effects in terms of environmental sustainability)(Jansen et al., 2023). There are different methods to design a DPP. However, it is essential to include an attribute without the loss of information and that it can be traced back to the agreed information model. This way, the information of the current- and future state will be interchangeable. The attributes in the DPP need to be able to be linked to the information model. This is only possible when the passport is made in a (semi) structured format, for example in Excel (CSV), JSON, or RDF. This is to prevent creating space for own interpretation (Platform CB'23, 2023). To manage the processing, sharing, and generation of data across the life cycle actors (e.g. manufacturers, operators, recyclers, etc) a complex software system will be needed to implement processes and information exchanges (Koppelaar et al., 2023).

4.4.1 FAIR data principles

The Construction Product Regulation (CPR) is currently being revamped, however it is unclear how the DPP will be implemented in the CPR requirements. The EU Commission states that potential requirements include that the DPP should adhere to open standards. This implies interoperable format that is machine-readable, structured, and searchable. Compatibility with the ESPR-established DPP is essential, without sacrificing interoperability with BIM. To achieve this, FAIR data is needed (Wilkinson et al., 2016).

The concept of FAIR data encompasses four key principles:

(1) data must be findable. This means it is machine-readable and unique identifiers are assigned.

(2) The data is accessible. This means that the data should be retrievable, possibly through a standard protocol, which means that the access permission should be secured by authentication and authorization (role-based access).

(3) It should be interoperable by using formal representation and standardization format to express the data that allows data exchange between databases and tools.

(4) Data should be reusable by both humans and machines. This requires clear and detailed metadata rules, and common semantics, dictionaries, and digital language.

Achieving these principles can be challenging, but they promote fairness, transparency, and consistency in data usage and management (Cobuilder International, 2023).

The final step requires the implementation of a common digital language in construction. To establish a standard technical vocabulary, the CPR and Harmonised Technical Specifications sets can be utilized. Meanwhile, the EN ISO 23386, EN ISO 23387, and EN ISO 22057 can be employed to establish a shared digital language as follows:

(NEN-)EN-ISO 23386:2020 en - Building information modelling and other digital processes used in construction - Methodology to describe, author and maintain properties in interconnected data dictionaries

ISO 23386 outlines the fundamental rules for developing data elements in a data dictionary that defines the metadata for every element. One of the most essential aspects of this standard is the incorporation of Globally Unique Identifiers, which ensures that the data is easily findable. Additionally, the standard describes and provides recommendations on how to interconnect various data dictionaries (ISO, 2020a).

EN ISO 23387

Building upon ISO 23386, and EN ISO 23387 comprises a series of context-specific rules that describe how to assign relevant characteristics to various building components, such as windows and doors. It also outlines the appropriate methods to connect the products to their exact measurement or test method, and how to establish connections to a specific unit of measurement. These guidelines are also known as data templates (ISO, 2020b).

(NEN-)EN-ISO 22057:2022 en - Sustainability in buildings and civil engineering works - Data templates for the use of environmental product declarations (EPDs) for construction products in building information modelling (BIM)

This standard outlines specific syntax guidelines for EPD data. It not only defines the syntax required for structuring and creating a common digital language enabling environmental EPD data, but also provides some of the semantics. This standard includes a normative Annex with a comprehensive list of various data elements and characteristics, complete with their respective metadata attributes and unique identifiers (ISO, 2022).

4.4.2 Legal obligations

The DPP is a subject to various regulations and standards, some of which are only now emerging. One such regulatory document is the ESPR (European Commission, 2022b). It provides a comprehensive overview of the voluntary and mandatory information requirements of the upcoming DPPs. Furthermore, it offers guidance on managing both the

DPP itself and its supporting IT infrastructure. Among its recommendations is the creation of a centralized registry to assign unique identifiers to DPPs and their corresponding physical objects. The ESPR advocates a decentralized approach, whereby data providers can store their information at their preferred location (Jansen et al., 2023). Additionally, the document notes that eco-design requirements for building products are governed by the CPR ('De bouwproductenverordering nr. 305/2011'). Nonetheless, the ESPR has received some criticism. Koppelaar et al. (2023) have pointed out that the proposal fails to address material declarations and critical raw material information.

Furthermore, the importance of EPR cannot be overstated when designing a DPP. According to the Organization for Economic Co-operation and Development (OECD), EPR is an environmental policy concept that extends the responsibility for a product beyond the consumption phase to the entire lifecycle (Hilton et al., 2019). By incorporating environmental quality data from production processes and products into the product chain, EPR can effectively reduce environmental impact. Therefore, the EPR should be considered when creating a DPP. Additionally, the "right to repair "should also be taken into consideration.

This relates to government legislation within the EU that prohibits manufacturers from implementing barriers that prevent consumers from modifying or repairing their consumer products. This is expected to promote refurbishment, repair, and reuse of products within the EU and beyond.

Finally, there is the General Data Protection Regulation (GDPR), which was established in 2018 specifically for the European market. This regulation stands as the most crucial when it comes to data privacy and the safeguarding of individuals 'personal information (such as any data that relates to identifiable natural persons). Additionally, it ensures the free flow of such data (European Union, 2016b). It is vital to note that the GDPR is expected to be significant for the DPP when dealing with personal data (e.g., employee information).

4.5 Other norms and regulations

In addition to the obligations and norms mentioned earlier, there are other factors that can impact the format and manner of working with a DPP. These factors include the potential for establishing a connection in the future or how the information is recorded.

4.5.1 NEN 2767 & NEN 2660 - Condition assessment built environment and conceptual modelling

An increasing numberof clients in the Netherlands and Belgium initiate projects while keeping the development of efficient and effective decomposition for the Built Environment in mind. However, this can result in decompositions that have not been developed according to a consistent method. The publication of NEN 2767 is further emphasized because of this demand for a consistent method. This norm describes a method for condition assessments, and decomposition structures based on NEN 2660. The NEN 2660 provides a framework for developing coherent models that address the use of, and the entire life cycle of, the built environment, and elements of this environment. The NEN 2767 is widely used by companies for the decomposition of their physical assets within asset management. However, this NEN standard is not developed for this purpose and there are multiple uncertainties about the structure and usage of the standard and the relation to other standards. Therefore, the standard committee 351225 (rules for information Modeling of the Built Environment) is working on creating uniformity, including decomposition throughout the Built Environment. The existing NEN 2660 is ‘updated’ to form a reference framework for standards/guidelines and information models that address physical and spatial concepts of the Built Environment, such as IFC, NEN 3610, and NL-SfB. Additionally, an alignment will be sought with standards that address the correct way of semantic modeling of assets, such as ISO 15926 and the open standard CB-NL (Platform CB’23, 2023).

The NEN 2660 has been divided into two distinct parts. First, NEN 2660-1 outlines the fundamental principles for creating cohesive conceptual models, including standard rules for entities, attributes, and models. The standard describes the general rules and terminology for an information system. (NEN, 2020a). Second, NEN 2660-2 provides a more practical interpretation of the configuration, implementation, and extension of conceptual models of part 1. The latter is in terms and concepts of the Semantic Web and Linked Data (NEN, 2021).

NEN 3610 - Basic schema for geo-information - Terms, definitions, relations and general rules for the interchange of information of spatial objects related to the earth
This standard provides guidelines for creating clear and precise conceptual and logical models of information that contain location-specific data, also known as geoinformation. The models are designed to describe and share semantic information related to specific industries or sectors. They are intended for use in publishing and sharing information on the internet (NEN, 2020b).

NL-SfB classification of building elements
NL-SfB is one of the most commonly used systems for classifying building objects in the Netherlands. Building and installation companies rely on these systems to classify objects in open standards and BIM and CAD systems to efficiently organize supplier information. Currently, the NL-SfB is expanding to connect with comparable goals, such as IFC, CB-NL, and bSDD (digiGO, n.d.-b).

ISO 15926 - Integration of life-cycle data for process plants, including oil and gas production facilities
This ISO standard involves integrating life cycle data for process plants, specifically those involved in oil and gas production. The ISO 15926 is a representation standard based on an ontology approach to information definition making use of Semantic Web technologies. This standard has been defined to treat information as independent of concrete choices of data storage, use, or representation. It can support data integration and exchange, with automated reasoning applied to information mapping (Skjaeveland et al., 2008).

CB-NL - Dutch concept library
The CB-NL establishes links among various open BIM standards, ensuring consistency in descriptions and definitions. A more recent iteration, CB-NL 2.0, is currently in the works to align with the updated NEN 2660-2 (digiGO, n.d.-a).

4.5.2 The Corporate Sustainability Reporting Directive (CSRD) and European Sustainable Reporting Standard E5 (ESRS E5)

The CSRD is a European directive requiring companies to report on various sustainability criteria from 2024 onwards. The areas covered are environmental, social, and governance (ESG). The reports will need to comply with several sustainability criteria and will significantly impact the industry. By this directive companies will be incentivized to measure, manage, and communicate their sustainability performance in a standardized and comparable way. This way reliable information on the companies' commitment to sustainability, waste management, and recycling efforts will be provided, thereby achieving more transparency (European Commission & Directorate-General for Financial Stability, 2023).

Recycling and waste occupy an important position within the CSRD legislation, positioned in the ESRS E5. This directive covers the use of resources and the circular economy. This includes resource inflows, resource outflows, and waste and emissions (European Commission & Directorate-General for Financial Stability, 2023).

This regulation might be of importance, as the DPP can become part of the reporting structure of selective topics. Therefore, the DPP can contribute to the requirement definition of the directive by giving substance to the information reporting

4.5.3 EU Taxonomy

The EU Taxonomy serves as a valuable tool for companies and investors, providing a classification system that aids in identifying environmentally sustainable economic activities. Such activities are defined as those that make a substantial positive impact towards contributing to at least one of the EU's climate and environmental objectives, without causing significant harm to any of these objectives, while also satisfying minimum safeguard requirements. Currently, the Taxonomy is not mandatory for the environmental performance of an industry organisation. Nevertheless, it is anticipated that over time, the EU taxonomy will drive a shift towards sustainability, leading to the achievement of the EU's climate and environmental goals (European Commission, n.d.-b).

The Taxonomy establishes an 'auditable metric 'of green revenue (including capital and operational expenditures). This metric has the potential to influence the DPP in the future. Currently, there are no regulations on many sustainability topics (e.g. the number of materials that need to be reusable). However, the Taxonomy can establish a foundation for companies to comply with in the future. Such changes could impact the DPP's input and validation requirements as they will need to meet specific criteria.

4.6 Challenges and limitations related to Digital Product Passport implementation

Implementing the DPP poses several challenges. Firstly, it must be **integrated into the existing regime and information requirements** while ensuring that **stakeholders do not view it as an additional burden**. Additionally, a viable **business model must be established** to achieve stakeholder acceptance and demonstrate the value of the DPP. Moreover, stakeholders may have **varying information needs**, necessitating clear and appropriately detailed information for each party (Adisorn et al., 2021). The manufacturers face initial costs when implementing material declarations, making it unlikely for a single company to bear the expense alone. Furthermore, it is crucial to consider technological advancements and learning effects in information provision (European Union, 2016a).

Most manufacturers and suppliers typically experience a unidirectional data flow. Nevertheless, discussions surrounding the asset administration shell and DPPs suggest a more multidirectional flow of information. The operational phase, in particular, may present challenges in **obtaining product information and maintaining the DPP's accuracy** (Adisorn et al., 2021;Eppinger et al., 2021). For example, during significant renovations that could potentially impact building materials, any changes to these materials should be appropriately documented and updated (Schützenhofer et al., 2022;Adisorn et al., 2021). Additionally, according to Adisorn et al. (2021) and Berger et al. (2022), there is a **lack of understanding** about the specific information that should be included in a product passport for a particular application.

One of the challenges lies in the way information is provided. Various types of data labels and -sources may be shared through **different portals and methods**, all of which must be consolidated in the DPP. Moreover, achieving a **unified approach to DPPs across different industries** may prove to be difficult (Eppinger et al., 2021). The **absence of clear specifications** also leads to divergent industry-driven visions (European Commission, 2020b; European Commission, 2020a). Additionally, documents or data may contain **sensitive information** that requires secure handling (Adisorn et al., 2021;Eppinger et al., 2021). A guarantee needs to be given that shared DPP information, if it comes to the process and collection of personal data, is safely stored. This can, for example, be done by fulfilling legal requirements such as the GDPR (Berg et al., 2022).

The Ellen MacArthur Foundation states that digital technologies have the potential to facilitate the shift towards a circular economy through advancements in virtualization, de-materialization, transparency, and feedback-driven intelligence (Ellen MacArthur Foundation, n.d.). This statement highlights the transformative power of digital technology in enabling sustainable practices. Similarly, the EU Battery regulations emphasize the importance of an interLinked Data space in promoting secure data sharing, enhancing transparency, and ensuring traceability throughout the entire life cycle (based on the batteries industry) (European Commission, 2020c; (European Commission, 2020c).

5. Data modeling and exchange in the AEC industry

This chapter provides information about data usage in the AEC industry. It focuses on the state-of-the-art of Building Information Modelling and Semantic Web technologies.

5.1 Building Information Modeling (BIM)

The AEC industry relies heavily on the seamless transfer of information from the initial design stages to the final handover of the product and throughout its operation. BIM tools and methods serve as the centerpiece in facilitating this information exchange (Sacks et al., 2018). Consequently, numerous BIM models necessitate consolidation, integration, and validation. In addition, BIM tools are frequently employed inconsistently, following different guidelines, libraries, methods, and internal information structures (Sacks et al., 2018). This inconsistency underscores the pressing need for a standardized data scheme to enable the exchange of building information. The most utilized standard data schema within the AEC industry is IFC (Pauwels et al., 2022).

5.1.1 Industry Foundation Classes (IFC)

IFC is an international open standard and data model that enables exchanging digital building models between (different) software applications. IFC is an essential basis of Big Open BIM (Borrmann et al., 2018). The IFC standard is defined in ISO 16739-1:2018 and is structured into several layers (Appendix A, Figure 3a) aiming to improve the maintainability and extensibility (which remains challenging). The core elements remain independent because the upper layers only can reference elements in lower layers and not the other way around. This hierarchy defines the generalization of relationships and specializations. This determines which attributes of which classes can be inherited by other classes. Figure 6 shows part of the inheritance hierarchy. When this structure is followed, objects (e.g., columns, walls, beams, etc.) can be described using entities (Borrmann et al., 2018).

5.1.2 Challenges and limitations in data exchange

The current IFC schema **lacks the required flexibility between disciplines when it comes to DPPs**. The buildings' elements and their attributes are covered. However, it does not meet the requirements of all participants in AEC, especially **life cycle considerations**. For example, the ecological parameters are insufficiently addressed (Santos et al., 2019). Furthermore, the **EoLphase,** as part of the ecological parameters, **is neglected** in any BIM software (Akbarieh et al., 2020). According to Akinade et al. (2018), many Construction and Demolition Waste (CDW) tools are not compatible with BIM, and data for LCA on CDW is scarce (Akinade et al., 2018). One solution is BIMRel, which provides a framework for embedding product information in BIM (Lupica Spagnolo et al., 2020), using a cloud-based Structured Query Language (SQL). This enables a standardized, phase-dependent output of product information.

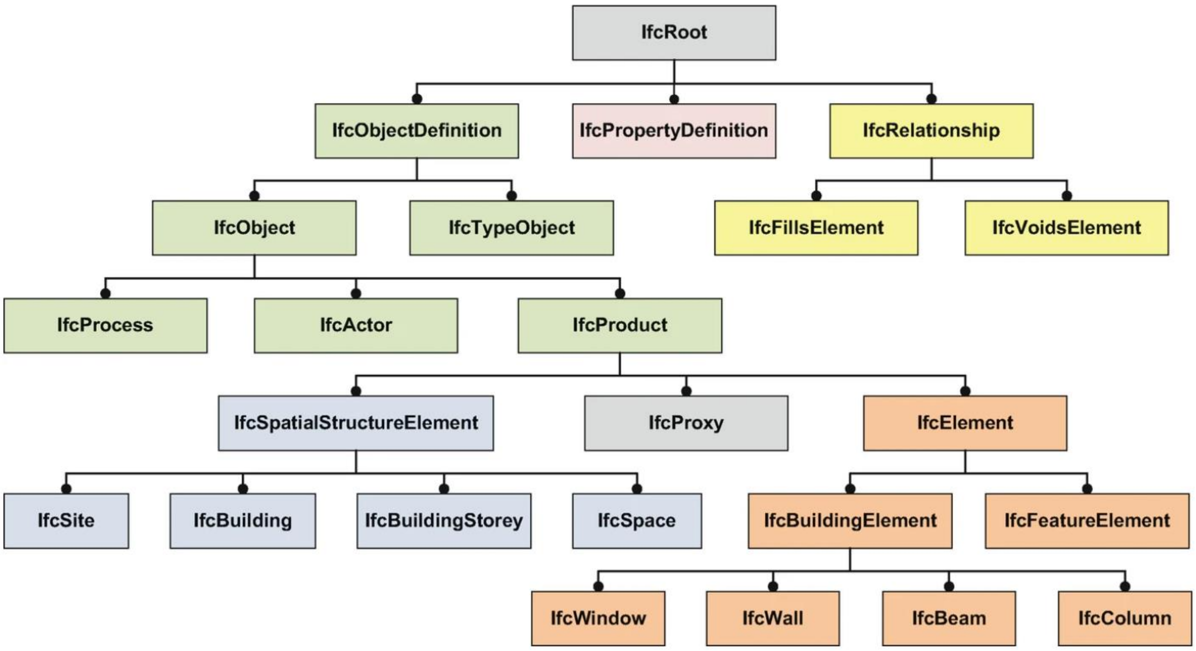


Figure 6: Part of the IFC data model, (Borrmann et al., 2018)

5.2 Linked Data and Semantic Web technologies in the AEC Industry

The concept of the Semantic Web was proposed in 2001 by Berners-Lee et al. (2001). The Semantic Web is a network in which information is defined in directed labeled graphs. These graphs contain nodes and links which are identified by an Uniform Resource Identifier (URI) and located by a Uniform Resource Locator (URL). The semantic graphs make use of the Resource Description Framework (RDF). "The Semantic Web is 'an extension of the current web in which information is given well-defined meaning, better-enabling computers and people to work in cooperation'' (Pauwels et al., 2022, p. 167). This enabled the World Wide Web to evolve from a web of documents to a "Web of Data" (Linked Open Data (LOD) cloud) (Bizer, Lehmann, et al., 2009). As such, Linked Data forms an important component of the Semantic Web.

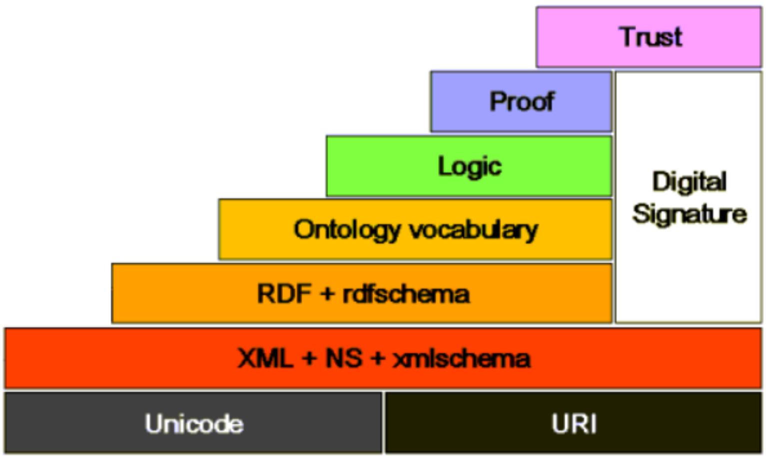


Figure 7: The semantic web stack, (W3C, 2024)

Linked Data is a relatively new concept within the AEC industry (Pauwels, Zhang, et al., 2017a), but has gained traction in research and industry throughout the past decade. It allows to publish, access, and share data openly. This way it becomes widely available to create new data interactions and enable usage for other purposes. By leveraging graph data structures, Linked Data enables an easier and more automatic (contextual) connection between different datasets and is a different way of storing data when comparing it to the more commonly used SQL database structure (which is row and column-based). However, the usage of Linked Data in the AEC industry still faces challenges, as thehe AEC industry is currently behind with such implementations. The need to leap forward is high, which further underpins the importance of standardization. It is, however, unknown which standards suit the requirements the best. Therefore, the quality of data brings difficulties. Additionally, Linked Data needs to be considered and developed within the existing BIM protocols and guidelines (Sobhkhiz et al., 2021).

5.2.1 Linked Data principles

The term Linked Data was formulated by Berners-Lee in 2006 and introduces a set of regulations for data published on the Web to create a single global dataspace. These regulations form the so-called 5-star open data principle. These principles include: (1) URIs being used for naming 'things' on the Web; (2) Using HTTP URIs so these 'things' can be found on the Web; (3) The use of standards providing functional information when searching for a specific URI (e.g., RDF, SPARQL); (4) Links being included to URIs so more 'things' can be discovered (Berners-Lee, 2006). The 5-star development steps are shown in Table 3 Using the 5-star principles, the maturity of Linked Data can be determined.

Table 3: 5-Star open data principle, (Berners-Lee, 2006)

Level (stars)	Development
1	Data available on the web using an open license.
2	Data available on the web and in a structured way which is machine readable.
3	Data is available on the web and in a structured and machine-readable way. This is by only using non-proprietary formats.
4	Data is available on the web and in a structured and machine-readable way. This is by only using non-proprietary formats, W3C open standard, and URIs.
5	Data is available on the web and in a structured and machine-readable way. This is by only using non-proprietary formats, W3C open standard, and URIs. The data should be linked to other available datasets (if possible).

5.2.2 Semantic Web technologies

As mentioned above, a fundamental building block in the Semantic Web is the RDF. RDF is a W3C standard data model that can be used for describing web resources. Linked Data structures are stated in RDF triples which consist of subject, predicate, and object representing 'things' and the belonging relationships (Figure 8). This means that any subject can be connected to any other object using of the predicate showing the type of relationship. For this reason, the Web of Data consists of a structure of graphs relying on triple structures to enable a uniform syntax and semantics to describe information (Pauwels et al., 2022). Figure 9 illustrates an instance of an RDF triple that incorporates literals. These literals are capable of being utilized in the object position, serving as representations of fundamental values like integers, strings, and decimals.

Multiple triple statements can be expanded to the nodes and edges (directed and labeled) that together form a semantic (knowledge) graph. All edges and nodes in this graph are uniquely identified by URIs, which play a vital role in the Semantic Web and graph-based data exchanges. The URIs serve as the primary means for uniquely identifying entities and naming anything on the Web. Due to the data being uniquely identified, and defined by its relation to other data, multiple unique data sources can be connected and used to gain additional insights, up-to-date information, etc. This is done through a compact sequence of characters that identifies an abstract or physical resource (Berners-Lee et al., 2005).

Figure 8: RDF triple structure

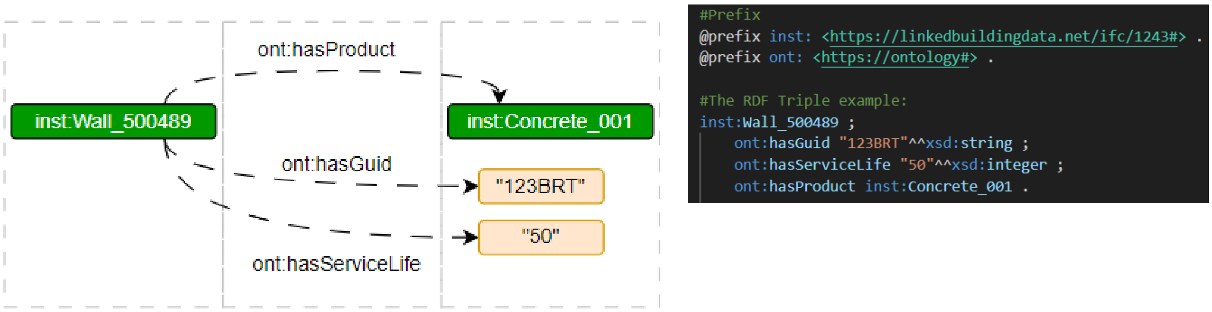


Figure 9: RDF triple structure with literals

5.2.3 Ontologies

An ontology is a ‘formal, explicit specification of a shared conceptualization’ (Studer et al., 1998). The ontology defines the data semantically and enables machines to interpret it according to the provided ontological definitions. ‘Sharing a common understanding of the structure and meaning of information among people or software agents’ is one of the common goals in developing ontologies (Puerta et al., 1992;Gruber, 1993).

Ontologies can be created using the Web Ontology Language (OWL) and the Resource Description Framework schema (RDFs). For the representation of the semantic meaning of concepts, the Semantic Web relies on OWL (Hitzler et al., 2012). OWL can be used to describe more expressive elements compared to RDF. OWL can create complex RDF statements, for example, type restrictions, cardinality restrictions, and complex class expressions. RDF graphs can be constructed using OWL, i.e., OWL ontologies (Pauwels et al., 2017b).

The Assertion Box (A-Box) and Terminology Box (T-Box) can be used to explain the concept of ontologies in a Semantic Web context. Functioning as a terminology layer, the TBoxis utilized to establish classes (describe concepts) in a domain of interest and impose rules and restrictions on the properties used as predicates. Meanwhile, the A-Box, serving as a data layer, houses instances that adhere to the ontology defined using the T-Box, see Figure 10.

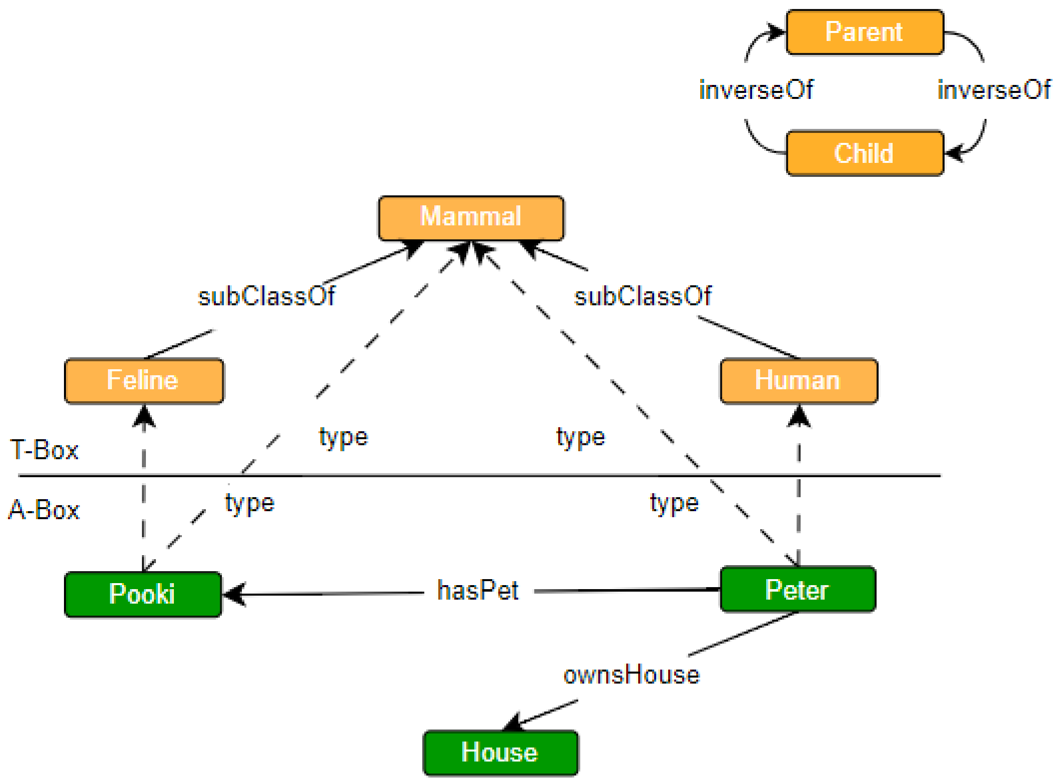


Figure 10: Example Assertion and Terminology Box, (Pauwels, 2021)

Constructing an ontology using OWL or RDFS facilitates the establishment of a common understanding of data representation. This process centers around two crucial elements. The first is classification, which distinguishes various data instances. The second is properties, which provide additional details about these identified data instances by linking them to other instances. This involves the use of taxonomy and topology, where taxonomy arranges the classes in a hierarchical manner within the ontology. The topology describes how different classes are connected in a specific domain. A modular methodology is preferred to organize building information. This entails breaking down data structures both vertically, by adding more detailed classifications and properties for various subdomains, and horizontally, by establishing relationships between different ontologies (Janssen Steenberg, 2023).

Semantic Web technologies make use of the Open World Assumption (OWA) contrary to the traditional technologies that use Closed World Assumption (CWA), including BIM tools and common database systems. According to CWA, every statement is considered false if it's not known to be true. However, when making use of OWA every statement that is unknown to be true is marked as unknown. This means it can be changed to false or true when more information is known but till then it is not determined (Pauwels et al., 2017b). Semantic Web technologies use OWA since not all information on the Web can be stated as true or false. Instead, there is incomplete information. The usage of CWA and OWA is important when using ontologies in BIM models. When information is not specified it cannot be concluded to be true or false.

SPARQL Protocol and RDF Query Language (SPARQL)

SPARQL is the standardized query language developed by W3C that enables the utilization of triple structures to access and analyze data derived from RDF, OWL, and RDFS. When making a query in SPARQL, it is possible to introduce an empty variable in any element of the triple (subject, predicate, object). Doing so will result in matching patterns within the dataset (see Figure 11).

```
PREFIX dpp: <https://jannekebosma.com/dpp#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>

select ?Product ?Material ?Name where {

        ?Product a dpp:product.
        ?Product dpp:hasMaterial ?Material.
        ?Material rdfs:name ?Name.
```

Product	Material	Name
inst:Concrete_001	inst:Material_001	"Cement"
inst:Concrete_001	inst:Material_002	"ConcreteSand"

Figure 11: Example SPARQL Query

Existing ontologies relevant for the circular construction domain

Prior to creating a new ontology, it is advisable to first examine existing ontologies and determine which of them (if any) can be reused. This practice of reusing ontologies is considered a best practice. It is not necessary to use an entire ontology; specific classes can be utilized as well when available in the right context. The table below displays the existing ontologies applicable to the AEC industry, the circular construction domain and MPs. However, it is important to note that no ontology has been identified for DPPs, and the most pertinent ones related to an MP are not available or reusable as they have not been published. The same applies for several circularity-related ontologies.

Table 4: Existing ontologies relevant to the AEC Industry and Material/Product Passports

Existing ontologies relevant to the AEC industry and Material/Product Passports	
Ontology	**Description**
Building Topology Ontology (BOT)	Defines relationships between elements within a building (Rasmussen et al., 2021).
Building Material Ontology (BMAT)	Recommended to use in conjunction with BROT (which defines bridge construction and its aggregated components) (Hamdan et al., n.d.).
Building Product Ontology (BPO)	A schematic description of the product only, not including geometry or material compositions (Wagner & Rüppel, 2019).

Ontology	Description
Building Element Ontology (BEO)	Ontology-based on the ifcBuildingElement subtree. It contains a taxonomy of classes that allows to define common building elements (Pauwels, 2018).
Digital Construction Building Material Ontology (DICBM)	Defines necessary relationships between building elements, construction details, materials, and their properties (Karlapudi & Valluru, 2019).
Ontology for Property Management (OPM)	Describing temporal properties that are subject to changes as the building design evolves (Rasmussen & Lefrançois, 2018).
Provenance ontology (PROV)	Can be used to filter by the most recent date when querying. It provides a set of classes, properties, and restrictions that can be used to represent and interchange provenance information generated in different systems and under different contexts (Lebo et al., 2013).
Construction Tasks Ontology (CTO)	Describes tasks operating on construction elements, spatial zones, and/or damages (Bonduel, n.d.).
Ontology for Managing Geometry (OMG)	Managing geometry descriptions in a Semantic Web context (Wagner et al., 2019).
File Ontology for Geometry (FOG)	Can extend on the OMG ontology. It provides geometry schema-specific relations between 'things' (e.g. building objects) and their geometry descriptions (Bonduel et al., 2020).
Friend Of A Friend ontology (FOAF)	Describes people and social relationships on the web. The focus is mostly on people's existence in the virtual world (W3C Wiki, 2015).
Location Core Vocabulary (LOCN)	It consists of a minimum set of classes and properties for describing the name, address, or geometry of a place. The status of most properties is 'testing.' (EU ISA Programme Core Vocabularies Working Group (Location Task Force), 2015).
Core Public Organization Vocabulary (CPOV)	Describes the organization itself. (Core Vocabularies Working Group, 2023).
The Organization Ontology (ORG)	This ontology is about organizational structures, reporting structures, location information, and organization history (Reynolds, 2014).
Building Material Performance (BMP)	This ontology is about material performances (Kaltenegger, 2024)
Circular Exchange Ontology (CEO)	Annotate materials under a CE classification scheme and describe the elements required for material exchange to occur (Sauter et al., 2018).
Circular Materials and Activities Ontology (CAMO)	Provides a CE classification system for the different materials, products, and activities. Based on EPEA (Pauwels et al., n.d.).
Building Circularity Assessment Ontology (BCAO)	To structure heterogenous manufacturer product data needed for a building circularity assessment (Morkunaite et al., 2021)

Ontology	Description
Unit ontology	Standardized description in units of measurement. Only specifies named individuals (instances of classes), and does not define any new classes or properties (Digital Construction Units, n.d.).
Quantities, Units, Dimensions, and Types ontology (QUDT)	Unified model of measurable quantities, units for measuring different kinds of quantities, etc (QUDT, 2024).
Building Lifecycle Ontology (BLCs)	Evolution of information over the construction lifecycle and refinement through LOD levels (Karlapudi, n.d.).
Material Passport Ontology (MPO)	Outlines the key components of MPs and their interrelationships (Kedir et al., 2021).
Circularity Decisions Model Ontology	This ontology can be used in circularity decision making (Mboli et al., 2022).

6. Data validation

This section encompasses the process of data validation and the necessary validation rules for validating the BIM model and DPP. Additionally, a comparison is conducted among various validation languages in order to determine the most suitable one to employ.

6.1 The data validation process

Currently, the creation process of a passport is highly manual. The required information, concerning products and materials, is heterogeneous, originating in different sources (e.g., company- and supplier databases) and often requires manipulation of the data to be correct. Unfortunately, there is no standardized format or process for creating and validating passports, which can lead to issues such as data misinterpretation and uncertainty (Goswein et al., 2020). This problem also extends to the related BIM models, which can serve as an input for the passport. However, validating the BIM model against relevant rules is often dependent on the cognitive skills of individuals, and improper validation can have negative consequences for the project's information stream (van den Bersselaar, 2022).

To minimize the issues stated above, implementing a functionally complete rule-checking and reporting system can be structured using the process outlined by Eastman et al. (2009). The process has four stages: (1) interpretation of rules and logical structuring, (2) preparation of the building model for checking, (3) execution of rules, and (4) reporting of results (Figure 12). Pauwels et al., (2017a) visualized the necessary components for a semantic rule-checking system (Figure 13). This structure can serve as the foundation for the development of BIM model validation and quality control, used in this thesis in the context of DPP validation. Depending on the format in which the material/product data (assuming different databases) is provided to complete the passports, it may need to be prepared in step (2) alongside the BIM model. Using a standardized language across the T-Box, A-Box, and RBoxcan be beneficial. These benefits include the ability to repurpose implementations for various source formats easily, the portability of written rules across different applications and platforms, and the potential to apply the language effectively in diverse domains and contexts (Eastman et al., 2009; Pauwels et al., 2017a).

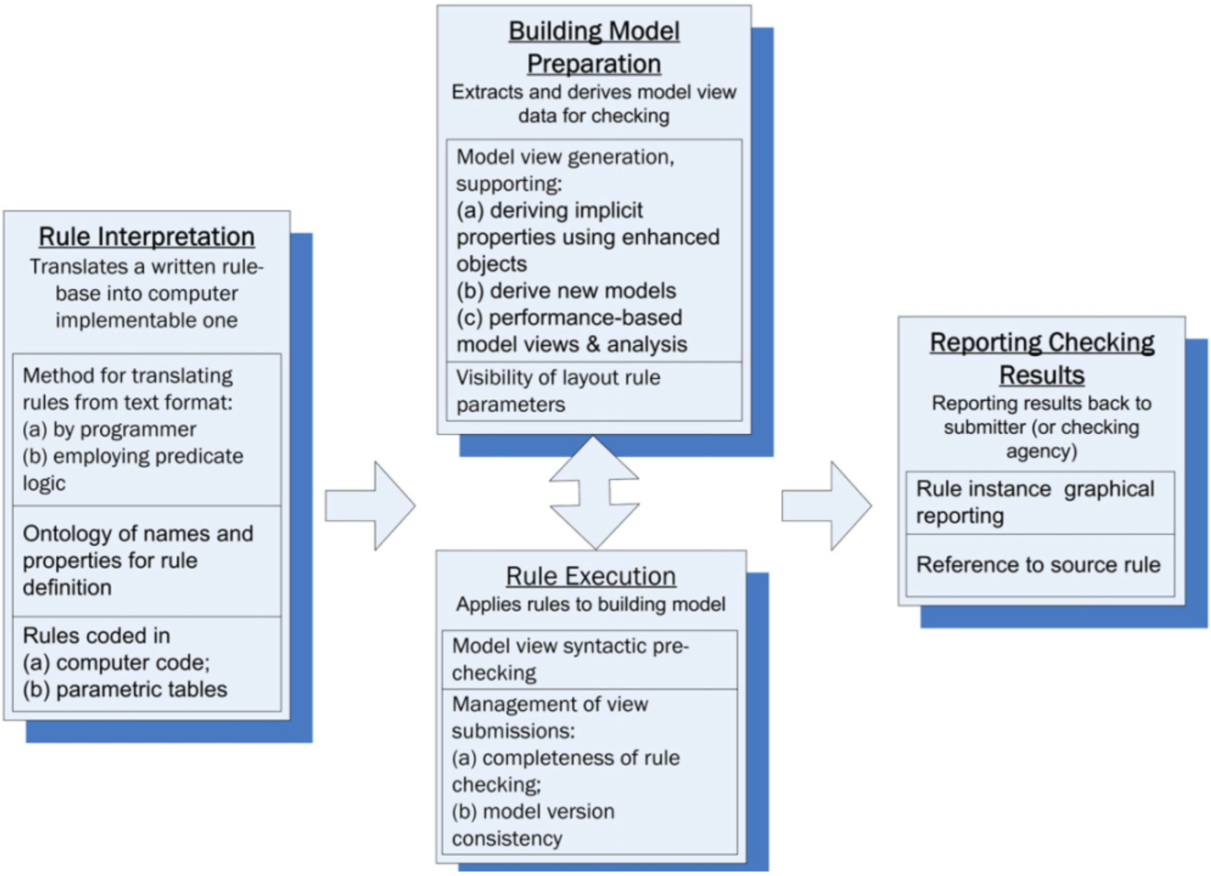


Figure 12: The four classes of functionality a rule checking system should support (Eastman et al., 2009)

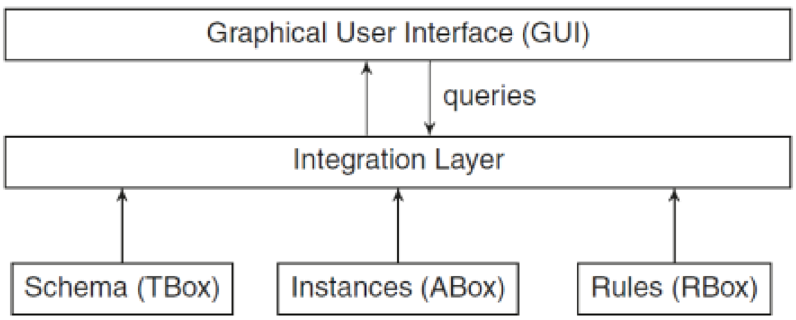


Figure 13: A representation of a semantic rule checking system, Pauwels, et al., (2017a)

6.2 Rule types

The initial step in the process of rule checking involves interpreting the rules. It is important to determine which rules are relevant to the project, whether they belong to specific content requirements or data formatting. At present, there are no requirements within the relevant themes of MPs or DPPs, so content-related demands are currently not applicable in a standard form. However, there is a need to standardize data and verify the presence of information that enables reuse and recycling. Lee et al. (2016) developed a Model View Definition (MVD) for the Precast Concrete Institute (PCI) intending to create a more modularized rule-based validation method for the validation of IFC models concerning their MVD specification. The results of this effort are presented in the Table 5, which includes three types of checking methods. These methods are designed to verify values (correctness, existence, and uniqueness), datatype, and references (Lee et al., 2016).

Table 5: Classified rule types, Lee et al. (2016)

Rule type			Type	Note
Checking method	Check value	Check correctness of value	V	Checking a correct value
			D	Checking a value of an attribute to be of a defined type
		Check existence of value	N	Checking null, existence of an instance attribute
			M	Evaluating a lower and upper bound: setting a limit on the number of attributes (cardinality)
		Check uniqueness of value	U	Checking uniqueness within a file:comparing a value within a model Checking uniqueness in aggregation: comparing an instance within a given list
	Check Type		T	Checking a correct type of an entity
			S	Checking a subtype entity
	Check referential entity		R	Checking a referencing entity
			I	Checking an inverse relationship

6.3 Rule checking and constraints

In the past decade, there has been a significant increase in the use of logic-based approaches largely due to the growing popularity of Semantic Web technologies (Berners-Lee et al., 2001;Pauwels et al., 2017c). Initially, this trend involved various implementations for analyzing building models using consecutive SPARQL queries (Yurchyshyna et al., 2007;Yurchyshyna & Zarli, 2009) or SPARQL Inference Notation (SPIN) queries (Zhang et al., 2018a), which remains a common method for code compliance checking (Pauwels et al., 2024).

Nowadays, multiple query languages are available (Pauwels et al., 2024). Additionally, dedicated formal logic-based rule languages such as the Semantic Web Rule Language (SWRL) and N3Logic have also been utilized (Pauwels et al., 2011;Pauwels et al., 2017). These rule languages make us of an "if-then" structure. These consist of an antecedent (IF) which specifies a condition leading to consequents (THEN) which specifies an action. SWRL is highly expressive and supports complex logical constructs such as disjunctions, conjunctions, negations, and quantifiers and is focused on expressing complex logical rules and inference mechanisms (Horrocks et al., 2004). However, challenges concerning the statement of rule chains and their corresponding consequences remain (Pauwels et al., 2011; Pauwels, de Farias, et al., 2017). Combining large ontologies, large datasets, and large sets of complex rules, results in an increased demand for computational power (Pauwels et al., 2011; Pauwels et al., 2017). Always requiring more computational power isn't a long-term solution; therefore, more modular and lean approaches are needed.

Modular languages allow IF-THEN relations based on fitting (constraining rather than checking). Therefore, they become harder to use but allow for better embedding of rules, which inherently can be more complex than rule-checking statements (Pauwels et al., 2024). The constraint-checking method, such as SHACL and ShEx, allow for fail- or pass-type outcomes that can be tailored to the required needs (Knublauch & Kontokostas, 2017;Pauwels et al., 2024).

6.3.1 Shapes Constraint Language (SHACL)

SHACL can be used to validate a Linked Data structure, as it will function as a control (constraint) mechanism. It is recommended by several research initiatives to use SHACL for data validation in the construction industry (Stolk & Mcglinn, n.d.;Werbrouck et al., 2019). SHACL serves as an evolution of the SPARQL Inference Notation (SPIN) language, where multiple SPARQL queries are executed in sequence (Pauwels, de Farias, et al., 2017;C. Zhang et al., 2018b). Furthermore, it is a W3C standardized language that states bounding functions to otherwise boundless statements. This allows the data to be stored only in a specific way, making it easier to check and maintain the quality of the data and uphold standards (Simkus & Varzinczak, 2022;Knublauch & Kontokostas, 2017).

SHACL is a language to define data schemes in which the allowable/valid structure and content of RDF-graphs can be specified in detail using SHACL shapes. It is used to define constraints on allowed structures and values of data. Additionally, it can also be used to define dynamic constraints, which means to define the allowed state transitions of the current situation of the RDF graph to the other allowed state of the RDF graph when it is updated to a new version (Github, 2021;Knublauch & Kontokostas, 2017). However, SHACL also has its limits; in case of more complex requirements, the language still often relies on the use of queries (Pauwels et al., 2024).

6.3.2 Shape Expression (ShEx)

ShEx enables the specification of constraints that can be evaluated against specific vocabularies and datasets. These constraints can encompass a variety of conditions, including structural requirements, cardinality constraints, and value types among others. ShEx is similar to SHACL as it validates RDF data against constraints, resulting in a pass-fail outcome. However, both languages have different features and syntaxes (W3C, 2017;ShEx Community Group, n.d.).

6.3.3 Comparison SHACL and ShEx

The W3C has created a list of differences between SHACL and ShEx. Some of these differences, of importance for this research, are shown in the list below:

- SHACL-SPARQL provides the ability for users to extend the language by creating their own constraint components, thus enhancing its extensibility. The semantics of these extensions are clearly defined.
- SHACL is currently on a W3C recommendation track, indicating its status as a standardized technology. On the other hand, ShEx is an effort by the Community Group and is not on a W3C recommendation track.
- One of the notable features of SHACL is its validation result vocabulary, which defines the structure and appearance of validation reports and results.
- SHACL offers a well-developed mechanism for scoping the validation process. Users can specify that a particular shape applies to all instances of a class, including its subclasses, or to specific Internationalized Resource Identifiers (IRIs). Additionally, it can be applied to all objects or subjects of triples with a given predicate. The advanced SPARQL features, although not currently on the recommendation track but mentioned in a WG note, provide even more advanced targeting options.
- Unlike SHACL, ShEx does not support the comparison of property values. For instance, it is not possible to specify that the value of ex:startDate must be less than the value of ex:endDate for a given resource. However, SHACL Core offers Property Pair Constraint Components to address this limitation. Additionally, SHACL-SPARQL allows the definition of additional constraint components.
- ShEx lacks the capability to express that a resource, which is a value of a certain property, must be a member of a specific class transitively. For example, both SHACL and ShEx can be employed to specify that the value of ex:resolvedBy should have rdf:type that falls under the subclass of ex:Developer, SHACL primarily employs the sh:class constraint, whereas ShEx relies on nested shapes. Nevertheless, in the event of any modifications in the class hierarchy, the intended functionality of the SHACL shape will remain intact, whereas the ShEx shape might face challenges(W3C, 2017).

Upon examining the comprehensive list of variances, it appears that the utilization of SHACL is preferred over ShEx due to its broader spectrum of capabilities and endorsement by W3C, the international consortium of entities and individuals dedicated to formulating web standards and protocols.

The Workshop

7. Qualitative data collection: expert workshop

This chapter will provide an overview of the process of creating a standard DPP using input from an expert workshop as a data collection method. Additionally, it will provide the methodoloical details concerning the questionnaire and workshop design and execution. After explaining the process will conclude with presenting the result.

7.1 A process view on Digital Product Passport

Figure 14 demonstrates an example definition flow of the DPP, allowing various stakeholders to provide specific information that can be accessed by others involved in the process. The DPP is a snapshot of a certain point in time in the object's life cycle and will be continuously updated. Each object will have a unique ID which enables tracking it and generating the object's relevant information (Cobuilder International, 2023). Figure 15 illustrates an example of this process using a concrete floor. The process starts from extracting the raw materials and ends with the floor being used in a building. Once the building's lifespan is over, the floor can be dismantled and either recycled or reused. If neither option is feasible, the floor can be disposed of as waste. The DPP is connected to most of the stages in the diagram and can be considered in the next step. Additionally, the responsible parties are illustrated at the top of the scheme. For instance, the manufacturer takes responsibility for a DPP concerning the concrete and floor, which can be incorporated into the contractor's DPP when creating the building. This process carries on throughout the following steps.

Utilizing Linked Data, the information is retrieved from the original economic operator to ensure it contains the most recent data. Adding validation in each step can reduce the likelihood of errors and data losses. Specifically for the contractor, the DPP can also serve as an optimization tool, rough analysis, and object inventory, similar to an MP (see chapter 3.1.1.) (Honic et al., 2019a). In this thesis, the focus is on validation from the perspective of the contractor organization.

It is important to note that the scheme presented is an exemplary scenario and may not always reflect real-life situations. For instance, it is possible that certain steps may not have a DPP available. Additionally, while the scheme suggests that the top stakeholders are responsible for providing a DPP, it is not always clear who is accountable in each stage or within specific stakeholder clusters. For instance, within the contractor's team, the responsibility of creating a DPP may fall on various roles such as a site engineer or a sustainability advisor.

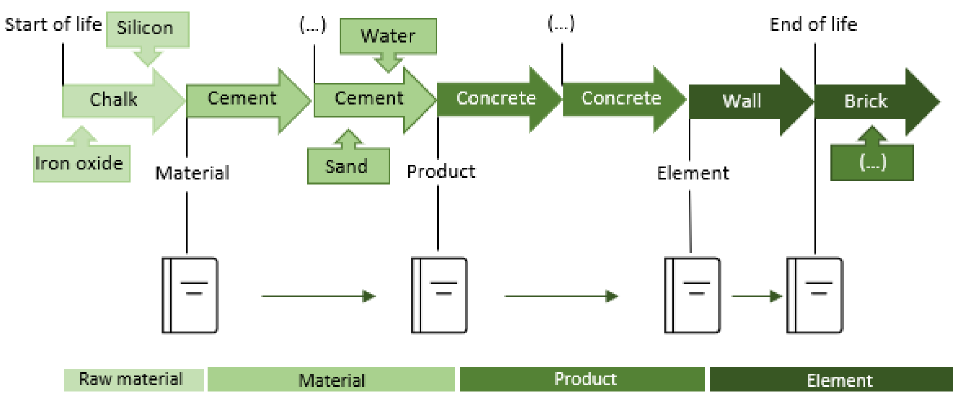


Figure 14: Example DPP input

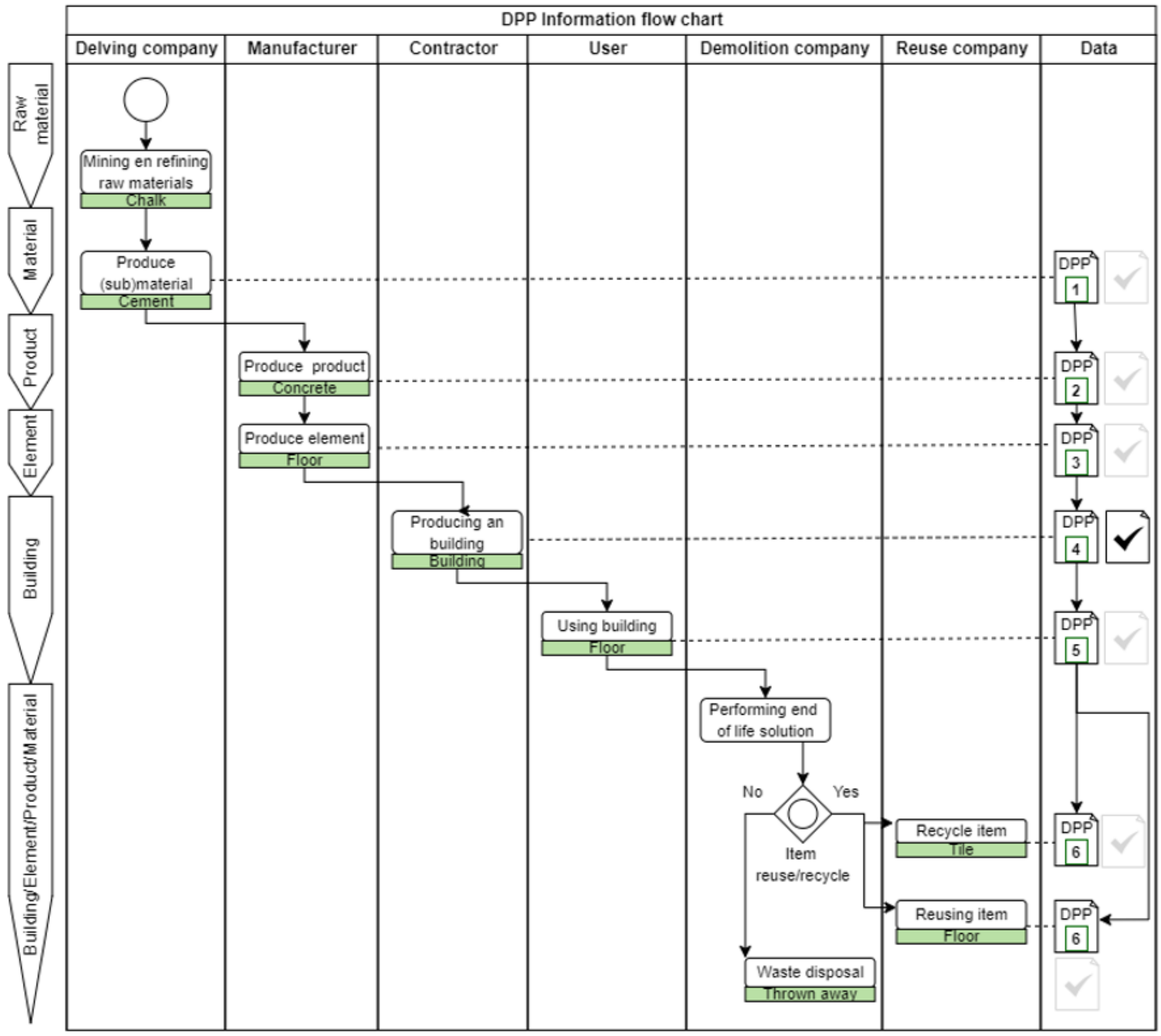


Figure 15: DPP process scheme

7.2 Defining Digital Product Passports: expert workshop design and execution

Currently, there are no standard format and content per passport. The aim of this workshop is to establish the must-haves for a standardized format. Çetin et al. (2023) performed a workshop in which required data points are selected to use in passport formats, primarily focused on the social housing industry and post-construction phases of the property. As this does not cover the contractor phase specifically, an additional questionnaire and workshop is designed within the affiliated company to receive information (i.e., DPP topics, "must-haves") from the contractor side.

First of all, the analysis of Çetin et al. (2023) is used as basis for the workshop with the contractor company. The topics, as synthesizes from the literature and the mentioned study, where integrated in a questionnaire used for discussion with the industry experts. Next, the results are analysed and combined with the results of Çetin et al. (2023). This input is used to define 'must-haves' according to the MoSCoW method (Dai Clegg, 1994) which prioritizes requirements in order of highest to lowest priority (must-haves, should-haves, could-haves, and won't-haves)(see Figure 16 for the methodology of the expert workshop) .

Figure 16: Methodology expert workshop

7.2.1 Literature input

Çetin et al. (2023) applied a mixed method research about the stakeholders involved with the passports and their needs. The study is focused on European social housing organizations. Three rounds of validation interviews took place with in total 38 participants (housing professionals (n=19) and potential users of the MP (n=10)). This is to create a data template for an MP covering maintenance, renovation, and demolition stages. One of the results of the research is that the MP can be made on different scale levels. According to the participants the majority emphasized that the "Product level" is the most appropriate scale. However, there is ambiguity between scales and "Element" and "Material" level can be relevant as well depending on the situation (Çetin et al., 2023).

Furthermore, the existing MPs/DPPs in the study are all combined in one overview with all topics mentioned in these passports Each topic that is present in the passports is marked below the name of the passport. This results in a list of total data points mentioned and for each passport an overview of the topics included. The results of the interviews are mapped into an overview of the data points each containing the amount of responses and the belonging 'importance'of the topic. These are categorized in 'must-have', 'nice to have' and 'not necessary' (Çetin et al., 2023).

7.2.2 Development of the contractor organization questionnaire

The research of Çetin et al. (2023) was used as a basis for developing the specific DPP questionnaire utilized in the workshop in this research. Different passport definitions were collected from the literature review and all related topics were determined. Based on that, an overview of all topics and the number of times they were present in the different MPs/DPPs was created and visualized. All these topics were included in the developed questionnaire.

Next, a group of experts, consisting of eight employees of BAM (1 Built Environment employee, 6 Civil engineers, and 1 Asphalt engineer) was gathered. These employees were selected because of prior experience with MPs. Next, the employees had to fill in the questionnaire providing their input on the importance of the defined MP/DPP topics and whether they should be considered must-haves or not (including all the topics from the overview of Çetin et al. (2023)). The employees had to grade each topic based on a likert scale (from strongly disagree to strongly agree – 7 point scale).

7.2.3 Validation of the DPP questionnaire

After filling in the questionnaires concerning the must-have topics (i.e., information requirements) for a DPP, a workshop took place in which the results were validated. Using the software application Miro, the results were visualized in two groups: the results in which the employees agreed and the results in which their opinions differed. Furthermore, there was space to leave general comments, missing information and to note the differences between the built environment and civil industry.

The workshop consisted of four rounds. First, the participants had to answer if all topics which they agreed on were clear. Next, the topics where people disagreed were discussed. For each topic, a question was asked if it was clear and the employees could add a confirmation. Furthermore, in case people wanted to clarify or leave a comment, digital notes could be posted in the environment around the related topic. In the third round, the question was whether any topics were missing in the list. The experts got two minutes to think about it and paste notes with their ideas in the environment. Further explanation was asked about some of the comments which were interesting or unclear at first sight. In the last round, the question was if there are any differences between the specializations of the employees. Again two minutes were given to post notes with comments. Some unclear or interesting comments were discussed before closing the workshop. The link to the Miro environment stayed open during the day in case the employees would come up with another idea which was forgotten during the workshop. The setup and responses during the workshop can be seen in Appendix C. Each employee corresponds to a specific color post it. Following the privacy and anonymity requirements, the names and roles do not appear in the final overview.

7.2.4 Analyze results

The results of the workshop were combined with the results from Çetin et al. (2023) to create an uniform DPP format suitable for multiple stages and stakeholders in the built environment. A number between 0-1 assigned to all results; these were summed up and divided by the amount of attendees responding to the questionnaire. This way, the results were normalized. This is also done for the results of Çetin et al. (2023). The three results were multiplied with 0.33 and added up. This results in a number between 0 and 1. Every item (i.e., DPP topic), which scored above 0.8 was graded as a ‘must-have topic’ for the DPP content. All scores between 7 and 8 were graded as a ‘should-have’, scores between 5-7 as ‘nice to have’, and everything below 5 constitutes inessential topics that will not be included in the DPP and noted as ‘not necessary’(see overview of the results in Appendix D).

7.3 Workshop results – proposed DPP structure and content

As described above, during the workshop, the participants were asked if all topics of the questionnaire were clear and no comments were made. The topics about which the experts showed different opinions were discussed. The employees were asked whether they would like to provise an argumentation of the result, i.e., why they agree or disagree and if everyone agreed on the result in the end. No answers were changed and the answers concerning the collection of the DPP topics remained the same.

During the workshop, the attendees also got the opportunity to write down missing topics or critical notes. The topics that were identified as missing in the initial topic set during the workshop include more general information about the objects (e.g., object coordinates, object number, etc.), EPDs, certification (of products), data on maturity measurements, strategically scarce materials, inspections during the construction phase, information about the environment (e.g., soil type and characteristics), and weather conditions during construction. Furthermore, some critical comments were made. It was mentioned that creating a Life Cycle

Cost analysis is strongly dependent on the moment of its creation. Furthermore, questions concerning what happens with the BIM models/ information after the project is finished, and if the client will use the passport in the future during maintenance work were also addressed. In addition, it was agreed that to standardize the format of the passport, agreements need to be made about data structures, and a connection need to be made with existing systems.

Finally, the results of the workshop and the literature review were combined to form a list of ‘must-have' topics to implement in the DPP format. The analysis of the results van be found in Appendix D. This results in a total amount of twenty-six topics which scored above 0.8. Only the ‘must-have' topics are included in this thesis research in order to prevent the proof-of-concept DPP from becoming overly granular.The full list of must-have DPP topics (i.e., the DPP information requirements) can be found in Table 6.

Table 6: Defined DPP must-have topics

Property	Type of data	
Dimensions	Length, width, and height. Milimeter	Decimal
Weight	Kg	Decimal
Density	Kg/m^3	Decimal
Geometry	The form of the object	String
Quantity	Amount	Integer
Building location	Address	String
Building year	Date of completion	DateTime
Recycling potential	Kg of the material being recycled and the amount of energy used is measured in mJ (embodied energy) (NEN, 2019). (This is later changed to CO_2-eq, see section 8.9.1)	Kg:decimal Embodied Energy: integer
Reusability potential	Kg of the material being reused and the amount of energy used is measured in mJ (embodied energy). Proof of reuse needs to be included (European Commission & Directorate-General for Financial Stability, 2023);(NEN, 2019). (This is later changed to CO_2-eq, see section 8.9.1)	Kg in decimal and embodied Energy integer
Disassembly potential	Number based on index of (Durmisevic, 2006)	Decimal
Disassembly instructions	Related to the disassembly potential. Textual or visual description.	String
Future functions	The function that the object may occupy in the future.	String
Circularity	The above topics are defined as ‘circularity' topics in this research.	-

Property	Type of data	
Material composition	The percentage of which raw material the object consists of.	Integer
Material criticality	Boolean: yes or no.	Boolean
Secondary material/product	Kg recycled material (can be found in manufacturer information or Environmental Product Declarations in percentages) (NEN, 2019).	Decimal
Origin	Country of origin.	String
Product name/details	Name of the product and option to add description.	String
Product object nr.	ID of the object.	String
Manufacturer article nr.	Article number from the manufacturer.	String
Location in building	For example, the location of the product in the element or the location of the element in the building.	string
Warranties	Date or amount of time.	DateTime
Updates	Included in the condition assessment (condition assessment and last update).	string
Service life	Number. Amount of years the object is in service.	Integer
Condition assessment	Refers so the documentation including the condition assessment. Furthermore, last update will be shown.	String
Temporal information	Information related to time (e.g. completion date).	DateTime

Prototype Development

8. Prototype Design

The following chapter will discuss the architecture of the DPP data validation system, including the methodology for its development. Based on the findings from the literature review and the expert workshop, the system requirements are restructured and defined. A comparison between existing MPs and DPPs will be conducted and Competency Questions are established. In addition, the chapter explains the data formatting and collection, including the creation of the DPP ontology. The data will then undergo transformation and enrichment necessary for the validation process. Finally, the development of the data validation tool will be discussed.

8.1 System architecture for DPP creationa and validation

To prepare for the prototype development, a system architecture was created. The architecture defines the different elements of the process and corresponding system components needed to create, update, validate, and use the DPP. Figure 17 shows the overall proposed creation and validation process. The figure shows that given an existing resource (for example an IFC and material database), the data is converted to and stored in the Linked Data format in which the must-haves of the DPP are included. Together, these form the DPP of an asset. From there, queries can be performed to retrieve the data needed for the DPP validation. This validation will be performed based on a predetermined ruleset. The results of the validation can be seen in the user interface after the user selects the required input (ruleset and DPP).

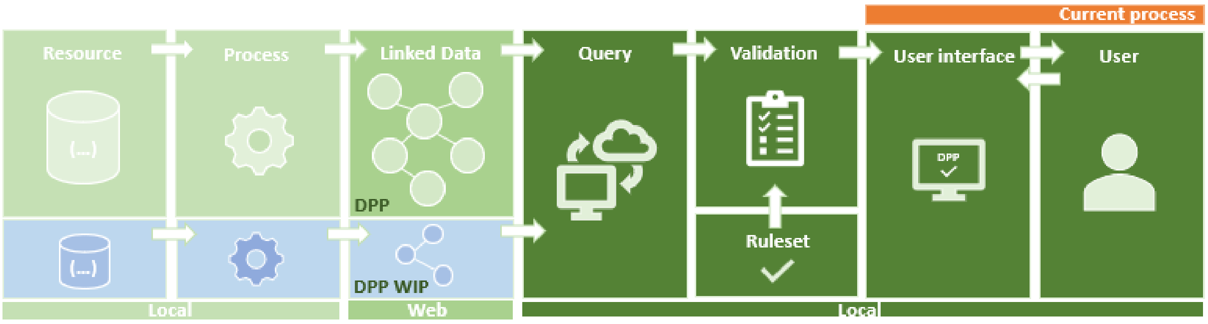


Figure 17: Initial overall process for creating and validating Linked Data-based DPPs

This current process can result in some challenges. When different parties want to include DPPs from previous stages, this will likely need to be done manually on the first place, since parties work based on their own data storage (data silo). This can lead to data loss or the lack of up-to-date data when updates are not communicated in time. Therefore, a more hybrid process is preferred (Figure 18).

Figure 18 shows that data can be uploaded and converted to the Linked Data format as part of the Extract, Transform, Load (ETL) procedure, where other (existing) DPPs can be added in the following process steps. From there, the information can be retrieved by all parties using standard semantic information retrieval mechanisms. This way, the user can ensure to use up-to-date data that is also easier to trace back to the economic operator who worked on and provided the DPP. The DPP remains the 'property' of its respective current owner (e.g., manufacturer).

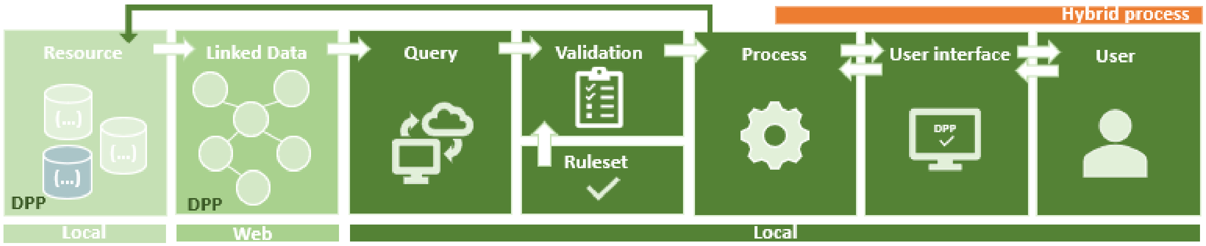


Figure 18: Preferred hybrid process for creating and validating Linked Data-based DPPs after second development iteration

8.2 Prototype approach

The research approach is based on a System Engineering process (based on the System Life Cycle Model of Kossiakoff et al., (2020)). This approach is illustrated in Figure 19 and comprising four phases: (1) data collection, (2) system architecture design, (3) prototype development, and (4) prototype validation. Initially, user requirements are defined following the workshop results, and the necessary data is gathered. The system architecture is designed to aid in the development of the prototype, focusing on a specific use case. Ultimately, the prototype is validated to ensure that it meets the requirements, and if necessary, iterations are made. As shown in Figure 19 there is a backward loop from prototype validation to system architecture design. This means the cycle begins again after validation until the desired outcome is achieved.

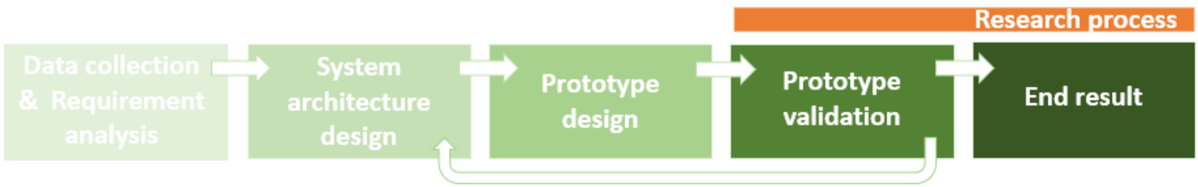


Figure 19: Research methodology

8.3 Prototype requirements classifications and summarization

Existing literature suggests the general requirements in section 4.4, but comparing and evaluating passports requires consideration of other factors. These include whether the passport format is accessible for free or restricted, its scalability for various project sizes and environments, and its current level of use and adoption (including who is using it and if there is a community. Furthermore, if it includes needed user authentication & authorization). It is also crucial to ensure that the passport is complete, based on workshop must-haves, and available in English for widespread use. Additionally, the passport must be immediately usable, without requiring additional research by the passport user. To determine the readiness of existing MPs/DPPs it is hereby proposed to consolidate these topics under the requirement **applicability**. This requirement is then translated so that it is also a valid requirement for the validation process.

The specified must-haves and DPP requirements (**R**) (Section 4.4 and Section 7.3) have served as the basis for formulating and categorizing the final set of requirements (Table 7). Three distinct categories of requirements have been identified: (1) user requirements, (2) validation process requirements, and (3) data requirements. User requirements (Table 8) define the needs from the perspective of the (potential) end user; in this instance, the construction engineer (e.g., site engineer, sustainability advisor, and BIM modeler). Within affiliated company, these roles are accountable for the content of the passports. The second set of requirements (Table 9) relates to the capabilities that the validation process must be capable of once implemented. The data requirements (Table 10) specify the criteria for the data. Furthermore, each requirement is assigned a priority level (**P**). Score 1 denotes the highest priority, while 3 indicates the lowest. Some requirements were not feasible to address due to the scope of the research. Consequently, these requirements received the lowest priority. The primary focus of this study is on establishing the creation and validation process and the associated must-haves, rather than on peripheral requirements such as data storage, modifications, and access provision.

Table 7: DPP requirements

DPP requirement (R)	Code
Must-have subject	MH
Legal obligations	L
Functional suitability	F
Security, confidentiality, and IP Protection	S
Accessibility	A
Interoperability	I
Modularity and Modifiability	MM
Availability and Time behavior	AT
Portability	P
Non-Redundancy	R
Applicability	AP

Table 8: DPP user requirements

User requirements			
The user is able to …		**P**	**R**
1	Validate whether the must-haves (Table 6) of the objects are represented correctly, using the IFC and DPP.	1	MH, F
2	Retrieve the information of the validation together with the corresponding IFC GUID of which object is wrong or missing.	1	MH, F
3	Make additions and modifications to the source data.	2	MM
4	Remove or adapt actors, products, or attributes as requirements evolve.	3	MM
5	Easily understand the validation process and its results.	1	A, AP
6	Access the tools needed for the validation process without costs involved.	2	AP
7	Perform the validation process without extra steps or research needed	2	AP

Table 9: DPP validation process requirements

Validation process requirements			
The validation process should be able to …		**P**	**R**
1	Query and validate the must-haves (Table 6) from the IFC model and DPP and communicate the results.	1	MH, F, AP
2	Comply with the following legal obligations: GDPR, the EPR, the 'right to repair', and the ESPR.	3	L, F
3	Not impede existing chain processes, product quality, or safety.	3	F
4	Provide a secure data exchange between the value chain members.	3	S
5	Remain the data control with the data providers to safeguard intellectual property.	3	S
6	Ensure access for assigned parties through an access control mechanism.	3	A
7	Ensure participation opportunities for the parties without stable internet connections or advanced IT systems.	3	A
8	Ensure permanent access to the whole life cycle data.	3	A
9	Visualize the data in an understandable manner.	2	A
10	Exchange validation information across different company boundaries.	2	I
11	Show the information when needed.		AT
12	Tranfer information between software systems to enable decentralized systems.	3	P
13	Guarantee origin, integrity, verifiable, compliance, and immutability.	3	S
14	Be scalable for various project sizes and environments, and its current level of use and adoption	2	AP

Table 10: DPP data requirements

Data requirements			
The data should allow to/be …		**P**	**R**
1	Show and validate the unit of measurements of the must-haves as stated in Table 6.	1	MH
2	Enable interoperability within and between systems by the use of shared semantics and standardized data schemes.	2	I, P, R
3	Available in real-time (availability and time behaviour).	3	AT
4	Uniquely identified, traceable, and time stamped.	1	P

8.3.1 Comparative analysis for standard passport selection

The research conducted by Çetin et al. (2023) involves a thorough comparative analysis to assess the current state of MPs and DPPs available in the market. This analysis encompasses all passports mentioned in both published literature and grey literature, therefore, it is also included in the current analysis. Additionally, the passports of the affiliated company were also considered. These passports follow a general format used by the infrastructure department, as well as a project-oriented format centered around the Transformer building (see Section 8.6).

Initially, the selection process evaluated the existing passports based on the number of must-haves they possessed and the overall number of topics covered, as outlined in the list provided by Çetin et al. (2023). The passports that received the highest scores were BAMB (2019), DGNB (2022), Madaster (2022), Jonge Honden (2019), and Platform CB'23. Additionally, the passports belonging to the affiliated company were automatically included in the next round to gain insights into their current status. Before comparing the passports based on the general requirements, three passports were excluded due to the applicability requirement. First, the passport of BAMB (2019) was excluded as attempts to access the platform were unsuccessful. Second, the passport of Jonge Honden (2019) was removed because it lacked a proper format, only providing a PDF with an explanation of what the format should entail. Last, the DGNB (2022) passport was eliminated as it is available in German.

Subsequently, the passports of CB'23, the affiliated company, and Madaster (2022) underwent an evaluation based on the general requirements. It is important to note that the legal obligations associated with these requirements were not considered in this assessment, as they are still under development. Each requirement was assigned a corresponding score. A score of 5 was awarded when the requirement was fully met, a score of 3 when it was partially met, and a score of 0 when only a small amount or none of the requirements were fulfilled. The outcomes of this scoring process are presented in Table 11 (for a comprehensive explanation, please refer to Appendix E and F).

Despite the company passport scoring very high on the 'must-have items', the remaining requirements receive lower scores. This is because the format is in Excel, not publicly available, written in Dutch, and although it includes most 'must-haves', it also appears to be too extensive. Consequently, it could pose challenges for an inexperienced employee to use. Madaster's passport currently holds the highest score. It functions as an online platform linked to company databases. While these databases may not always contain all necessary products, manual addition of products is possible. Additionally, a digital model can be uploaded to the platform. However, although the platform claims the passport is suitable for infrastructure, its primary focus is on the building sector. Currently, the Madaster platform cannot match predefined infra-technical specifications (bestek), making it challenging to use in the infrastructure sector. As a result, the current passport formats have been considered unsuitable for further use in this research as they do not meet the criteria outlined in this study.

The following sections, therefore, outline the transformation of the defined must-haves into an ontological model for DPPs that would enable the creation and validation of the passports, the implementation of which is presented later in the report.

Table 11: Comparative analysis for standard passport selection

	Madaster, 2022	Platform CB'23	BAM 'Standard' infra	Tennet
Level	Area Complex Building Product	Area Complex Building Element Product Material	Building (object) Element Product Materiaal	Product
Total must have items	10	9*	25**	12**
Total items (used during the workshop)	20	24*	52**	22*
Legal obligations	Complies with regulation and building certification programs (e.g. CSRD, Taxonomy, BREEAM, etc)	Laws and regulations (Dutch) are mentioned in the PDF with explanation about the material passport	-	-
Functional suitability	3	5	3	3
Security, confidentiality & IP protection	5	0	0	0
Accessibility	3	3	3	3
Interoperability	5	3	0	0
Modularity & modifiability	5	5	5	5
Availability & time behavior	5	0	0	0
Portability	5	3	0	0
Non-redunancy	5	5	3	5
Applicability	3	5	3	3
Score (except must haves)	**39**	**29**	**17**	**19**

*CB'23 the items can differ per stadium and level the assessment takes place
**the items are included if it is stated in the passport, also when the information given is minimal

8.4 Competency Questions (CQ)

Section 7.3 provides a comprehensive overview of the must-have components included in a product passport, which are crucial for the development of databases and information models. These databases and models play a vital role in enabling stakeholders to access and extract the necessary information. To ensure the validity of the proposed DPP ontology and validation tool, specific Competency Questions (CQ) have been formulated. These questions are designed to involve engineering experts who possess the expertise required to validate the theory in practical scenarios, particularly within the construction industry. The team of engineering experts consists of a site engineer, who possesses in-depth knowledge about passports within the affiliated company, and a sustainability advisor (typically dealing with product passports as well). The BIM engineer is not involved, since their expertise is mainly within BIM modelling instead of DPPs and because of this does not have knowledge about the passport content and structure Two sets of questions have been compiled by incorporating the engineering experts' insights and expertise. One set represents the perspective of the site engineers, (Table 12) while the other reflects the viewpoint of the sustainability advisor (Table 13). Finally, Table 14 displays the set of must-haves presented. The purpose of this table is to ascertain whether all the necessary elements are encompassed at the product level. The possibility exists that the information may be required at a specific level. However, the exact level at which the information is needed is not always clearly defined. For this reason, the product level is maintained in these cases.

Table 12: Competency questions Site engineer

Competency Questions site engineer		Explanation
CQ1a	What materials do the products contain?	Understanding the composition of the product and providing accurate belonging information.
CQ2a	What products are the elements made of?	Understanding the composition of the element and providing accurate belonging information.
CQ3a	What is the lifespan of the products?	To recognize the appropriate time to replace or provide maintenance to a product
CQ4a	What is the origin of the materials used in the building?	The origin of a substance can be important, considering factors like its ecological impact or the manufacturing conditions it undergoes.
CQ5a	Do all products have assurance for reuse?	Know if the product can be reused in the future
CQ6a	How to disassemble the products used in the building? And what is the belonging disassembly potential?	Understanding the ease of disassembling a product and exploring ways to improve its reusability.
CQ7a	Are there critical materials used in the building?	To know which materials need to be preserved/reused after service life. Important to know in which product are these located.

Competency Questions site engineer		Explanation
CQ8a	Is the condition of the products assessed? (start measurements and the current condition)	To determine the latest status of the item and know whether maintenance is required. It is also essential to evaluate its suitability for reuse.
CQ9a	What future function can the products fulfill?	Recommending a possible future function might increase the possibility of reusing the product. What is the future function on the element, product, and material level to enable a new function on the highest level of 10R principle.
CQ10a	What are the classification codes for the object?	This code matches with other documentation to ensure each document provides information about the same object.
CQ11a	What elements contain the material cement?	Example question
CQ12a	What is the recycling potential and reusability potential of concrete?	Example question
CQ13a	What is the recommended future function of the products containing the material polyisocyanurate?	Example question
CQ14a	What is the nen2767 code of the walls?	Example question
CQ15a	What is the GUID of the concrete wall?	Example question

Table 13: Competency questions Sustainability advisor

Competency Questions sustainability advisor		Explanation
CQ1c	Where is the building located?	Identifying the specific project for which the passport is intended is essential, although it can also serve multiple other purposes. For instance, in the realm of infrastructure, details regarding the surface can be relevant.
CQ2b	Who are the manufacturers of the products?	The importance of this data serves multiple purposes, such as obtaining details about products, being able to reach out in case of any problems, and so on.
CQ3b	What materials does the building contain?	A comprehensive summary that can serve as a resource for future repurposing or recycling.

Competency Questions sustainability advisor		Explanation
CQ4b	What are the dimensions of the elements and products?	The employee is responsible for identifying the key components and verifying their dimensions. Additionally, the employee can ensure that the dimensions conform to standard measurements.
CQ5b	What is the density of all materials in the building?	The density is essential for determining the weight of the materials present within the structure. This weight in kilograms can subsequently aid in assessing the potential for reuse, among other applications.
CQ6b	What is the remaining life expectancy of the elements/products/materials	To recognize the appropriate time to replace or provide maintenance to an object.
CQ7b	What is the recycling and reusability potential of the materials/products?	To understand if the material/product can be reused after service life. To form a material cadaster.
CQ8b	Can the elements/products/materials be disassembled?	It is possible to consider a new purpose for an item once its service life has ended, allowing for reuse or recycling. Therefore it is important an object can be disassembled.
CQ9b	What products contain secondary material?	This data may be required for reporting purposes and to furnish details regarding the object's sustainability.
CQ10b	Which materials in the building are critical?	To know which materials need to be preserved/reused after service life.
CQ11b	What condition assessments have been made to the elements/products over the years?	To determine the latest status of the item and know whether maintenance is required. It is also essential to evaluate its suitability for reuse.

Table 14: Competency Questions DPP must-haves

	DPP Must-haves	Competency Questions must-haves
CQ1c	Dimensions	See question Q4b
CQ2c	Weight	Included in density
CQ3c	Density	What is the density of all products?
CQ4c	Geometry	What is the geometry of all products?
CQ5c	Quantity	How many products are there in the building?
CQ6c	Building location	See question Q1c
CQ7c	Recycling potential	See question Q7b
CQ8c	Reusability potential	See question Q7b
CQ9c	Disassembly potential	See question Q6a
CQ10c	Disassembly instructions	See question Q6a
CQ11c	Future functions	See question Q9a

	DPP Must-haves	Competency Questions must-haves
CQ12c	Circularity	Combined with the above subjects
CQ13c	Material composition	What is the material composition of the present products?
CQ14c	Material criticality	See question Q7a
CQ15c	Secondary material/product	See question Q9b
CQ16c	Origin	Material level, See question Q4a
CQ17c	Product name/details	What are the names and descriptions of the products?
CQ18c	Product object nr.	What are the product's object numbers?
CQ19c	Manufacturer article nr.	What are the manufacturers' article numbers of the products?
CQ20c	Location in building	What is the location of the products in in the building?
CQ21c	Warranties	What are the warranties of the products?
CQ22c	Updates	See question Q11b
CQ23c	Service life	See question Q3a
CQ24c	Condition assessment	See question Q11b
CQ25c	Temporal information	What is the delivery date of the products?

8.5 Information model development using Unified Modelling Language (UML)

To create the DPP validation tool, it is important to understand the various concepts that must be validated and their relationships. The list of DPP must-haves, determined during the workshop, serves as the foundation for selecting the required components for validation. Only the must-haves with priority level 1 are included in the validation process, as the other requirements are subject to change. To gain a better understanding of the must-haves, a UML class diagram with corresponding UML data classes has been created based on decompositions of building systems. These classes contain the must-haves as a separate class or as an attribute of a class (Appendix G). Next, the circularity-related classes are created. This classes employ a "parent-child" relationship where sublasses have an "inverseOf" relationship with one another (a parent has a child, and a child has a parent). This study only includes the must-have components under the concept of circularity, although the term consists of several subjects.

Additionally, several parts beyond the identified must-haves have also been added. These include proof of reuse, log, owner, and external party, also modelled as classes. These help comply with regulations and allow the DPP to function as a track-and-trace mechanism. For example, the CSRD requires proof of reuse. Furthermore, a classification code class has been added to provide an overview of object classification for use in the DPP and to connect with current classification methods (specifically, the NEN2767-4 and NL-SfB, which are relevant to the affiliated company and the data models used in this thesis).

When considering an element, product, or material, the building object can consist of multiple components. This self-association within the objects can be identified through a loop that exits and re-enters the class (Figure 20). The element class does not contain a self-association but there is a class 'subelement' connected to it based on the Building Topology Ontology (BOT).

The main UML classes and attributes are presented in Table 15 and Figure 20.

Table 15: Classes and attributes data structure

Classes	Attributes
Decomposition of building system	
Site	ID, and geolocation
Building	ID, name, description, address, service life, and completion date
Storey	ID, description, unique name, and elevation
Space	ID, unique name, description, length, width, height, and completion date
Element	ID, name, description, length, width, height, angle, completion date, warranty, and service life
Subelement	ID, and name
Product	ID, name, description, manufacture number, length, width, height, angle, density, completion date, warranty, and service life
Material	ID, name, description, manufacture number, length, width, height, criticality, density, secondary, completion date, warranty, and service life
Raw material	ID, name, and criticality
General classes	
Manufacturer	Name, description, address, and email address
Classification code	Classification code, and decomposition level
Circularity classes	
Circularity property set	ID, and name
Future function	ID, and future function
Reusability potential	ID, reusability potential, and embodied energy
Recycling potential	ID, recycling potential and embodied energy
Origin	ID, and country of origin
Condition assessment	ID, version, version date, last update, and condition assessment
Disassembly potential	ID, description, and disassembly potential
Proof of reuse	ID, description, and proof available
External party	ID, and name
Log	ID, version, and link to database
Owner	ID, and name

Figure 20: UML class diagram representing the proposed data structure of the DPP (based on the identified must-haves)

8.6 Data selection

To establish a validation tool for Digital Product Passport data, the tool's configuration must be developed and its outcomes must be verified. Three essential inputs are needed for the configuration of the DPP validation tool: the BIM model, the relevant passport, and the validation requirements. Furthermore, a second use case model and the related data are incorporated in this research to authenticate the rule-checking system.

8.6.1 Data selection

In this thesis, two BIM models were utilized. The first model, which was obtained from the affiliated company, features a Transformer building and was employed to establish the foundation of the validation tool. However, this model does not adhere to the necessary modeling standards. As a result, a second model, obtained from Eindhoven University of Technology, was utilized to test both the creation and validation process and tool. This second model, which depicts a 'basic' house, has been accurately modelled and completed. See Figure 21 and 22.

In both models, a careful selection is made of the elements to be used for further expansion into a database containing product and material information and to use as input for the validation tool. For the Transformer building, four elements are chosen based on the availability of clear and reliable information. These elements are: two prefab walls and two coverings (insulation and wall cladding). In the house model, three elements are chosen based on the richness and diversity of the information available. These elements are: a wall, a window, and a door.

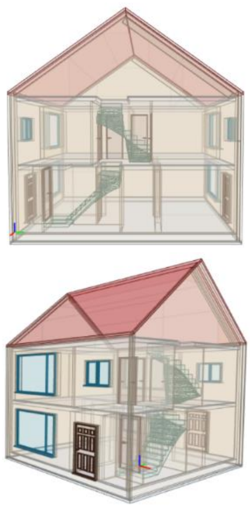


Figure 21: Terraced house

Figure 22: Transformer building

Element 1 Transformation building

A basic prefab wall. The element can be found in Revit model by the label: Basic Wall:NLRS_21_WA_beton prefab met blokverband, wit d=70/20_gen25711243 with the corresponding IFC GUID:OM2CR8ktv2tuvYCimnWoWv. See Figure 23.

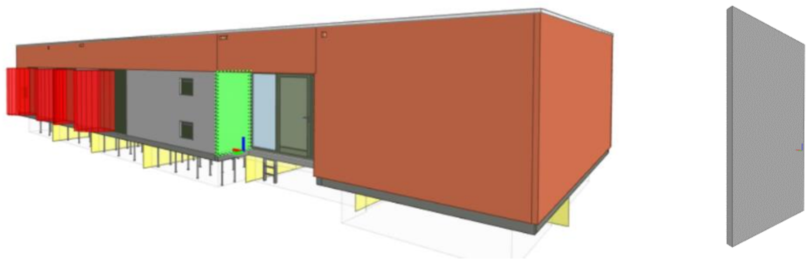


Figure 23: Prefab wall element Transformation building (1)

Element 2 Transformation building

A basic prefab wall patterned on the site of the building. The element can be found in Revit model by the label: Basic Wall:NLRS_21_WA_beton prefab met patroon, antraciet d=70/20_gen25711341. The corresponding GUID is 0M2CR8ktv2tuvYCimnWoXV. See Figure 24.

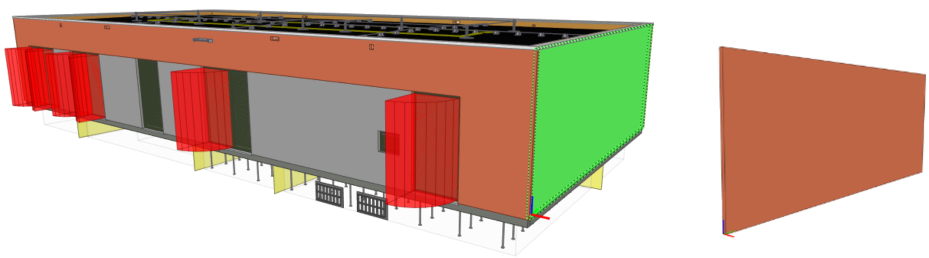


Figure 24: Prefab wall element Transformation building (2)

Element 3 Transformation building

A element consist of cavity wall insulation. The element can be found in Revit model by the label: Basic Wall: NLRS_21_WA_spouwmuurisolatie PIR platen, antraciet d=102_gen25707110. The corresponding GUID is 0M2CR8ktv2tuvYCimnWpZK. See Figure 25.

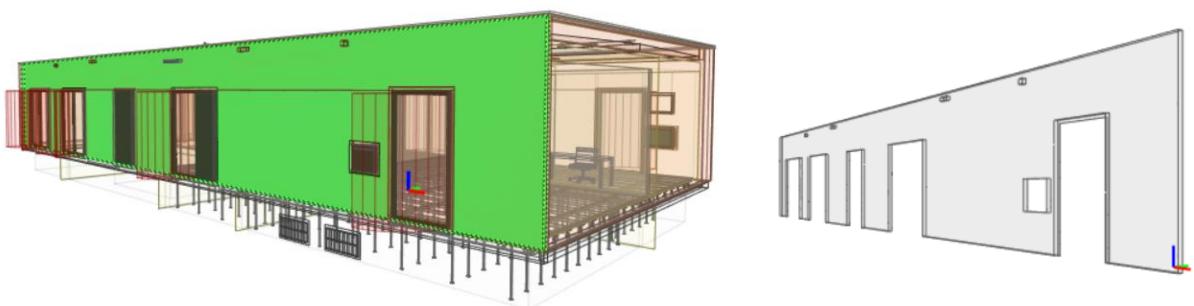


Figure 25: Cavity wall insulation Transformation building

Element 4 Transformation building

This element is wall cladding. The element can be found in Revit model by the label: Basic Wall:NLRS_42_WA_wandbeplating mdf d=22mm_gen:28852558. The corresponding GUID is 0Pek_wvoH5JAigEkDVxTNn. See Figure 26.

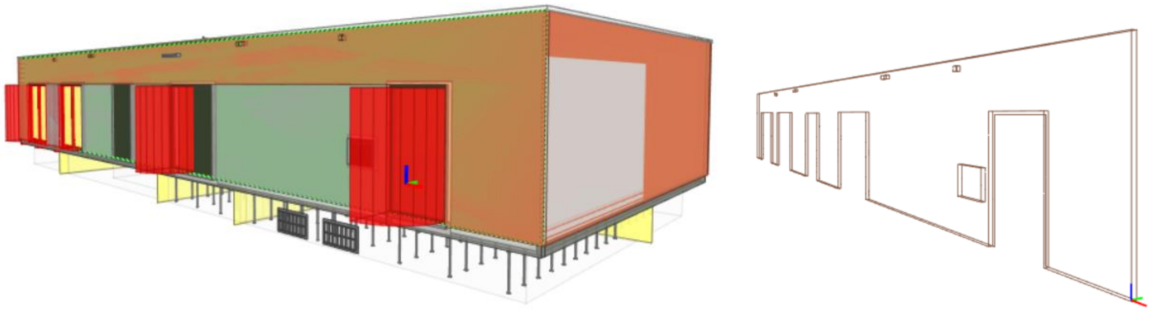


Figure 26: Wall cladding Transformation building

Element 1, 2 & 3 Terraced house

Furthermore, three elements are selected in the Terraced house. The first element is a standard wall located inside the house. The label of the wall is: Basic Wall:NLRS_22_WA_250mm:830959 and the corresponding GUID 2l0Jzj3Tf3oQOCHrbYc0g$. The next element is the back door with label: Doors_ExtSgl_3:1010x2110mm:878657 and the GUID: 3192I6b2H3P9YpB65ZvvVI. Finally, a window is selected at the back of the house. This element has the label: Windows_Concept_Plain_Sgl:2416x1900mm:880971 and GUID: 3192I6b2H3P9YpB65ZvuxO.

Figure 27: Wall, door and window of the Terraced house

8.6.2 Missing data

An assessment is conducted to verify the presence of the necessary topics in the Revit models. BIM Vision (BIMvision, n.d.) is utilized for this purpose. Table 16 and Table 17 display the topics that are missing from the supplied Revit models. If dummy data was utilized in the model, the topic is not included in the table (thus recorded as present). It is essential to manually input this data in further steps to develop and assess the DPP validation tool efficiently.

Table 16: Missing data Transformation building IFC

Transformation building	
Missing classes	
Missing classes	Classification code, Manufacturer, Subelement, Material, Raw material, Circularity Property set, Log, Owner, Future function, Reusability potential, Recycling potential, Origin, Condition assessment, External party, Proof of reuse, and Disassembly potential.
Building level classes	**Missing attributes**
Site	Geolocation
Building	Description, service life, and completion date
Storey	Description
Space	Description, height, and completion date
Element	Description, completion date, warranty, and service life
Product	Manufacture number, density, completion date, service life, and warranty.

Table 17: Missing data Terraced house IFC

Terraced house	
Missing classes	
Missing classes	Subelement, Raw material, Circularity Property set, Log, Owner, Future function, Reusability potential, Recycling potential, Origin, Condition assessment, External party, Proof of reuse, and Disassembly potential.
Building level classes	**Missing attributes**
Site	Geolocation
Building	Description, and service life
Storey	Description
Space	Description, and completion date
Element	Description, completion date, warranty, and service life
Subelement	ID, and name
Product	Manufacture number, density, completion date, service life, and warranty.
Material	ID, description, manufacture number, length, width, height, criticality, density, secondary, completion date, warranty, and service life
General classes	
Manufacturer	Description, address, and email address
Classification code	Decomposition level

8.7 Ontology development and reuse

The forthcoming paragraphs will provide an explanation of the employed (reused) ontologies and the development of the DPP ontology. Additionally, a description regarding the utilization of ontologies in Protégé will also be presented.

8.7.1 Reuse ontologies

When creating an ontology it is recommended as 'best practice' to utilize already established ontologies whenever possible to avoid unnecessary duplication and confusion. Therefore, existing ontologies were examined (Section 5.2.3) for each class and its properties based on the identified DPP must-haves (see Figure 28).

First of all, the Building Topology Ontology (BOT) is selected for reuse, since it provides a high-level description of the topology of buildings. Therefore, this ontology is used for the classes, Site, Building, Story, and Space. Furthermore, the Building Material Performance (BMP) ontology is used for the Manufacturer class. This class contains the property Name, Description, E-mail, and Address. For the property Name and E-mail the BMP ontology is used whereas the address definition relies on the ISA Core Location Vocabulary Ontology (LOCN), since the latter is not included in BMP. Furthermore, RDFS is used for all general properties within the product and material data. The Quantities, Units, Dimensions, and Types ontology (QUDT) is used for the data related to measurable quantities, and units. Additionally, the Property Management Ontology (PROPS) is used in the Transformation building and Terraced house conversions as well. This ontology is automatically generated when converting the IFC files to a Turtle file, as explained in Section 8.8.1. Last, the existing Provenance Ontology (PROV) is used on the element, product, and material levels. This ontology is used for time-related properties, such as completion date and atTime in case of an update.

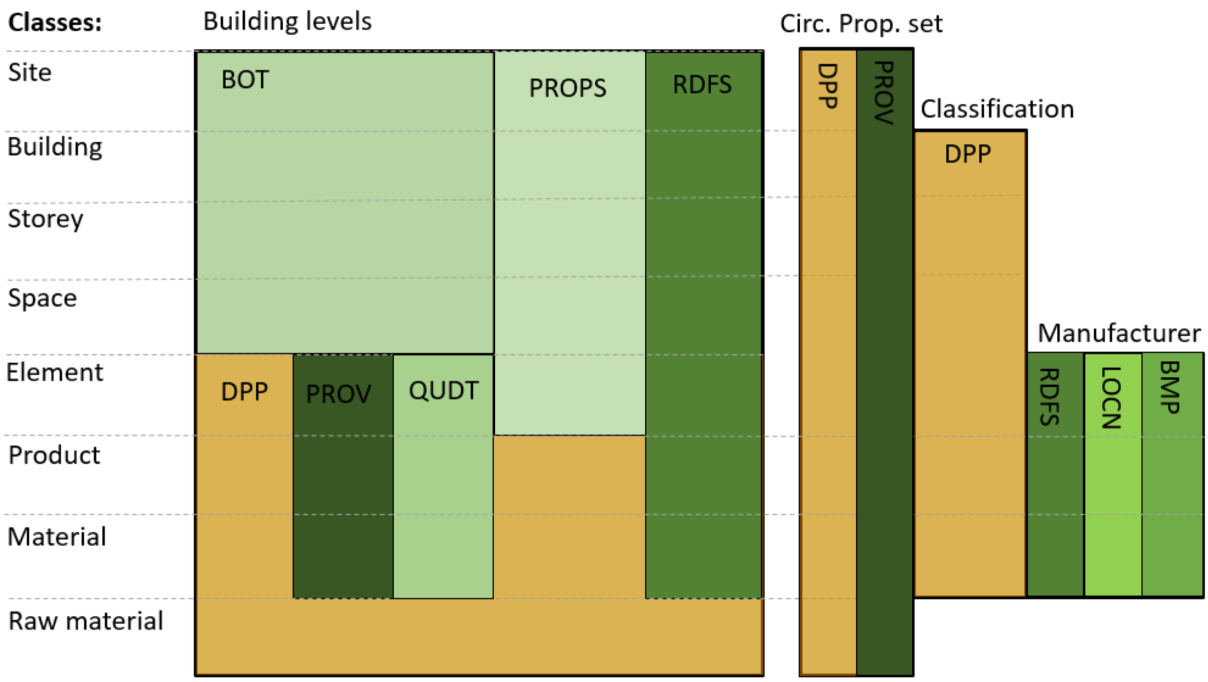


Figure 28: The used ontologies ordered by level

8.7.2 Creation of the DPP Ontology

A new ontology, known as the Digital Product Passport Ontology (DPP ontology), has been developed due to the absence of any published ontology for describing the relevant information, including the Circularity classes and the Classification Code class. This ontology incorporates elements, products, materials, and raw materials to align with the definitions of Platform CB'23 (2019), as the current ontologies do not adhere to this specific definition. This is due to different sources using different definitions for these levels (currently there is no solid foundation). The definition of Platform CB'23 (2019) is selected since it is related to standard circularity and MP definitions in the Netherlands. Nevertheless, there is a possibility of linking the existing alternative ontologies (such as BMP and DICBM) at these levels to the circularity property set, if an alternative definition is desired (See the TBox in Figure 30, where the light green boxes indicate the alternative ontologies).

In the TBox, in which the ontologies and relations are shown, there is a light orange box situated around the circularity property set classes and the material and product class. This indicates the part that is translated into the ABox in Figure 31. The ABox showcases the properties associated with the classes, accompanied by an example input.

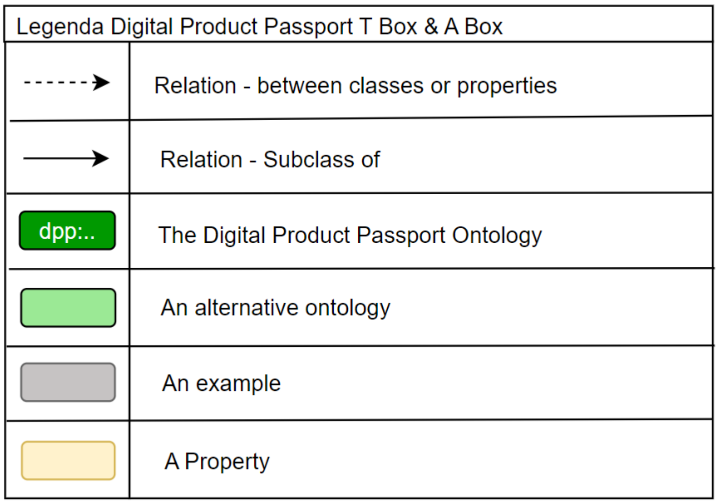


Figure 29: Legend TBoxand A-Box

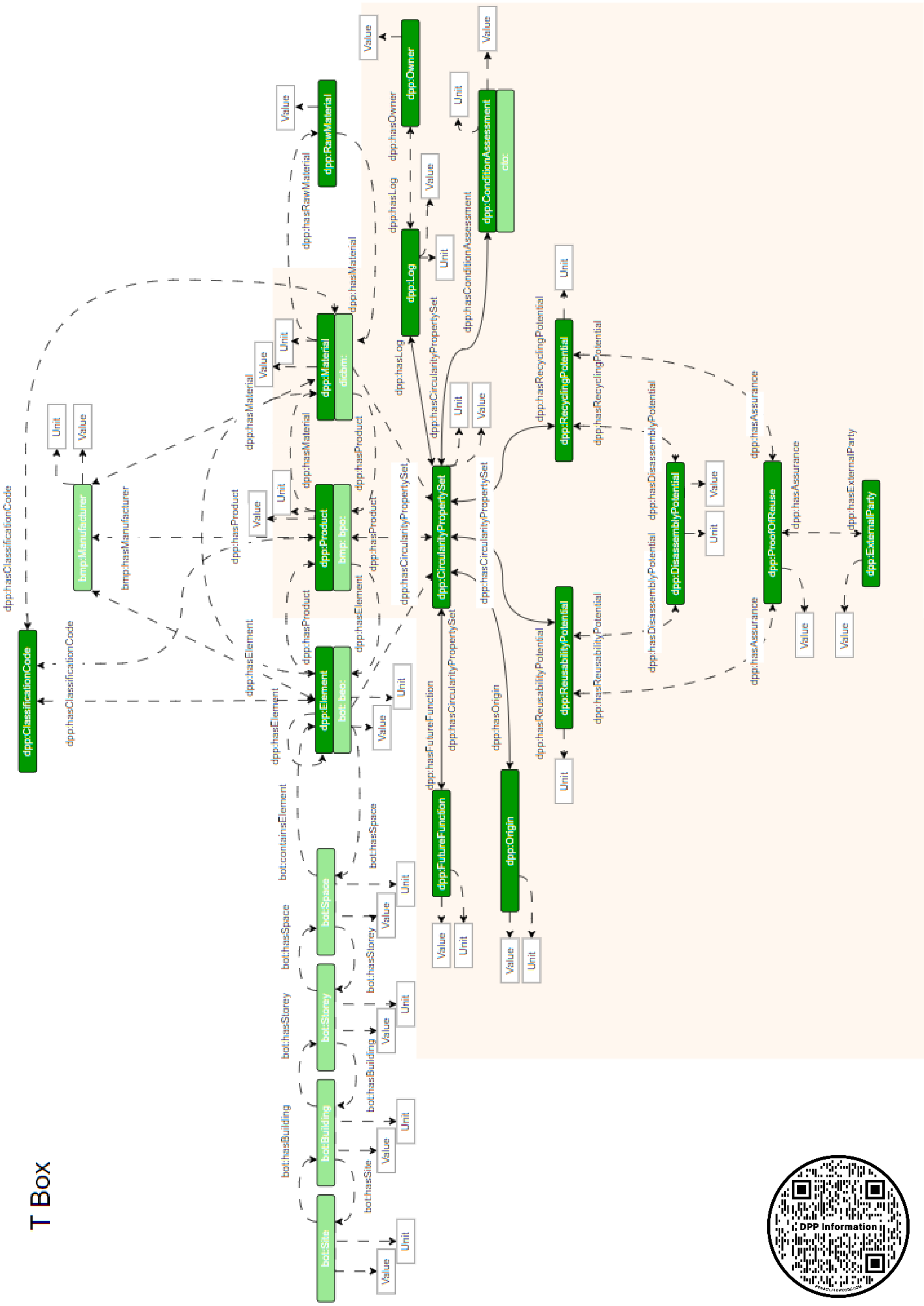


Figure 30: TBox DPP Ontology

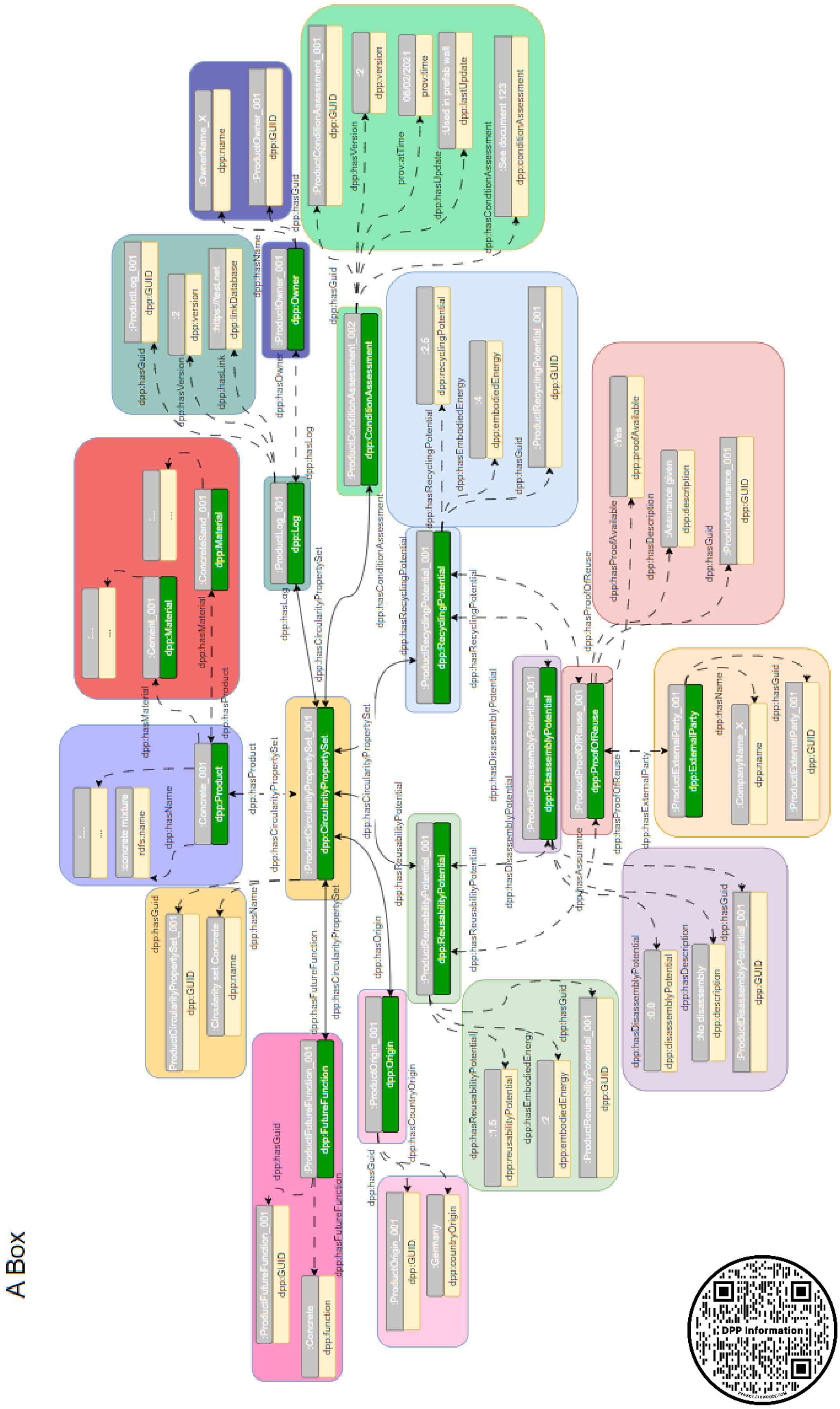


Figure 31: ABox DPP Ontology

8.7.3 DPP ontology development in Protégé

Protégé (Stanford University, n.d.) is employed for constructing the DPP ontology, which includes the modeling of classes such as Element, Product, and Material, as well as all Circularity Property Set classes and the Classification Code class (see Appendix J). Various alternative ontologies that can be utilized for a number of classes and properties are presented. For instance, the QUDT or OM ontology can be utilized within the measurement parts (length, width, and height) in the properties. Furthermore, another alternative is the BOT ontology which is incorporated into the Element class, for instance.

There are several ways to reuse ontologies within Protégé. These ways include: citation method , linked (open) data method, linked (internal) data method, and Protégé merge & (hand) Dedupe Method (Faith, 2023).

The first method is not recommended due to its failure to offer a valuable connection to the alternative or variant ontologies that are made available. Although these ontologies are referenced, they can only be accessed by searching for them outside of the DPP ontology. The same limitation applies to the linked (internal) data method. In this method, an IRI is utilized within Protégé, but it lacks an IRI that directs to its online location.

In the next method the DPP ontology incorporates an external ontology, resulting in the merging of the two or more ontologies. Subsequently, there are two methods available to establish connections between the components for reuse. The first method involves utilizing the 'equivalent to' option. For instance, a class from the DPP ontology can be associated with a class from the OM ontology. However, in this specific scenario, this option is not feasible. This is because the OM ontology is primarily designed for measurement reuse, where length is represented as a class. Conversely, within the DPP ontology, length is represented as a property. Consequently, these two components cannot be linked to each other using the 'equivalent to' option. An additional approach is to integrate the IRI of the OM ontology into the length attribute of the DPP. Nonetheless, this process requires a significant amount of manual effort to establish these linkages and to prevent crucial data from being eliminated.

Ultimately, the decision is made to utilize the linked (open) data approach. This approach involves incorporating the IRI of the ontologies that need to be linked into the annotations field of associated DPP classes and properties. This method is implemented in two different ways. First, the ontologies that were suggested for reuse within classes and properties were specified in the 'variant annotation'. Additionally, there were alternative ontologies available for reuse, which were denoted by an 'alternative option' within the annotations field.

8.8 Data preparation

The subsequent sections describe the process of data preparation, encompassing the conversion of IFC data to RDF and the enrichment of RDF data in preparation for DPP validation.

8.8.1 IFC to LBD Converter

To begin with, the Revit file must undergo a conversion process (export) to the IFC STEP format. During this export, it is crucial to consider the various parameters associated with the file. These parameters can be categorized into three types: (1) system parameters, (2) type parameters, and (3) instance parameters. Typically, when using the standard IFC export options, only the system and type parameters are exported. However, depending on the required information, additional export settings may need to be applied to include this information. For instance, if there is a need to export measurements or classification codes (such as NL-SfB), the “export Revit property set,” “Export IFC common property sets,” and “Export base quantities” options need to be utilized. In this thesis, the Transformation building is exported using only the standard IFC export options. The Terraced house model is exported with all parameters included.

The- further conversion of the Transformation building and Terraced house to RDF utilizes the IFCtoLBD converter (Pauwels, 2020) to transform IFC file into Turtle files (RDF data). This process enables the data to be compatible with other graph data and facilitates the execution of SPARQL queries. The converter makes use of several existing ontologies such as BOT, PROPS, and RDF Schema. The converted Turtle file describes the objects, classes, properties, instances, and belonging literals. Furthermore, this code generates the Ifc GUID as Compressed GUID. This is necessary to track the object during the validtion process. Figure 32 shows a fragment of the data from the Transformer building. In this snippet, the general information of the building is shown. Not all literals are filled in with real data.

8.8.2 Data enrichment

The IFC files do not fully provideall the required must-haves needed in the Turtle files (see paragraph 6.1.1). Consequently, the IFC models (Transformation building and Terraced house) will be manually enhanced with this missing data (according to the DPP ontology). Two RDF files are generated for each building - one file without enhancements and another file with the necessary additions. Both Turtle files cannot be used without any modifications. This is, for example, due to quotation marks in the literal options, which are used to indicate inch values. Initially, these quotation marks are eliminated and substituted with text (“inch”) to ensure the file's usability. Another error occurs in some literals which are filled incorrectly based on the datatype. Therefore, small changes need to be made in the original files to enable their direct usage. Furthermore, based on the needed ontologies, belonging prefixes are added on top of the files (Appendix K). Additionally, the matching prefix for the IFC instance needs to be added to the product and material level of each building. The conversion of the Transformation building is carried out exclusively through the standard export options, as noted earlier. Consequently, there are missing dimensions and other discrepancies. Therefore, the measurements are manually included in the modified version of the building.

This results in the following files:

- IFC_Tranformatiegebouw.ttl
- IFC_Tranformatiegebouw_Altered.ttl
- Rijwoning-BM.ttl
- Rijwoning-BM_Altered.ttl

Not all topics that are missing are included on every level. The product level and material level both encompass all the must-haves as the product level is determined to be the desired level of the passport. However, on the building and element level, the circularity property set classes are not included. Only the properties of the building level, element level, and the classification code class are included. This is done to test the structure in the validation tool for each level. The missing classes on these levels can be added later and still be validated according to the same structure that is created for the material and product levels (when adjusting these to the right level).

Furthermore, it is observed that the names of existing properties in the IFC files do not match the used concepts inside the DPP, despite containing the same information. This is due to naming conventions in the Revit model. Therefore, terminology and instance value for those properties are manually added to ensure that the structure remains intact. Figure 32 depicts a fragment of the Transformation building. Each modified or added piece of data is identifiable by the hashtag and accompanying text at the end of the line.

```
inst:covering_49916
    a bot:Element ;
    a beo:Covering ;
    a dpp:Element ; #added
    rdfs:label "Basic Wall:NLRS_WA_wandbeplating mdf d=22mm_gen:28852558"^^xsd:string ;
    rdfs:comment ""^^xsd:string ;
    bot:hasGuid "19a2efba-e724-454c-ab2a-3ae35fedd5f1"^^xsd:string ;
    props:tag "28852558"^^xsd:string ;
    props:reference "NLRS_42_WA_wandbeplating mdf d=22mm_gen"^^xsd:string ;
    props:category "Generic Models"^^xsd:string ;
    props:reference "Basic Wall:NLRS_42_WA_wandbeplating mdf d=22mm_gen"^^xsd:string ;
    props:category "Generic Models"^^xsd:string ;
    props:family "Direct Shape"^^xsd:string ;
    props:type "Basic Wall-NLRS_42_WA_wandbeplating mdf d=22mm_gen"^^xsd:string ;
    props:typeId "1200361"^^xsd:string ;
    props:phaseCreated "New Construction"^^xsd:string ;
    props:rebarCover "Interior (framing, columns) <0' - 1 1/2 inch>"^^xsd:string ; #inch
    props:category "Generic Models"^^xsd:string ;
    props:familyName "Direct Shape"^^xsd:string ;
    props:typeName "Basic Wall-NLRS_42_WA_wandbeplating mdf d=22mm_gen"^^xsd:string ;
    props:category "Generic Models"^^xsd:string ;
    rdfs:hasName "Basic wall prefab"^^xsd:string ; #added
    rdfs:hasDescription "basic wall wandbeplating"^^xsd:string ; #added
    rdfs:hasLength "0.0"^^xsd:decimal ; #added
    rdfs:hasWidth "0.0"^^xsd:decimal ; #added
    rdfs:hasHeight "0.0"^^xsd:decimal ; #added
    prov:hasCompletionDate "2022-11-11T15:30:00"^^xsd:dateTime ; #added
    rdfs:hasAngle "0.0"^^xsd:decimal ; #added
    dpp:hasWarranty " x days"^^xsd:string ; #added
    dpp:hasServicelife "50"^^xsd:integer ; #added
    dpp:hasClassificationCode inst:ElementNEN2767_4_004 ; #added
    dpp:hasProduct inst:ConcreteWallCladding_001 . #added
```

Figure 32: Fragment IFC Tranformatiegebouw_Altered.ttl

Creation of material and product databases

Given the absence of any pre-existing product and material data (DPP), the establishment of a product and material database is necessary to provide input for the validation tool. For both the Transformation house and the Terraced house, a material and product database containing synthetic data is created. The databases are interpreted as RDFs and linked among each other. Instances inside the RDF of the Transformation house are assigned with object properties that link to instances defined in the product and material database. For example, the instance dpp:Concrete_001 holds an object property dpp:hasMaterial that refers to an instance inst:Cement_001 (Figure 33).

```
inst:Concrete_001
   a dpp:product ;
   a prov:entity ;
   dpp:hasGuid "Concrete_001"^^xsd:string ;
   rdfs:hasDescription "Concret in prefab wall_500489"^^xsd:string ;
   rdfs:hasName "Concrete mixture"^^xsd:string ;
   rdfs:hasLength "1.0"^^xsd:decimal ;
   rdfs:hasWidth "0.1"^^xsd:decimal ;
   rdfs:hasHeight "0.1"^^xsd:decimal ;
   prov:hasCompletionDate "2022-11-11T15:30:00"^^xsd:dateTime ;
   rdfs:hasAngle "1.0"^^xsd:decimal ;
   rdfs:hasDensity "150.0"^^xsd:decimal ;
   dpp:hasServicelife "50"^^xsd:integer ;
   dpp:hasWarranty "30 days"^^xsd:string ;
   dpp:hasCircularityPropertySet inst:ProductCircularityPropertySet_01 ;
   dpp:hasMaterial inst:Cement_001 ;
   dpp:hasMaterial inst:ConcreteSand_001 ;
   dpp:hasClassificationCode inst:ProductNEN2767_4_001 ;
   bmp:hasManufacturer inst:ProductManufacturer_001 .
```

Figure 33: Fragment Product database

8.9 Development of validation prototype/tool

The subsequent sections will explain the development of the DPP validation tools. Initially, the validation rules will be shown, then the process of rule preparation in SHACL and the subsequent rule execution using pySHACL will be outlined. The sections will conclude with an overview of the validation outcomes.

8.9.1 Validation rules

As stated before, sustainability themes (e.g. circularity) do not have specific rules regarding the defined DPP must-haves. Therefore, the validation process focuses mainly on verifying the presence and accuracy of the necessary data, as discussed in Section 8.8.2. Table 18 outlines the validation criteria that will be evaluated using the validation tool. The validation of topics is conducted at different levels to ensure thorough validation under the current conditions.

Furthermore, apart from the suggested categories of Lee et al. (2016), an additional category is introduced: 'Does the data fit within the set limits' (denoted as 'X'). This category relates to determining whether the data falls within the predetermined boundaries. This is important, for instance, when measuring reusability potential and specifically for evaluating the CO_2-eq. When a threshold is established and considered as "favorable," any deviation beyond it can result in an error. Consequently, this facilitates the identification of whether the objects satisfy the predefined criteria. To assess reusability and recycling potential, the CO_2-eq will be utilized for validation instead of kilograms. This approach allows for a measurable evaluation of whether the materials or products used are (potentially) deemed more or less harmful to the environment. The process involves determining an average CO_2-eq per material and establishing specific limits based on desired or future requirements.

Table 18: The validation criteria

Restriction		**Explanation**
The data should be present	N	Check null existence
The data is not duplicated	M	Limit on the number of properties (cardinality)
The data is filled in	V	Existence of values within the property
The type of data is correct	D	If the value of the property is the defined type
The insertion of the data is correct	V	Check for a correct value
Does the data fit within the set limits	X	Check that the numerical value is within the specified limits.

The mentioned restrictions are subsequently linked to the defined classes and properties. Table 19 below shows the correlation between the classes and properties and their limitations. Certain properties have to comply with a greater number of restrictions compared to others and the level of strictness varies. This process was conducted to validate the maximum amount of information within practical limitations. The validation process involves checking for the presence of properties and the class itself. Currently, only the Building, Element, Product, and Material categories are being tested. The Circularity classes and Manufacturer class are excluded at the building and element levels due to the predetermined focus on the product level. Additionally, the specific Circularity Property Set class is not included because of its parent-child relationship with subclasses, which complicates the validation process. As a result, the validation covers the specific constraints of this class and extends to its subclasses.

Table 19: Type of validation per class and property

Building classes	Properties	Type
Building	ID, name, description, address, service life, and completion date. The completion date will be validated on rule V using the following format: YYYY-MM-DD HH:MM:SS	N/M/D /V
Element	ID, name, description, length, width, height, angle, completion date, and service life. The completion date will be validated on rule V using the following format: YYYY-MM-DD HH:MM:SS	N/M/D /V
Product	ID, name, description, manufacture number, length, width, height, angle, density, completion date, and service life. The completion date will be validated on rule V using the following format: YYYY-MM-DD HH:MM:SS	N/M/D /V
Material	ID, name, description, manufacture number, length, width, height, criticality, density, secondary, completion date, and service life. The completion date will be validated on rule V using the following format: YYYY-MM-DD HH:MM:SS	N/M/D /V
General classes		
Manufacturer	Name, description, address, and email address. Email address is checked on the presence of @	N/M/D /V
Classification code	Classification code, and decomposition level. Classification code needs to match the format the nLSfB or NEN2767_4. The composition level needs to match preselected words/abbreviations (E.g. Element, EL, and mat)	N/M/D /V
Circularity classes		
Future function	ID, and future function	N/M/D
Reusability potential	ID, reusability potential, and embodied energy. The potential is supposed to score a minimum number of CO_2-eq. to rate it as 'good.' Currently, the limit consists of dummy data.	N/M/D /V/X
Recycling potential	ID, recycling potential, and embodied energy. The potential is supposed to score a minimum number of CO_2-eq. to rate it as 'good.' Currently, the limit consists of dummy data.	N/M/D /V/X
Origin	ID, and country of origin. Country of origin needs to be an existing country (preselected list of all countries in the world).	N/M/D /V
Condition assessment	ID, version, version date, last update, and condition assessment. Version date will be validated on rule V using the following format: YYYY-MM-DD HH:MM:SS	N/M/D /V
Disassembly potential	ID, description, and disassembly potential. The potential is supposed to score a minimum number of CO_2-eq. to rate it as 'good.' Currently, the limit consists of dummy data.	N/M/D /V/X
Proof of reuse	ID, description, and proof available. Proof available should comply the answer True or False (Boolean).	N/M/D /V
External party	ID, and name	N/M/D
Log	ID, version, and link to database	N/M/D

8.9.2 Rule preparation

The SHACL shapes (shapes graph) must include the rules defined in Section 8.9.1. to perform the check on the RDF data (data graphs). The SHACL playground is utilized to construct the SHACL shape and verify their functionality. Subsequently, it is integrated into Visual Studio code. An illustration of the reusability potential's shape graph is presented in Figure 34. In this fragment, a combination of a node shape and property shape is shown. Within lines 1 and 2 show the node shape which targets all instances of the type dpp:reusabilityPotential. This is followed by two property shapes (belonging to the instance): the GUID, and Reusability Potential which are indicated by the sh:path in line 4 and 11. Each of these properties is evaluated against the corresponding defined rules. First, the data type is checked in lines 5 and 12 (D). Additionally, it is ensured that the properties occur at least once and at most once, as specified in lines 6, 8, 13, and 16 (Type N,M, see Table 19). Lines 7 and 14 stipulate that the properties must contain at least one word or letter, indicating that the data must be filled in (Type V). Moreover, an additional line is included in the reusability potential property to verify if the data is greater than 1.00, as depicted in line 15 (Type X). Finally, line 17 signifies the end of the reusability potential class, as no new lines or properties follow thereafter. See Appendix L for the full SHACL script.

A topic of consideration includes confirming the existence of target classes. If the specified target class is absent in the RDF documentation for validation, the SHACL file fails to acknowledge its absence. Consequently, under the existing configuration, only the properties of the specified instances undergo validation (provided the instance exists). To highlight missing instances, a modification is implemented in a Python script to address this issue. This adjustment is detailed in section 8.9.3.

```
1. dpp:Shape_ReusabilityPotential a sh:NodeShape ;
2.    sh:targetClass dpp:reusabilityPotential ;

3.    sh:property [
4.        sh:path dpp:hasGuid ;
5.        sh:datatype xsd:string ;
6.        sh:minCount 1 ;
7.        sh:minLength 1 ;
8.        sh:maxCount 1 ;
9.     ] ;
10.    sh:property [
11.        sh:path dpp:hasReusabilityPotential ;
12.        sh:datatype xsd:decimal ;
13.        sh:minCount 1 ;
14.        sh:minLength 1 ;
15.        sh:minInclusive 1.00 ;
16.        sh:maxCount 1 ;
17.    ] .
```

Figure 34: Fragment SHACL including SHACL nodeshape and two property shapes

8.9.3 Rule execution

Once the SHACL file is prepared for Building, Element, Product, and Material levels, a Python script is expand upon to execute the SHACL file on the RDF data. The PySHACL script (Sommer & Car, 2022) is utilized for this task, ensuring that the constraints specified in the SHACL file are validated against the RDF representations of the IFC models (building and element level), product, and material. By incorporating the file names of the documentation into the standard script, a new terminal is triggered within the Visual Studio Code environment, presenting the DPP validation results.

In the event of errors arising during the validation process, they must be communicated to the individual accountable actor for resolving thema nd improving the input. To facilitate this, the PySHACL script has been enhanced and modified to generate a PDF alongside the new display, enabling convenient sharing of the validation information. Figure 35 shows the interface of Studio Visual Code with the data graph of the Terraced house on the left, the shapes graph (SHACL) in the middle, andthe validation report (PDF) on the right.

As outlined in Section 8.9.2, the existing SHACL file does not verify the presence of the mandatory classes. However, this validation has been incorporated into the Python script. The Python script examines whether the class names are present and if not, it includes this information in the validation report. On the other hand, if the classes are present, the SHACL file assumes responsibility for validating the properties. Furthermore, the script solely identifies the error message by its associated instance. However, if the error necessitates modification at its source, the IFC GUID must be provided. Therefore, an addition in the script is made which prints the belonging IFC GUID in the PDF validation report as well.

For further reference, a split and zoomed-in version of Figure 35 can be found in Appendix M and the complete Python script can be found in Appendix N.

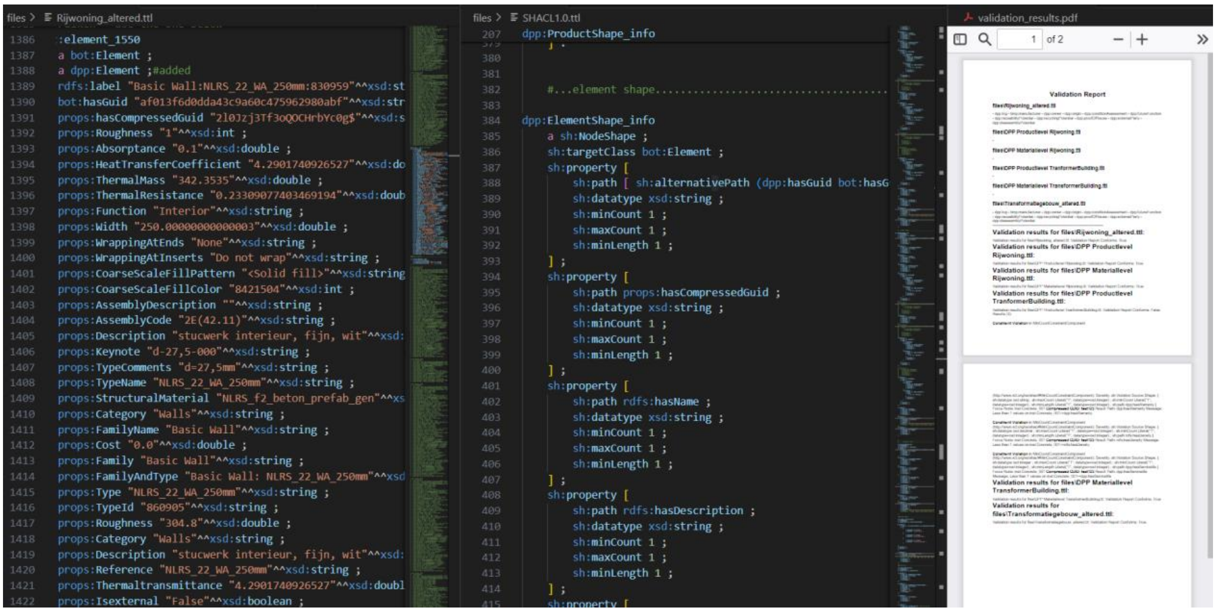


Figure 35: Rule checking system in Studio Visual Code

Modifying the existing Python script

As previously mentioned, the original PySHACL script has undergone several modifications, with the addition of various components. This sectionwill focus on two specific parts that have been further elaborated upon - the inclusion of the IFC GUID and the identification of missing classes. The detailed explanations off these components are accompanied by relevant code snippets For a comprehensive understanding of the code and the specific placement of these snippets, please refer to Appendix N.

The following lising shown on the next page (Figure 36) demonstrates the code portion responsible for detecting and naming the missing classes. The specific classes that need to be checked are indicated from line 7 to line 11. Afterwards, from line 12 to 16, these terms are compared with the Turtle files that have been previously uploaded (found earlier in the Python file). Any classes that are not present are then included in the PDF validation report, starting from line 18. Additionally, these lines establish the formatting rules for this particular section of the file.

In the second fragment (Figure 37), the validation report includes the addition of the IFC GUID (compressed GUID). The search for files containing the RDF graph, where the IFC GUID is located, is conducted in lines 1 through 12. More specifically, the search is performed within the uploaded Turtle files. Subsequently, starting from line 14, the Focus Node is sought to correspond with the IFC GUID at a later stage. The Focus Node can be interpreted as a type of node within the RDF graph. Following this, line 17 captures all matches, while line 19 eliminates any duplicate entries. It is assumed here that each instance possesses only one IFC GUID. From line 25 onwards, a specific pattern is established, indicating that the search for the compressed GUID must be carried out. Upon identifying this pattern, the focus node is substituted with the IFC GUID, which is then positioned after the instance in the validation report.

```python
# List to check missing words
missing_words = {}
for data_file in data_files:
    data_graph = Graph().parse(data_file, format="turtle")

# Classes to check
words_to_check = ['dpp:log', 'dpp:classificationCode',
'bmp:manufacturer', 'dpp:owner', 'dpp:origin',
'dpp:conditionAssessment', 'dpp:futureFunction',
'dpp:reusabilityPotential', 'dpp:recyclingPotential',
'dpp:proofOfReuse', 'dpp:externalParty', 'dpp:disassemblyPotential']

# Checks classes and add missing classes in PDF
missing_words[data_file] = []
for word in words_to_check:
    if word not in data_graph.serialize(format="turtle"):
        missing_words[data_file].append(word)

if missing_words:
pdf_content.append(Paragraph("Validation Report", styles['Title']))
for file, words in missing_words.items():
    pdf_content.append(Paragraph(file, styles['Heading2']))
    pdf_content.append(Paragraph("- " + "\n- ".join(words),
styles['Normal']))
pdf_content.append(Paragraph("------------------------------------------
-----------------------------------------------", styles['Normal']))
```

Figure 36: Fragment Python script missing words

```
if parts:
 # For each index in the total list
       for index, part in enumerate(parts):
 # Search file in which the validation results belong
           for file_name in file_names:
               if file_name in part:
 # File found in which we search for the GUID

 # Search for compressed GUID beloning to focus node
                   data_graph = Graph().parse(folder_name+file_name,
                   format="turtle")
                   full_file_in_memory = 12.
                   data_graph.serialize(format="turtle")

 # Extract data from input_string
                   pattern = r'Focus Node:(.*?)\n'
                   matches = re.findall(pattern, part, re.DOTALL)

 # Store data in a list
                   data_list = [match.strip() for match in matches]

 # Assume that one inst can only have one GUID
                   data_list = list(set(data_list))

                   guid_value = []
 # Search in another string using entries from data_list
                   for entry in data_list:
                      entry_index = full_file_in_memory.find(entry)
                      if entry_index != -1:
 # Look for the first occurrence of "props:hasCompressedGuid"
                       guid_pattern = r'props:hasCompressedGuid "(.*?)"'
                       search_substring =
                       full_file_in_memory[entry_index:]
                     guid_match = re.search(guid_pattern,
                     search_substring)
                     if guid_match:
 # Now add the GUID after the inst
                       parts[index] = part.replace(f"Focus Node:
                       {entry}", f"Focus Node: {entry}"+f"\n\tCompressed
                       GUID: {guid_match.group(1)}")
```

Figure 37: Fragment Python script adding IFC GUID

8.9.4 DPP validation report

The DPP validation process encompasses both the Transformation building and the Terraced house, along with the product and material database. The file from each building undergoes two tests: one with minimal changes to ensure its functionality (as outlined in Section 8.8.2), and another one with additional data (according to the DPP ontology) included. It is worth noting that the product and material database do not exhibit any errors, as it was constructed solely using dummy data. The same product and material file is utilized for validating both the minimally modified and fully modified versions of the buildings' files. Consequently, the IFC files hold greater significance due to the presence of error messages. The used files for the validation process include:

- Tranformatiegebouw.ttl
- Tranformatiegebouw_Altered.ttl
- Rijwoning.ttl
- Rijwoning _Altered.ttl
- DPP Productlevel Rijwoning.ttl
- DPP Materiallevel Rijwoning.ttl
- DPP Productlevel TranformerBuilding.ttl
- DPP Materiallevel TranformerBuilding.ttl

Figure 38 provides a fragment of a validation report, where the missing classes are indicated at the top. Beyond the dotted line, the validation of properties for the Transformation building level can be observed (an error is intentionally added to test and validate the approach). The first line indicates that 1 error has been detected, followed by a list of the errors (each violation of a constraint is considered an error). Within this snippet, one error is visible. The error is identified in the last line under "Result Path," which specifies the property associated with the error. The "Message" section provides details about the error and the specific instance in which it occurs. For instance, this error is found within the instance “Element_96989," where the value for service life is missing. This error can then be communicated to the BIM modeler, who can rectify it by adding the missing value at the element level within the model.

Validation IFC_Transformatiegebouw.ttl at material and product level

To execute this file, the components that were discussed in Chapter 8.6 were specifically chosen. The remaining components are marked as annotations to prevent them from being read. When these annotations are not disabled, more than 9960 error messages are generated at both the building and element levels. However, when only the selected components are tested alongside the building, material, and product levels, several classes are found to be missing, and it results in 41 error messages at the building and element levels. The missing classes include: dpp:log, dpp:classificationcode, bmp:manufacturer, dpp:owner, dpp:origin, dpp:conditionAssessment, dpp:futureFunction, dpp:reusabilityPotential, dpp:recyclingPotential, dpp:proofOfReuse, dpp:externalParty, and dpp:disassemblyPotential.

Validation Rijwoning-BM.ttl at material and product level

After validating the selected elements considering the element, product, and material levels, certain missing classes are identified at both the building and element level. These missing classes include: dpp:log, dpp:classificationcode, bmp:manufacturer, dpp:owner, dpp:origin, dpp:conditionAssessment, dpp:futureFunction, dpp:reusabilityPotential, dpp:recyclingPotential, dpp:proofOfReuse, dpp:externalParty, and dpp:disassemblyPotential. Subsequently, the properties are examined, revealing a total of 30 errors at the building and element level.

Validation of altered versions at materials and product level

The validation of the modified Transformation building's version and the Terraced house version reveals the absence of several classes at both the building and element levels. These classes include dpp:log, bmp:manufacturer, dpp:owner, dpp:origin, dpp:conditionAssessment, dpp:futureFunction, dpp:reusabilityPotential, dpp:proofOfReuse, dpp:externalParty, and dpp:disassemblyPotential. The absence of these classes is expected, as they are exclusively included in the material and product level databases. Additionally, no further errors are encountered during this process.

Validation Report

files\Transformatiegebouw_altered.ttl

- dpp:log - bmp:manufacturer - dpp:owner - dpp:origin - dpp:conditionAssessment - dpp:futureFunction - dpp:reusabilityPotential - dpp:recyclingPotential - dpp:proofOfReuse - dpp:externalParty - dpp:disassemblyPotential

----

Validation results for files\Transformatiegebouw_altered.ttl:

Validation results for files\Transformatiegebouw_altered.ttl: Validation Report Conforms: False Results (1):

Constraint Violation in MinCountConstraintComponent (http://www.w3.org/ns/shacl#MinCountConstraintComponent): Severity: sh:Violation Source Shape: [sh:datatype xsd:integer ; sh:maxCount Literal("1", datatype=xsd:integer) ; sh:minCount Literal("1", datatype=xsd:integer) ; sh:minLength Literal("1", datatype=xsd:integer) ; sh:path dpp:hasServicelife] Focus Node: inst:element_96989 **Compressed GUID: 0M2CR8ktv2tuvYCimnWoWv** Result Path: dpp:hasServicelife Message: Less than 1 values on inst:element_96989->dpp:hasServicelife

Figure 38: Fragment PDF Validation Report Transformation building altered version

Prototype Evaluation

9. Prototype Evaluation

Section 8.3 outlined the requirements for the DPP validation process. To assess the effectiveness of the DPP creation and validation tool, several tests and validations were conducted. Initially, the tool was tested with employees of the affiliated company to ensure proper functionality and content options in a prepared prototype mock-up. Next, the ontology's scope was evaluated to determine if it aligns with the Competency Questions outlined in Section 8.4. In the last section, the specified requirements and validation results will be discussed and assessed.

9.1 Testing and validating the DPP creation and validation tool

First of all, the tool and its functioning are validated with end users (usability). The validation process and validation report generation were reviewed by employees who would utilize the tool within the company. These individuals include two site engineers, two sustainability advisors, and two BIM engineers. Each employee was guided through three key sections: (1) the process of reaching the DPP validation report, (2) the validation report itself, and the (3) mock-up of an interface of the prototype as it is a subject of future implementation (full explanation and overview of the results in Appendix O). Specific questions were posed to each employee to determine the usability of these components.

1. Can you use the validation tool as it is now (and the required process beforehand)?
2. Explain, yes/no, what needs to change?
3. Can you work with the results of the validation report?
4. Explain, yes/no, what needs to change?
5. Can you work with this dashboard?
6. Explain, yes/no, what needs to change?
7. Do you have additional feedback/questions?

9.1.1 Tool validation with end users

Initially, individuals were asked about their familiarity with Python. Python expertise is essential for configuring the environment of the scripts and texts for utilization. It is presumed that without prior knowledge, one will struggle to navigate through this process independently, given the somewhat complex steps involved. The configuration of the environment is not encompassed in the validation procedures. The explanation commenced on how to convert the IFC to LBD using the available converter. Even though in reality the software development and configuration would not have to depend on the end user, but on the developer. These parts were also explained and assessed with the end users to assess overall understanding of the process and tool (including its potential given a proper setup and accurate input). Participants were questioned if the conversion could be done autonomously, assuming that the IFC to LBD converter already integrated the DPP ontology. Subsequently, it was emphasized that the RDF file must be checked, and various common errors were explained (such as the improper use of quotation marks or periods in property titles). If the process is correctly established from the Revit model, there is a slight possibility of encountering these errors. Nevertheless, it is needed to conduct a thorough check at present; otherwise, it may lead to an inoperable file. Questions 1 and 2 were associated with this phase of the validation.

During the second round of the validation with end users, the attention was directed towards the content of the DPP validation report. Each line was briefly interpreted, with a particular focus on the final lines containing the subject and error message. Questions 3 and 4 were integral components of this section. In the third round, participants were presented with a Mock-up of a dashboard. This dashboard was initially created based on their individual interpretations of the necessary information, with a focus on ensuring user-friendliness. To assess its clarity, participants were asked questions 5 and 6. Subsequently, the validation interviews concluded by inquiring whether there was any feedback or general questions, encompassing question 7.

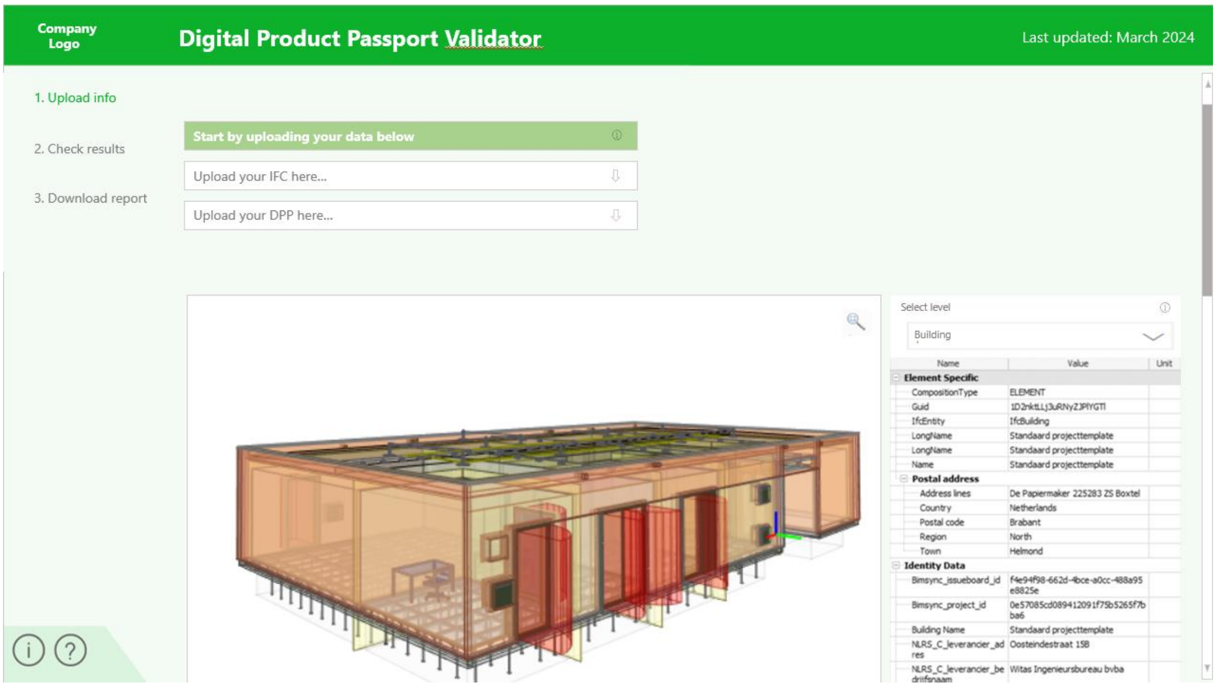


Figure 39: Mock-up dashboard validation tool part 1

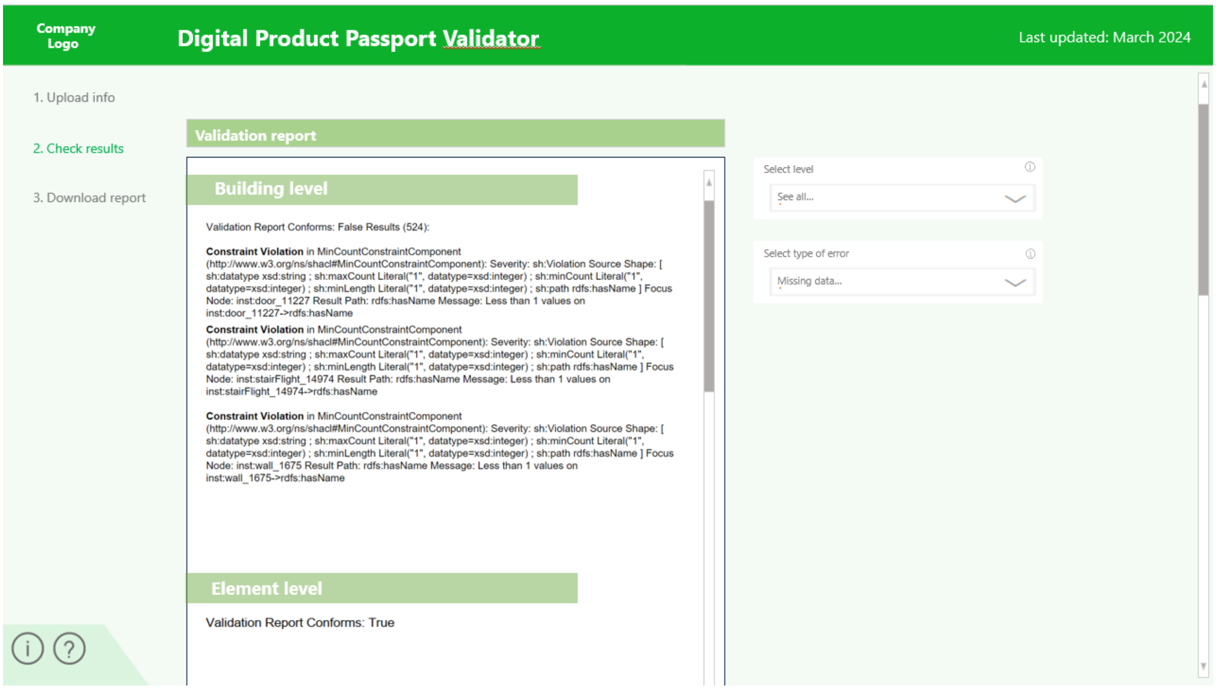


Figure 40: Mock-up dashboard validation tool part 2

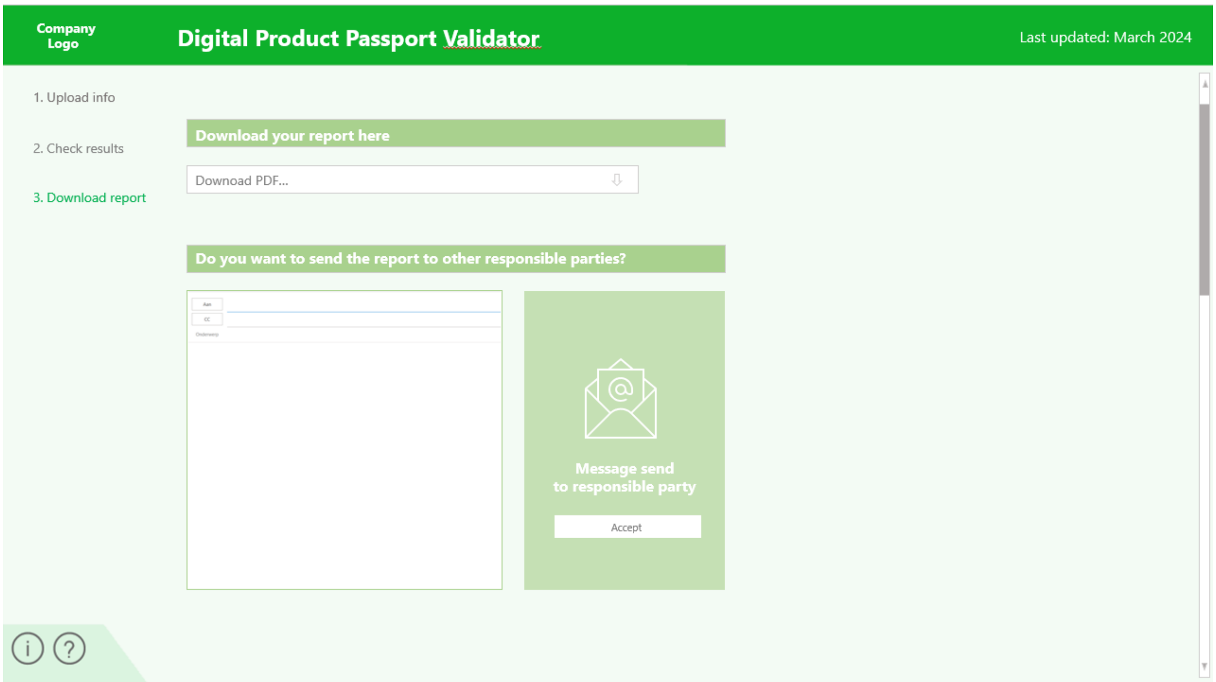


Figure 41: Mock-up dashboard validation tool part 3

9.1.2 Results from the tool testing and validation process

Initially, the individuals were questioned regarding their familiarity with Python. Out of the respondents, only a single employee acknowledged having prior exposure to Python (at a basic level). Consequently, it is presumed that the employee may encounter difficulties in setting up the Python environment and script. Subsequently, during the setup process, the employee expressed their limited expertise in the data domain, indicating their inability to fully complete the task or only partially accomplish it. However, it was suggested that by utilizing a manual, the employee would be able to overcome these challenges. Furthermore, a concise flow chart outlining the key steps was proposed to facilitate a quick recap of the process. Additionally, it is recommended to assign an "owner" for the process who can address any queries or concerns. To enhance user-friendliness, a dashboard is proposed as a viable solution (implemented in a next iteration in the mock up interface).

In the second round, there was a discussion about the content of the DPP validation report. Once again, it was found that the section is difficult to understand without any clarification. However, people can navigate through it more easily if they know the main focus, especially the error message and the corresponding item mentioned in the error message's final lines. The received end user feedback suggests that the error messages should be highlighted and the explanation should be included in a manual. Additionally, there is a suggestion to present the information in a less technical way or to automatically include it in Revit.

In the last part of the tool validation, the mock up of an user interface was presented. All participants agreed that it was easily understandable. The sustainability advisors expressed that they do not see validation as part of their responsibilities. They are more concerned with the content of the building rather than its accuracy. Nevertheless, they acknowledged the importance of understanding the concept of validation and its processes. They emphasized the significance of effectively communicating this information to clients. They also suggested highlighting the total of positive aspects during customer interactions. Feedback was provided on the visual representation of information on the initial page, which was well-received. The filter feature was also positively acknowledged. A recommendation was made to include additional filter options, such as by element type, and the ability to print selected sections separately from the entire report. In the infrastructure sector, working with multiple models is common. Therefore, the ability to load multiple models is essential. The user-friendliness of the user interface (dashboard) is crucial, and it should not be overly complex. Furthermore, incorporating a 'question mark' option in the report could enhance the clarity of the validation printout.

Furthermore, there have been several other enhancements identified, specifically the inclusion of the company name or article number to facilitate contacting the appropriate (responsible) individuals. Additionally, the incorporation of a storage feature for past reports, along with the ability to e-mail them to oneself, has been suggested. This would enable users to easily access and review previously submitted reports. Finally, it has been proposed to provide multiple viewing options for the model on the initial page, allowing for a more comprehensive understanding of its various aspects.

The validation interviews concluded by inquiring about any feedback or general questions. During these discussions, participants expressed concerns regarding data export and expressed curiosity about the possibility of generating enthusiasm among the BIM department for this tool. Furthermore, a suggestion was made to introduce control measures earlier in the process, even before the models and drawings are available. It is crucial to coordinate the timing of the validation throughout the entire construction cycle. In addition, there were questions and comments about what should happen next, among other things. For instance, an individual expressed the desire to have an implementation strategy in place. Furthermore, the necessary requirements for the IFC (i.e., Information Delivery Specifications (IDS)) need to be determined including defining the parameter set and an explanation of what needs to be examined in the RDF needs to be given. It is also important to establish and implement proper procedures and processes for effective data management. Last, it is mentioned that the tool has been well-received and is seen as a strong foundation for advancing the organization in terms of data management in the given context.

9.2 Validating the Competency Questions (CQ)

It is crucial to ensure that the DPP validation report not only functions properly but also meets the specific content requirements of the employee. The functional suitability requirement involves meeting industry-specific needs, while the applicability requirement focuses on the completeness of the data provided. These requirements can be assessed against the CQs outlined in Section 8.4, which are based on employee preferences and essential criteria. These CQs help determine if the ontology adequately covers the scope and contains enough information to address these questions. The competency questions will be tested using queries in GraphDB (Ontotext, 2023), the Transformation building data is integrated with the ontological model. The queries are designed to provide answers to the questions posed and are detailed in Appendix P. All CQs can be answered by performing the queries. In this section, three of the performed queries will be discussed to give an idea of the appearance of a query and the associated result.

Retrieving the GUID of a precast concrete wall

This query is seeking the GUID linked to the precast wall utilized in the construction project. Initially, the relevant prefixes are identified at the top of the interface where the query is input. These prefixes align with those found in the data files. As the query is executed, a table is generated within GraphDB. The first line of the query specifies the labels to be displayed above the table, ensuring that the accurate information corresponds with the appropriate label. The second line examines the relationships that fulfill the specified criteria. The name of the element is then displayed in the corresponding column of the table. Moving on to the third line, the names of the corresponding elements are requested. Subsequently, in the fourth line, the associated GUID is retrieved and displayed in the table. Given that the query focuses solely on the element of the precast wall, a filter is applied in the fifth line to search for elements labeled "basic wall prefab." Finally, the inquiry concludes by setting a limit of 100, which can be useful when extracting data from a large file while maintaining computational efficiency. An extract from GraphDB is presented in Figure 43.

```
select ?Element ?Name ?GUID where {
        ?Element a dpp:Element.
        ?Element rdfs:hasName ?Name.
        ?Element props:hasCompressedGuid ?GUID
        FILTER (?Name = 'Basic wall prefab')
} limit 100
```

Figure 42: Query to retrieve the GUID of the prefab wall

Retrieving the location of the used products

The second query aims to retrieve the locations of the products in the building. To obtain these locations, multiple components need to be requested. More specifically, that includes the floor, room, element, and product relations, which are requested in this query. This comprehensive approach allows for precise tracing of the product all the way back to the building. Additionally, if needed, it is also possible to query the corresponding GUID, which further facilitates locating the product within the associated Revit model. It is important to note that there are currently no filters or limit functions applied in this query.

```
select ?LabelStorey ?LabelSpace ?NameElement ?Name  where {
        ?Storey        a bot:Storey.
        ?Storey rdfs:label ?LabelStorey.
        ?Storey bot:hasSpace ?Space.
        ?Space rdfs:label ?LabelSpace.
        ?Element a dpp:Element.
        ?Element rdfs:hasName ?NameElement.
        ?Element dpp:hasProduct ?Product.
        ?Product a dpp:product.
        ?Product rdfs:hasName ?Name.
```

Figure 43: Query to retrieve the location of the products

Retrieving future function cement

The final query relates to the future function of the cement material. Initially, the query involves retrieving the products and materials. Subsequently, the future role is determined through the Circularity Property Set. The relationship between the future function and Circularity Property Set is a parent-child relationship, necessitating the retrieval of information in this manner. Afterwards, the cement material is filtered, excluding other materials. The query could potentially be expanded to include the future role at the product and component levels. This could prove useful when making decisions regarding the reutilization of various items.

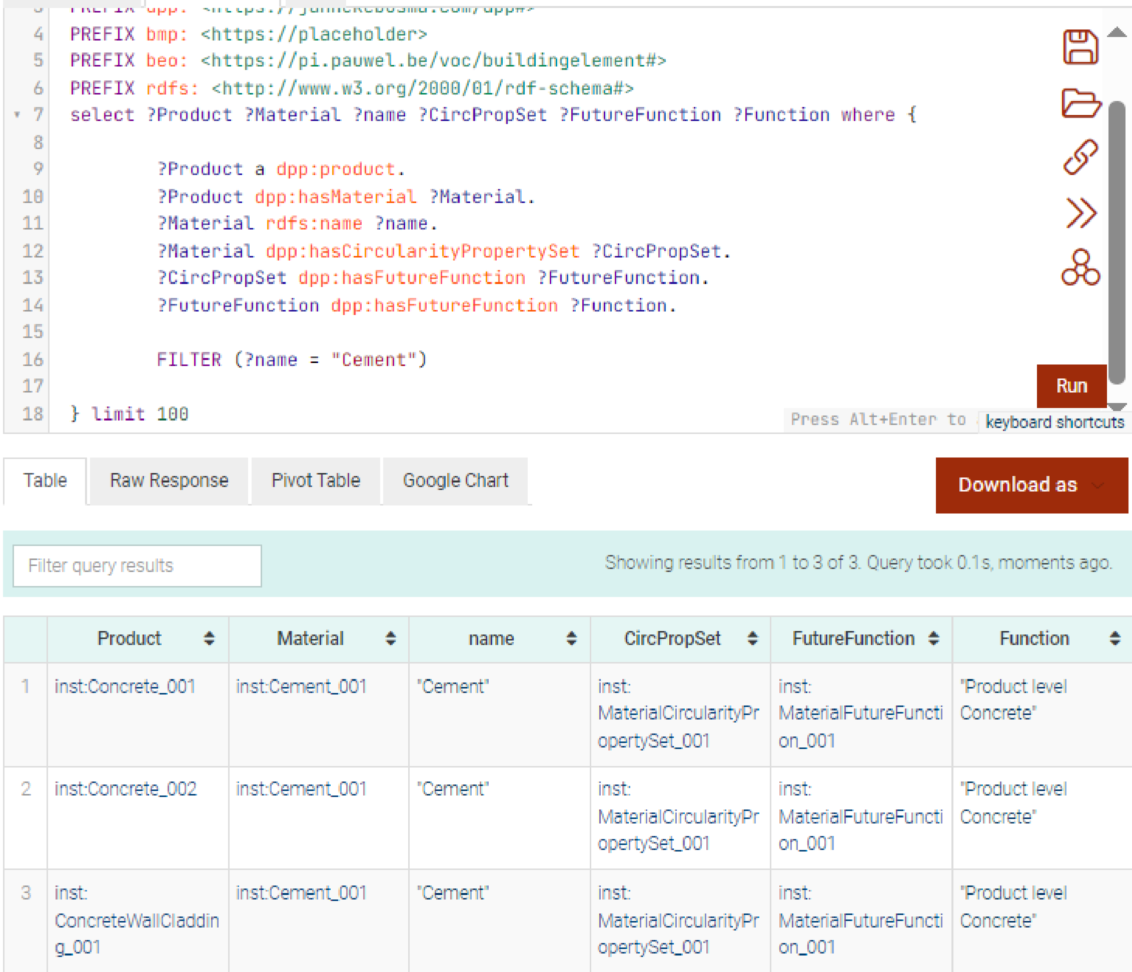


Figure 44: Screenshot of the query retrieving the future function of the material cement

9.3 Requirements validation

This section explains the validation of the established requirements and the outcomes attained. Through prior validations, numerous requirements were fulfilled and verified. The requirements designated with priority "1" were the most important. Conversely, the requirements labeled with priority "3" fell outside the scope of this research. In certain instances, these requirements may have already been partially evaluated, as the existing procedure has already addressed these subjects. The requirements are categorized as either achieved (check mark), partially achieved/in progress (bar), or not achieved (cross).

The user requirements labeled as priority "1" have been successfully fulfilled, except for requirement 5. The evaluation of the process indicates that individuals still encounter difficulties in comprehending the steps and the generated report without assistance. Furthermore, the lack of experience in Python among many users further complicates the utilization of the tool. To address this issue, a detailed explanation in a step-by-step format has been requested to provide clarity on the tool's functionality. Consequently, a dedicated folder containing comprehensive explanations has been created within a Github environment[1]. (All the necessary scripts have been uploaded, and the information and

[1] https://github.com/JannekeBosma/DPP/

roadmap have been summarized in PowerPoint presentations. Furthermore, a test script has been made available to guide users through the steps and help them familiarize themselves with the tool. As a result, the requirement has been evaluated as partially achieved, as a user interface that eliminates the need to follow the steps offers a more accessible solution for all employees.

The primary requirement labeled as "1" within the process validation criteria has been successfully met. All necessary information can be obtained through queries (refer to Section 9.2) and verified during the DPP validation procedure. Furthermore, several requirements categorized as "2" and "3" have been either fully or partially fulfilled. For instance, requirement 2 was only partially accomplished, particularly concerning legal responsibilities. The specific implementation of these regulations was mostly excluded due to the uncertainties surrounding them. Nevertheless, certain elements were integrated into the ontology design, such as the inclusion of a log for tracking and tracing purposes and the involvement of a regulatory body responsible for approving recycling and reusing activities. Requirement 5 has also been partially satisfied, as individuals have the ability to monitor and conduct checks on their own data before sharing it. However, a clear delineation of roles for data providers within the associated organization has not been established, leading to the incomplete fulfillment of this requirement. Additionally, requirements 9 and 10 have been met through the utilization of a validation report presented in a PDF format. This enables the report to be shared with other relevant parties, making it immediately actionable upon review. Requirement 11 is considered partially met due to the availability of the PDF when required. Similarly, requirement 14 is also partially fulfilled since the validation rules can be adjusted and extended within the SHACL file, although this necessitates a certain level of expertise. See Table 20, 21, and 22.

Table 20: Checklist user requirements

User requirements				
The user is able to …		**P**	**R**	**Check**
1	Validate their IFC and DPP whether the must-haves (Table 6) of the object are represented correctly.	1	MH, F	✓
2	Retrieve the information of the validation together with the corresponding IFC GUID of which object is wrong or missing	1	MH, F	✓
3	Make additions and modifications in the source data.	2	MM	✓
4	Remove or adapt actors, products, or attributes as requirements evolve	3	MM	✗
5	Easily understand the validation process and its results	1	A, AP	—
6	Access the tools needed for the validation process without costs involved	2	AP	✓
7	Perform the validation process without extra steps or research needed	2	AP	—

Table 21: Checklist process validation requirements

Validation process requirements				
The validation process should be able to …		**P**	**R**	**Check**
1	Query and validate the must-haves (Table 6) from the IFC model and DPP and communicate the results.	1	MH, F	✓
2	Comply with the following legal obligations: GDPR, the EPR, the 'right to repair', and the ESPR.	3	L, F	—
3	Not impede existing chain processes, product quality, or safety.	3	F	✗
4	Provide a secure data exchange between the value chain members.	3	S	✗
5	Remain the data control with the data providers to safeguard intellectual property.	3	S	—
6	Ensure access for assigned parties through an access control mechanism.	3	A	✗
7	Ensure participation opportunities for the parties without stable internet connections or advanced IT systems.	3	A	✗
8	Ensure permanent access to the whole life cycle data.	3	A	✗
9	Visualize the data in an understandable manner.	2	A	✓
10	Exchange validation information across different company boundaries.	2	I	✓
11	Show the information when needed.	3	AT	—
12	Tranfer information between software systems to enable decentralized systems.	3	P	—
13	Guarantee origin, integrity, verifiable, compliance, and immutability.	3	S	—
14	Be scalable for various project sizes and environments, and its current level of use and adoption	2	AP	—

Table 22: Checklist data requirements

Data requirements				
The data should allow to/be …		**P**	**R**	**Check**
1	Show and validate the unit of measurements of the must-haves as stated in Table 6	1	MH	✓
2	Enable interoperability within and between systems by the use of shared semantics and standardized data schemes	2	I, P, R	✓
3	Available real time (availability and time behaviour)	3	AT	✗
4	Uniquely identified, traceable, and time stamped	1	P	✓

Conclusion

10. Conclusion

This chapter presents the discussion and conclusion of this research, as well as its contributions to the societal and scientific field. It also provides recommendations for future research.

10.1 Main contribution

This research has contributed to various societal and scientific aspects as listed below. The datafiles named in the contribution can be found in the Github environment (see Appendix L for the access link).

10.1.1 Scientific contribution

- **Standard format and representation of DPPs:** A standard representation for DPPs was provided in a Linked Data format. This is based on the defined must-have items derived from literature and the expert workshop. In addition, the DPP can be extended in the future with the defined should-have topics.
- **Proof-of-concept of DPP validation process**: The study has introduced a validation procedure suitable for DPPs relying on Linked Data. By integrating the DPP ontology into the IFCtoLBD converter, the currently individual process steps can be linked together to enable a seamless workflow.
- **State-of-the-art MP and DPP:** The study has outlined the state-of-the-art within MPs and DPPs. While there remains a significant amount of uncertainty surrounding DPPs and ongoing developments, this serves as an initial guide on the topic.
- **Use case relying on Linked Data:** This study makes a valuable contribution by showcasing the applicability of Linked Data within the AEC industry through the utilization of BIM and DPPs.
- **Extension pySHACL:** In this research, the pySHACL script was adapted to include an additional functionality of verifying the existence of (DPP) classes. Furthermore, it now has the capability to display the IFC GUID and produce a PDF report, thereby enhancing the accessibility and manageability of the report findings.
- **DPP ontology:** At present, there are no ontologies available for reuse in the MP or DPP domain. While literature on the subject exists, the actual ontologies are not accessible. The study has introduced a DPP ontology that adheres to specified requirements, which can be accessed through a Github repository and is available for reuse in the AEC sector.

10.1.2 Societal contribution

- **Standard format and representation of DPPs:** The research outlined in this study has introduced a data model that is grounded in the FAIR and Linked Data principles. The proposed DPP has been constructed using the defined must-haves from literature and industry stakeholders. Despite the fact that the DPP ontology has not been integrated into the IFCtoLBD converter, individuals can still utilize the must-have components to initiate the use of DPPs.
- **State-of-the art MP and DPP:** In this study, a summary of the latest advancements in MPs and DPPs has been presented, as referenced in the preceding section. This review of existing literature may serve as a basis for implementing DPPs within the AEC sector.

Organisations in the construction industry interested in exploring this subject can utilize the details provided as an introductory guide.

- **Open Science:** The research project established a Github environment containing essential scripts for the validation process. Furthermore, an RDF test file was created alongside an explanatory PowerPoint presentation to enable individuals with limited expertise to engage in the validation process and explore Linked Data in a more user-friendly manner.
- **DPP ontology:** As stated in the preceding section, the research introduced a DPP ontology. This ontology has been made accessible in a Github environment, enabling its practical reusability.

10.2 Recommendations and future work

A number of recommendations and future work are made. These recommendations are as follows:

- Develop a dashboard;
- Incorporate feedback from the validation rounds;
- Maximize the utilization of pre-existing ontologies;
- Validate the DPP throughout the entire chain ;
- Add should-have components;
- Correctly configure BIM models;
- Retain a maximum amount of data.

Throughout the thesis, a mock-up of a user interface (dashboard) was developed. Due to time constraints, the mock up was not further developed in this process. However, it is crucial to address this aspect in future work. Additionally, due to time limitations, not all feedback from the validation rounds could be incorporated into the process. These feedback points will also be addressed in the follow-up phase. The absence of the dashboard can potentially complicate the utilization of the DPP validation tool. Considering the importance of user-friendliness and practicality, the current process is not an optimal solution. In order to encourage user engagement, the fully functioning dashboard should be designed in a way that minimizes the number of steps required to obtain the desired report. If the steps are overly complex or time-consuming, there is a risk that users may not complete them or that it will take an unnecessary amount of time to obtain the desired outcome.

It is best practice to maximize the utilization of pre-existing ontologies as a standard practice. This principle is applicable to various elements encompassed by the DPP ontology. The development of the DPP ontology took place within the Protégé software, where the integration of all ontologies was regrettably not feasible. Consequently, these ontologies are currently identified in the 'annotation' field. A potential enhancement would involve the seamless integration of the existing ontologies into the DPP ontology, eliminating the need for independent connections.

At present, the primary disciplinary emphasis of the research is on the contractor organisation. Nevertheless, it is crucial to validate DPPs throughout the entire value chain to guarantee the reliability and currency of the data before it is utilized by external entities. It is possible that the validation focus for other parties, such as manufacturers, may differ. Consequently, additional research is necessary to address this aspect.

The DPP validation tool now includes only must-have components, but a potential next phase could involve incorporating should-have components to establish a more comprehensive validation process. It is crucial for companies in the AEC sector to correctly configure BIM models and adhere to the buildingSMART guidelines (also for IDS). Failure to do so may result in challenges connecting to the DPP validation process (and any forthcoming processes). Data standardization plays a key role in this aspect. Once this is effectively implemented, the subsequent step is to retain a maximum amount of data. The more information available about an object in the future, the higher the likelihood of its reuse.

10.3 Discussion

The DPP ontology introduced in this study, can be utilized in the field of DPPs and MPs relying on Linked Data representations. Nevertheless, the current conversion process from IFC to LBD relying on available tools does not incorporate this ontology. To allow a conversion that includes the corresponding and necessary DPP information, an enhancement to the converter will be necessary. Furthermore, the link between the transformed IFC and the product and material database is currently established manually. Automating this process could prove advantageous in enhancing efficiency. In addition, the ontology has been developed based on the inputs form the systematic literature review and expert workshop. Following its application in various real-world scenarios, an assessment should be conducted to ensure accurate classification and applicability of its components.

It is crucial to ensure that terminologies between the datasources are aligned. This involves accurately stating products and materials based on the specified terminology. Moreover, if there are alterations in sustainability or circularity regulations, adjustments must be made to the DPP validation tool and ontology in line with the evolving requirements.

At present, the reusability and recycling capabilities of building elements and components are populated with placeholder information. In order to establish a reliable evaluation based on these data, it is crucial to establish connections with other ontologies and databases. This will enable the identification of the specific object being addressed, which is essential for determining the appropriate CO_2-eq boundary. A material-specific average can be established as a reference point for setting the boundary.

Implementing the mentioned modifications to the tool necessitates a specialized understanding of Linked Data and SHACL. Hence, it is crucial to assign an individual as the "owner" of the tool, who will bear the responsibility of upkeeping and introducint the necessary alterations in a timely manner.

The scientific literature is continuously providing new insights into the DPPs, along with ongoing advancements in MPs, including the CB'23 passport. A recent update to the CB'23 passport, not considered in previous comparisons, has introduced additional subjects, necessitating a reassessment of the 'applicability' requirement. Initial observations suggest that other criteria remain unchanged. As the DPP is a new subject, significant changes may occur, underscoring the importance of staying informed and adjusting ontology and validation tools as needed to keep pace with developments and standardization efforts.

Different companies may have different employees responsible for the DPP. Currently, there is no clear definition of who should be responsible for creating and validating the DPP. However, it would be logical for the employee who is responsible for drafting the DPP to also perform the validation, as they have knowledge of the input provided. Additionally, there is the question of what should be done with the passport once the building is completed. It is necessary to determine who will be responsible for maintaining the passport, as new data will need to be added when the building undergoes renovation or change of ownership. One of the main objectives of the DPP is to promote the reuse of objects, which typically occurs at the end of the building's lifespan. Until then, it is important to keep the passport in mind and preserve it.

Feedback was provided during the validation iterations for loading numerous models at the same time. Nevertheless, this may lead to various issues, including such concerning the data size. When the data models encompass a substantial amount of information, generating the validation report in PDF format can be time-consuming. On the other hand, a report is generated more swiftly within the terminal of Visual Studio Code. Nonetheless, the details regarding absent classes are not included here, hence emphasizing the importance of the PDF format in this specific case. This necessitates further streamlining of the process or loading the models individually.

In this research, a compilation of must-have DPP topics was formulated based on the literature review and expert workshop. Among these topics, two were omitted from the subsequent stages. More specifically, these include storage details and toxicity information. To ensure data quality and completeness, it is necessary to incorporate these two components as well. This integration can be achieved by adding the information within the DPP ontology by extening it or by establishing links with other existing ontologies defining this information.

10.4 Conclusion

This research aims to develop a creation and a validation tool for Linked Data-based Digital Product Passports. This is summarized in the main research question below:

How can a Digital Product Passport for the AEC industry be created and validated using BIM and semantic technologies?

To answer this main question, several subquestions were formulated and answered based on literature review and expert input. This input was then used to create the prototype of the DPP creation and validation tool.

The performed systematic literature review addressed the first sub-question: *What is the current state-of-the-art of Mps, DPPs, automatic validation tools, BIM-based technologies, and semantic technologies?*

The investigation demonstrates the absence of a standardized format for MPs and DPPs Different interpretations, structures, and titles are present regarding the concept, with terms often being used interchangeably (including cradle-to-cradle passport, Digital Building

Logbook, and Digital Twins). Nevertheless, it is important to note that not all formats carry the same significance, and variations exist in terms of scope and usage.

The DPP is proposed as a solution to “the lack of consistent and precise information flow about resources, products, and processes.”. Apart from functioning as a means of monitoring and tracing, it has the potential to enhance life cycle assessments by consolidating both unique and aggregated product details. Furthermore, it can act as an inventory of substances to encourage the future reuse of items. Each physical product can have its own passport, necessitating the exchange of a substantial amount of information. To mitigate the risk of data loss during this exchange, the implementation of a Linked Data-based approach could offer a viable solution. The mandatory adoption of the DPP is anticipated in 2026, yet there remains considerable uncertainty surrounding the specific requirements and format of the final DPP. Existing literature proposes various requirements based on current legislation and the progress made in developing the DPP. Nonetheless, there are still numerous steps that need to be taken.

BIM is a valuable method utilized in the AEC industry for creating, sharing storing, and resuing detailed information about buildings and presenting it visually. Converting BIM models to open standards such as IFC allows for seamless data exchange with stakeholders due to its international standard. Nevertheless, challenges in this field persist, such as the absence of life cycle data and the integration of various indicators, parameters and tools.

Linked Data, a relatively novel concept in the AEC sector, facilitates automated contextual connections between diverse datasets. Despite its potential benefits, Linked Data and its associated technologies such as ontologies, RDF, and SPARQL are underutilized in the AEC industry, necessitating significant advancements. It is crucial to establish standardization that aligns with existing BIM protocols and guidelines.

To enable and complete the DPP validation process, various languages can be utilized to verify a Linked Data based representation of a passport. Among these languages are SHACL and ShEx. Ultimately, SHACL was chosen due to its robust capabilities and endorsement by W3C.

The second subquestion relates to the validation of a DPP, which is addressed through expert input (workshop) and literature review. The question at hand is: *Which parts of a DPP will need to be validated and which part of the validation process is required by the contractor?* Currently, there is no established standard for MPs and DPPs. To identify the components requiring validation, important subjects were identified through a workshop conducted within the associated organization, in conjunction with insights from the reviewed relevant literature. This framework was considered during the creation of a DPP data model and the corresponding validation process.

In the context of product passports, the responsibility for the DPP component rests with the associated creator. In other words, the manufacturer who develops the object bears a significant portion of the responsibility for providing the necessary data. Subsequently, this information is transferred to the contractor, who is tasked with documenting the object's applications and modifications. Ideally, a validation process should occur before each step of the process, ensuring that accurate and up-to-date information is utilized. Consequently, it is essential to validate the DPP components before transferring the object to the next party. This validation process applies to both internal and external communications within the company. The timing of the validation within the company is contingent upon the flow of data communication, considering who requires specific data and when. However, the specifics of this aspect are beyond the scope of the current study. It is worth noting that the contractor's role has been broadly summarized, focusing on a high-level overview.

In order to ascertain the crucial DPP components that also require validation, a comprehensive approach was adopted. This involved conducting a questionnaire and organizing a workshop within the affiliated company employees (contractor organisation). The outcomes of this collaborative workshop were subsequently merged with the findings from relevant literature, resulting in the compilation of a comprehensive list. This list was categorized into four distinct sections, namely not-include, nice-to-have, should-have, and must-have DPP items. For this thesis research, the focus was primarily on the must-have items, which were deemed essential for the validation process.

The third sub-question is addressed by incorporating expert input, relevant literature and systems engineering techniques. The sub-question *How can a proof-of-concept for the DPP validation method be developed and tested in a real-world use case?* To evaluate whether the validation tool aligns with the requirements of the DPP, the specified DPP requirements are translated into the tool itself. Consequently, the tool generally fulfills the requirements, although there remains a point of discussion regarding its applicability requirement. This is due to the tool's limited adaptability, which necessitates specialized knowledge. In addition to the literature-based requirements, the must-haves and Competency Questions defined from an expert perspective were validated using SPARQL. This process ensured that the DPP ontology was appropriately constructed to extract the desired information. Last, the tool underwent validation itself, including the generated validation report format and a mock-up of a user interface. This validation was conducted with potential users of the tool, including sustainability advisors, BIM employees, and site engineers.

The prototype is relevant in addressing the final sub-question, i.e., *How can the validation process and output be visualized and feedback- provided to the end user?* The visualization of the validation process can be achieved through the utilization of a user interface (dashboard). However, due to time limitations, the current state of the dashboard remains as a prototype mock-up. This mock-up has undergone evaluation and received input and feedback from experts. The subsequent step involves the development of the production version of the software application, including the user interface. At present, a manual is accessible to guide the individuals through the existing process. As a result of the validation process, a validation report is generated in the form of a PDF. This report can be shared with employees who are responsible for processing the feedback. The PDF report encompasses the error message along with the specific instance in which the error occurs. Furthermore, it includes the compressed GUID for each instance of the error message. This GUID is a unique identifier that can be traced back to the originally input data, such as the IFC and the Revit models. This approach enables the early rectification of errors in the process, prior to sharing the products with other parties.

The main question is answered by combining all of these sub-questions. To achieve this, a DPP was formulated by considering the defined must-haves and utilizing an IFC model. Subsequently, these files were transformed into a Linked Data format using the IFCtoLBD converter, and the data is enriched and integrated. In addition, the validation rules were established and converted into SHACL shapes. By utilizing and adapting the pySHACL script, the Linked Data-based DPP underwent validation by running it through the SHACL validation. As a result, a validation report was generated. By referencing the IFC GUID in the validation report, any error messages within the report can be adjusted in the source documentation. Collectively, these steps constitute the creation and validation process for DPPs in AEC.

References

Adisorn, T., Tholen, L., & Götz, T. (2021). Towards a digital product passport fit for contributing to a circular economy. *Energies*, *14*(8). https://doi.org/10.3390/EN14082289

Akbarieh, A., Jayasinghe, L. B., Waldmann, D., & Teferle, F. N. (2020). BIM-Based End-of-Lifecycle Decision Making and Digital Deconstruction: Literature Review. *Sustainability 2020, Vol. 12, Page 2670*, *12*(7), 2670. https://doi.org/10.3390/SU12072670

Akinade, O. O., Oyedele, L. O., Ajayi, S. O., Bilal, M., Alaka, H. A., Owolabi, H. A., & Arawomo, O. O. (2018). Designing out construction waste using BIM technology: Stakeholders' expectations for industry deployment. *Journal of Cleaner Production*, *180*, 375–385. https://doi.org/10.1016/J.JCLEPRO.2018.01.022

Anderson, J. E., Wulfhorst, G., & Lang, W. (2015). Energy analysis of the built environment—A review and outlook. *Renewable and Sustainable Energy Reviews*, *44*, 149–158. https://doi.org/10.1016/J.RSER.2014.12.027

Autodesk. (n.d.). *Building Information Modeling*.

BAMB. (2019). *BAMB*. https://www.bamb2020.eu/topics/pilot-cases-in-bamb/rem/

Berg, H., Kulinna, R., Stöcker, C., Guth-Orlowski, S., Thiermann, R., & Porepp, N. (2022). *Overcoming information asymmetry in the plastics value chain with digital product passports : how decentralised identifiers and verifiable credentials can enable a circular economy for plastics*. *197*. https://doi.org/10.48506/OPUS-7940

Berger, K., Schöggl, J. P., & Baumgartner, R. J. (2022). Digital battery passports to enable circular and sustainable value chains: Conceptualization and use cases. *Journal of Cleaner Production*, *353*. https://doi.org/10.1016/J.JCLEPRO.2022.131492

Berners-Lee, T. (2006, July 27). *Linked Data - Design Issues*. https://www.w3.org/DesignIssues/LinkedData.html

Berners-Lee, T., Fielding, R., & Masinter, L. (2005). *Uniform Resource Identifier (URI): Generic Syntax*. https://doi.org/10.17487/RFC3986

Berners-Lee, T., Hendler, J., & Lassila, O. (2001, May 1). *The Semantic Web | Scientific American*. https://www.scientificamerican.com/article/the-semantic-web/

BIMvision. (n.d.). *BIMvision - freeware IFC model viewer*. Retrieved May 17, 2024, from https://bimvision.eu/

Bizer, C., Heath, T., & Berners-Lee, T. (2009). Linked data: The story so far. *International Journal on Semantic Web and Information Systems*.

Bizer, C., Lehmann, J., Kobilarov, G., Auer, S., Becker, C., Cyganiak, R., & Hellmann, S. (2009). DBpedia - A crystallization point for the Web of Data. *Journal of Web Semantics*, *7*(3), 154–165. https://doi.org/10.1016/J.WEBSEM.2009.07.002

Bonduel, M. (n.d.). *CTO: Construction Tasks Ontology*. Retrieved March 19, 2024, from https://mathib.github.io/cto-ontology/

Bonduel, M., Wagner, A., & Pauwel, P. (2020, January 14). *FOG: File Ontology for Geometry formats*. https://mathib.github.io/fog-ontology/

Borrmann, A., Beetz, J., Koch, C., Liebich, T., & Muhic, S. (2018). Industry foundation classes: A standardized data model for the vendor-neutral exchange of digital building models. *Building Information Modeling: Technology Foundations and Industry Practice*, 81–126. https://doi.org/10.1007/978-3-319-92862-3_5

Breteler, F. H. R. (2022). *Enhancement of the process of reusing building products: Connecting reusable products from the Construction Demolition Waste flows with construction sites to improve the process and stimulate the use of reusable building products*.

Buchholz, M., & Lutzkendorf, T. (2022). Building passports and material inventories - concepts, trends, job sharing. *Earth and Environmental Science*, 9.

Buchholz, M., & Lützkendorf, T. (2022). Building passports and material inventories - concepts, trends, job sharing. *IOP Conference Series: Earth and Environmental Science*, *1122*(1). https://doi.org/10.1088/1755-1315/1122/1/012038

buildingSMART. (n.d.). *Industry Foundation Classes*.

Caldera, S., Ryley, T., & Zatyko, N. (2020). Enablers and Barriers for Creating a Marketplace for Construction and Demolition Waste: A Systematic Literature Review. *Sustainability 2020, Vol. 12, Page 9931*, *12*(23), 9931. https://doi.org/10.3390/SU12239931

Çetin, S., Gruis, V., & Straub, A. (2022). Digitalization for a circular economy in the building industry: Multiple-case study of Dutch social housing organizations. *Resources, Conservation and Recycling Advances*, *15*. https://doi.org/10.1016/J.RCRADV.2022.200110

Çetin, S., Raghu, D., Honic, M., Straub, A., & Gruis, V. (2023). Data requirements and availabilities for material passports: A digitally enabled framework for improving the circularity of existing buildings. *Sustainable Production and Consumption*, *40*, 422–437. https://doi.org/10.1016/J.SPC.2023.07.011

Charef, R., Morel, J.-C., Rakhshan, K., Raimo, N., Vitolla, F., Malandrino, O., Esposito, B., & Fokaides, P. (2021). Barriers to Implementing the Circular Economy in the Construction Industry: A Critical Review. *Sustainability 2021, Vol. 13, Page 12989*, *13*(23), 12989. https://doi.org/10.3390/SU132312989

Cirdax. (2023). *Cirdax Vastgoed Digitalisering*. https://www.cirdax.com/

Cobuilder International. (2023, November 22). *Navigating new EU Regulations and digital tranformation in Construction*.

Core Vocabularies Working Group. (2023, May 15). *Core Public Organisation Vocabulary*. https://semiceu.github.io/CPOV/releases/2.1.0/

Cramer, J. (2017a). The Raw Materials Transition in the Amsterdam Metropolitan Area: Added Value for the Economy, Well-Being, and the Environment. *Https://Doi.Org/10.1080/00139157.2017.1301167*, *59*(3), 14–21. https://doi.org/10.1080/00139157.2017.1301167

Cramer, J. (2017b). The Raw Materials Transition in the Amsterdam Metropolitan Area: Added Value for the Economy, Well-Being, and the Environment. *Environment: Science and Policy for Sustainable Development*.

Dai Clegg. (1994). *MoSCoW Method*.

de Römph, T. J., & Cramer, J. M. (2020). How to improve the EU legal framework in view of the circular economy. *Journal of Energy & Natural Resources Law*, 245–260. https://doi.org/10.1080/02646811.2020.1770961

Deloitte. (2015). *Screening template for Construction and Demolition Waste management in The Netherlands*.

digiGO. (n.d.-a). *digiGO BIM Loket - CB-NL*. Retrieved March 14, 2024, from https://www.bimloket.nl/p/527/CB-NL

digiGO. (n.d.-b). *NL-SfB - digiGO*. Retrieved March 14, 2024, from https://www.digigo.nu/standaarden/nlsfb

Digital Construction Units. (n.d.). *Digital Construction Units*. Retrieved March 19, 2024, from https://digitalconstruction.github.io/Units/v/0.5/

Digital Europe. (n.d.). *CIRPASS – Shaping the future of the Digital Product Passport - DIGITALEUROPE*. Retrieved December 22, 2023, from https://www.digitaleurope.org/events/cirpass-shaping-the-future-of-the-digital-product-passport/

Durmisevic, E. (2006). *Tranformable Building Structures - Design for disassembly as a way to introduce sustainable engineering to building design & construction*.

Eastman, C., Lee, J. min, Jeong, Y. suk, & Lee, J. kook. (2009). Automatic rule-based checking of building designs. *Automation in Construction*, *18*(8), 1011–1033. https://doi.org/10.1016/J.AUTCON.2009.07.002

Economisch Instituut voor de Bouw. (2022). *Materiaalstromen in de bouw en infra*.

Ellen MacArthur Foundation. (n.d.). *Introduction | What is the circular economy? | Guides*. Retrieved December 21, 2023, from https://guides.co/g/mv5ue63s0a/165164

Ellen Macarthur Foundation. (2013). *What is a circular economy? | Ellen MacArthur Foundation*. https://ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview?gad=1&gclid=Cj0KCQjwj_ajBhCqARIsAA37s0wl8cfe9UzZeMr35sXSxTuzHbg6LlyoQBYoKBQB1kNHwAoHkyVE-qkaAmJoEALw_wcB

Eppinger, E., Jain, A., Vimalnath, P., Gurtoo, A., Tietze, F., & Hernandez Chea, R. (2021). Sustainability transitions in manufacturing: the role of intellectual property. *Current*

Opinion in Environmental Sustainability, *49*, 118–126. https://doi.org/10.1016/J.COSUST.2021.03.018

EU ISA Programme Core Vocabularies Working Group (Location Task Force). (2015, March 23). *ISA Programme Location Core Vocabulary*. https://semiceu.github.io/Core-Location-Vocabulary/releases/w3c/

European Commission. (n.d.-a). *Buiding and construction*.

European Commission. (n.d.-b). *EU Taxonomy Navigator*. Retrieved March 15, 2024, from https://ec.europa.eu/sustainable-finance-taxonomy/

European Commission. (n.d.-c). *Funding & tenders*. Retrieved December 22, 2023, from https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/how-to-participate/org-details/999999999/project/101083432/program/43152860/details

European Commission. (2020a). *Circular economy action plan*. https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en

European Commission. (2020b). *Regulation of the European parliament and of the council - concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (Eu) no 2019/1020*.

European Commission. (2020c, December 10). *Sustainable batteries*. https://ec.europa.eu/commission/presscorner/detail/en/ip_20_2312

European Commission. (2021a). *Recovery plan for Europe*. https://commission.europa.eu/strategy-and-policy/recovery-plan-europe_en

European Commission. (2021b). *Study on the development of a European Union framework for digital building logbooks - Publications Office of the EU*. https://op.europa.eu/en/publication-detail/-/publication/40f40235-509e-11eb-b59f-01aa75ed71a1/language-en

European Commission. (2022a). *Buildings and construction*. https://single-market-economy.ec.europa.eu/industry/sustainability/buildings-and-construction_en

European Commission. (2022b). *Establishing a framework for setting exodesign requirements for sustainable products and repealing Directive 2009/125/EC*.

European Commission. (2022c). *Green digital sector | Shaping Europe's digital future*. https://digital-strategy.ec.europa.eu/en/policies/green-digital

European Commission. (2022d). *Proposal for REGULATION OF THE EUROPEAN PARLIAMENT AND THE COUNCIL establishing a framework for setting ecodesign requirements for sustainable products and repealing Directive 2009/125/EC*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52022PC0142

European Commission, & Directorate-General for Financial Stability. (2023, 7). *COMMISSION DELEGATED REGULATION (EU) /... supplementing Directive 2013/34/EU of the European*

Parliament and of the Council as regards sustainability reporting standards. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=PI_COM:C(2023)5303

European Union. (2016a). *Environmental expenditures in EU industries : time series data for the costs of environmental legislation for selected industries over time : final report.* https://doi.org/10.2779/467059

European Union. (2016b). *REGULATION (EU) 2016/679 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 27 April 2016 on the protection of natural persons with regard to the processing of personal data and on the free movement of such data, and repealing Directive 95/46/EC (General Data Protection Regulation) (Text with EEA relevance)*.

Faith, A. (2023). *Ontology and Taxonomy Mapping, Merging, and Depuding in Protege*.

Github. (2021). *NEN 3610 - Linked Data*. https://geonovum.github.io/NEN3610-Linkeddata/

Gligoric, N., Krco, S., Hakola, L., Vehmas, K., De, S., Moessner, K., Jansson, K., Polenz, I., & Van Kranenburg, R. (2019). SmartTags: IoT Product Passport for Circular Economy Based on Printed Sensors and Unique Item-Level Identifiers. *Sensors (Basel, Switzerland)*, *19*(3). https://doi.org/10.3390/S19030586

Göswein, V., Carvalho, S., Cerqueira, ; C, & Lorena, A. (2022). *Circular material passports for buildings-Providing a robust methodology for promoting circular buildings*. https://doi.org/10.1088/1755-1315/1122/1/012049

Goswein, V., Carvalho, S., Cerqueira, C., & Lorena, A. (2020). Circular material passports for buildings - Providing a robust methodology for promoting circular buildings. *Earth and Environmental Science*, 11. https://doi.org/:10.1088/1755-1315/1122/1/012049

Götz, T., Berg, H., Jansen, M., Adisorn, T., Cembrero, D., Markkanen, S., & Chowdhury, T. (2022). *Digital Product Passport: the ticket to achieving a climate neutral and circular European economy? | European Circular Economy Stakeholder Platform*. https://circulareconomy.europa.eu/platform/en/knowledge/digital-product-passport-ticket-achieving-climate-neutral-and-circular-european-economy

Gruber, T. R. (1993). A translation approach to portable ontology specifications. *Knowledge Acquisition*, *5*(2), 199–220. https://doi.org/10.1006/KNAC.1993.1008

Guth-Orlowski, S. (2021, October 18). *The digital product passport and its technical implementation | by Dr. Susanne Guth-Orlowski | Medium*. https://medium.com/@susi.guth/the-digital-product-passport-and-its-technical-implementation-efdd09a4ed75

Hamdan, A.-H., Kozak, T., & Krebs & Kiefer. (n.d.). *Ontology Documentation generated by WIDOCO*. Retrieved March 19, 2024, from https://alhakam.github.io/bmat/

Hansen, K., Braungart, M., & Mulhall, D. (2013). Resource Repletion resource repletion , Role of Buildings. *Sustainable Built Environments*, 502–525. https://doi.org/10.1007/978-1-4614-5828-9_420

Harrison, K., & Conrad, T. (2011, August). *Predicting Emerging Product Design Trend by Mining Publicly Available Customer Review Data | Request PDF*. https://www.researchgate.net/publication/257919571_Predicting_Emerging_Product_Design_Trend_by_Mining_Publicly_Available_Customer_Review_Data

Hart, J., Adams, K., Giesekam, J., Tingley, D. D., & Pomponi, F. (2019). Barriers and drivers in a circular economy: the case of the built environment. *Procedia CIRP*, *80*, 619–624. https://doi.org/10.1016/J.PROCIR.2018.12.015

Hartenberger, U., Ostermeyer, Y., & Lützkendorf, T. (2021, September 17). *The Building Passport: A Tool for Capturing and Managing Whole Life Data and Information in Construction and Real Estate | Globalabc*. https://globalabc.org/resources/publications/building-passport-tool-capturing-and-managing-whole-life-data-and

Heinrich, M., & Lang, W. (2019, February). *Materials Passports - Best Practice - Innovative Solutions for a Transition to a Circular Economy in the Built Environment*. https://www.researchgate.net/publication/331384592_Materials_Passports_-_Best_Practice_-_Innovative_Solutions_for_a_Transition_to_a_Circular_Economy_in_the_Built_Environment

Heisel, F., & Rau-Oberhuber, S. (2020). Calculation and evaluation of circularity indicators for the built environment using the case studies of UMAR and Madaster. *Journal of Cleaner Production*, *243*. https://doi.org/10.1016/J.JCLEPRO.2019.118482

Hilton, M., Sherrington, C., Mccarthy, A., & Börkey, P. (2019). *Extended Producer Responsibility (EPR) and the Impact of Online Sales*. https://doi.org/10.1787/cde28569-en

Hitzler, P., Krötzsch, M., Pasia, B., Patel-Schneider, P. F., & Rudolph, S. (2012, December 11). *OWL 2 Web Ontology Language Primer (Second Edition)*. https://www.w3.org/TR/2012/REC-owl2-primer-20121211/

Honic, M., Kovacic, I., Aschenbrenner, P., & Ragossnig, A. (2021). Material Passports for the end-of-life stage of buildings: Challenges and potentials. *Journal of Cleaner Production*, *319*. https://doi.org/10.1016/J.JCLEPRO.2021.128702

Honic, M., Kovacic, I., & Rechberger, H. (2019a). Concept for a BIM-based Material Passport for buildings. *IOP Conference Series: Earth and Environmental Science*, *225*(1). https://doi.org/10.1088/1755-1315/225/1/012073

Honic, M., Kovacic, I., & Rechberger, H. (2019b). Improving the recycling potential of buildings through Material Passports (MP): An Austrian case study. *Journal of Cleaner Production*, *217*, 787–797. https://doi.org/10.1016/J.JCLEPRO.2019.01.212

Hoosain, M. S., Paul, B. S., Raza, S. M., & Ramakrishna, S. (2020). Material Passports and Circular Economy. *An Introduction to Circular Economy*, 131–158. https://doi.org/10.1007/978-981-15-8510-4_8/TABLES/5

Horrocks, I., Patel-Schneider, P. F., Boley, H., Tabet, S., Grosof, B., & Dean, M. (2004, May 21). *SWRL: A Semantic Web Rule Language Combining OWL and RuleML*. https://www.w3.org/submissions/SWRL/

Huesemann, M., & Huesemann, J. (2011). *Techno-Fix: Why Technology Won't Save Us Or the Environement*. New Society Publishers.

International Energy Agency. (2022). *Buildings – Topics - IEA*. https://www.iea.org/topics/buildings

ISO. (2020a). *ISO 23386:2020 - Building information modelling and other digital processes used in construction — Methodology to describe, author and maintain properties in interconnected data dictionaries*. https://www.iso.org/standard/75401.html

ISO. (2020b). *ISO 23387:2020 - Building information modelling (BIM) — Data templates for construction objects used in the life cycle of built assets — Concepts and principles*. https://www.iso.org/standard/75403.html

ISO. (2022). *ISO 22057:2022 - Sustainability in buildings and civil engineering works — Data templates for the use of environmental product declarations (EPDs) for construction products in building information modelling (BIM)*. https://www.iso.org/standard/72463.html

Jansen, M., Gerstenberger, B., Bitter-Krahe, J., Berg, H., Sebestyén, J., Schneider, J., Jansen, M., & Berg, J. (2022). *Current Approaches to the Digital Product Passport for a Circular Economy An overview of projects and initiatives*. 1–24. www.wupperinst.org

Jansen, M., Meisen, T., Plociennik, C., Berg, H., Pomp, A., & Windholz, W. (2023). Stop Guessing in the Dark: Identified Requirements for Digital Product Passport Systems. *Systems*, *11*(3). https://doi.org/10.3390/SYSTEMS11030123

Janssen Steenberg, M. A. (2023). *Connected object data in heritage conservation - the value in natural stone restoration projects*.

Kaltenegger, J. (2024). *BMP Ontology*.

Karlapudi, J. (n.d.). *Digital Construction Lifecycle*. Retrieved March 20, 2024, from https://digitalconstruction.github.io/Lifecycle/latest/#InformationProvider

Karlapudi, J., & Valluru, P. (2019, December 10). *Digital Construction - BuildingMaterials*. https://digitalconstruction.github.io/BuildingMaterials/latest/

Kedir, F., Bucher, D. F., & Hall, D. M. (2021). A Proposed Material Passport Ontology to Enable Circularity for Industrialized Construction. *Proceedings of the 2021 European Conference on Computing in Construction*, *2*, 91–98. https://doi.org/10.35490/EC3.2021.159

Kirchherr, J., Reike, D., & Hekkert, M. (2017). *Conceptualizing the circular economy: An analysis of 114 definitions A R T I C L E I N F O*. https://doi.org/10.1016/j.resconrec.2017.09.005

Knublauch, H., & Kontokostas, D. (2017, July 20). *Shapes Constraint Language (SHACL)*. https://www.w3.org/TR/2017/REC-shacl-20170720/

Koppelaar, R. H. E. M., Pamidi, S., Hajósi, E., Herreras, L., Leroy, P., Jung, H. Y., Concheso, A., Daniel, R., Francisco, F. B., Parrado, C., Dell'Ambrogio, S., Guggiari, F., Leone, D., & Fontana, A. (2023). A Digital Product Passport for Critical Raw Materials Reuse and Recycling. *Sustainability (Switzerland)*, *15*(2). https://doi.org/10.3390/SU15021405

Kossiakoff, A., Seymour, S. J., Flanigan, D. A., & Biemer, S. M. (2020). Systems Engineering Principles and Practice. *Systems Engineering Principles and Practice*. https://doi.org/10.1002/9781119516699

Kovacic, I., Honic, M., & Sreckovic, M. (2020). Digital Platform for Circular Economy in AEC Industry. *Engineering Project Organization Journal*, *9*.

Lebo, T., Sahoo, S., & McGuiness, D. (2013, April 30). *PROV-O: The PROV Ontology*. https://www.w3.org/TR/prov-o/

Lee, Y. C., Eastman, C. M., Solihin, W., & See, R. (2016). Modularized rule-based validation of a BIM model pertaining to model views. *Automation in Construction*, *63*, 1–11. https://doi.org/10.1016/J.AUTCON.2015.11.006

Lell, O., Muster, V., Thorun, C., & Gossen, M. (n.d.). *Förderung des nachhaltigen Konsums durch digitale Produktinformationen: Bestandsaufnahme und Handlungsempfehlungen | Umweltbundesamt*. Retrieved November 30, 2023, from https://www.umweltbundesamt.de/publikationen/foerderung-des-nachhaltigen-konsums-durch-digitale

Loppies, W. W. (2015). *Bouwen aan de Circulaire Economie: "Een betere wereld begint bij het stellen van een betere vraag"*

Lupica Spagnolo, S., Amosso, G., Pavan, A., Daniotti, B., Lupica Spagnolo, S., Amosso, G., Pavan, A., & Daniotti, B. (2020). *BIMReL: The Interoperable BIM Library for Construction Products Data Sharing*. https://doi.org/10.1007/978-3-030-33570-0_4

Luscuere, L. M. (2017). Materials Passports: Optimising value recovery from materials. *Proceedings of Institution of Civil Engineers: Waste and Resource Management*, *170*(1), 25–28. https://doi.org/10.1680/JWARM.16.00016

Madaster. (2023). *Madaster: the cadastre for materials and products*. https://madaster.com/

Mboli, J. S., Thakker, D. K., & Mishra, J. L. (2022). *An IoT-enabled Decision*. https://doi.org/10.1002/spe.2825

Mehra, S., Singh, M., Sharma, G., Kumar, S., Navishi, & Chadha, P. (2022). Impact of Construction Material on Environment. *Ecological and Health Effects of Building Materials*, 427–442. https://doi.org/10.1007/978-3-030-76073-1_22

Ministerie van Infrastructuur en Milieu, & Ministerie van Economische zaken. (2016). *Nederland circulair in 2050 - Rijksbreed programma Circulaire Economie*.

Morkunaite, L., Naber, F. Al, Petrova, E., & Svidt, K. (2021). *An Open Data Platform for Early-Stage Building Circularity Assessment*. https://research.tue.nl/en/publications/an-open-data-platform-for-early-stage-building-circularity-assess

Munaro, M. R., Fischer, A. C., Azevedo, N. C., & Tavares, S. F. (2019). Proposal of a building material passport and its application feasibility to the wood frame constructive system in Brazil. *IOP Conference Series: Earth and Environmental Science*, *225*(1). https://doi.org/10.1088/1755-1315/225/1/012018

NEN. (2019, November 1). *NEN-EN 15804:2012+A2:2019*.

NEN. (2020a, May 20). *NEN 2660-1:2022 nl*. https://www.nen.nl/en/nen-2660-1-2022-nl-291666

NEN. (2020b, June 20). *NEN 3610:2022 nl*. https://www.nen.nl/nen-3610-2022-nl-296137

NEN. (2021, April 7). *Normontwerp informatiemodellering van gebouwde omgeving ter commentaar*. https://www.nen.nl/nieuws/energie-distributie/normontwerp-informatiemodellering-van-gebouwde-omgeving-ter-commentaar/

Ontotext. (2023). *GraphDB*.

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *International Journal of Surgery*, *88*, 105906. https://doi.org/10.1016/J.IJSU.2021.105906

Pauwels, P. (2018, December 27). *Building Element Ontology*. https://pi.pauwel.be/voc/buildingelement/index-en.html

Pauwels, P. (2020). *IFCtoLBD-0.1* (0.1).

Pauwels, P., Costin, A., & Rasmussen, M. H. (2022). Knowlegde Graphs and Linked Data for the Built Environment. In M. Bolpagni, R. Gavina, & D. Ribeiro (Eds.), *Industry 4.0 for the Built Environment* (p. 20). Springer. https://doi.org/https://doi.org/10.1007/978-3-030-82430-3_7

Pauwels, P., de Farias, T. M., Zhang, C., Roxin, A., Beetz, J., De Roo, J., & Nicolle, C. (2017a). A performance benchmark over semantic rule checking approaches in construction industry. *Advanced Engineering Informatics*, *33*, 68–88. https://doi.org/10.1016/J.AEI.2017.05.001

Pauwels, P., de Farias, T. M., Zhang, C., Roxin, A., Beetz, J., De Roo, J., & Nicolle, C. (2017b). A performance benchmark over semantic rule checking approaches in construction industry. *Advanced Engineering Informatics*, *33*, 68–88. https://doi.org/10.1016/J.AEI.2017.05.001

Pauwels, P., Holten, M., & Schneider, G. F. (n.d.). *Product: Building Product Ontology*. Retrieved March 19, 2024, from https://github.com/w3c-lbd-cg/product

Pauwels, P., van den Bersselaar, E., & Verhelst, L. (2024). Validation of technical requirements for a BIM model using semantic web technologies. *Advanced Engineering Informatics*, *60*, 102426. https://doi.org/10.1016/J.AEI.2024.102426

Pauwels, P., Van Deursen, D., Verstraeten, R., De Roo, J., De Meyer, R., Van De Walle, R., & Van Campenhout, J. (2011). A semantic rule checking environment for building performance checking. *Automation in Construction*, *20*(5), 506–518. https://doi.org/10.1016/J.AUTCON.2010.11.017

Pauwels, P., Zhang, S., & Lee, Y. C. (2017a). Semantic web technologies in AEC industry: A literature overview. *Automation in Construction*, *73*, 145–165. https://doi.org/10.1016/J.AUTCON.2016.10.003

Pauwels, P., Zhang, S., & Lee, Y. C. (2017b). Semantic web technologies in AEC industry: A literature overview. *Automation in Construction*, *73*, 145–165. https://doi.org/10.1016/J.AUTCON.2016.10.003

Pauwels, P., Zhang, S., & Lee, Y. C. (2017c). Semantic web technologies in AEC industry: A literature overview. *Automation in Construction*, *73*, 145–165. https://doi.org/10.1016/J.AUTCON.2016.10.003

Platform CB’23. (2019). *Framework Circulair Bouwen*.

Platform CB’23. (2022). *Meten van circulariteit*. 1–70.

Platform CB’23. (2023). *Paspoorten voor de bouw Deel 1 + 2*.

Plociennik, C., Pourjafarian, M., Nazeri, A., Windholz, W., Knetsch, S., Rickert, J., Ciroth, A., Precci Lopes, A. D. C., Hagedorn, T., Vogelgesang, M., Benner, W., Gassmann, A., Bergweiler, S., Ruskowski, M., Schebek, L., & Weidenkaff, A. (2022). Towards a Digital Lifecycle Passport for the Circular Economy. *Procedia CIRP*, *105*, 122–127. https://doi.org/10.1016/J.PROCIR.2022.02.021

Plociennik, C., Pourjafarian, M., Saleh, S., Hagedorn, T., do Carmo Precci Lopes, A., Vogelgesang, M., Baehr, J., Kellerer, B., Jansen, M., Berg, H., Ruskowski, M., Schebek, L., & Ciroth, A. (2022). Requirements for a Digital Product Passport to Boost the Circular Economy. *Lecture Notes in Informatics (LNI), Proceedings - Series of the Gesellschaft Fur Informatik (GI)*, *P-326*, 1485–1494. https://doi.org/10.18420/INF2022_127

Puerta, A. R., Egar, J. W., Tu, S. W., & Musen, M. A. (1992). A multiple-method knowledge-acquisition shell for the automatic generation of knowledge-acquisition tools. *Knowledge Acquisition*, *4*(2), 171–196. https://doi.org/10.1016/1042-8143(92)90025-V

QUDT. (2024, February 26). *QUDT Ontologies: Schemas and Vocabularies*. https://www.qudt.org/2.1/catalog/qudt-catalog.html

Rasmussen, M. H., & Lefrançois, M. (2018, November 22). *Ontology for Property Management*. https://w3c-lbd-cg.github.io/opm/

Rasmussen, M. H., Pauwels, P., Lefrançois, M., & Schneider, G. F. (2021, June 28). *Building Topology Ontology*. https://w3c-lbd-cg.github.io/bot/

Reynolds, D. (2014, January 16). *The Organization Ontology*. https://www.w3.org/TR/vocab-org/

Rijkswaterstaat. (2020). *Materialenpaspoort*.

Rockström, J., Steffen, W., & Noone, K. (2009). *A safe operating space for humanity*. *461*, 472–475.

Sacks, R., Eastman, C., Lee, G., & Teicholz, P. (2018). BIM Handbook. *BIM Handbook*. https://doi.org/10.1002/9781119287568

Santos, R., Costa, A. A., Silvestre, J. D., & Pyl, L. (2019). Integration of LCA and LCC analysis within a BIM-based environment. *Automation in Construction*, *103*, 127–149. https://doi.org/10.1016/J.AUTCON.2019.02.011

Sauter, E., Lemmens, R., & Pauwels, P. (2018). *CEO & CAMO Ontologies: a circulation medium for materials in the construction industry* (pp. 1645–1652). CRC Press/Balkema. https://research.tue.nl/en/publications/ceo-amp-camo-ontologies-a-circulation-medium-for-materials-in-the-2

Schützenhofer, S., Kovacic, I., & Rechberger, H. (2022). Assessment of Sustainable Use of Material Resources in the Architecture, Engineering and Construction Industry - a Conceptual Framework Proposal for Austria. *Journal of Sustainable Development of Energy, Water and Environment Systems*, *10*(4). https://doi.org/10.13044/J.SDEWES.D10.0417

SGS Search. (2021). *Beslisboom Hergebruik (ge)bouwelementen*.

ShEx Community Group. (n.d.). *ShEx - Shape Expressions*. Retrieved March 20, 2024, from https://shex.io/

Simkus, M., & Varzinczak, I. (2022). *Reasoning Web. Declarative Artificial Intelligence* (M. Simkus & I. Varzinczak, Eds.). Springer.

Skjaeveland, M. G., Klüwer, J. W., & Valen-Sendstad, M. (2008, January). *ISO 15926 templates and the Semantic Web*. https://www.researchgate.net/publication/251636131_ISO_15926_templates_and_the_Semantic_Web

Sobhkhiz, S., Taghaddos, H., Rezvani, M., & Ramezanianpour, A. M. (2021). Utilization of semantic web technologies to improve BIM-LCA applications. *Automation in Construction*, *130*, 103842. https://doi.org/10.1016/J.AUTCON.2021.103842

Sommer, A., & Car, N. (2022). *pySHACL*. https://github.com/RDFLib/pySHACL

Stanford University. (n.d.). *protégé*. Retrieved May 17, 2024, from https://protege.stanford.edu/

Statista. (2024). *EU-27: construction & demolition waste recovery by country | Statista*. https://www.statista.com/statistics/1316268/recovery-rate-of-construction-and-demolition-waste-eu-by-country/

Steffen, W., Richardson, K., & Rockström, J. (2015). *Planetary boundaries: Guiding human development on a changing planet*. *347*(6223).

Stolk, S., & Mcglinn, K. (n.d.). *Validation of IfcOWL datasets using SHACL*. Retrieved March 20, 2024, from https://www.buildingsmart.org/about/what-is-openbim/ifc-introduction/

Studer, R., Benjamins B'c, V. R., & Fensel, D. (1998). I DATA & KNOWLEDGE ENGINEERING Knowledge Engineering: Principles and methods. *Data & Knowledge Engineering*, *25*, 161–197.

The Swedish National Board of Housing, B. and P. (2023). *Greenhouse gas emissions from the construction and real estate sector*.

United Nations Environment Programme. (2020). *2020 GLOBAL STATUS REPORT FOR BUILDINGS AND CONSTRUCTION Towards a zero-emissions, efficient and resilient buildings and construction sector* . www.globalabc.org.

van Capelleveen, G., Vegter, D., Olthaar, M., & van Hillegersberg, J. (2023). The anatomy of a passport for the circular economy: a conceptual definition, vision and structured literature review. *Resources, Conservation and Recycling Advances*, *17*. https://doi.org/10.1016/J.RCRADV.2023.200131

van den Bersselaar, E. (2022, August 30). *Automatic validation of technical requirements for a BIM model using semantic web technologies — Eindhoven University of Technology research portal*. https://research.tue.nl/en/studentTheses/automatic-validation-of-technical-requirements-for-a-bim-model-us

W3C. (2017, March 29). *SHACL-ShEx-Comparison - RDF Data Shapes Working Group*. https://www.w3.org/2014/data-shapes/wiki/SHACL-ShEx-Comparison

W3C. (2024). *The Semantic Web Made Easy*.

W3C Wiki. (2015, May 7). *Good Ontologies - W3C Wiki*. https://www.w3.org/wiki/Good_Ontologies

Wagner, A., Bonduel, M., Pauwels, P., & Rüppel, U. (2019). Ontology for Managing Geometry (OMG). *Proceedings of the European Conference on Computing in Construction*, 304–313. https://doi.org/10.35490/EC3.2019.146

Wagner, A., & Rüppel, U. (2019). *BPO: The Building Product Ontology for Assembled Products*. https://w3id.org/bot

Walden, J., Steinbrecher, A., & Marinkovic, M. (2021). Digital Product Passports as Enabler of the Circular Economy. *Chemie-Ingenieur-Technik*, *93*(11), 1717–1727. https://doi.org/10.1002/CITE.202100121

Watson, K., Patzer, F., & Schöppenthau, F. (2023). Achieving a Sustainable Economy with Digital Product Passports. *IIC Journal of Innovation*.

Werbrouck, J., Senthilvel, M., Beetz, J., & Pauwels, P. (2019). *A Checking Approach for Distributed Building Data*. https://www.researchgate.net/publication/335794666_A_Checking_Approach_for_Distributed_Building_Data

Wilkinson, M. D., Dumontier, M., Aalbersberg, Ij. J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J. W., da Silva Santos, L. B., Bourne, P. E., Bouwman, J., Brookes, A. J., Clark, T., Crosas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C. T., Finkers, R., … Mons, B. (2016). The FAIR Guiding Principles for scientific data management and stewardship. *Scientific Data 2016 3:1*, *3*(1), 1–9. https://doi.org/10.1038/sdata.2016.18

Yurchyshyna, A., Faron Zucker, C., Le Thanh, N., Lima, C., Zarli, A., & Faron-Zucker, C. (2007). *Towards an Ontology-based Approach for Conformance Checking Modeling in Construction*. https://hal.science/hal-03503009

Yurchyshyna, A., & Zarli, A. (2009). An ontology-based approach for formalisation and semantic organisation of conformance requirements in construction. *Automation in Construction*, *18*(8), 1084–1098. https://doi.org/10.1016/J.AUTCON.2009.07.008

Zhang, C., Beetz, J., & De Vries, B. (2018a). BimSPARQL: Domain-specific functional SPARQL extensions for querying RDF building data. *Semantic Web*, *9*(6), 829–855. https://doi.org/10.3233/SW-180297

Zhang, C., Beetz, J., & De Vries, B. (2018b). BimSPARQL: Domain-specific functional SPARQL extensions for querying RDF building data. *Semantic Web*, *9*(6), 829–855. https://doi.org/10.3233/SW-180297

Zhang, N., Han, Q., De Vries, B., Dong, L., Bonenberg, A., & Bonenberg, W. (2021). Building Circularity Assessment in the Architecture, Engineering, and Construction Industry: A New Framework. *Sustainability 2021, Vol. 13, Page 12466*, *13*(22), 12466. https://doi.org/10.3390/SU132212466

Appendices

APPENDIX A: Figures introduction and literature

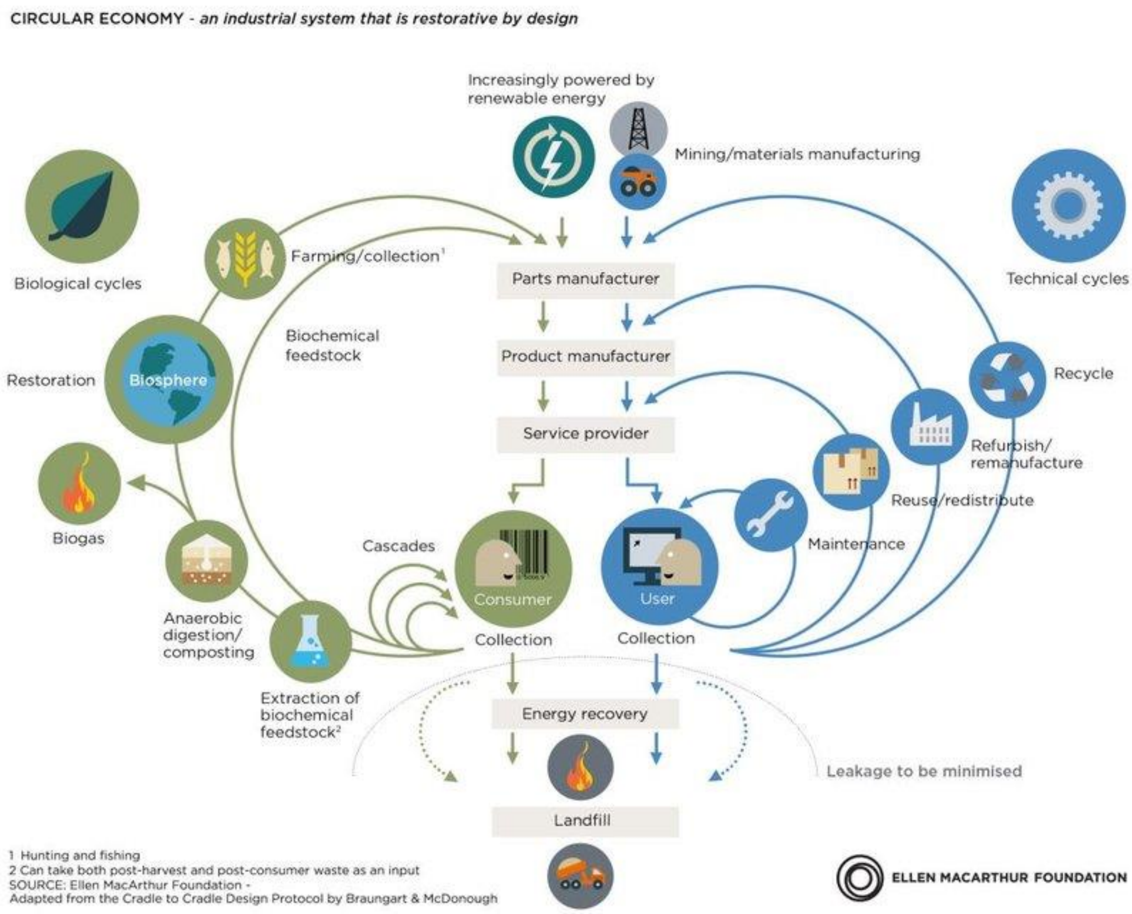


Figure 1a: Circular Economy, (Ellen Macarthur Foundation, 2013)

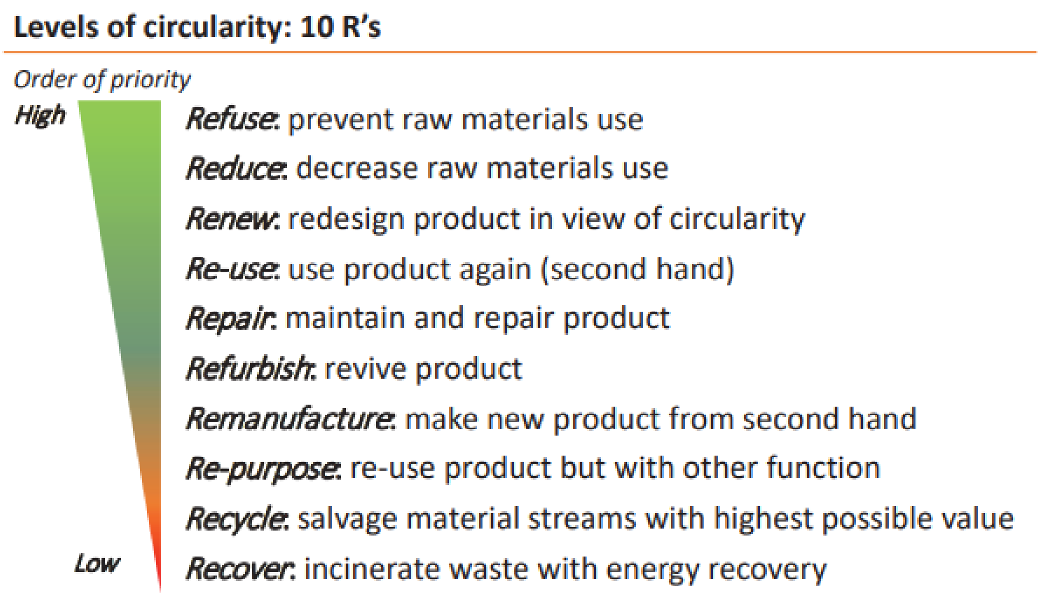


Figure 2a: 10R Levels of circularity, (Cramer, 2017b)

6 Industry Foundation Classes 9

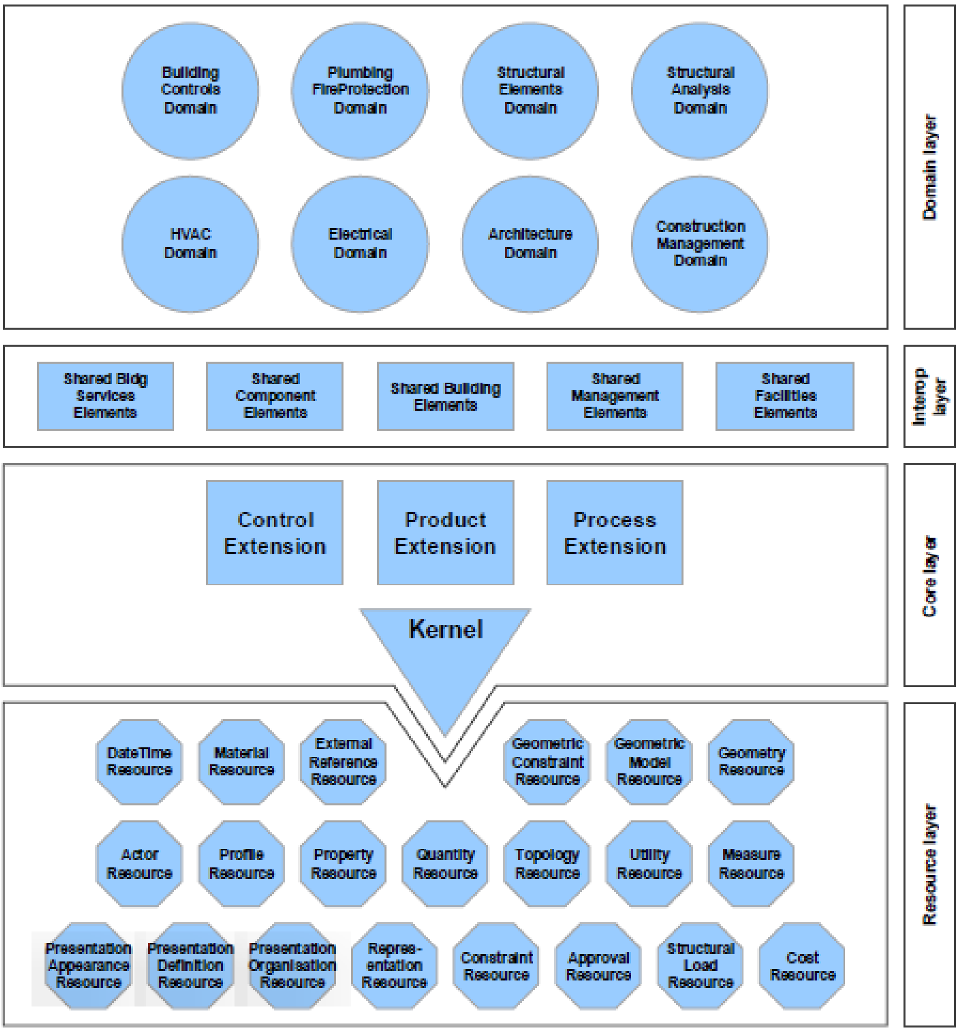


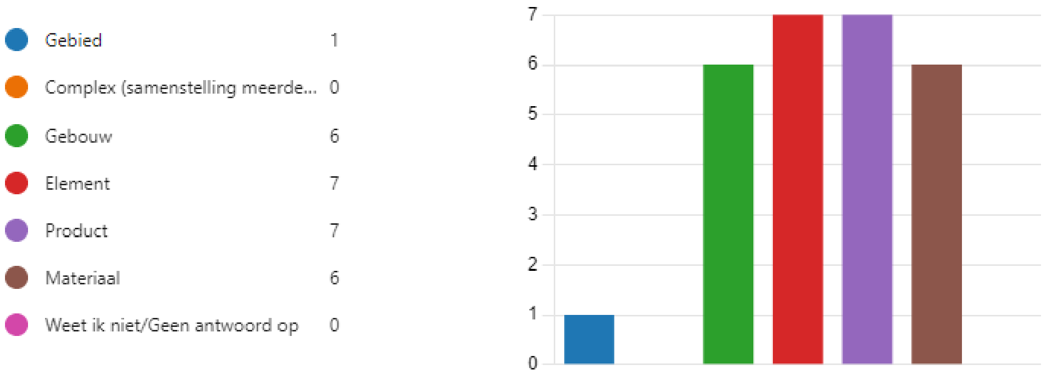
Fig. 6.5 The layers of the IFC data model. Source: IFC Documentation, ©buildingSMART

Figure 3a:The layers of the IFC data model, (buildingSMART, n.d.)

APPENDIX B: Results questionnaire (Dutch)

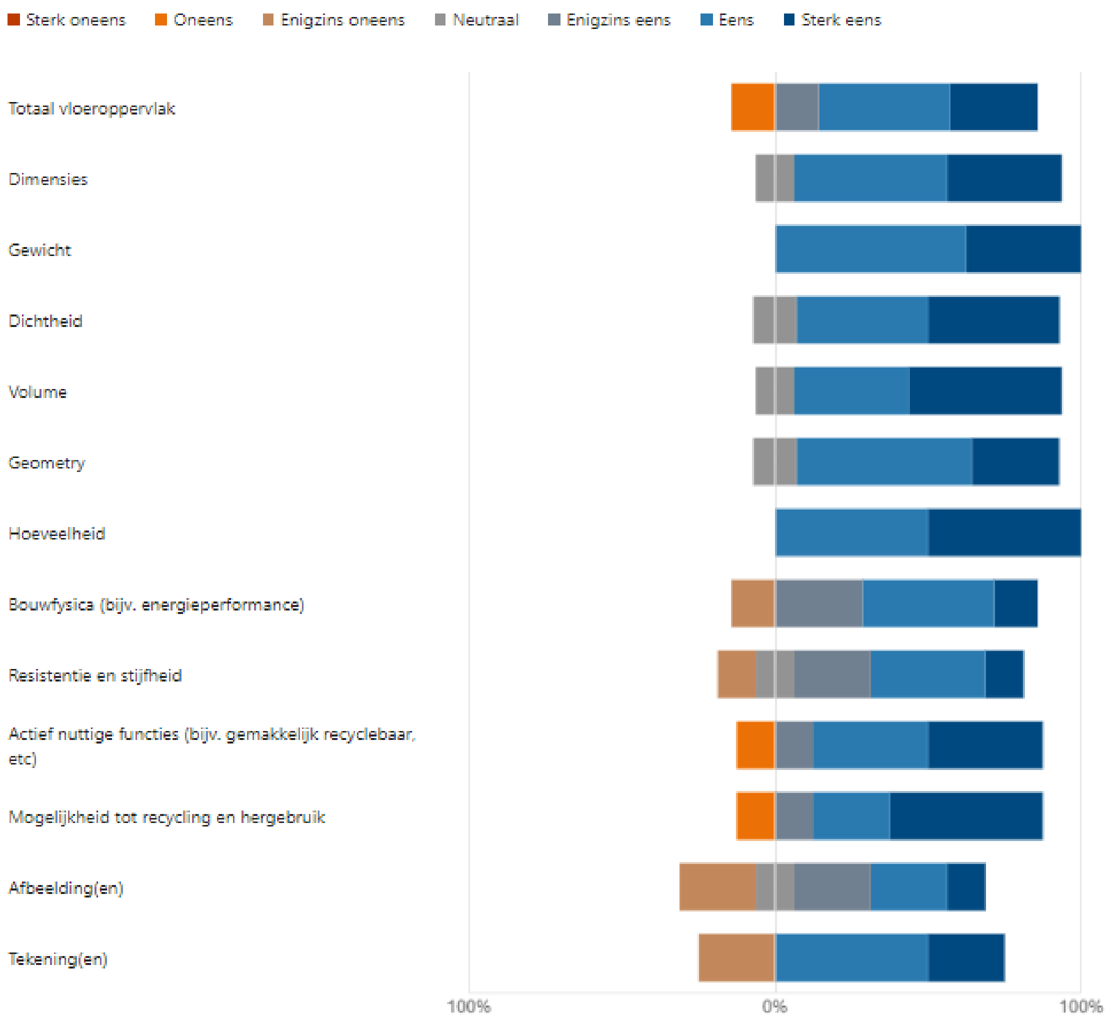
9. Op welk niveau moet een materiaalpaspoort format gemaakt worden (meerdere antwoorden mogelijk) ?

Meer details



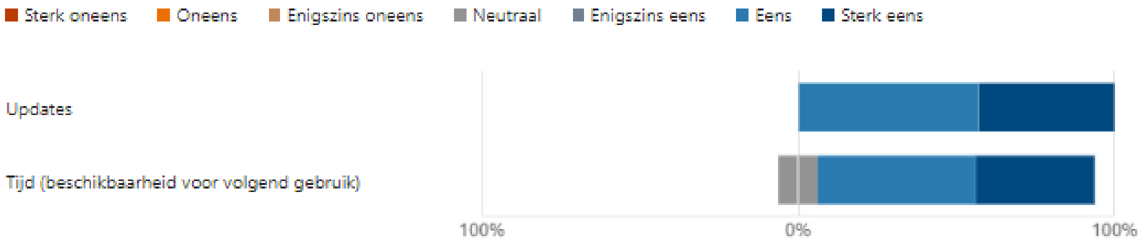
11. Vindt u dat onderstaande onderwerpen m.b.t. **fysieke en technische eigenschappen** in het materiaalpaspoort format horen? (Heeft u geen antwoord op de vraag, laat dan de keuze optie open)

Meer details



13. Vindt u dat onderstaand onderwerp m.b.t. **geschiedenis** in het materiaal paspoort format hoort (Heeft u geen antwoord op de vraag, laat dan de keuzeoptie open)?

Meer details

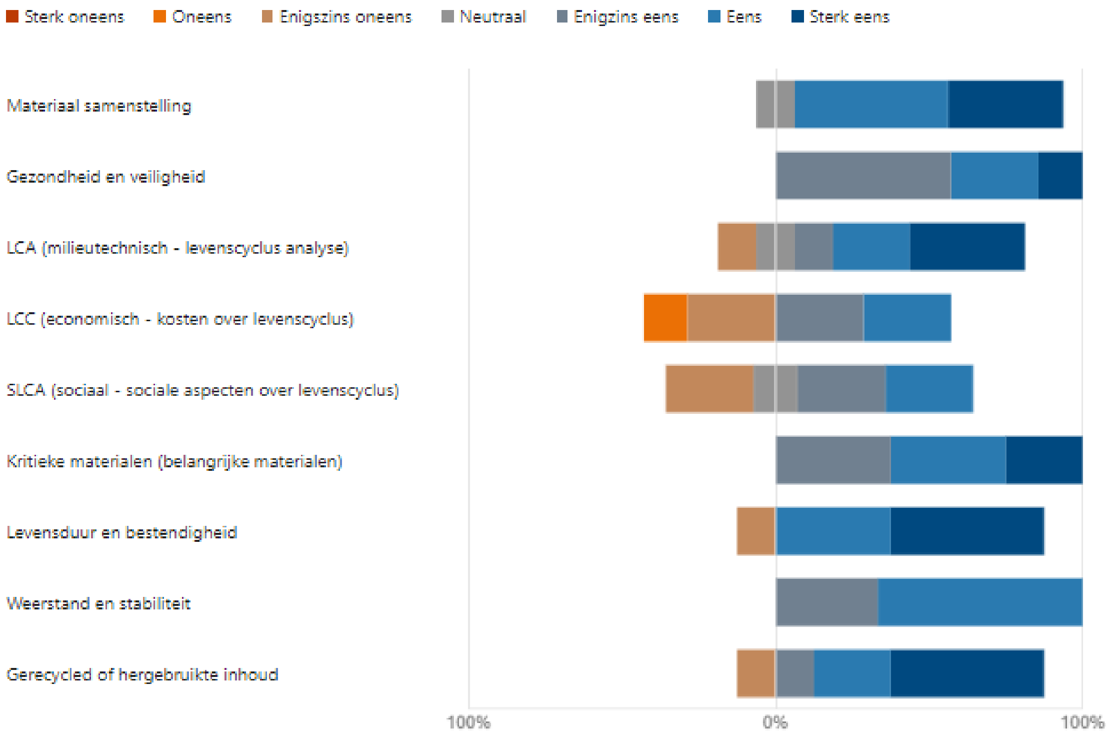


15. Vindt u dat onderstaand onderwerp **eigendom en gebruikers/betrokkenen** in het materiaal paspoort format hoort (Heeft u geen antwoord op de vraag, laat dan de keuzeoptie open)?

Meer details

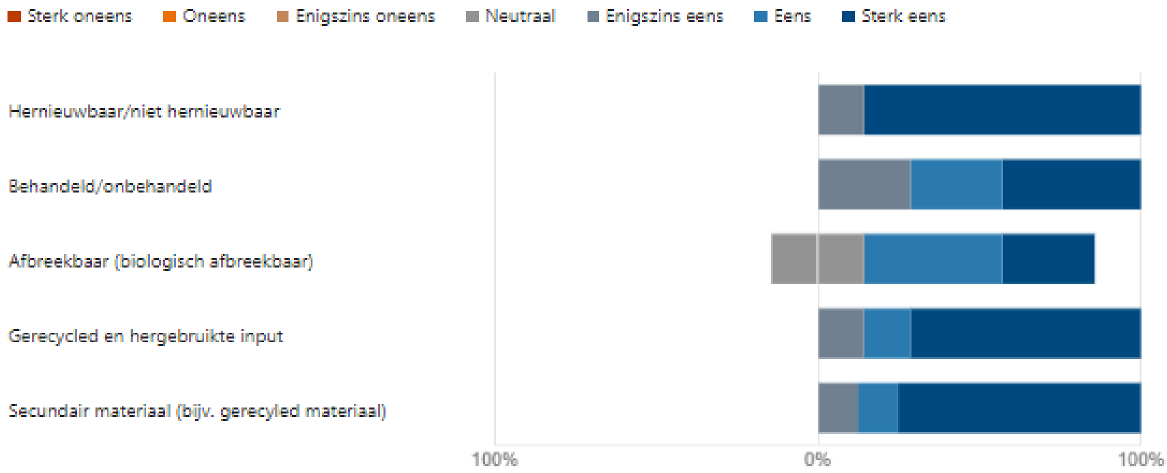
17. Vindt u dat onderstaande onderwerpen m.b.t. **chemische eigenschappen** in het materiaalpaspoort format horen? (Heeft u geen antwoord op de vraag, laat dan de keuze optie open)

Meer details



19. Vindt u dat onderstaande onderwerpen m.b.t. **biologische eigenschappen** in het materiaal paspoort format horen (Heeft u geen antwoord op de vraag, laat dan de keuzeoptie open)?

Meer details

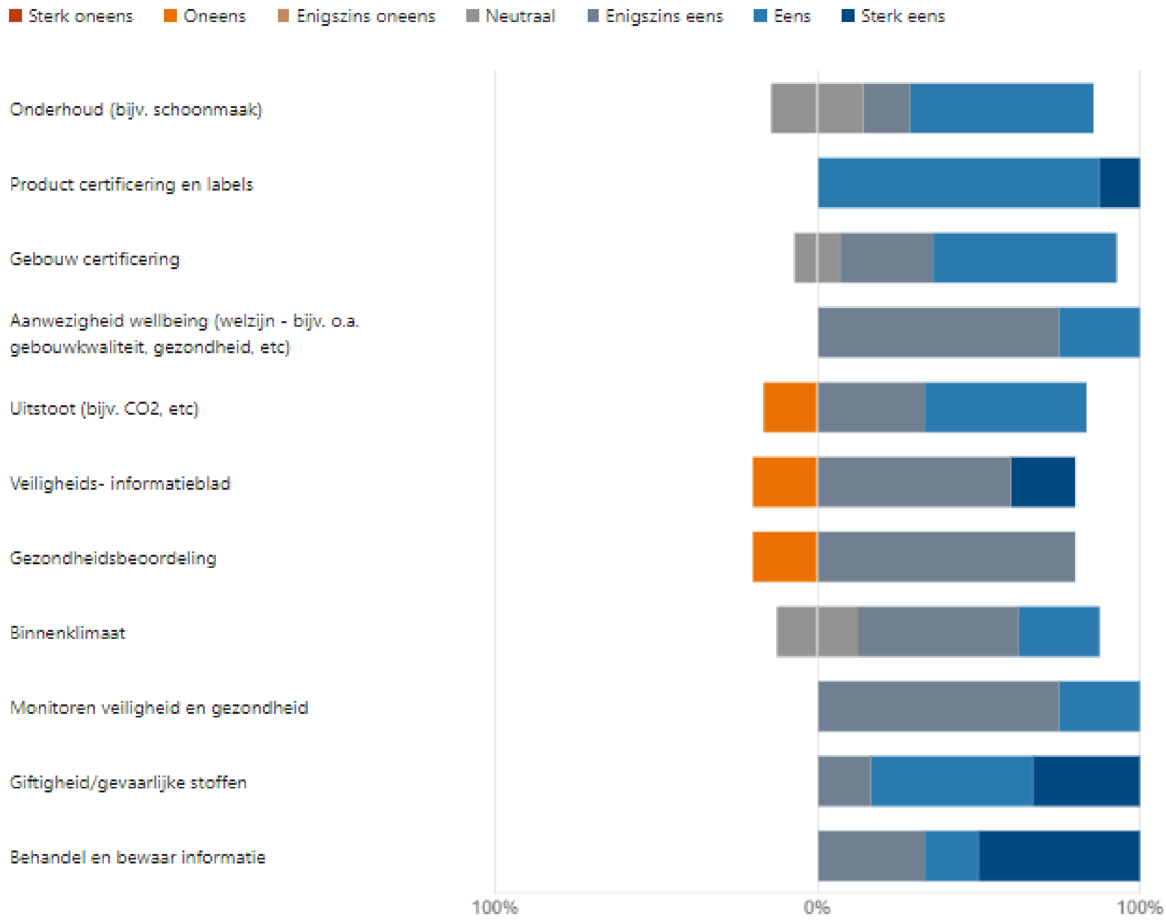


21. Vindt u **circulariteit** belangrijk in het materiaal paspoort format?

Meer details

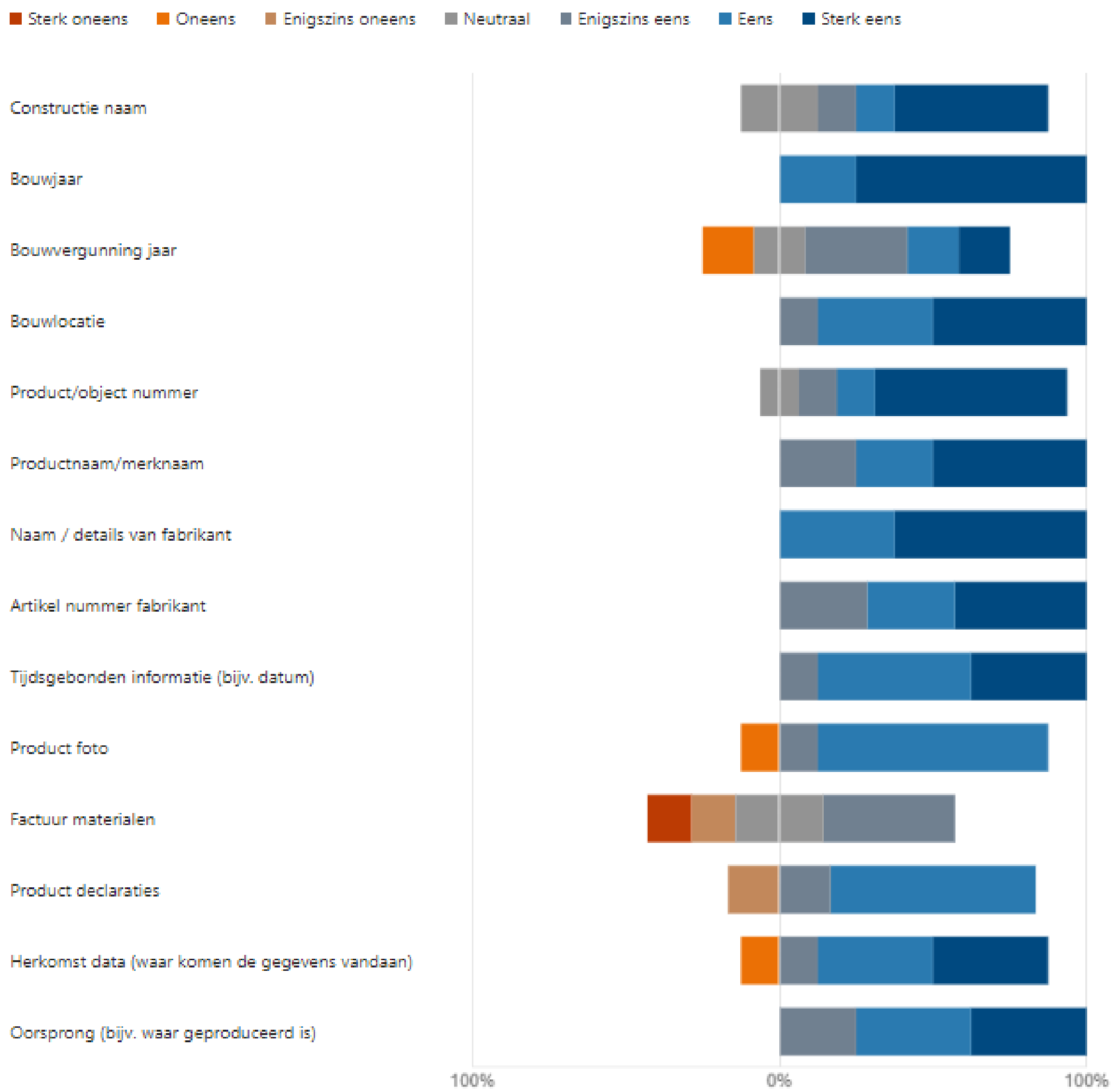
23. Vindt u dat onderstaande onderwerpen m.b.t. **gezondheid en veiligheidsaspecten** in het materiaal paspoort format horen (Heeft u geen antwoord op de vraag, laat dan de keuzeoptie open)?

Meer details



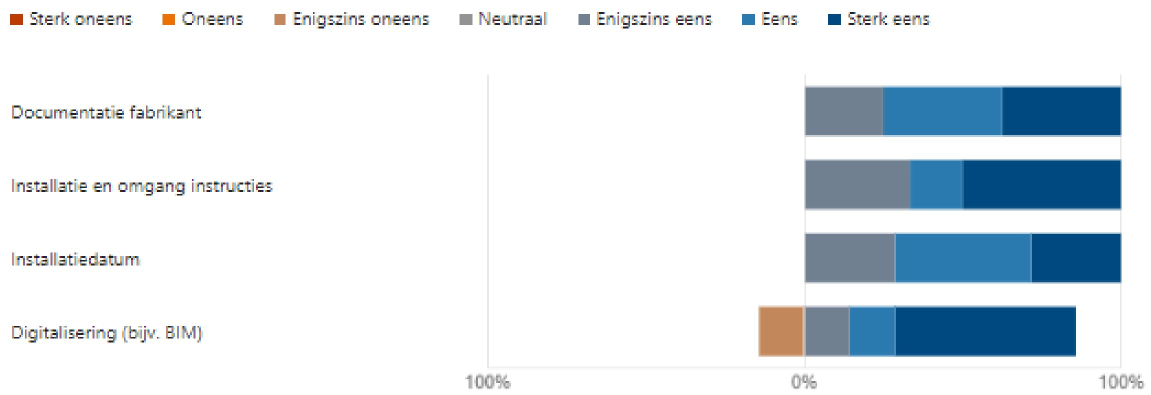
25. Vindt u dat onderstaande onderwerpen m.b.t. **unieke product aanduidingen en algemene informatie** in het materiaal paspoort format horen (Heeft u geen antwoord op de vraag, laat dan de keuzeoptie open)?

Meer details



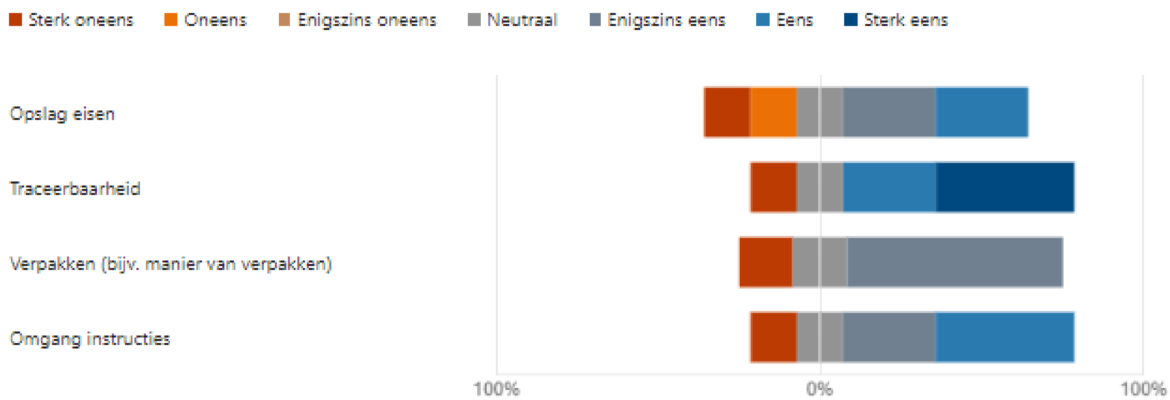
27. Vindt u dat onderstaande onderwerpen m.b.t. **productie informatie** in het materiaal paspoort format horen (Heeft u geen antwoord op de vraag, laat dan de keuzeoptie open)?

Meer details



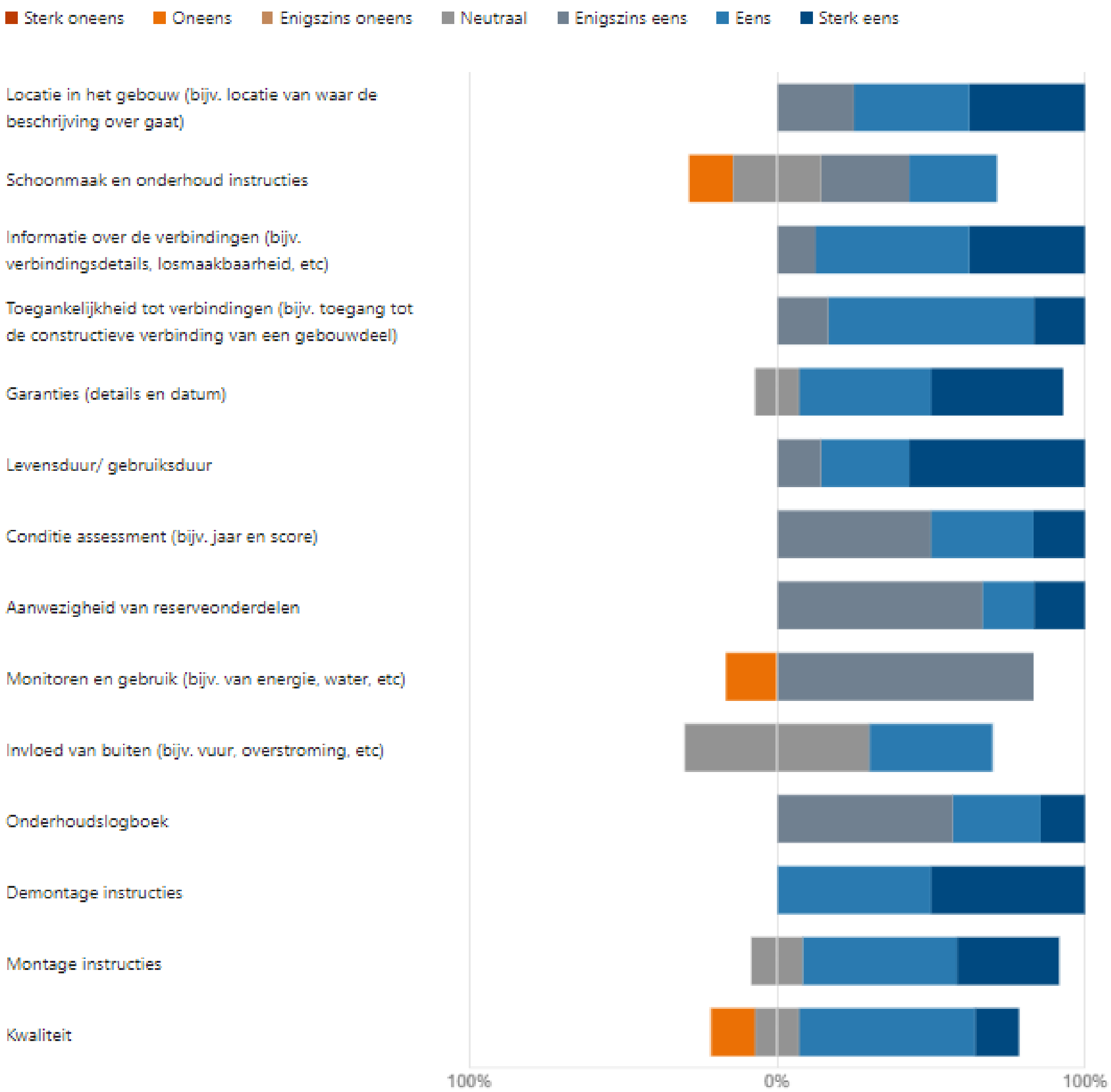
29. Vindt u dat onderstaande onderwerpen m.b.t. **transport en logistiek** in het materiaal paspoort format horen (Heeft u geen antwoord op de vraag, laat dan de keuzeoptie open)?

Meer details



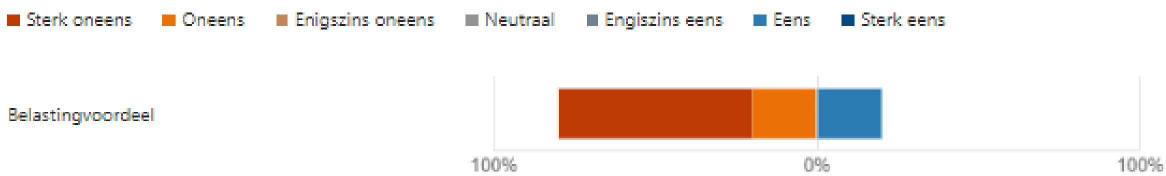
31. Vindt u dat onderstaande onderwerpen m.b.t. de **gebruiks- en operationaliseringsfase** in het materiaal paspoort format horen (Heeft u geen antwoord op de vraag, laat dan de keuzeoptie open)?

Meer details



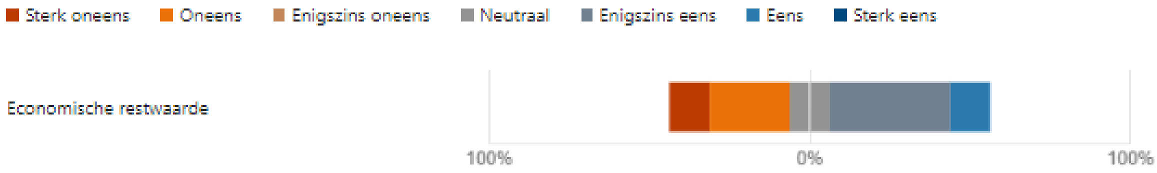
33. Vindt u dat onderstaand onderwerp **belastingvoordeel** opgenomen dient te worden in het materiaalpaspoort format? (Heeft u geen antwoord op de vraag, laat dan de keuzeoptie open)

Meer details



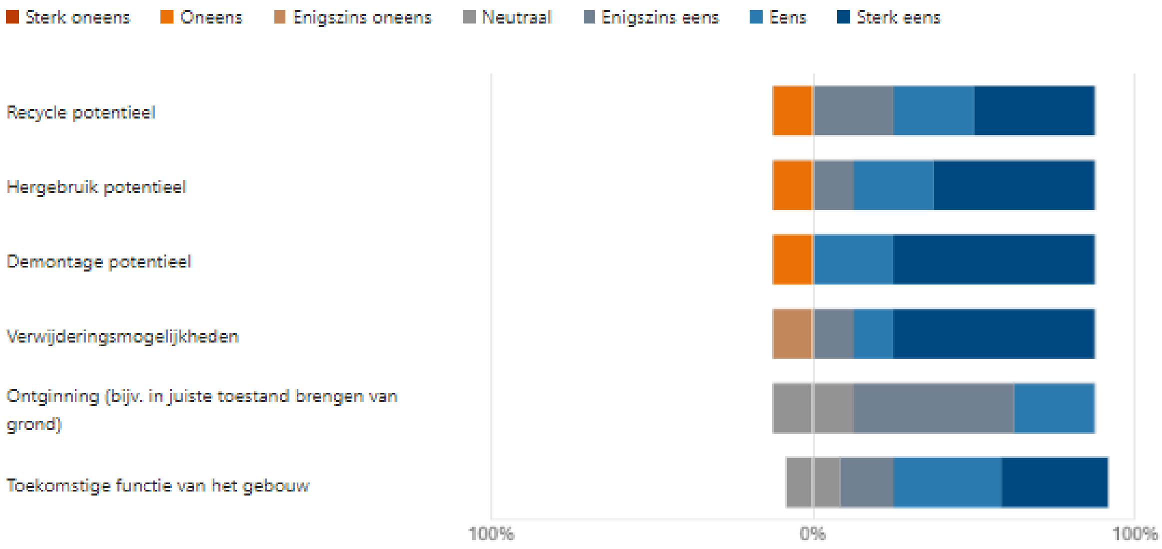
35. Vindt u dat onderstaand onderwerp **economische restwaarde** in het materiaal paspoort format hoort (Heeft u geen antwoord op de vraag, laat dan de keuzeoptie open)?

Meer details



37. Vindt u dat onderstaande onderwerpen m.b.t. de **einde levensduur** in het materiaal paspoort format horen (Heeft u geen antwoord op de vraag, laat dan de keuzeoptie open)?

Meer details



APPENDIX C: Overview Miro board

Figure 1c: Overview Miro Board

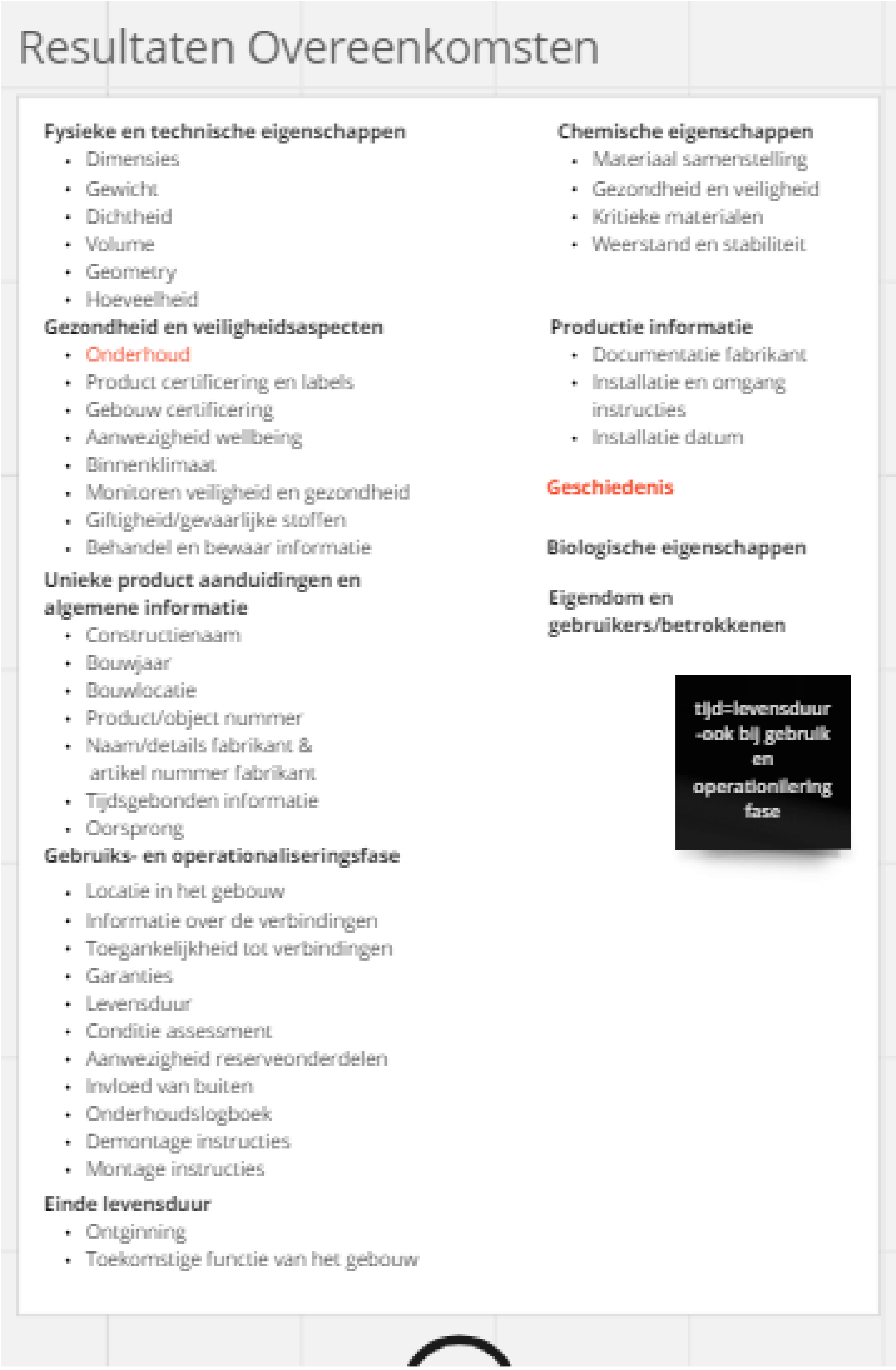


Figure 2c: Miro Results (1)

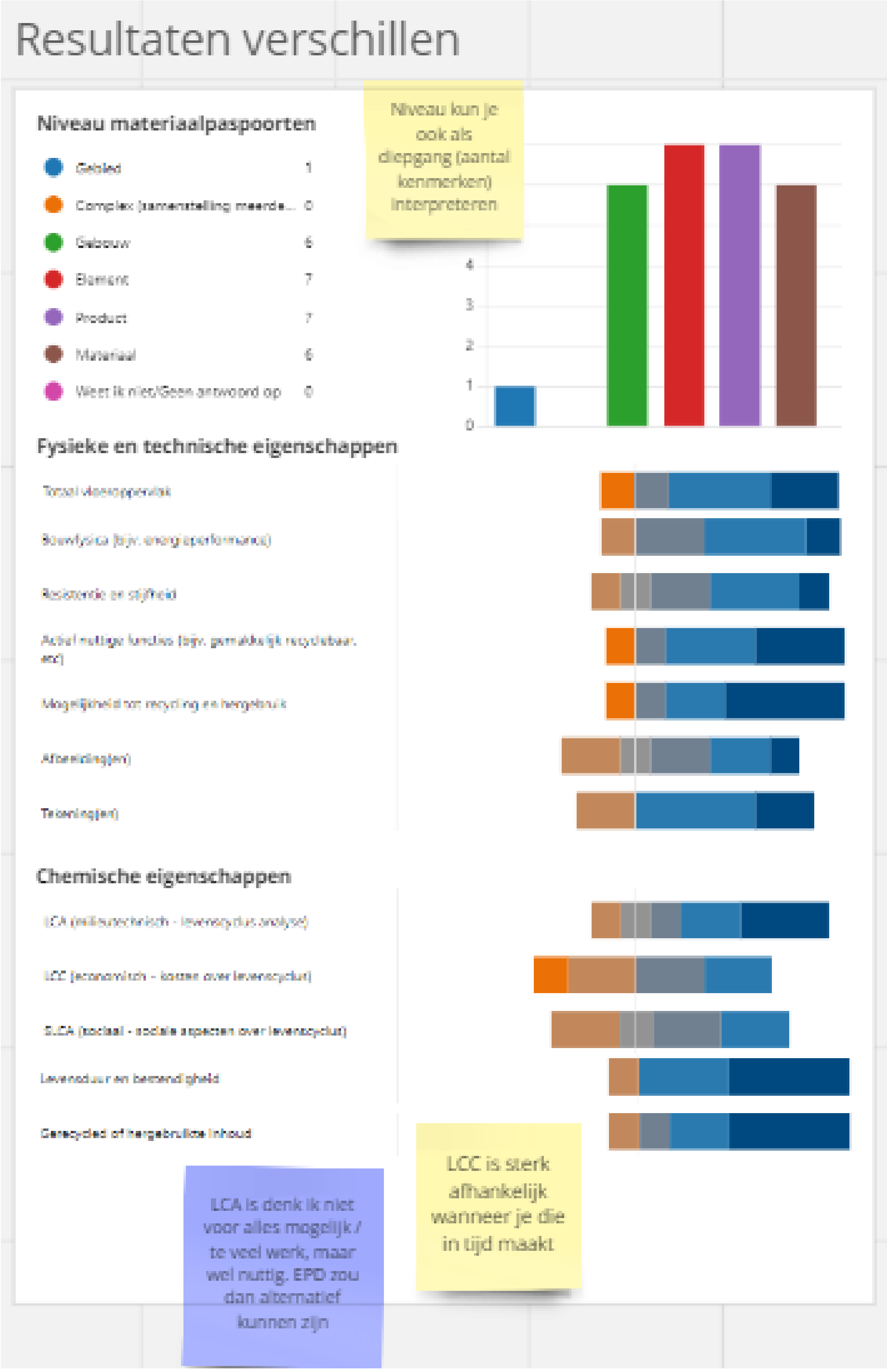


Figure 3c: Miro Results (2)

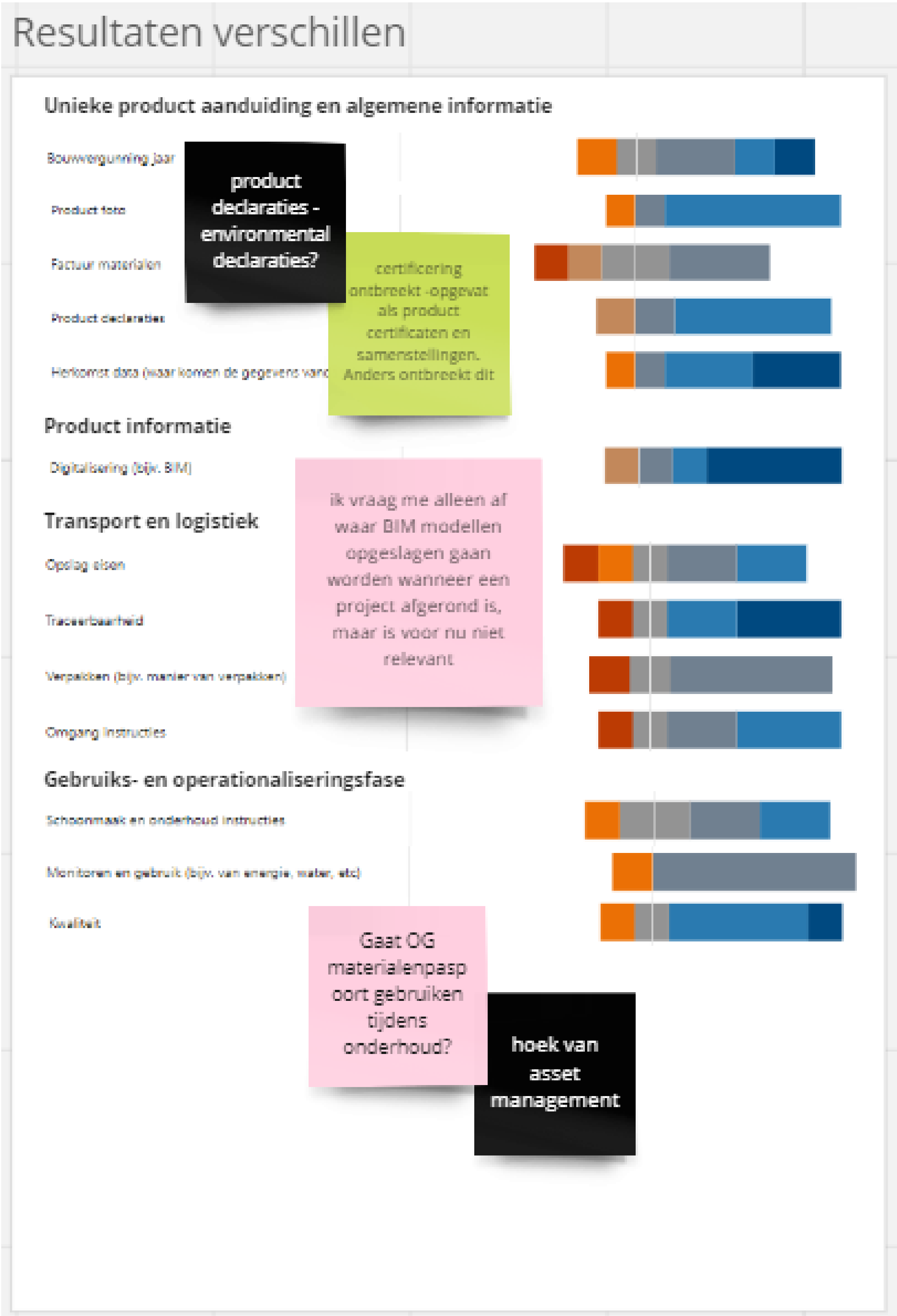


Figure 4c: Miro Results (3)

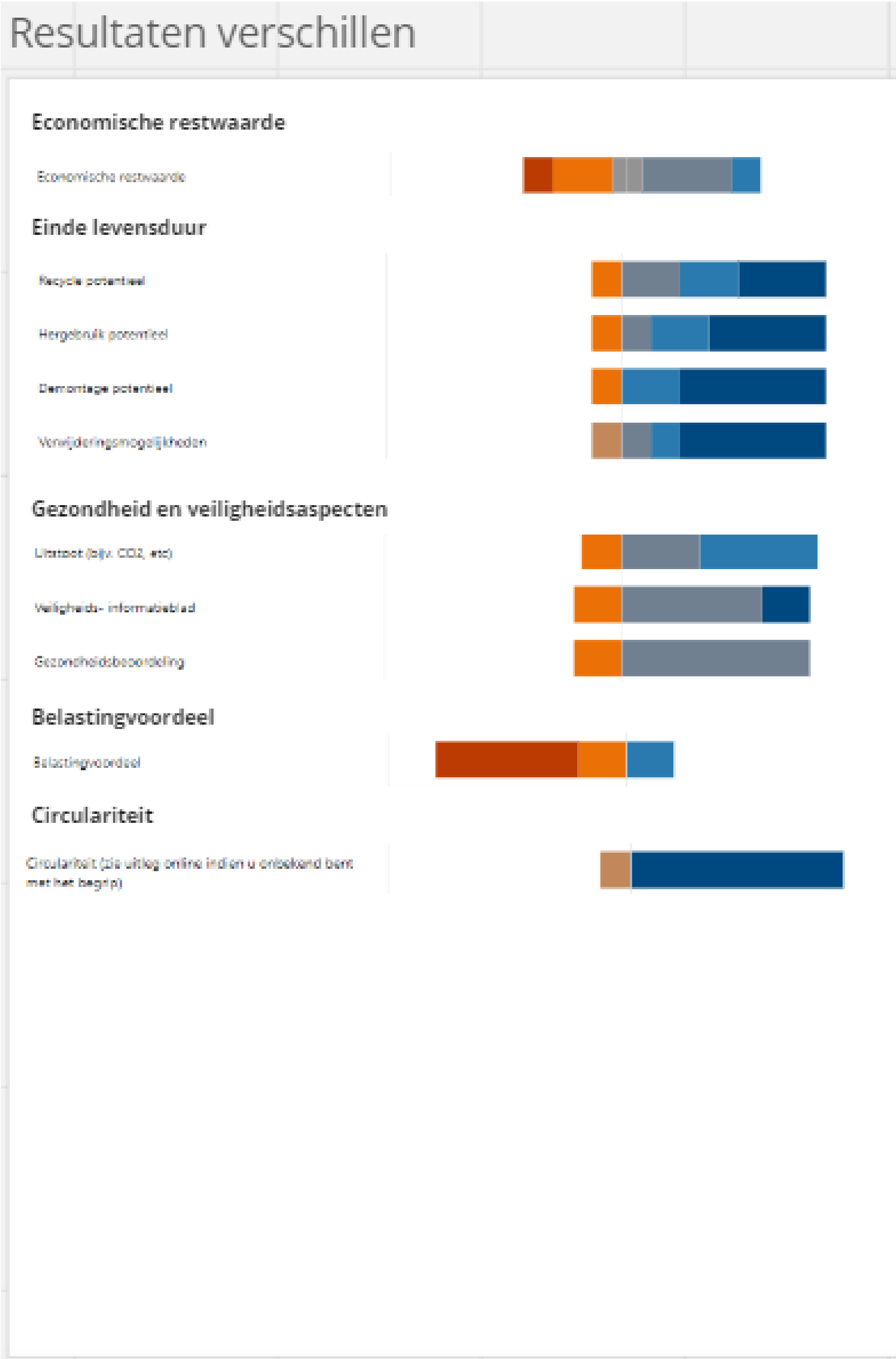


Figure 5c: Miro Results (4)

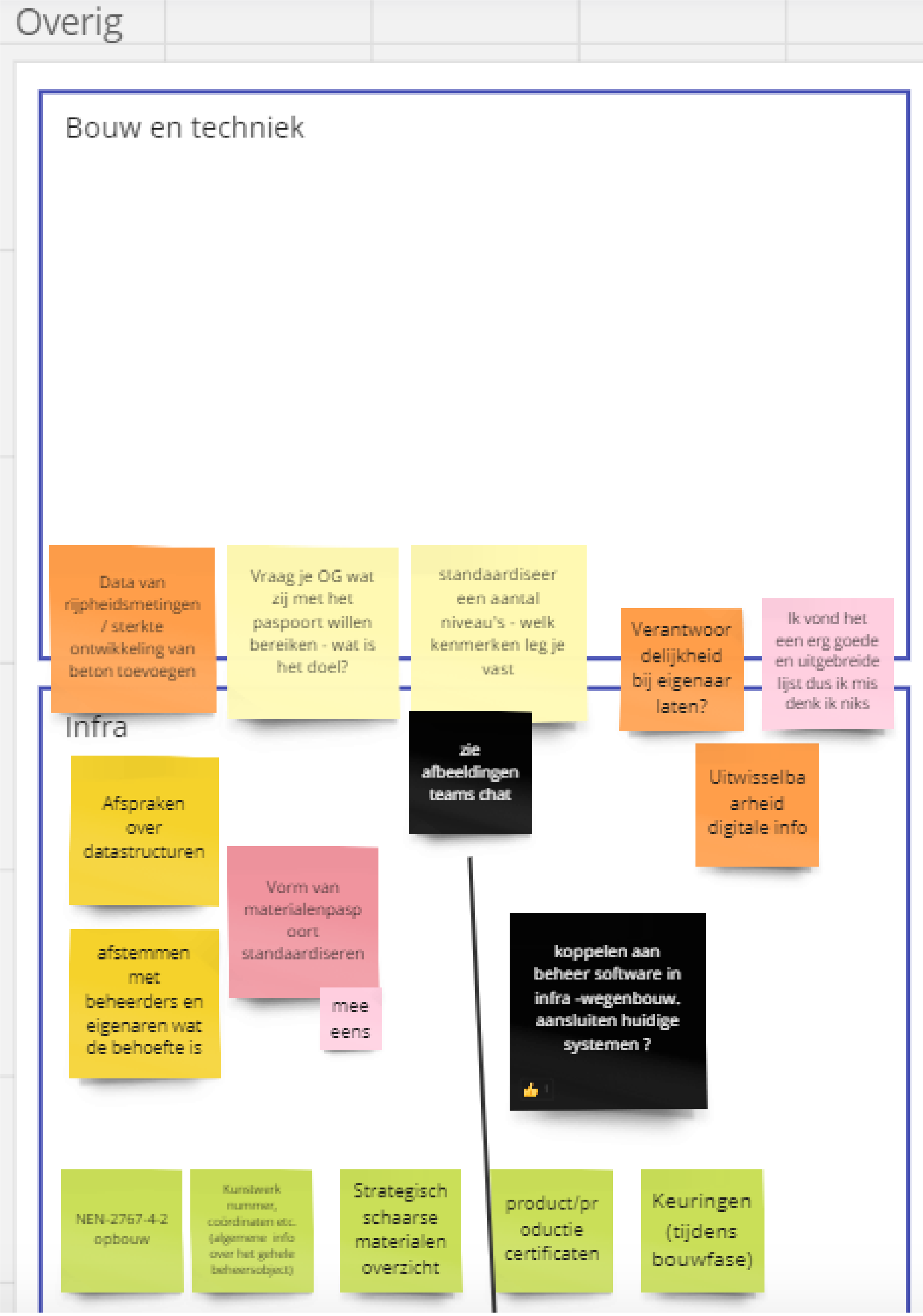


Figure 6c: Miro Results (5)

Figure 7c: Miro Results (6)

APPENDIX D: Analyze the results

Github link: https://github.com/JannekeBosma/DPP/

Table 1d: Results must-haves literature and expert workshop

		Attendees	Results workshop							Sum	Sum/attendees	Attendees	Results housing professionals			Sum	Attendees	ntial Users MP existing housing s			Sum	Result	Used results
	Data catagory	N=x	Strongly disagree 0	Disagree 0,1666	Somewhat disagree 0,3333	Neutral 0,4999	Somewhat agree 0,666	Agree 0,8333	Strongly agree 1			19	No 0	Nice 0,5	Must 1		10	No 0	Nice 0,5	Must 1			
Physical properties/technical	Building total floor area	7	0	1	0	0	1	3	2	5,333	0,762		0	7	12	0,816		0	5	5	0,750	0,775	
	Dimensions	8	0	0	0	1	0	4	3	6,833	0,854		0	1	18	0,974		0	0	10	1,000	0,942	
	Weight	8	0	0	0	0	0	5	3	7,167	0,896		1	9	9	0,711		0	1	9	0,950	0,851	
	Density	7	0	0	0	1	0	3	3	6,000	0,857					0					0,000	0,857	
	Volume	8	0	0	0	1	0	3	4	7,000	0,875		2	8	9	0,684		1	3	6	0,750	0,769	
	Geometry	7	0	0	0	1	0	4	2	5,833	0,833					0					0,000	0,833	
	Quantity	8	0	0	0	0	0	4	4	7,333	0,917		0	0	19	1		0	3	7	0,850	0,921	
	Building physics (energy performance, etc)	7	0	0	1	0	2	3	1	5,165	0,738		2	9	8	0,658		5	2	3	0,400	0,598	
	Resistance & rigidity	8	0	0	1	1	2	3	1	5,665	0,708					0					0,000	0,708	
	Actively beneficial functions (ease of recycling, etc.)	8	0	1	0	0	1	3	3	6,333	0,792					0					0,000	0,792	
	Recycling potential	8	0	1	0	0	1	2	4	6,499	0,812		2	1	16	0,868		0	2	8	0,900	0,859	
	Reusability potential	8	0	1	0	0	1	2	4	6,499	0,812		2	2	15	0,842		0	1	9	0,950	0,867	
	Picture	8	0	0	2	1	2	2	1	5,165	0,646		2	8	9	0,684		0	5	5	0,750	0,693	
	Drawings	8	0	0	2	0	0	4	2	6,000	0,750		0	14	5	0,632		4	6	0	0,300	0,560	
Chemical properties	Material composition	8	0	0	0	1	0	4	3	6,833	0,854		0	4	15	0,895		0	4	6	0,800	0,849	
	Health & safety	7	0	0	0	0	4	2	1	5,331	0,762		3	10	6	0,579		1	7	2	0,550	0,630	
	LCA (environmental)	8	0	0	1	1	1	2	3	6,166	0,771		4	7	8	0,605		1	7	2	0,550	0,641	
	LCC (economic)	7	0	1	2	0	2	2	0	3,832	0,547					0					0,000	0,547	
	SLCA (social)	7	0	0	2	1	2	2	0	4,165	0,595					0					0,000	0,595	
	Material criticality	8	0	0	0	0	3	3	2	6,498	0,812					0					0,000	0,812	
	Lifespan & durability	8	0	0	1	0	0	3	4	6,833	0,854		1	8	10	0,737		1	6	3	0,600	0,730	
	Resistance & stability	6	0	0	0	0	2	4	0	4,665	0,778					0					0,000	0,778	
	Recycled or reused content	8	0	0	1	0	1	2	4	6,666	0,833		1	7	11	0,763		1	7	2	0,550	0,715	
Biological properties	Renewable/non-renewable	7	0	0	0	0	1	0	6	6,666	0,952		0	6	13	0,842		2	5	3	0,550	0,781	
	Untreated/treated	7	0	0	0	0	2	2	3	5,999	0,857		0	6	13	0,842		0	6	4	0,700	0,799	
	Decomposability	7	0	0	0	2	0	3	2	5,500	0,786		2	6	11	0,737		0	6	4	0,700	0,740	
	Recycled & reused input	7	0	0	0	0	1	1	5	6,499	0,928		1	7	11	0,763		1	7	2	0,550	0,746	
	Secondary material	8	0	0	0	0	1	1	6	7,499	0,937					0					0,000	0,937	
Health & safety aspects	Maintenance (e.g. cleaning)	7	0	0	0	2	1	4	0	4,999	0,714					0					0,000	0,714	
	Product certification & labels	8	0	0	0	0	0	7	1	6,833	0,854		1	7	11	0,763		1	6	3	0,600	0,738	
	Building certification	7	0	0	0	1	2	4	0	5,165	0,738					0					0,000	0,738	
	Occupancy wellbeing	8	0	0	0	0	6	2	0	5,663	0,708					0					0,000	0,708	
	Emissions	6	0	1	0	0	2	3	0	3,999	0,666					0					0,000	0,666	
	Material safety data sheet	5	0	1	0	0	3	0	1	3,165	0,633		3	10	6	0,579		1	7	2	0,550	0,587	
	Health assessment	5	0	1	0	0	4	0	0	2,831	0,566					0					0,000	0,566	
	Indoor air quality	4	0	0	0	1	2	1	0	2,665	0,666					0					0,000	0,666	
	Monitoring	4	0	0	0	0	3	1	0	2,831	0,708					0					0,000	0,708	
	Toxicity/hazardous substances	6	0	0	0	0	1	3	2	5,166	0,861				19	1			2	8	0,900	0,919	
	Handling & storage information	6	0	0	0	0	2	1	3	5,165	0,861					0					0,000	0,861	
Unique product identifiers/general information	Building name	8	0	0	0	2	1	1	4	6,499	0,812		3	6	10	0,684		1	4	5	0,700	0,731	
	Building year	8	0	0	0	0	0	2	6	7,667	0,958		0	6	13	0,842		0	2	8	0,900	0,899	
	Building permit year	6	0	1	0	1	2	1	1	3,832	0,639		4	8	7	0,579		2	5	3	0,550	0,589	
	Building location	8	0	0	0	0	1	3	4	7,166	0,896		0	2	17	0,947		0	2	8	0,900	0,913	
	Product/ object no	8	0	0	0	1	1	1	5	6,999	0,875		1	5	13	0,816		0	5	5	0,750	0,813	
	Product name/brand name	8	0	0	0	0	2	2	4	6,999	0,875		0	4	15	0,895		0	4	6	0,800	0,856	
	Manufacturer's name/details	8	0	0	0	0	0	3	5	7,500	0,937		1	11	7	0,658		0	5	5	0,750	0,781	
	Manufacturer's article number	7	0	0	0	0	2	2	3	5,999	0,857					0					0,000	0,857	
	Temporal information (e.g. man. Date)	8	0	0	0	0	1	4	3	6,999	0,875					0					0,000	0,875	
	Product picture	8	0	1	0	0	1	6	0	5,832	0,729		2	8	9	0,684		0	5	5	0,750	0,720	
	Bill of materials	7	1	0	1	2	3	0	0	3,331	0,476					0					0,000	0,476	
	Product declarations	6	0	0	1	0	1	4	0	4,333	0,722					0					0,000	0,722	
	Data source	8	0	1	0	0	1	3	3	6,333	0,792					0					0,000	0,792	
	Origin	8	0	0	0	0	2	3	3	6,832	0,854					0					0,000	0,854	
Production data	Manufacturer documentation	8	0	0	0	0	2	3	3	6,832	0,854		1	7	11	0,763		1	6	3	0,600	0,738	
	Installation & handling instructions	6	0	0	0	0	2	1	3	5,165	0,861		1	7	11	0,763		1	4	3	0,500	0,707	
	Date installed	7	0	0	0	0	2	3	2	5,832	0,833		2	5	12	0,763		1	6	3	0,600	0,731	
	Digitalization (e.g. Bim object, tech drawings, etc)	7	0	0	1	0	1	1	4	5,833	0,833		0	11	8	0,711		3	5	2	0,450	0,664	
Transportation & logistics	Storage requirements	7	1	1	0	1	2	2	0	3,665	0,524					0					0,000	0,524	
	Traceability	7	1	0	0	1	0	2	3	5,167	0,738					0					0,000	0,738	
	Packaging	6	1	0	0	1	4	0	0	3,164	0,527					0					0,000	0,527	
	Handling instructions	7	1	0	0	1	2	3	0	4,332	0,619					0					0,000	0,619	
Use & operate phase	Location in building	8	0	0	0	0	2	3	3	6,832	0,854		0	6	13	0,842		0	3	7	0,850	0,848	
	Cleaning instructions	7	0	1	0	2	2	2	0	4,165	0,595		0	16	3	0,579		4	6	2	0,500	0,557	
	Maintenance instructions	7	0	1	0	2	2	2	0	4,165	0,595		1	13	5	0,605		2	3	5	0,650	0,616	
	Connection details	8	0	0	0	0	1	4	3	6,999	0,875		3	8	8	0,632		1	3	6	0,750	0,751	
	Connection accessibility	6	0	0	0	0	1	4	1	4,999	0,833		3	8	8	0,632		1	4	5	0,700	0,721	
	Warranties (details and dates)	7	0	0	0	1	0	3	3	6,000	0,857					0					0,000	0,857	
	Service life & expected use times	7	0	0	0	0	1	2	4	6,333	0,905		1	8	10	0,737		1	6	3	0,600	0,746	
	Condition assessment (ref year & score)	6	0	0	0	0	3	2	1	4,665	0,777		0	2	17	0,947		0	1	9	0,950	0,891	
	Availability of spare parts	6	0	0	0	0	4	1	1	4,497	0,750		3	11	5	0,553		1	6	3	0,600	0,633	
	Monitoring & consumption (energy, water, etc)	6	0	1	0	0	5	0	0	3,497	0,583					0					0,000	0,583	
	Outside influences (fire, flooding, etc)	5	0	0	0	3	0	2	0	3,166	0,633					0					0,000	0,633	
	Maintenance log	7	0	0	0	0	4	2	1	5,331	0,762		2	9	8	0,658		1	5	4	0,650	0,689	
	Disassembly instructions	6	0	0	0	0	0	3	3	5,500	0,917		0	10	9	0,737		0	5	5	0,750	0,800	
	Assembly instructions	6	0	0	0	1	0	3	2	5,000	0,833		2	9	8	0,658		2	3	5	0,650	0,713	
	Quality	7	0	1	0	1	0	4	1	5,000	0,714					0					0,000	0,714	
Circularity	Circularity	8	0	0	1	0	0	0	7	7,333	0,917					0					0,000	0,917	
End-of-life scenario (recycle, landfill, etc)	Recycling potential	8	0	1	0	0	2	2	3	6,165	0,771		2	1	16	0,868		0	2	8	0,900	0,846	
	Reuse potential	8	0	1	0	0	1	2	4	6,499	0,812		2	2	17	0,947		0	1	9	0,950	0,902	
	Disassembly potential	8	0	1	0	0	0	2	5	6,833	0,854					0					0,000	0,854	
	Disposal options	8	0	1	0	0	1	1	5	6,666	0,833		3	3	13	0,763		1	4	5	0,700	0,765	
	Degregation	4	0	0	0	1	2	1	0	2,665	0,666		2	5	12	0,763		0	3	7	0,850	0,759	
	Future function of the building	6	0	0	0	1	1	2	2	4,833	0,805					0					0,000	0,805	
Ownership & users/actors	Ownership & users/actors	8	0	0	0	0	5	3	0	5,830	0,729		1	6	12	0,789		2	1	7	0,750	0,755	
History	Updates	7	0	0	0	0	0	4	3	6,333	0,905					0					0,000	0,905	
	Time (availability for the next use)	8	0	0	0	1	0	4	3	6,833	0,854		1	5	13	0,816			4	6	0,800	0,822	
Residual economic value	Residual economic value	8	1	2	0	1	3	1	0	3,664	0,458		3	7	9	0,658			4	6	0,800	0,638	
Tax benefits	Tax benefits	5	3	1	0	0	0	1	0	1,000	0,200					0					0,000	0,200	

Table 2d: Results passport level literature and expert workshop

Level	workshop		Literature		Result
Area	1		0		1
Complex	0		5		5
Building	6		19		25
Element	7		25		32
Product	7		31		38
Material	6		22		28

APPENDIX E: Comparison of existing Material and Product passports

Github link: https://github.com/JannekeBosma/DPP/

Table 1e: Comparison of existing Material and Product Passports

	BAMB, 2019	Atta et al., 2021	Göswein et al., 2022	Heisel & Rau-Oberhuber, 2020	Honic et al., 2019	Honic et al., 2021a	Honic et al., 2021b	Kedir et al., 2021	Kovacic & Honic, 2021	Mulhall et al., 2022	Munaro et al., 2021	Munaro et al., 2018	Plociennik et al., 2022	Schaubroeck et al., 2022	Smeets et al., 2019	Soman et al., 2022	Zhang et al., 2021	C2C Material Passport	DGNB, 2022	EPEA, 2022	Madaster, 2022	Orms Architects, 2021	Upcyclea, 2022	Associação Smart Waste Portugal, 2021	Communication concert, 2021	Jonge Honden, 2019	Platform CB'23, 2022	Platform CB'23 (building level, use phase & maintena	Platform CB'23 (building level, use phase, end-use p	Platform CB'23 (product level, use phase & maintena	Platform CB'23 (product level, use phase, end-use p	Standard' MP Company	Project MP
Total Must have	9	3	8	5	3	4	2	0	3	3	7	8	6	4	4	2	8	7	9	4	10	3	1	8	5	10	0	2	6	7	9	24*	9*
Total general	45	6	19	10	9	7	8	2	7	4	28	18	14	10	8	4	13	20	20	11	20	8	5	19	10	25	0	7	21	21	24		

	BAMB, 2019	DGNB, 2022	EPEA, 2022	Madaster, 2022	Jonge Honden, 2019	Platform CB'23 (product level, use phase, end-use p	Standard' MP Company	Project MP
Legal obligations				Complies with regulations and building certification programs. (BREEAM, Taxonomy, CSRD, DGNB, etc)				
Functional suitability	material passport for buildings, instances and products			It is mentioned to be usefull for built environment and infrastructure (different kind of parties). It can be used by exporting 3D CAD applications, but also by using an excel template. However, for the infra sector it might be not applicable since Madaster cannot match the specifications (bestek).	In the document they mosly refer to buildings. However, it is stated to adjust the MP to the sector it is made for. There is no format, but information about what needs to be in the MP can be found in the PDF.	The format can be used in the built environment and in civiel projects. A shortlist can be generated for the kind of project you need and otherwise a long list is available to select the needed topics from/generate a more excessive list.	Material passport specifically made for an infrastructure project. However, the format can be adjusted for other projects	Material passport specifically made for the Tennet project. Therefore, it fits the wishes of the client but is more difficult to adjust for other projects
Security, confidentiality, and IP protection	A validation of the data can be performed by third parties. Furthermore, the data is stored on the account of the user. The information stored for the materials passport should be accessible by those parties capable of connecting it to an action. Therefore, information stored which cannot be accessed due to secrecy is not beneficial for this.			Information is checked on completeness by madasters program itself. No information found about data safety, etc. However information cannot be entered without the user sharing the information or log into the system. The data can be generated from a database filled with information from manufacturers.	?	No security, confidentially, and IP protection is provided. A excel format can be downloaded and the user can protect is according to its own company standards	No security, confidentially, and IP protection is provided. A excel format can be downloaded and the user can protect is according to its own company standards	No security, confidentially, and IP protection is provided. A excel format can be downloaded and the user can protect is according to its own company standards
Accessibility	Account based and accessible through the internet			It is account based and manuals are written to ensure a standard level. It is accessible by the internet. The passports can be downloaded and previous passports remain accessible. Users can be assigned different roles and different rights. However, it is cloud based. Madaster is easy in use for a BIM modeler, but for someone without experience it might be more difficult.	PDF can be found online	The format can be found online. It is given in excel. The user can save and share the format according to own company standards. Understandable format is provided and can be used without the use of internet (not shared)	The format can be found online. It is given in excel. The user can save and share the format according to own company standards. The format requires some time to understand because of the big amount of information that can be entered. Format can be used without internet connection	The format can be found online. It is given in excel. The user can save and share the format according to own company standards. Understandable format is provided. Format can be used without internet connection (not shared)
Interoperability	Cloud based. An account is needed.			Platform, account needed. The structure can be determined by the user. Different rights and roles. Other companies can be invited to work in the template as well. Enable use of semantics unclear (it is mentioned the program recognizes dutch and internation data structures).	? - need to communicate it yourself	The passport is provided in excel and this can be tranformed to a csv file. This is an open standard. There is no shared semantics. However, it is a 'standardized data scheme' but there still can be a difference in the way the user provides input. CB'23 recommends rdf and linked data usage. CB'23 provides more information behind the format to create better understanding to fill in the form	The passport is provided in excel and this can be tranformed to a csv file. This is an open standard. There is no shared semantics. However, it is a 'standardized data scheme' but there still can be a difference in the way the user provides input.	The passport is provided in excel and this can be tranformed to a csv file. This is an open standard. There is no shared semantics. However, it is a 'standardized data scheme' but there still can be a difference in the way the user provides input.
Modularity and modifiability	Not possible to make adaptions to criteria over time. Later this is revised with the use of workbook 2.0. It is mentioned that the redevelopment encompassed structural modifications (e.g. data sets, changes to criteria, description, and related meta data).			Add own materials/products with belonging info and information can be adjusted within a certain template. However, there are a wide range of possibilities.	In PDF so can make adjustments yourself	The template is provided in excel and can be adjusted where needed. Flexibility is given in the format. The format is fully costumizable. This is not necesarry the intention, however there is no control mechanism which hold the user from making changes.	The template is provided in excel and can be adjusted where needed. Flexibility is given in the format. The format is fully costumizable. This is not necesarry the intention, however there is no control mechanism which hold the user from making changes.	The template is provided in excel and can be adjusted where needed. Flexibility is given in the format. The format is fully costumizable. This is not necesarry the intention, however there is no control mechanism which hold the user from making changes.
Availabity and time behavior	Connected to database with materials. It can be marked as 'old.' I assume this is meant to notify the makers to update the material			Connected to databases ensuring 'up to date' information. The information is available when needed by logging in the system. When information from the databases is changed a manual update needs to be performed. It is automated, but needs manual control.	?	The document can only be available whenever the user needs it when this is saved in an environment by the user. The data needs to be updated by the user	The document can only be available whenever the user needs it when this is saved in an environment by the user. The data needs to be updated by the user	The document can only be available whenever the user needs it when this is saved in an environment by the user. The data needs to be updated by the user
Portability	The tool is cloud based and a connection van be made between two systems. It is connected to the SundaHus Material Data system.			Connect to IFC, excel and databases. Product identifiers can be connected by the use of the database (track and trace possible). Madaster is available for usage in Europe. An EAN code can be added so it can be identified in Europe.	They mention it will be good to connect the MP to the digital market space.	Format in excel. They want to use linked data/RDF however the format does not show this (yet). The format can be found online and therefore it can be refered to	Cannot be connected to portable product identifiers (or needs to be done manually). Format is excel within company. Cannot be refered to from outside the company. Not transferable between software systems	Cannot be connected to portable product identifiers (or needs to be done manually). Format is excel within company. Cannot be refered to from outside the company. Not transferable between software systems
Non-redundancy	The software will facilitate thte appropriate acccessibility of information for different stakeholders at specific stages in the process. The necessary information about materials, products and components for a circular use are provided			The material passport contains a lot of information and topics to be filled in. Not all topics need to be filled in for each project. And the information is available based on the area defined. Furthermore, information from the manufacturer is provided by the use of a database. An excel or IFC can be uploaded to create the material passport.		They mention it will be good to keep as much information at the source as possible. Furthermore, the format is adjusted when selecting for what goal it will be used (on beforehand). This way unnecessary information is elimanted as much as possible	The material passport contains a lot of information and topics to be filled in. Not all topics need to be filled in for each project. Furthermore, information from the manufacturer is provided. This kind of information can also be shown via a connection to keep the format 'cleaner' (E.g.).	In this format minimum information needs to be filled in. Only the requested information of the client is shown. Therefore, this format contains too little rather than too much information
Level of reporting	Product/material			Area, complex, building, product	Building, element, product, material			
Applicable	it is mentioned that the prototype of the passport is currently live and can be accessed online. However, this is not the case. Furthermore, the provided email address to contact about the platform is not available (anymore) either. The information is given in english	The format, given in excel, is provided for free. However, it is all written in German. Therefore, it is excluded in reviewing the topics		English (however, there might be small differences between the one available in the netherlands and outside). It is currently in use by companies. Paywall	It is written in Dutch. Can be found online. However, it is no format. The information stated can be put in an own format	English, it is in excel. The user can alter and add topics. The format is free to use.	The passport is not free available and written in dutch. It is made in excel and can be adjusted easily. However, it is no 'standard' format which can make it more difficult to use for other projects	The passport is provided in excel in English. Topics can be added or altered. However, it is not free accessible. It is no standard format which can make it more difficult to use for other projects
Notes	BAMB MP prototype. The attemps to enter the platform failed (link and email address not available anymore). Therefore this item is graded based on the information available on the website and in provided pdf documents. It is not taken into account for the final comparison	Not assesed because it is only provided in German	Not assesed (problems with making an account		It is a research not a 'format' (yet). Therefore not taken into account.		MP made for specific project	MP made for specific project

APPENDIX F: Breakdown grading per requirements

Github link: https://github.com/JannekeBosma/DPP/

Table 1f: Breakdown structure grading per requirement

Functional suitability	No allignment sector-specific needs and it impedes existing chain processes, product quality, or safety. Or no information given	0
	Semi allignment sector-specific needs and it slightly impedes existing chain processes, product quality, or safety	3
	Allignment sector-specific needs and it does not impedes existing chain processes, product quality, or safety	5
Security, confidentiality, and IP protection	The data cannot guarantee origin, integrity, verifiable, and compliance and the data control does not remain with the data providers. Data is adaptable and there is no secure data exchange	0
	One or multiple statements of the following topics are met: The data can guarantee origin, integrity, verifiable, and compliance and the data control does remain with the data providers. The data is immutable and there is secure data exchange	3
	The data can guarantee origin, integrity, verifiable, and compliance and the data control does remain with the data providers. The data is immutable and there is secure data exchange	5
Accessibility	No access for assigned parties through an access control mechanism, no participation opportunities for parties without stable internet connection/advanced IT systems, no permant access whole life cycle data and difficult to understand	0
	One or multiple statements of the following topics are met: Access for assigned parties through an access control mechanism, participation opportunities for parties without stable internet connection or advanced IT systems, permant access whole life cycle data and easily understandable	3
	Access for assigned parties through an access control mechanism, participation opportunities for parties without stable internet connection or advanced IT systems, permant access whole life cycle data and easily understandable	5
Interoperability	Not exchangeable across different company boundaries. Does not enables the use of shared semantics and standardized data schemes	0
	One or multiple statements of the following topics are met: Must be exchangeable across different company boundaries. Enables the use of shared semantics and standardized data schemes	3
	Must be exchangeable across different company boundaries. Enables the use of shared semantics and standardized data schemes	5
Modularity and Modifiability	No additions, modifications and adaptions can be made. No flexibility is offered	0
	One or multiple statements of the following topics are met: flexibility, making additions, modifications and/or adaptions	3
	It offers flexibility. Users can make additions and modifications. Adaptations can be made as requirements evolve.	5
Availability and time behavior	Information is nog accessible when needed and no changes can be made. No parts are real time capable and data cannot be valid and up to date	0
	One or mulitple statements are met: accessible information, changes can be made, real time capable, up to date and/or valid data	3
	Information accessible when needed, changeable requirements for real time data in various cases. Certain parts real time capable. Data needs to be valid and up to date	5
Portability	There is no possibility to tranfer between software systems to enable decentralized systems. No portable product identifiers can be used. It is not harmonizable and referenceable across the EU	0
	One or mulitple statements are met: Transferable between software systems to enable decentralized systems. Portable product identifiers are needed to track a products' life cycle. And/or it is harmonizable and referenceable across the EU	3
	Transferable between software systems to enable decentralized systems. Portable product identifiers are needed to track a products' life cycle. Harmonizable and referenceable across the EU	5
Non-redundancy	The full passport consists excessive information	0
	The passport consists excessive information on certain topics	3
	The passport should not contain excessive information	5
Applicability*	The passport format is not free accessible, scalable, is currently not in use, and not available in english.	0
	one or multiple statements of the following topics is met: The passport format is free accessible, scalable, is currently in use, and available in english.	3
	The passport format is free accessible, scalable, is currently in use, and available in english.	5
*The completeness of the passport format is tested seperatly from the overarching requirement applicability		

APPENDIX G: UML class diagram

Figure 1g: UML class diagram

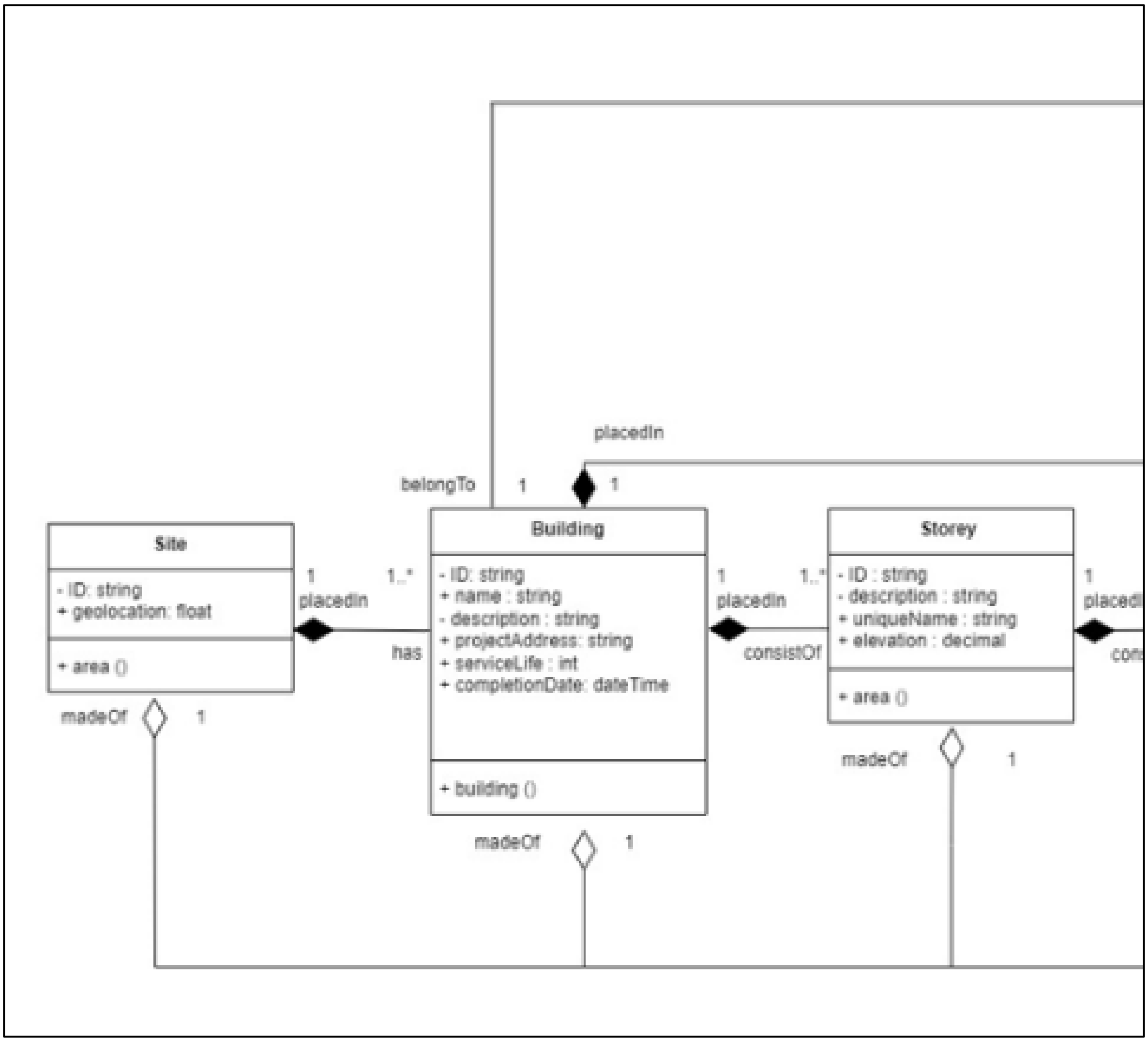


Figure 2g: Zoomed in part 1

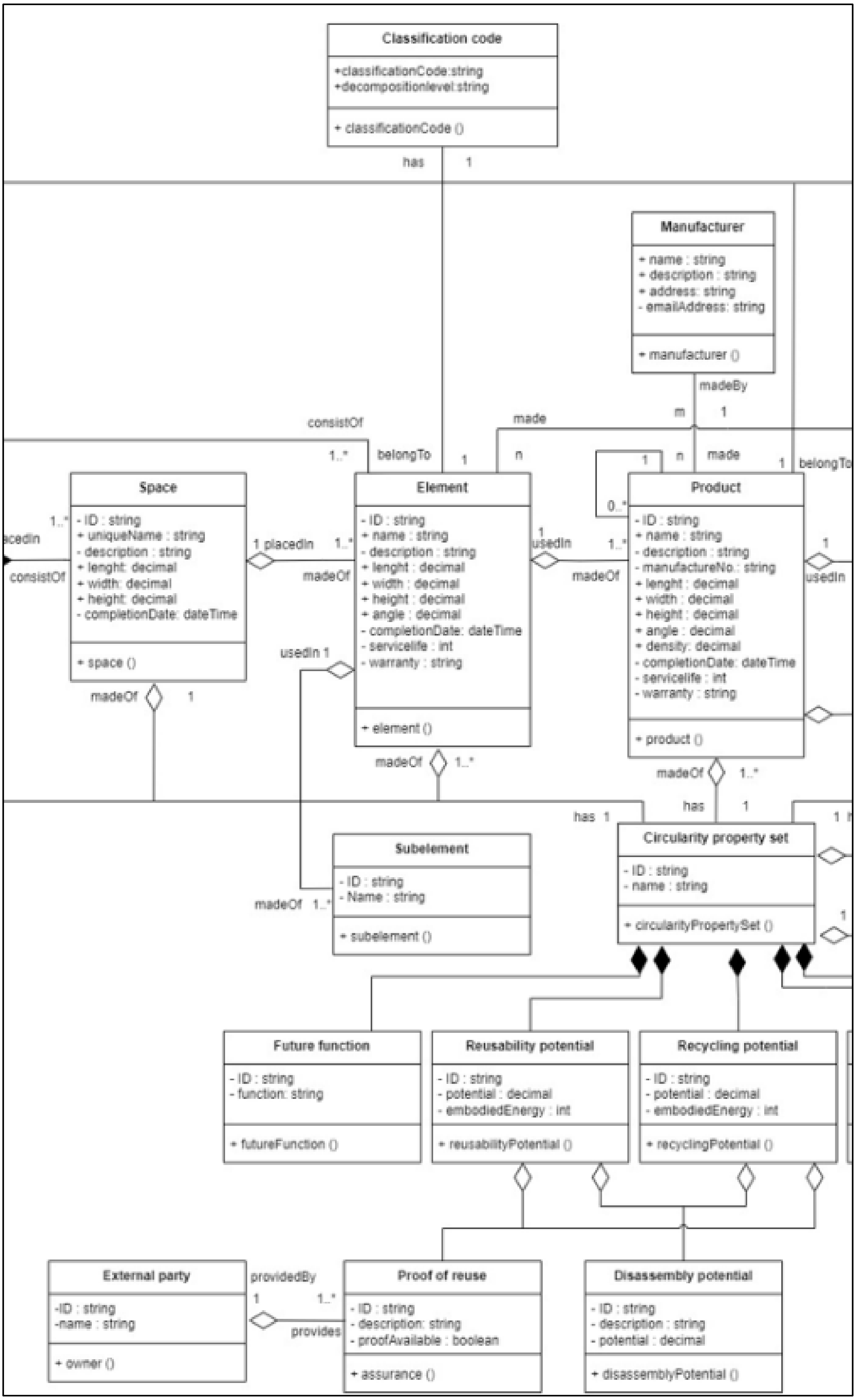


Figure 3g: Zoomed in part 2

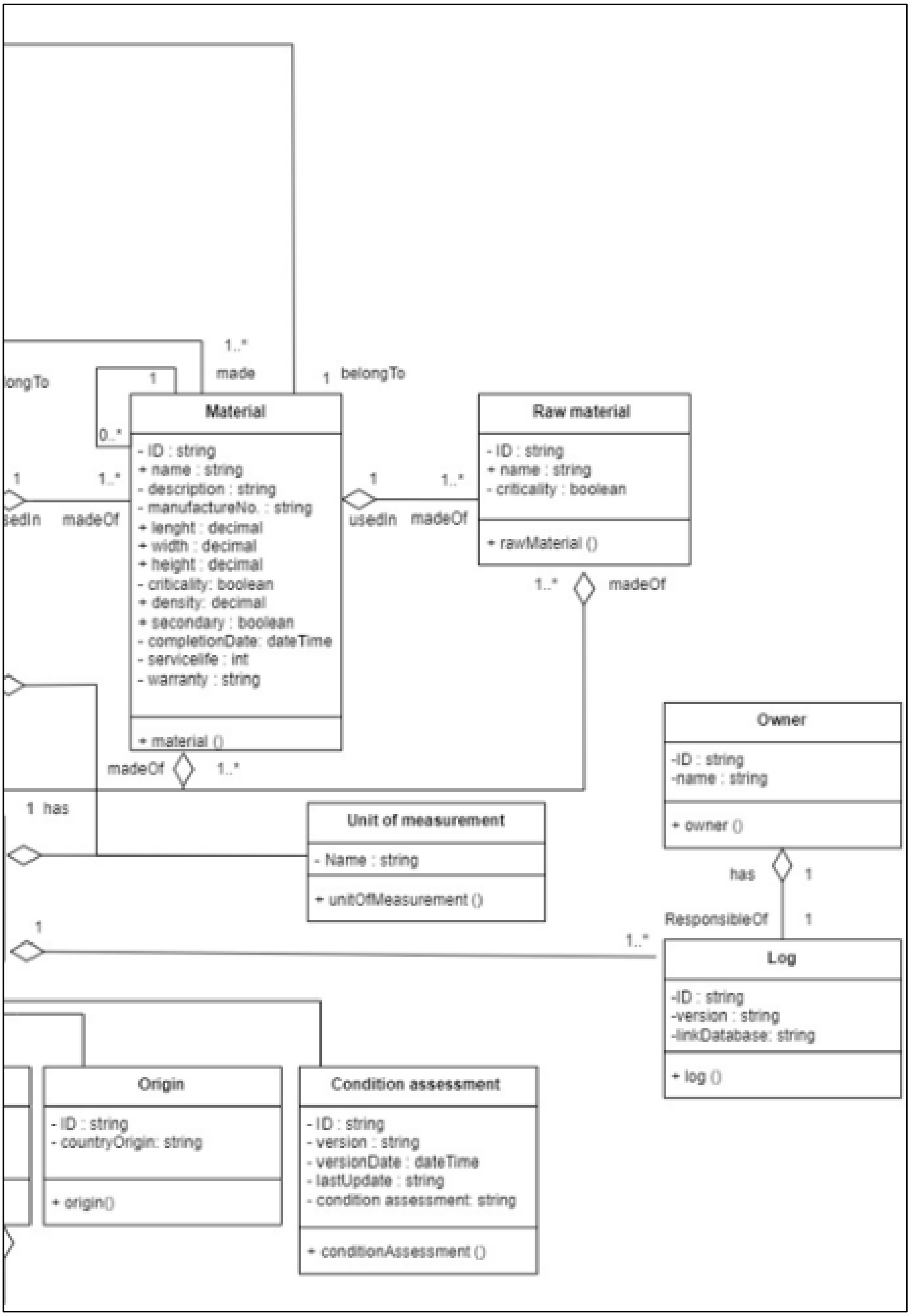


Figure 4g: Zoomed in part 3

APPENDIX H: TBOX DPP Ontology

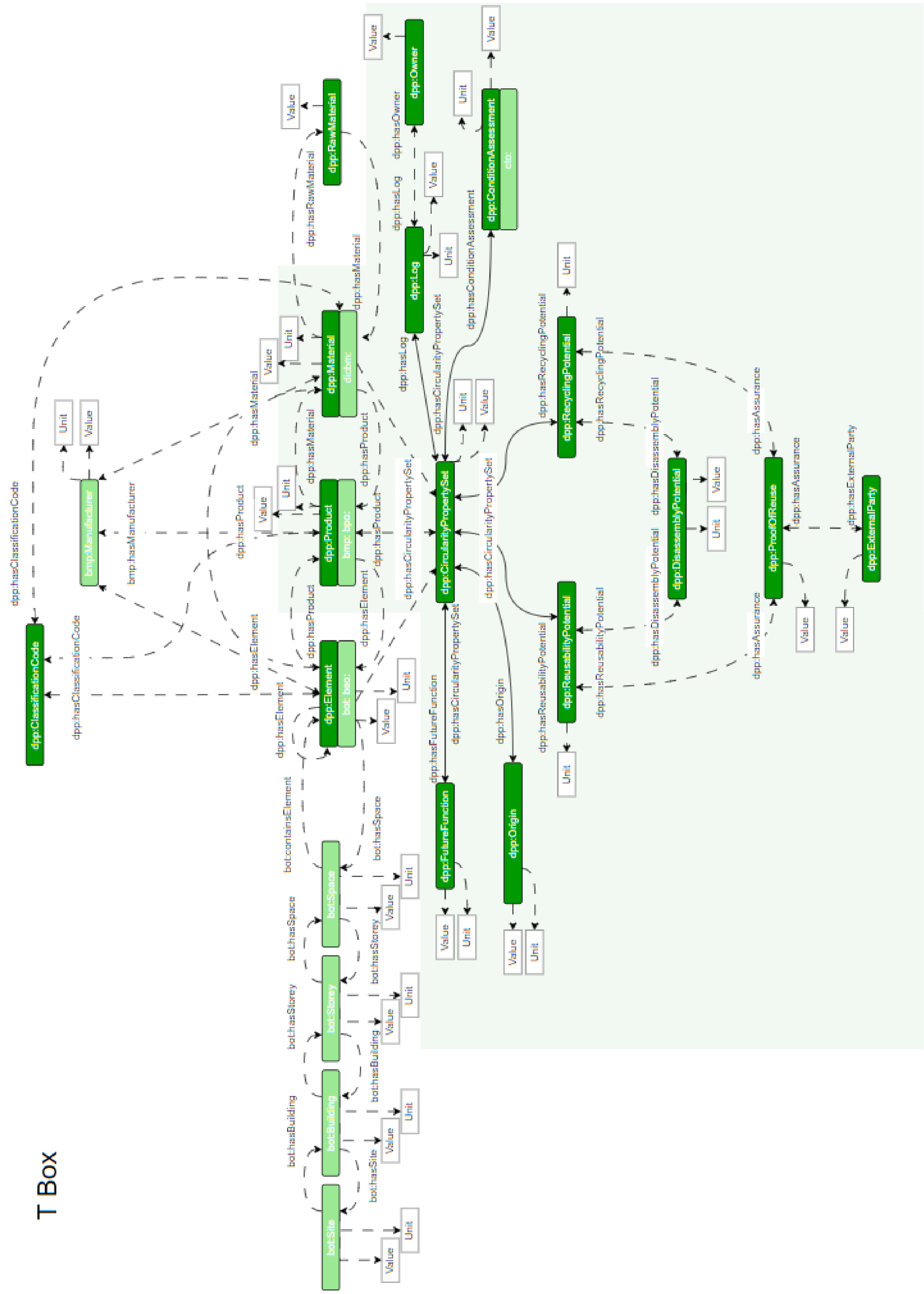


Figure 1h: TBox DPP Ontology

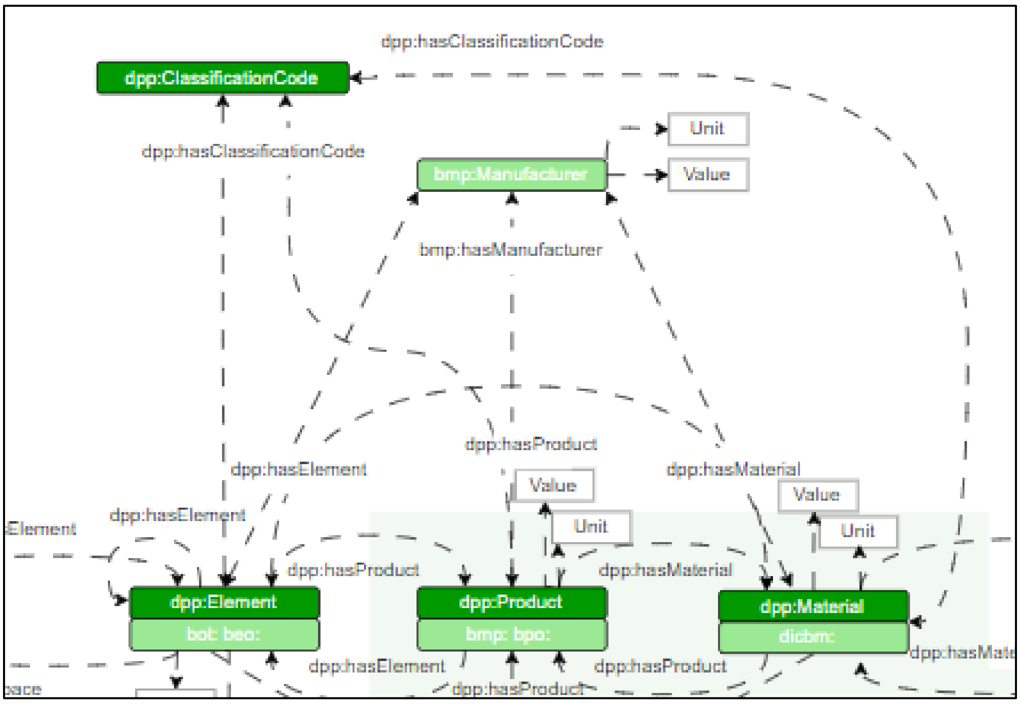


Figure 2h: Zoomed in part 1

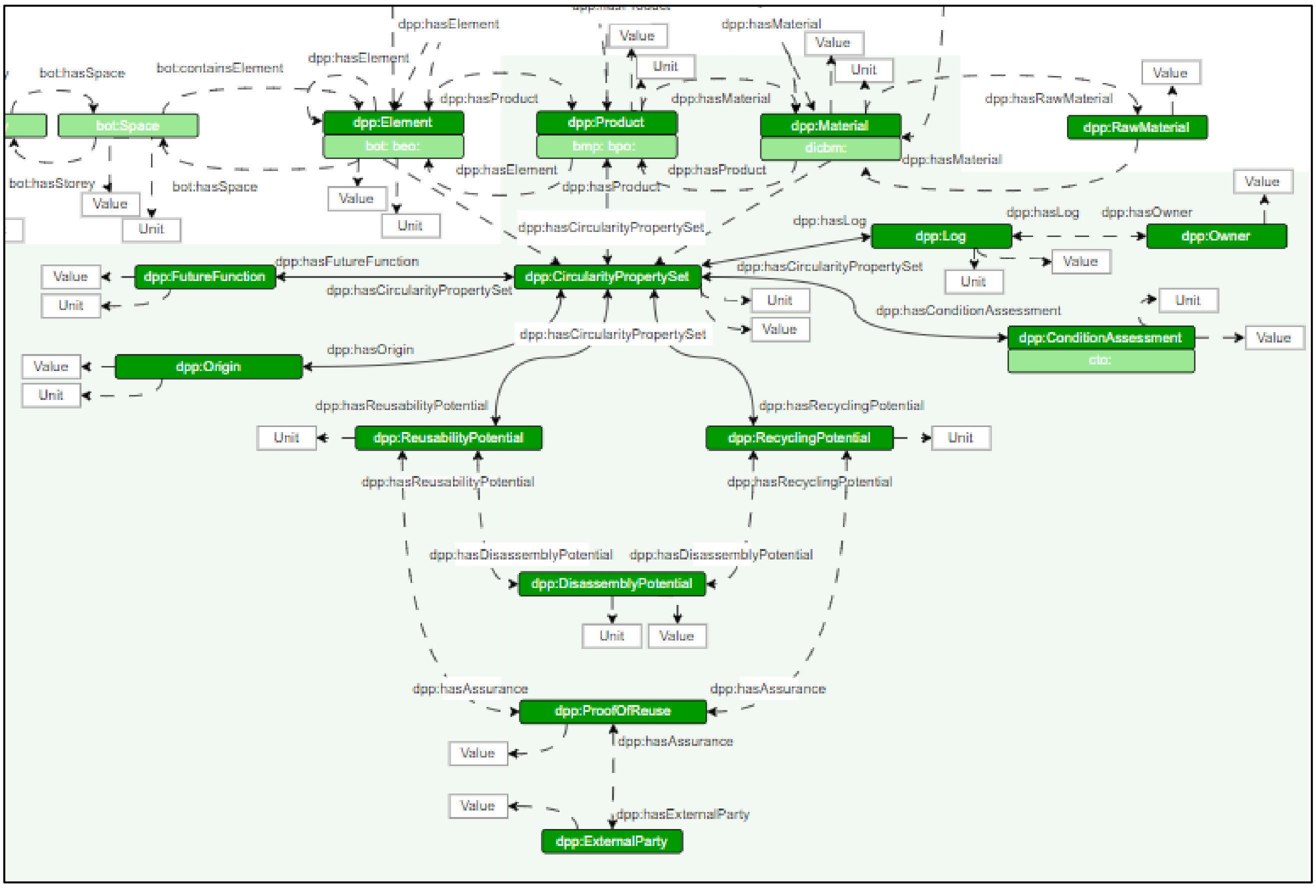


Figure 3h: Zoomed in part 2

APPENDIX I: ABox DPP Ontology

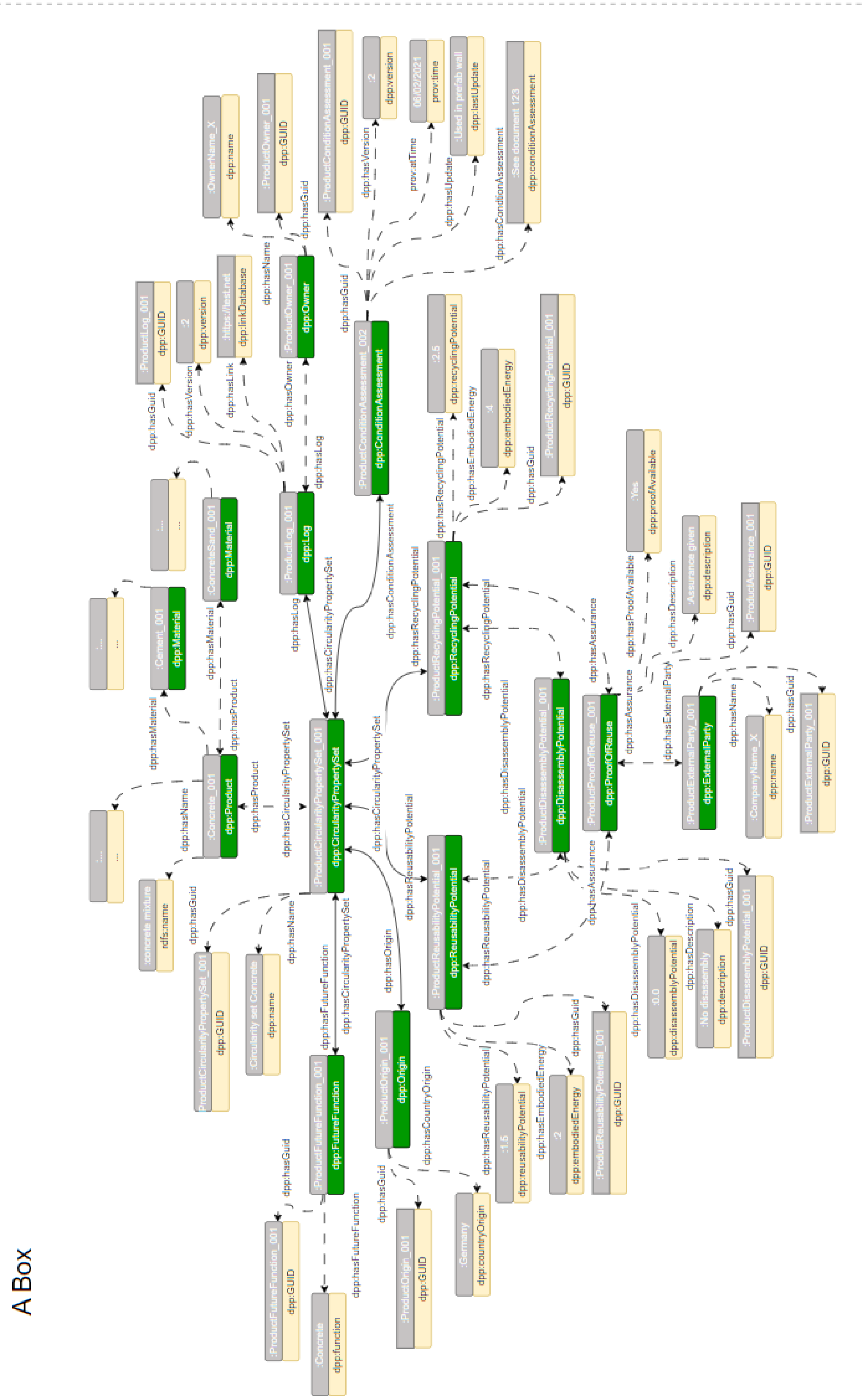


Figure 1i: ABox DPP Ontology

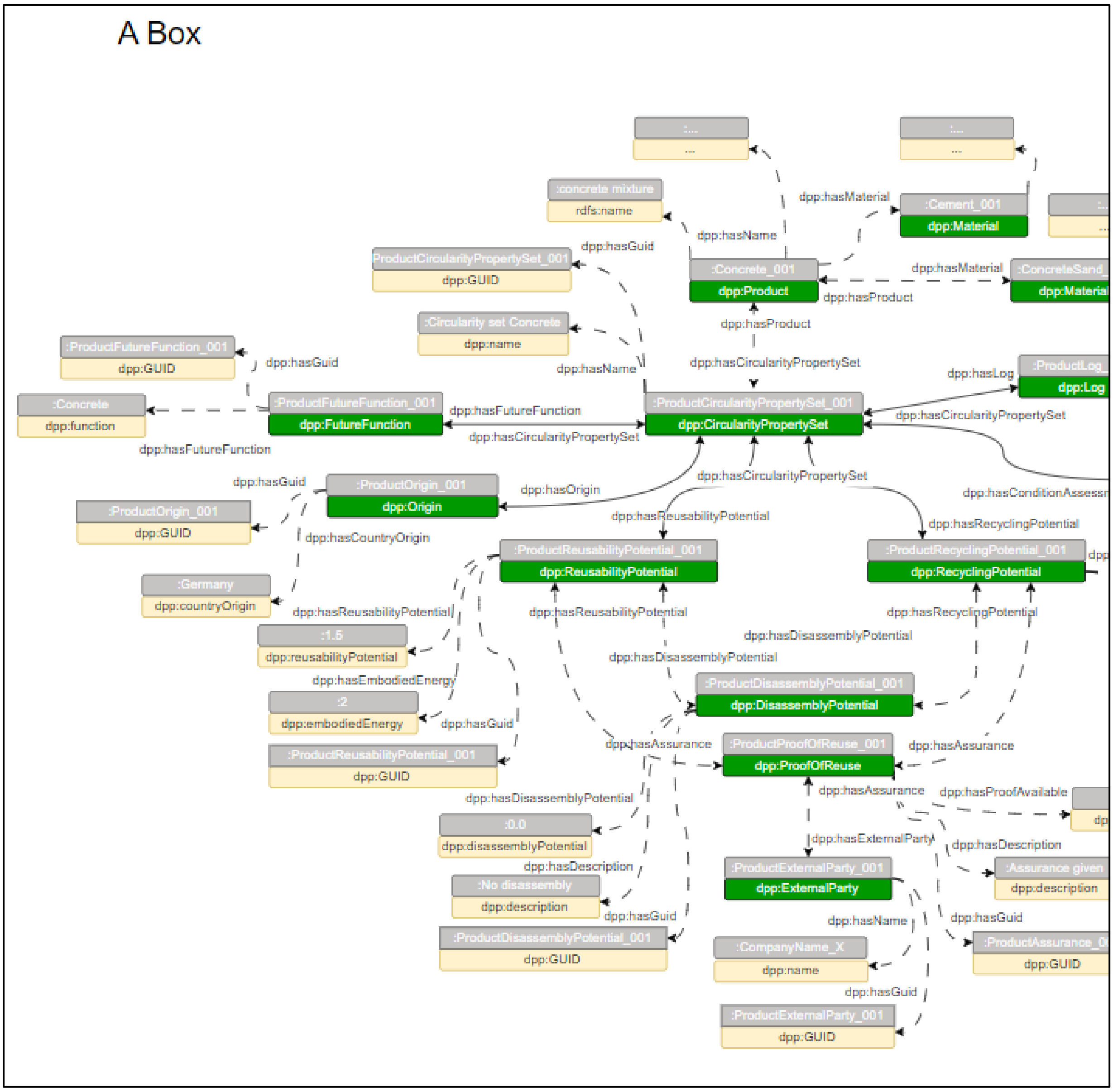


Figure 1i: Zoomed in part 1

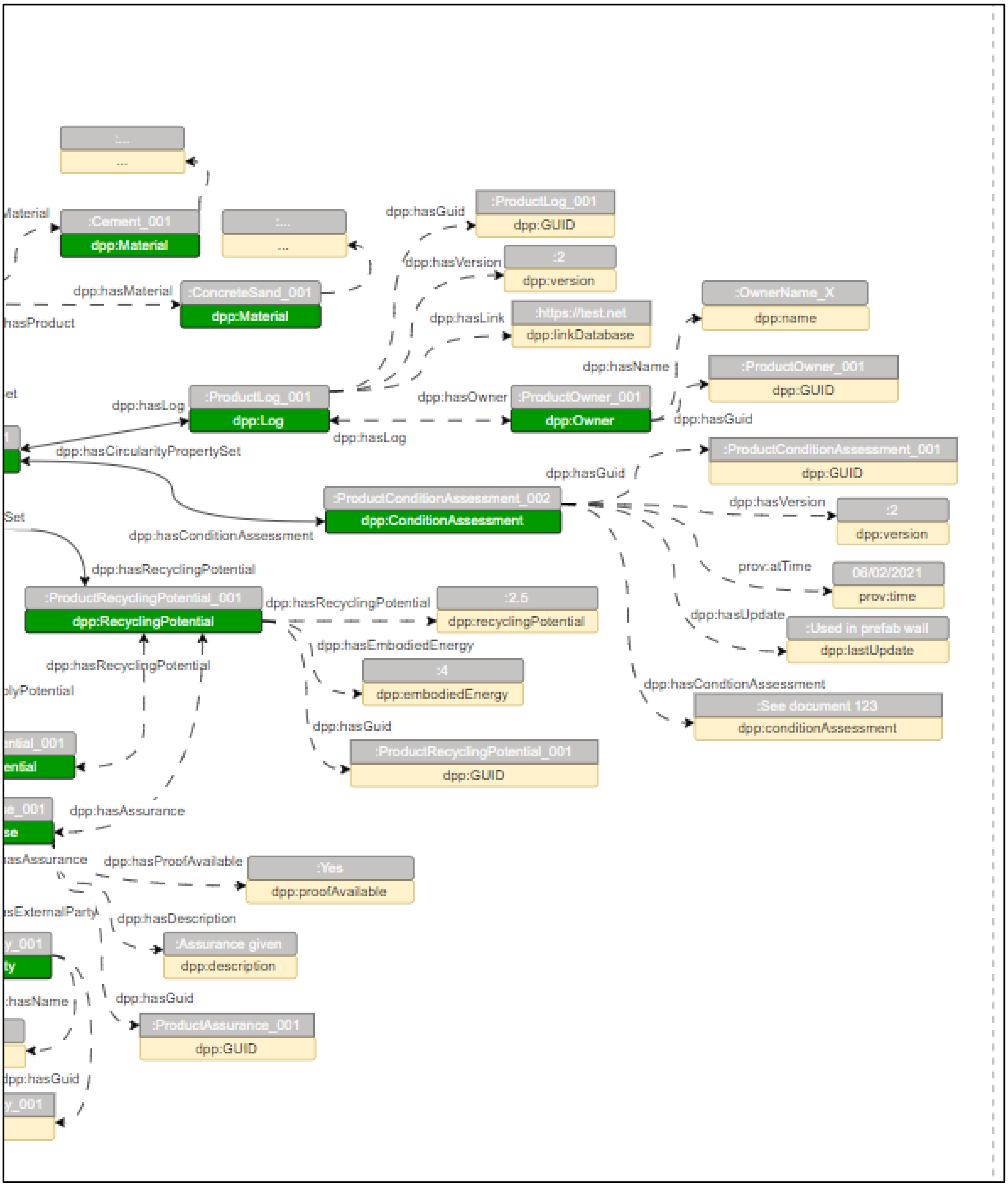


Figure 1i: Zoomed in part 2

APPENDIX J: DPP ontology in Protégé

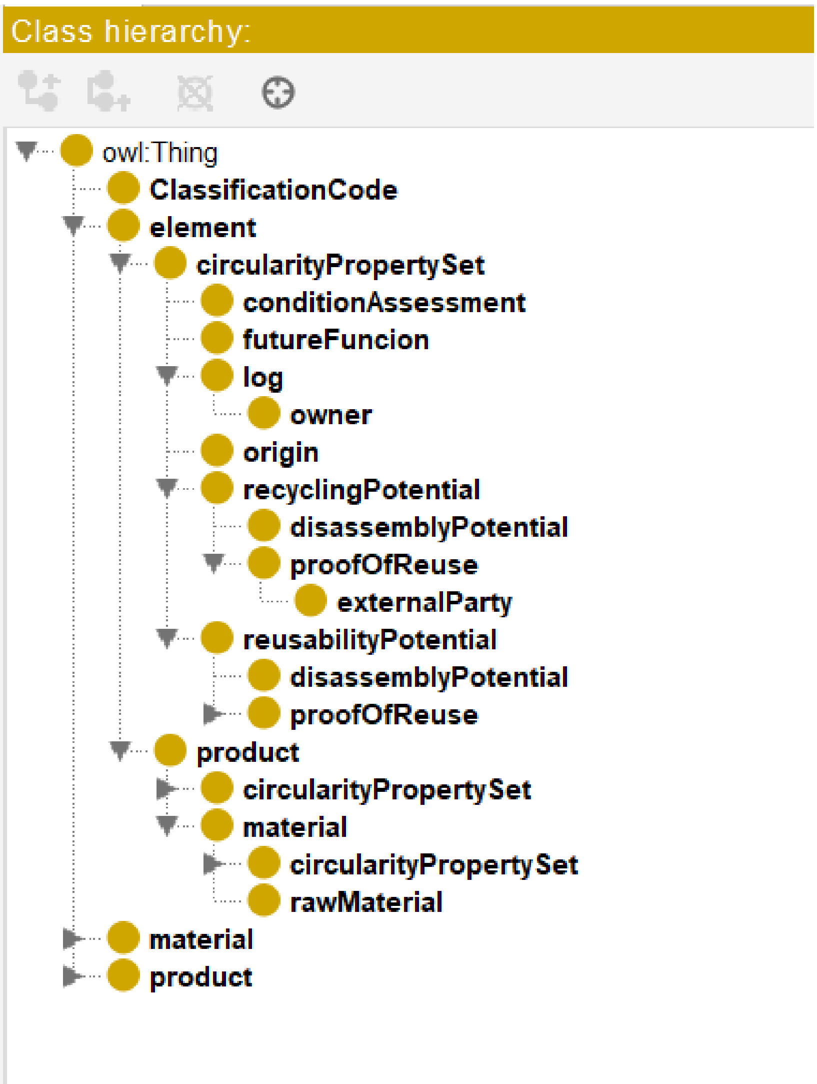


Figure 1j: DPP Ontology Class hierarchy Protégé

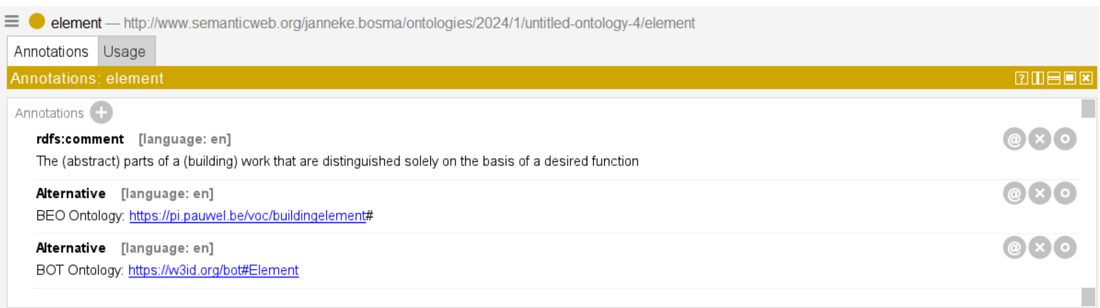


Figure 2j: DPP Ontology Alternatives Protégé

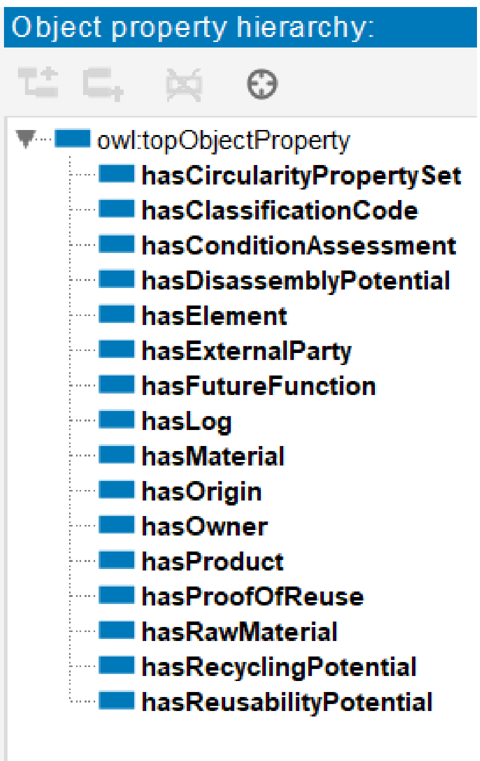


Figure 3j: DPP Ontology Object property hierarchy Protégé

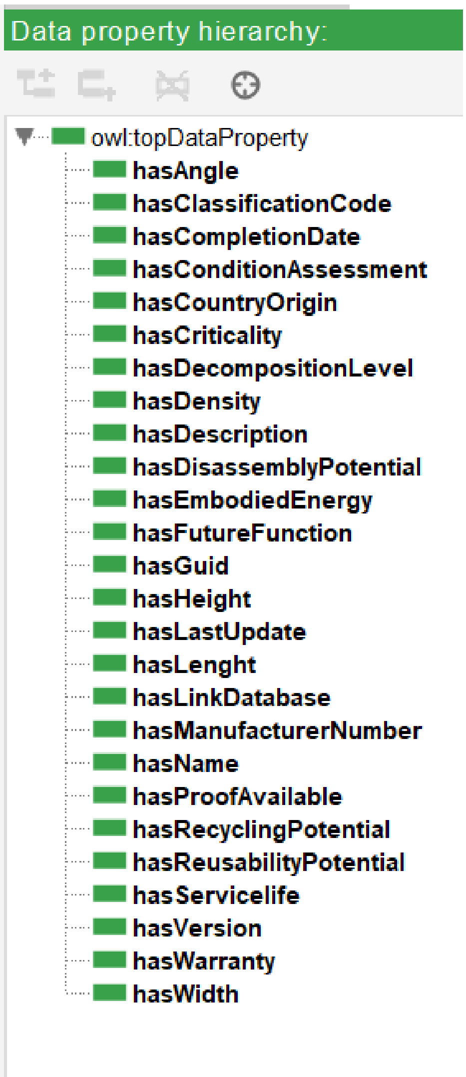


Figure 4j: DPP Ontology Data property hierarchy Protégé

APPENDIX K: Prefixes

@prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .

@prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#> .

@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .

@prefix bot: <https://w3id.org/bot#> .

@prefix beo: <https://pi.pauwel.be/voc/buildingelement#> .

@prefix mep: <https://pi.pauwel.be/voc/distributionelement#> .

@prefix geom: <https://w3id.org/geom#> .

@prefix props: <https://w3id.org/props#> .

@prefix dpp: <https://jannekebosma.com/dpp#> .

@prefix prov: <http://www.w3.org/ns/prov#> .

@prefix bcao: <https://github.com/linmor-sys/BCAO.owl#> .

@prefix bpo: <https://w3id.org/bpo#> .

@prefix bmp: <https://w3id.org/bmp#> .

@prefix dash: <http://datashapes.org/dash#> .

@prefix schema: <http://schema.org/> .

@prefix sh: <http://www.w3.org/ns/shacl#> .

@prefix locn: <http://www.w3.org/ns/locn#> .

@prefix qudt: <http://qudt.org/schema/qudt/> .

@prefix quantitykind: <http://qudt.org/vocab/quantitykind/> .

@prefix unit: <http://qudt.org/vocab/unit/> .

APPENDIX L: SHACL script

Github link: https://github.com/JannekeBosma/DPP/

```
@prefix inst: <http://linkedbuildingdata.net/ifc/resources20240411_123900/> .
@prefix rdf:  <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .
@prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#>.
@prefix xsd:  <http://www.w3.org/2001/XMLSchema#> .
@prefix bot:  <https://w3id.org/bot#> .
@prefix beo:  <https://pi.pauwel.be/voc/buildingelement#> .
@prefix mep:  <https://pi.pauwel.be/voc/distributionelement#> .
@prefix props: <https://w3id.org/props#> .
@prefix dpp: <https://jannekebosma.com/dpp#> .
@prefix prov: <http://www.w3.org/ns/prov#> .
@prefix bcao: <https://github.com/linmor-sys/BCAO.owl#> .
@prefix bpo: <https://w3id.org/bpo#> .
@prefix bmp: <https://placeholder> .
@prefix dash: <http://datashapes.org/dash#> .
@prefix schema: <http://schema.org/> .
@prefix sh: <http://www.w3.org/ns/shacl#> .
@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .
@prefix locn: <http://www.w3.org/ns/locn#> .
@prefix qudt: <http://qudt.org/schema/qudt/> .
@prefix quantitykind: <http://qudt.org/vocab/quantitykind/> .
@prefix unit: <http://qudt.org/vocab/unit/> .

#material
info.............................................................................
.................................................................................
........
dpp:MaterialShape_info
    a sh:NodeShape ;
    sh:targetClass dpp:material ;
    sh:property [
        sh:path dpp:hasGuid ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] ;
    sh:property [
        sh:path props:hasCompressedGuid ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] ;
    sh:property [
```

```
        sh:path dpp:hasManufacturerNumber ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] ;
    sh:property [
        sh:path rdfs:hasName ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] ;
    sh:property [
        sh:path rdfs:hasDescription ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] ;
    sh:property [
        sh:path dpp:hasLength ;
        sh:node [
            a sh:NodeShape ;
            sh:property [
                sh:path qudt:quantityValue ;
                sh:datatype xsd:decimal ;
                sh:minCount 1 ;
                sh:maxCount 1 ;
            ] ;
            sh:property [
                sh:path qudt:applicableUnit ;
                sh:node [
                    sh:in (unit:MilliM) ;
                ] ;
                sh:minCount 1 ;
                sh:maxCount 1 ;
            ] ;
        ] ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
    ] ;


    sh:property [
        sh:path dpp:hasWidth ;
        sh:node [
            a sh:NodeShape ;
            sh:property [
```

```
            sh:path qudt:quantityValue ;
            sh:datatype xsd:decimal ;
            sh:minCount 1 ;
            sh:maxCount 1 ;
        ] ;
        sh:property [
            sh:path qudt:applicableUnit ;
            sh:node [
                sh:in (unit:MilliM) ;
            ] ;
            sh:minCount 1 ;
            sh:maxCount 1 ;
        ] ;
    ] ;
    sh:minCount 1 ;
    sh:maxCount 1 ;
] ;

sh:property [
    sh:path dpp:hasHeight ;
    sh:node [
        a sh:NodeShape ;
        sh:property [
            sh:path qudt:quantityValue ;
            sh:datatype xsd:decimal ;
            sh:minCount 1 ;
            sh:maxCount 1 ;
        ] ;
        sh:property [
            sh:path qudt:applicableUnit ;
            sh:node [
                sh:in (unit:MilliM) ;
            ] ;
            sh:minCount 1 ;
            sh:maxCount 1 ;
        ] ;
    ] ;
    sh:minCount 1 ;
    sh:maxCount 1 ;
] ;

sh:property [
    sh:path dpp:hasCriticality ;
    sh:datatype xsd:boolean ;
    sh:in ( true false ) ;
    sh:minCount 1 ;
    sh:maxCount 1 ;
    sh:minLength 1 ;
] ;
```

```
    sh:property [
        sh:path dpp:hasSecondary ;
        sh:datatype xsd:boolean ;
        sh:in ( true false) ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] ;
    sh:property [
        sh:path rdfs:hasDensity ;
        sh:datatype xsd:decimal ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] ;
    sh:property [
        sh:path dpp:hasWarranty ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] ;
    sh:property [
        sh:path prov:hasCompletionDate ;
        sh:datatype xsd:dateTime ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:pattern "^[0-9]{4}-[0-9]{2}-[0-9]{2}T[0-9]{2}:[0-9]{2}:[0-9]{2}$" ;

    ] ;
    sh:property [
        sh:path dpp:hasServicelife ;
        sh:datatype xsd:integer ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] .


#....Product
level..................................................................

dpp:ProductShape_info
    a sh:NodeShape ;
    sh:targetClass dpp:product ;
    sh:property [
        sh:path dpp:hasGuid ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
```

```
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] ;
    sh:property [
        sh:path props:hasCompressedGuid ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] ;
    sh:property [
        sh:path dpp:hasManufacturerNumber ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] ;
    sh:property [
        sh:path rdfs:hasName ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] ;
    sh:property [
        sh:path rdfs:hasDescription ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] ;
    sh:property [
        sh:path dpp:hasLength ;
        sh:node [
            a sh:NodeShape ;
            sh:property [
                sh:path qudt:quantityValue ;
                sh:datatype xsd:decimal ;
                sh:minCount 1 ;
                sh:maxCount 1 ;
            ] ;
            sh:property [
                sh:path qudt:applicableUnit ;
                sh:node [
                    sh:in (unit:MilliM) ;
                ] ;
                sh:minCount 1 ;
                sh:maxCount 1 ;
            ] ;
```

```
    ] ;
    sh:minCount 1 ;
    sh:maxCount 1 ;
] ;

sh:property [
    sh:path dpp:hasWarranty ;
    sh:datatype xsd:string ;
    sh:minCount 1 ;
    sh:maxCount 1 ;
    sh:minLength 1 ;
] ;

sh:property [
    sh:path dpp:hasWidth ;
    sh:node [
        a sh:NodeShape ;
        sh:property [
            sh:path qudt:quantityValue ;
            sh:datatype xsd:decimal ;
            sh:minCount 1 ;
            sh:maxCount 1 ;
        ] ;
        sh:property [
            sh:path qudt:applicableUnit ;
            sh:node [
                sh:in (unit:MilliM) ;
            ] ;
            sh:minCount 1 ;
            sh:maxCount 1 ;
        ] ;
    ] ;
    sh:minCount 1 ;
    sh:maxCount 1 ;
] ;

sh:property [
    sh:path dpp:hasHeight ;
    sh:node [
        a sh:NodeShape ;
        sh:property [
            sh:path qudt:quantityValue ;
            sh:datatype xsd:decimal ;
            sh:minCount 1 ;
            sh:maxCount 1 ;
        ] ;
        sh:property [
            sh:path qudt:applicableUnit ;
            sh:node [
```

```
                    sh:in (unit:MilliM) ;
                ] ;
                sh:minCount 1 ;
                sh:maxCount 1 ;
            ] ;
        ] ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
    ] ;

    sh:property [
        sh:path rdfs:hasAngle ;
        sh:datatype xsd:decimal ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] ;

    sh:property [
        sh:path rdfs:hasDensity ;
        sh:datatype xsd:decimal ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] ;
    sh:property [
        sh:path prov:hasCompletionDate ;
        sh:datatype xsd:dateTime ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:pattern "^[0-9]{4}-[0-9]{2}-[0-9]{2}T[0-9]{2}:[0-9]{2}:[0-9]{2}$" ;
    ] ;
    sh:property [
        sh:path dpp:hasServicelife ;
        sh:datatype xsd:integer ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] .


    #...element
shape.............................................................................
.....................................................

dpp:ElementShape_info
    a sh:NodeShape ;
    sh:targetClass bot:Element ;
    sh:property [
```

```
        sh:path [ sh:alternativePath (dpp:hasGuid bot:hasGuid)  ];
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] ;
    sh:property [
        sh:path props:hasCompressedGuid ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] ;
    sh:property [
        sh:path rdfs:hasName ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] ;
    sh:property [
        sh:path rdfs:hasDescription ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] ;
    sh:property [
        sh:path dpp:hasLength ;
        sh:node [
            a sh:NodeShape ;
            sh:property [
                sh:path qudt:quantityValue ;
                sh:datatype xsd:decimal ;
                sh:minCount 1 ;
                sh:maxCount 1 ;
            ] ;
            sh:property [
                sh:path qudt:applicableUnit ;
                sh:node [
                    sh:in (unit:MilliM) ;
                ] ;
                sh:minCount 1 ;
                sh:maxCount 1 ;
            ] ;
        ] ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
    ] ;
```

```
sh:property [
    sh:path dpp:hasWarranty ;
    sh:datatype xsd:string ;
    sh:minCount 1 ;
    sh:maxCount 1 ;
    sh:minLength 1 ;
] ;
sh:property [
    sh:path dpp:hasWidth ;
    sh:node [
        a sh:NodeShape ;
        sh:property [
            sh:path qudt:quantityValue ;
            sh:datatype xsd:decimal ;
            sh:minCount 1 ;
            sh:maxCount 1 ;
        ] ;
        sh:property [
            sh:path qudt:applicableUnit ;
            sh:node [
                sh:in (unit:MilliM) ;
            ] ;
            sh:minCount 1 ;
            sh:maxCount 1 ;
        ] ;
    ] ;
    sh:minCount 1 ;
    sh:maxCount 1 ;
] ;

sh:property [
    sh:path dpp:hasHeight ;
    sh:node [
        a sh:NodeShape ;
        sh:property [
            sh:path qudt:quantityValue ;
            sh:datatype xsd:decimal ;
            sh:minCount 1 ;
            sh:maxCount 1 ;
        ] ;
        sh:property [
            sh:path qudt:applicableUnit ;
            sh:node [
                sh:in (unit:MilliM) ;
            ] ;
            sh:minCount 1 ;
            sh:maxCount 1 ;
        ] ;
```

```
        ] ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
    ] ;

    sh:property [
        sh:path rdfs:hasAngle ;
        sh:datatype xsd:decimal ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] ;
    sh:property [
        sh:path prov:hasCompletionDate ;
        sh:datatype xsd:dateTime ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:pattern "^[0-9]{4}-[0-9]{2}-[0-9]{2}T[0-9]{2}:[0-9]{2}:[0-9]{2}$" ;
    ] ;
    sh:property [
        sh:path dpp:hasServicelife ;
        sh:datatype xsd:integer ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] .


    #.......building/
(IFC)..............................................................................
...................

    dpp:BuildingShape_info
    a sh:NodeShape ;
    sh:targetClass bot:Building ;
    sh:property [
        sh:path [ sh:alternativePath (dpp:hasGuid bot:hasGuid)  ] ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] ;
    sh:property [
        sh:path props:hasCompressedGuid ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] ;
```

```
    sh:property [
        sh:path props:BuildingName ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] ;
        sh:property [
        sh:path props:ProjectAddress;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] ;
        sh:property [
        sh:path dpp:hasServicelife ;
        sh:datatype xsd:integer ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
        sh:maxlength 3 ;
    ] ;
    sh:property [
        sh:path rdfs:hasDescription ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
    ] ;
    sh:property [
        sh:path prov:hasCompletionDate ;
        sh:datatype xsd:dateTime ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
        sh:pattern "^[0-9]{4}-[0-9]{2}-[0-9]{2}T[0-9]{2}:[0-9]{2}:[0-9]{2}$" ;

    ] .

    # NEN.and
NLSFB...............................................................
....................................................................
.......................

    dpp:Shape_Classification
    a sh:NodeShape ;
    sh:targetClass dpp:classificationCode ;

   sh:property [
        sh:path [ sh:alternativePath (dpp:hasClassificationCode
props:NLSfB)  ] ;
```

```
        sh:or (
            [
                sh:datatype xsd:string ;
                sh:pattern "^[0-9]{1,4}$" ;
            ]
            [
                sh:datatype xsd:string ;
                sh:pattern "^[a-zA-Z]{1,2}$" ;
            ]
            [
                sh:datatype xsd:string ;
                sh:pattern "^[A-Z][a-z][0-9]$" ;
            ]

    );
    sh:minCount 1 ;
    sh:maxCount 1 ;
    ] ;

    sh:property [
        sh:path dpp:hasDecompositionLevel ;
        sh:datatype xsd:string ;
        sh:pattern
"^(BO|EL|BD|MAT|bo|el|bd|mat|Object|Element|Bouwdeel|Materiaal|object|element|
bouwdeel|materiaal|Bouwobject|bouwobjectl|constructievorm|productiemiddel|gebo
uwtype|gebouwtypen|woongebied|woongebieden|ruimte|ruimten)$" ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] .

    #Manufacturer.............................................................
...................................

    dpp:Shape_Manufacturer
    a sh:NodeShape ;
    sh:targetClass bmp:manufacturer ;

    sh:property [
        sh:path bmp:hasManufacturerName ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:maxCount 5 ;
        sh:minLength 1 ;
    ] ;

    sh:property [
        sh:path bmp:hasManufacturerContactEmail ;
        sh:datatype xsd:string ;
```

```
        sh:minCount 1 ;
        sh:maxCount 5 ;
        sh:pattern ".*@.*" ;
        sh:minLength 2 ;
    ] ;

    sh:property [
        sh:path locn:fullAddress ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] ;

    sh:property [
        sh:path rdfs:hasDescription ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] .


#Log ......................................................................

    dpp:Shape_log
    a sh:NodeShape ;
    sh:targetClass dpp:log ;

    sh:property [
        sh:path dpp:hasGuid ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] ;
        sh:property [
        sh:path dpp:hasVersion ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:minLength 1 ;

     ] ;

        sh:property [
        sh:path dpp:hasLinkDatabase ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:minLength 1 ;
```

```
     ] .
#owner.............................................................................................................
    dpp:Shape_owner
    a sh:NodeShape ;
    sh:targetClass dpp:owner ;

    sh:property [
        sh:path dpp:hasGuid ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] ;
    sh:property [
        sh:path dpp:hasName ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] .

#origin
...................................................................................................

    dpp:Shape_origin
    a sh:NodeShape ;
    sh:targetClass dpp:origin ;

    sh:property [
        sh:path dpp:hasGuid ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] ;

    sh:property [
        sh:path dpp:hasCountryOrigin ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:pattern "^(Afghanistan|the Netherlands|The Netherlands|the
netherlands|germany|belgium|Albania|Algeria|Andorra|Angola|Antigua and
Barbuda|Argentina|Armenia|Australia|Austria|Azerbaijan|Bahamas|Bahrain|Banglad
esh|Barbados|Belarus|Belgium|Belize|Benin|Bhutan|Bolivia|Bosnia and
Herzegovina|Botswana|Brazil|Brunei|Bulgaria|Burkina Faso|Burundi|Cabo
Verde|Cambodia|Cameroon|Canada|Central African
```

```
Republic|Chad|Chile|China|Colombia|Comoros|Congo (Congo-Brazzaville)|Costa
Rica|Croatia|Cuba|Cyprus|Czechia (Czech
Republic)|Denmark|Djibouti|Dominica|Dominican Republic|Ecuador|Egypt|El
Salvador|Equatorial
Guinea|Eritrea|Estonia|Eswatini|Swaziland|Ethiopia|Fiji|Finland|France|Gabon|G
ambia|Georgia|Germany|Ghana|Greece|Grenada|Guatemala|Guinea|Guinea-
Bissau|Guyana|Haiti|Holy
See|Honduras|Hungary|Iceland|India|Indonesia|Iran|Iraq|Ireland|Israel|Italy|Iv
ory
Coast|Jamaica|Japan|Jordan|Kazakhstan|Kenya|Kiribati|Kuwait|Kyrgyzstan|Laos|La
tvia|Lebanon|Lesotho|Liberia|Libya|Liechtenstein|Lithuania|Luxembourg|Madagasc
ar|Malawi|Malaysia|Maldives|Mali|Malta|Marshall
Islands|Mauritania|Mauritius|Mexico|Micronesia|Moldova|Monaco|Mongolia|Montene
gro|Morocco|Mozambique|Myanmar (formerly
Burma)|Namibia|Nauru|Nepal|Netherlands|the Netherlands|The Netherlands|New
Zealand|Nicaragua|Niger|Nigeria|North Korea|North Macedonia (formerly
Macedonia)|Norway|Oman|Pakistan|Palau|Palestine State|Panama|Papua New
Guinea|Paraguay|Peru|Philippines|Poland|Portugal|Qatar|Romania|Russia|Rwanda|S
aint Kitts and Nevis|Saint Lucia|Saint Vincent and the Grenadines|Samoa|San
Marino|Sao Tome and Principe|Saudi Arabia|Senegal|Serbia|Seychelles|Sierra
Leone|Singapore|Slovakia|Slovenia|Solomon Islands|Somalia|South Africa|South
Korea|South Sudan|Spain|Sri
Lanka|Sudan|Suriname|Sweden|Switzerland|Syria|Tajikistan|Tanzania|Thailand|Tim
or-Leste|Togo|Tonga|Trinidad and
Tobago|Tunisia|Turkey|Turkmenistan|Tuvalu|Uganda|Ukraine|United Arab
Emirates|United Kingdom|United States of
America|Uruguay|Uzbekistan|Vanuatu|Venezuela|Vietnam|Yemen|Zambia|Zimbabwe)$"
;
        sh:minLength 1 ;
    ] .

    # Condition
assessment..............................................................
..........................

    dpp:Shape_ConditionAssessment
    a sh:NodeShape ;
    sh:targetClass dpp:conditionAssessment ;


    sh:property [
        sh:path dpp:hasGuid ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:minLength 1 ;

    ] ;
    sh:property [
        sh:path dpp:hasVersion ;
```

```
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:minLength 1 ;

     ] ;

    sh:property [
        sh:path dpp:hasLastUpdate ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:minLength 1 ;

    ] ;

     sh:property [
        sh:path prov:atTime ;
        sh:datatype xsd:dateTime ;
        sh:pattern "^[0-9]{4}-[0-9]{2}-[0-9]{2}T[0-9]{2}:[0-9]{2}:[0-9]{2}$" ;
        sh:minCount 1 ;


    ] ;

         sh:property [
        sh:path dpp:hasConditionAssessment ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:minLength 1 ;

    ] .

    #future
function........................................................................


    dpp:Shape_FutureFunction
    a sh:NodeShape ;
    sh:targetClass dpp:futureFunction ;


    sh:property [
        sh:path dpp:hasGuid ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:minLength 1 ;

    ] ;
    sh:property [
        sh:path dpp:hasFutureFunction ;
```

```
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:minLength 1 ;

     ] .

     #reusability potential
...............................................................


    dpp:Shape_ReusabilityPotential
    a sh:NodeShape ;
    sh:targetClass dpp:reusabilityPotential ;


    sh:property [
        sh:path dpp:hasGuid ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:minLength 1 ;
        sh:maxCount 1 ;

    ] ;

    sh:property [
        sh:path dpp:hasReusabilityPotential ;
        sh:datatype xsd:decimal ;
        sh:minCount 1 ;
        sh:minLength 1 ;
        sh:minInclusive 1.00 ;
        sh:maxCount 1 ;

     ] ;

         sh:property [
        sh:path dpp:hasEmbodiedEnergy ;
        sh:datatype xsd:integer ;
        sh:minCount 1 ;
        sh:minLength 1 ;
        sh:maxCount 1 ;

    ] .

    #.recycling
potential.........................................................................

    dpp:Shape_RecyclingPotential
    a sh:NodeShape ;
    sh:targetClass dpp:recyclingPotential ;
```

```
sh:property [
    sh:path dpp:hasGuid ;
    sh:datatype xsd:string ;
    sh:minCount 1 ;
    sh:minLength 1 ;
    sh:maxCount 1 ;

] ;

sh:property [
    sh:path dpp:hasRecyclingPotential ;
    sh:datatype xsd:decimal ;
    sh:minCount 1 ;
    sh:minLength 1 ;
    sh:minInclusive 0.1 ;
    sh:maxCount 1 ;

 ] ;

     sh:property [
    sh:path dpp:hasEmbodiedEnergy ;
    sh:datatype xsd:integer ;
    sh:minCount 1 ;
    sh:minLength 1 ;
    sh:maxCount 1 ;

] .

#assurance.........................................................
..

dpp:Shape_ProofOfReuse
a sh:NodeShape ;
sh:targetClass dpp:proofOfReuse ;


sh:property [
    sh:path dpp:hasGuid ;
    sh:datatype xsd:string ;
    sh:minCount 1 ;
    sh:minLength 1 ;
    sh:maxCount 1 ;

] ;

sh:property [
    sh:path dpp:hasDescription ;
```

```
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:minLength 1 ;
        sh:maxCount 1 ;

     ] ;

         sh:property [
        sh:path dpp:hasProofAvailable ;
        sh:datatype xsd:boolean ;
        sh:in ( true false) ;
        sh:minCount 1 ;
        sh:minLength 1 ;
        sh:maxCount 1 ;

     ].

#External
party.........................................................................
............................
    dpp:Shape_externalParty
    a sh:NodeShape ;
    sh:targetClass dpp:externalParty ;

    sh:property [
        sh:path dpp:hasGuid ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] ;
    sh:property [
        sh:path dpp:hasName ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] .

#disassembly
potential.........................................................

    dpp:Shape_DisassemblyPotential
    a sh:NodeShape ;
    sh:targetClass dpp:disassemblyPotential ;


    sh:property [
        sh:path dpp:hasGuid ;
```

```
    sh:datatype xsd:string ;
    sh:minCount 1 ;
    sh:minLength 1 ;
    sh:maxCount 1 ;

] ;

sh:property [
    sh:path dpp:hasDescription ;
    sh:datatype xsd:string ;
    sh:minCount 1 ;
    sh:minLength 1 ;


 ] ;

sh:property [
    sh:path dpp:hasDisassemblyPotential ;
    sh:datatype xsd:decimal ;
    sh:minCount 1 ;
    sh:minLength 1 ;
    sh:minInclusive 1 ;
    sh:maxCount 1 ;

 ] .
```

APPENDIX M : Zoomed in figures validation process

files > Rijwoning_altered.ttl

```
:element_1550
 a bot:Element ;
 a dpp:Element ;#added
 rdfs:label "Basic Wall:NLRS_22_WA_250mm:830959"^^xsd:st
 bot:hasGuid "af013f6d0dda43c9a60c475962980abf"^^xsd:str
 props:hasCompressedGuid "2l0Jzj3Tf3oQOCHrbYc0g$"^^xsd:s
 props:Roughness "1"^^xsd:int ;
 props:Absorptance "0.1"^^xsd:double ;
 props:HeatTransferCoefficient "4.2901740926527"^^xsd:do
 props:ThermalMass "342.3535"^^xsd:double ;
 props:ThermalResistance "0.233090774034691 94"^^xsd:doub
 props:Function "Interior"^^xsd:string ;
 props:Width "250.00000000000003"^^xsd:double ;
 props:WrappingAtEnds "None"^^xsd:string ;
 props:WrappingAtInserts "Do not wrap"^^xsd:string ;
 props:CoarseScaleFillPattern "<Solid fill>"^^xsd:string
 props:CoarseScaleFillColor "8421504"^^xsd:int ;
 props:AssemblyDescription ""^^xsd:string ;
 props:AssemblyCode "2E(42.11)"^^xsd:string ;
 props:Description "stucwerk interieur, fijn, wit"^^xsd:
 props:Keynote "d-27,5-000"^^xsd:string ;
 props:TypeComments "d=27,5mm"^^xsd:string ;
 props:TypeName "NLRS_22_WA_250mm"^^xsd:string ;
 props:StructuralMaterial "NLRS_f2_beton_prefab_gen"^^xs
 props:Category "Walls"^^xsd:string ;
 props:FamilyName "Basic Wall"^^xsd:string ;
 props:Cost "0.0"^^xsd:double ;
 props:Family "Basic Wall"^^xsd:string ;
 props:FamilyAndType "Basic Wall: NLRS_22_WA_250mm"^^xsd
 props:Type "NLRS_22_WA_250mm"^^xsd:string ;
 props:TypeId "860905"^^xsd:string ;
 props:Roughness "304.8"^^xsd:double ;
 props:Category "Walls"^^xsd:string ;
 props:Description "stucwerk interieur, fijn, wit"^^xsd:
 props:Reference "NLRS_22_WA_250mm"^^xsd:string ;
 props:Thermaltransmittance "4.2901740926527"^^xsd:doubl
 props:Isexternal "False"^^xsd:boolean ;
```

Figure 1m: Validation process turtle file fragment

```
files > SHACL1.0.ttl
dpp:ProductShape_info
    ] ;


    #...element shape.....................................

dpp:ElementShape_info
    a sh:NodeShape ;
    sh:targetClass bot:Element ;
    sh:property [
        sh:path [ sh:alternativePath (dpp:hasGuid bot:hasG
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] ;
    sh:property [
        sh:path props:hasCompressedGuid ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] ;
    sh:property [
        sh:path rdfs:hasName ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] ;
    sh:property [
        sh:path rdfs:hasDescription ;
        sh:datatype xsd:string ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
        sh:minLength 1 ;
    ] ;
    sh:property [
```

Figure 2m: Validation process shacl file fragment

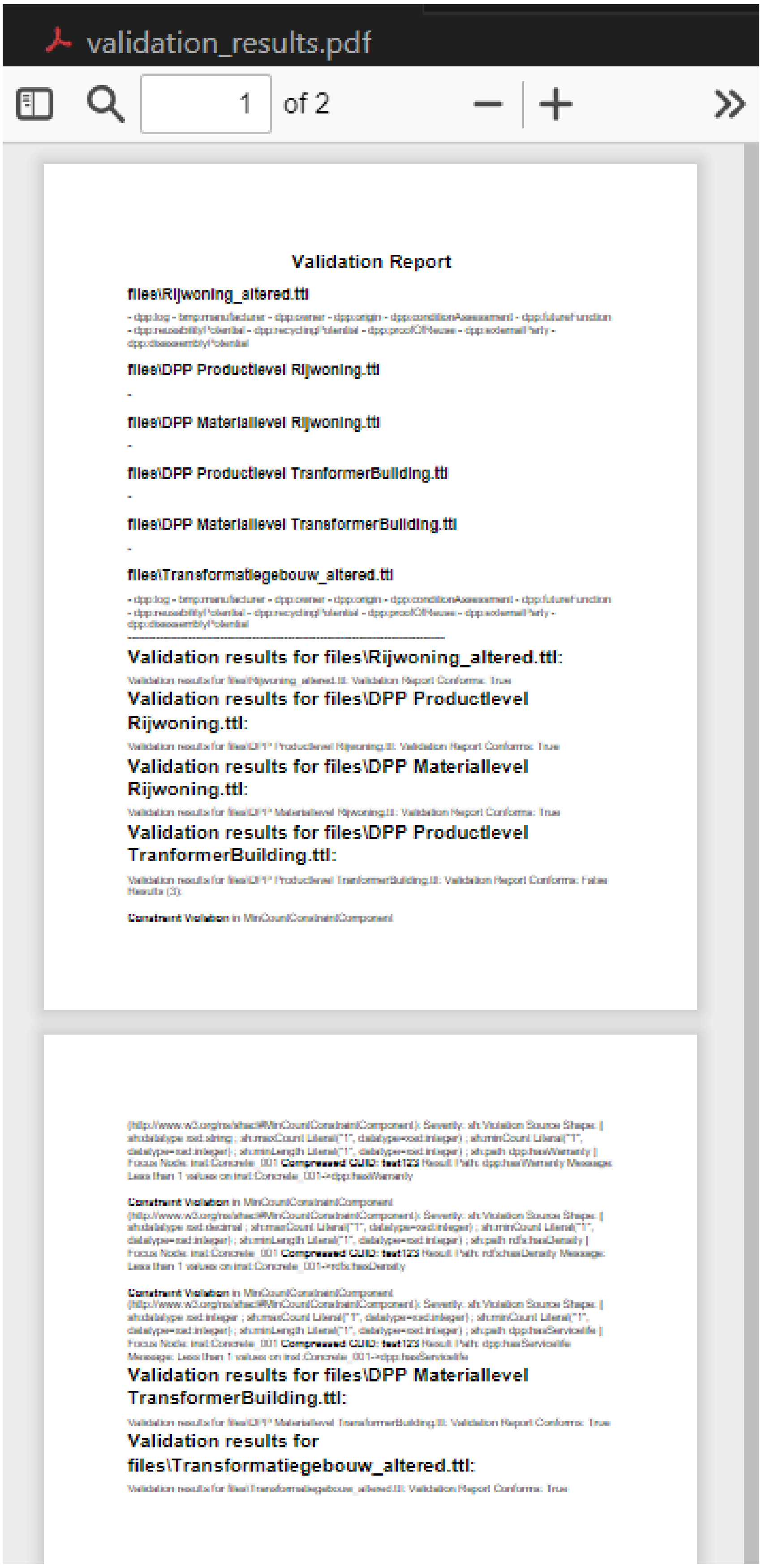


Figure 3m: Validation process validation report fragment

APPENDIX N: Python script

Github Link: https://github.com/JannekeBosma/DPP/

```
from reportlab.lib.pagesizes import letter
from reportlab.platypus import SimpleDocTemplate, Paragraph
from reportlab.lib.styles import ParagraphStyle, getSampleStyleSheet  #
Importeer getSampleStyleSheet
from pyshacl import validate
from rdflib import Graph, Namespace
import re


# URI ontology
dpp = Namespace("http://www.semanticweb.org/janneke.bosma/DPP#")

# Loads shacl and ontology
sg = Graph().parse(r"files\\SHACL1.0.ttl", format="turtle")
# ont = Graph().parse(r"files\\DPP_Ont.ttl", format="turtle")

# Load the data graphs to check (save these files in the python environment
and put the filename below in case it is saved in a file)
folder_name = "files\\"

# In the file_names below write down the name of the turtle file you want to
validate
file_names = [
        #  "Rijwoning.ttl",
          "Rijwoning_altered.ttl",
          "DPP Productlevel Rijwoning.ttl",
          "DPP Materiallevel Rijwoning.ttl",
          "DPP Productlevel TranformerBuilding.ttl",
          "DPP Materiallevel TransformerBuilding.ttl",
        #  "Transformatiegebouw.ttl",
           "Transformatiegebouw_altered.ttl",
]
data_files = [folder_name + s for s in file_names]


# Name of Validation report in PDF (text between "titel" can be altered)
pdf_file = "validation_results.pdf"

# Create PDF
pdf_doc = SimpleDocTemplate(pdf_file, pagesize=letter)
styles = getSampleStyleSheet()

# Title
```

```
title_style = ParagraphStyle('Title', parent=styles['Normal'])
title_style.alignment = 0  # text is linked out on the left side

pdf_content = []

# List to check missing words
missing_words = {}

for data_file in data_files:
    data_graph = Graph().parse(data_file, format="turtle")

    # Classes to check
    words_to_check = ['dpp:log', 'dpp:classificationCode', 'bmp:manufacturer',
'dpp:owner',
                      'dpp:origin', 'dpp:conditionAssessment',
'dpp:futureFunction',
                      'dpp:reusabilityPotential', 'dpp:recyclingPotential',
'dpp:proofOfReuse',
                      'dpp:externalParty', 'dpp:disassemblyPotential']

    # Checks classes and add missing classes in PDF
    missing_words[data_file] = []
    for word in words_to_check:
        if word not in data_graph.serialize(format="turtle"):
            missing_words[data_file].append(word)

if missing_words:
    pdf_content.append(Paragraph("Validation Report", styles['Title']))  # add
titel
    for file, words in missing_words.items():
        pdf_content.append(Paragraph(file, styles['Heading2']))  # bold file
name
        pdf_content.append(Paragraph("- " + "\n- ".join(words),
styles['Normal']))
    pdf_content.append(Paragraph("---------------------------------------------
---------------------------------------------", styles['Normal']))

# SHACL validation
for data_file in data_files:
    data_graph = Graph().parse(data_file, format="turtle")

    r = validate(data_graph,
                 shacl_graph=sg,
               #  ont_graph=ont,
              #   inference=None,
                 #   abort_on_first=False,
                 #   allow_infos=False,
                 #   allow_warnings=False,
                 #   meta_shacl=False,
```

```
                    #   advanced=False,
                    #   js=False,
                    #   debug=False
                    )
    conforms, results_graph, results_text = r

    val_results_str = f"Validation results for {data_file}:\n"
    append_file_name = val_results_str + results_text
    parts = append_file_name.split("message:")

    if parts:
        # For each index in the total list
        for index, part in enumerate(parts):
            # Search file in which the validation results belong
            for file_name in file_names:
                if file_name in part:
                    # File found in which we search for the GUID

                    # Search for compressed GUID beloning to the focus node
                    data_graph = Graph().parse(folder_name+file_name,
format="turtle")
                    full_file_in_memory =
data_graph.serialize(format="turtle")

                    # Extract data from input_string
                    pattern = r'Focus Node:(.*?)\n'
                    matches = re.findall(pattern, part, re.DOTALL)

                    # Store data in a list
                    data_list = [match.strip() for match in matches]

                    # Assume that one inst can only have one GUID
                    data_list = list(set(data_list))

                    guid_value = []
                    # Search in another string using entries from data_list
                    for entry in data_list:
                        entry_index = full_file_in_memory.find(entry)
                        if entry_index != -1:
                            # Look for the first occurrence of
"props:hasCompressedGuid"
                            guid_pattern = r'props:hasCompressedGuid "(.*?)"'
                            search_substring =
full_file_in_memory[entry_index:]
                        guid_match = re.search(guid_pattern, search_substring)
                        if guid_match:
                            # Now add the GUID after the inst
```

```
                            parts[index] = part.replace(f"Focus Node:
{entry}", f"Focus Node: {entry}"+f"\n\tCompressed GUID:
{guid_match.group(1)}")


        # Results in text file and terminal
        with open("validation_results.txt", "a") as output_file:
            for part in parts:
                output_file.write("message:" + part.strip() + "\n\n")

    # Results in PDF
    pdf_content.append(Paragraph(f"Validation results for {data_file}:",
styles['Heading1']))

    # Format in PDF
    if parts:
        for part in parts:
            # Marker voor Constraint Violation
            if "Constraint Violation" in part:
                part = part.replace("Constraint Violation",
"<br/><br/><b>Constraint Violation</b>")
            # Marker voor de compressed GUIDs (Compressed GUID: ...)
            part = re.sub(r'(Compressed GUID: .*?)\n', r'<b>\1</b>\n', part)
            pdf_content.append(Paragraph(part.strip(), styles['Normal']))
            pdf_content.append(Paragraph("\n", styles['Normal']))
    else:
        pdf_content.append(Paragraph("No validation results found.",
styles['Normal']))  # Add message if no results found

pdf_doc.build(pdf_content)

print('done')
```

APPENDIX O: Validation process evaluation

1. Can you use the validation tool as it is now (and the required process beforehand)?
2. Explain, yes/no, what needs to change?
3. Can you work with the results of the validation report?
4. Explain, yes/no, what needs to change?
5. Can you work with this dashboard?
6. Explain, yes/no, what needs to change?
7. Do you have additional feedback/questions?

Table 1o: Evaluation results validation process

1.	Can you use the validation tool as it is now (and the required process beforehand)?
1a	No, because I don't have data knowledge. No experience with Python or other data languages/tools.
1b	No, because, I don't have data knowledge. No experience with Python or other data languages/tools. Unclear what needs to be filled in exactly to get the validation report.
1c	It requires some advanced knowledge, but the explanations are clear.
1d	Without an explanation partly. With a manual, I can figure it out. (Has basic knowledge of Python). When I run into an error, it does get tough right away.
1e	Not everyone will be able to work with this. Then you have to go to a specialist. No experience Python
1f	Without instructions not. No experience with Python.
2.	Explain, yes/no, what needs to change?
2a	A manual about the workflow will be needed. For example, with screenshots. A dashboard will help.
2b	A manual about the workflow will be needed. Furthermore, an addition in the manual with frequent mistakes being made and how to solve them. Currently, passports are made in Excel. Therefore, a converter from Excel to LBD will be needed. A dashboard will help.
2c	A visualization of the steps (flow chart) and a brief explanation with it.
2d	Addition of a manual and dashboard (make it visual for the people working with it).
2e	I think it's always helpful with things like this that there's a good manual. Or that there's an owner where you can put these kinds of things down. Because not everybody within BAM knows python or other languages. I look at the process at a slightly higher level. For this, I look at applicability within the company and ease of use. This tool you would actually want to present in some way in the company that people can just upload a model somewhere and press the button to run the validation. And maybe an x number of fields to possibly put the titles in.
2f	If there are instructions and explanations, I can figure it out. In addition, the instructions will have to include what programs are needed, what the main steps are, the purpose of each step, and the actions attached to it (and to the results).
3.	Can you work with the results of the validation report?
3a	Can read the message, but unclear what it means and what to do with it.
3b	The output of the validation report is unclear.
3c	It is clear to be able to work with it if you know what you need (so focusing on the last lines)

3d	Clear, can go to the BIM modeler with this to make the adjustments.
	I understand the idea and know what is happening. Of course, when one gets this sheet in front of them for some people it will be a bit of a search as to what it actually is about. If you talk to the right people it doesn't have to be very exciting with the right text and explanation, but otherwise it's pretty confusing.
3f	Not without explanation
4.	Explain, yes/no, what needs to change?
4a	Another format of the validation report can help to make the results more clear.
4b	Convert output text also in a less technical format (one technical format and one more readable format, e.g. in a table). It is dependent on the target group and how to visualize the results.
4c	Highlighting the required information in the pdf can be helpful in quickly identifying the error message.
4d	It would be good if the material information is also already added in Revit. In addition, the GUID of Revit is required to retrieve associated elements.
4e	Actually, there should be an instruction on how to read the report (i.e., that the last lines matter most). Perhaps a good next step would be to look at how to easily match this with other software packages, so you don't have to put two systems side by side. In addition, GUIDS-based searches in the system are needed and then you can at least get it visually. I think this can also be built into Revit. We often tend to write our own edit and automate it.
4f	If I've done it more often, at some point it gets easier. Must also on know beforehand that the last sentences are the most important. Instructions help.
5.	Can you work with this dashboard?
5a	The perspective from my role is more interested in what products/elements are in the building and what belongs in the passport. And if all elements are correctly placed. Not necessarily the validation.
5b	It is not necessarily the responsibility of my role to do the validation, but more to know what materials/products there are in the building. However, I think it is important to know that the validation exists and how it works. I am working with the client, so I am more curious about how to present this to the client. In the dashboard I like the option to filter the different validation results and to see the information from the IFC (first page).
5c	Yes, clear. It is nice that the information is made visual on the first page of the dashboard. This way you can already do a first check if, for example, the right model has been uploaded and if any major elements are already missing. In addition, it is nice that you can filter by error type in the validation report. This is a must-have.
5d	Clear
5e	I think it is clear
5f	Clear. Fine layout to see
6.	Explain, yes/no, what needs to change?
6a	Do not send a standard email, but make a standard template that employees can adjust when sending the email. The dashboard should look as simple as possible and the substantive details can remain in the validation report pdf. Furthermore, when I want to share the results with the client it might be good to also show how many elements/products are correct/complete.

6b	Click on the validation messages for further explanation of what it means, or an option on the right which shows an easier translation of the validation results next to the technical version. The dashboard should look as simple as possible and the substantive details can remain in the validation report pdf.
6c	A feature to see the model on the first page from different angles would be a good addition. In addition, in civil, multiple separate models are often created (with one passport overarching). For this reason, it would be convenient if multiple models could be uploaded simultaneously. Furthermore, it would be nice to have an option to print the selection made in page two instead of the entire report. Then you don't get those huge PDF files. Information about the supplier (website or item number) of the object can also be displayed so that they can be contacted in case of errors, but also to be able to look up the object.
6d	Perhaps add multiple filters to pull everything out, especially with a large amount of error messages. And maybe add a bar where you can filter by element type, for example. If passport information is already in there, perhaps a passport could also be downloaded to communicate to other parties.
6e	I think with this kind of thing, ease of use is always very important. Instead of the whole PDF thing, there should be a filtering that can then be taken out.
6f	Perhaps replace the word level in the filter, as it can be confusing with building levels in the form of floors, for example. In addition, adding a history. This should make it possible to retrieve when you have previously emailed reports and to whom. This could possibly include an option to have the email sent to yourself as a confirmation.
7.	Do you have additional feedback/questions?
7a	-
7b	-
7c	I think it applies well, but there are still a lot of steps that we as an organization within this field are going to (need to) do over the next 10 years to make sure we have perfect Material Passports. In any case, I think this is a nice step to make the basics more complete.
7d	I'm curious to see if you manage to get someone from our BIM department excited about working with this. Super that you have developed this. It may also have a lot of value for the organization.
7e	I always get a little itchy about exporting data, because then you lose part of it and of course the IFC is not 100% watertight either. From the design department's point of view, you actually also want some kind of check on the source data and not just on the IFC. I think this is a very good tool for an outsider or someone who is not designing, modeling or adding data. However, I personally would like it a little earlier in the process at design or before a drawing is produced at all. That there's a pre-audit report in there as well. If you look at the passport in itself, of course it has to be continuously completed. So you have design phase, execution, and then you start managing asset and in each cycle you start assigning information. When you validate within this cycle you would have to tune for that.
7f	Interesting tool. The dashboard also seems to be well laid out. Checking an RDF file is currently gray area for me. An instruction is required or a responsible person to manage and review these checks. In addition, a process/implementation plan would be a good addition about managing data for this tool. In addition from the

	role/responsible person that you can note Spoc (single point of contact). This might be useful. This could possibly also be arranged from a project basis, but you could also specify/require that there be an accountability note for the tool (project basis or by department/business unit). In addition, what are the requirements for the IFC (define parameter sets)? And what else should be controlled within the RDF. What are procedures and processes for data management maintenance.

- **A: sustainability advisor (vergeten relatie leggen te laten zien a-c)**
- **B: sustainability advisor**
- **C: work preparation engineer/site engineer**
- **D: work preparation engineer/site engineer**
- **E: design coordinator**
- **F: bim engineer**

APPENDIX P: Validation competency questions

Table 1p: Queries Competency Questions Site engineer

Competency questions site engineer		Explanation
Q1a	What materials do the products contain?	select ?Product ?Material ?NameProduct ?NameMaterial where { ?Product a dpp:product. ?Product dpp:hasMaterial ?Material. ?Product rdfs:hasName ?NameProduct. ?Material rdfs:hasName ?NameMaterial. } limit 100 Lijst van material en productnamen welk bij elkaar horen in een horizontale lijn
Q2a	From what products the elements are made?	select ?Element ?Product ?NameElement ?NameProduct where { ?Element a bot:Element. ?Element dpp:hasProduct ?Product. ?Element rdfs:label ?NameElement. ?Product rdfs:hasName ?NameProduct. } limit 100
Q3a	What is the lifespan of the products?	select ?Product ?Name ?LifeSpan where { ?Product a dpp:product. ?Product dpp:hasServicelife ?LifeSpan. ?Product rdfs:hasName ?Name } limit 100
Q4a	What is the origin of the materials used in the building?	select ?Material ?CircPropSet ?Origin ?CountryOrigin where { ?Material a dpp:material. ?Material dpp:hasCircularityPropertySet ?CircPropSet. ?CircPropSet dpp:hasOrigin ?Origin. ?Origin dpp:hasCountryOrigin ?CountryOrigin } limit 100

Q5a	Do all products have assurance for reuse?	select ?Material ?CircPropSet ?RecyclingPotential ?Proof ?ProofAvailable where { ?Material a dpp:material. ?Material dpp:hasCircularityPropertySet ?CircPropSet. ?CircPropSet dpp:hasRecyclingPotential ?RecyclingPotential. ?RecyclingPotential dpp:hasProofOfReuse ?Proof. ?Assurance dpp:hasProofAvailable ?ProofAvailable. } limit 100
Q6a	How to disassemble the products used in the building? And what is the belonging disassembly potential?	select ?Product ?CircPropSet ?Recycling ?Type ?Description ?Potential where { ?Product a dpp:product. ?Product dpp:hasCircularityPropertySet ?CircPropSet. ?CircPropSet dpp:hasRecyclingPotential ?Recycling. ?Recycling dpp:hasDisassemblyPotential ?Type. ?Type dpp:hasDescription ?Description. ?Type dpp:hasDisassemblyPotential ?Potential } limit 100 In de descriptie staat wat ermee kan gebeuren en de potential is het nummer
Q7a	Are there critical materials used in the building?	select ?Material ?Name ?Critical where { ?Material a dpp:material. ?Material rdfs:hasName ?Name. ?Material dpp:hasCriticality ?Critical. } limit 100 Zorgt voor een lijst met de materialen in het gebouw en daarachter true of false of deze critical is of niet
Q8a	Is the condition of the products assessed? (start measurements and the current condition)	select ?Product ?CircPropSet ?Name ?Update ?StorageDocument where { ?Product a dpp:product. ?Product dpp:hasCircularityPropertySet ?CircPropSet.

		?CirPropSet dpp:hasConditionAssessment ?Name. ?Name dpp:hasConditionAssessment ?StorageDocument. ?AssessmentName dpp:hasLastUpdate ?Update. } limit 100 Krijgt de laatste update en waar de assesment documentatie opgeslagen is (link). In de documentatie zijn de voorgaande updates terug te vinden.
Q9a	What future function can the products fulfill?	select ?Product ?CircPropSet ?FutureFunctionName ?Function where { ?Product a dpp:product. ?Product dpp:hasCircularityPropertySet ?CircPropSet. ?CirPropSet dpp:hasFutureFunction ?FutureFunctionName. ?FutureFunctionName dpp:hasFutureFunction ?Function. } limit 100 De toekomstige functie wordt zichtbaar bij deze query. Er kan ook op materiaal en element level gequeried worden zodat men kan bepalen welk niveau het beste passend is voor het hergebruik.
Q10a	What are the classification codes for the object?	select ?Building ?CodeName ?ClassificationCode ?Element ?CodeNameE ?ClassificationCodeE ?Product ?CodeNameP ?ClassificationCodeP ?Material ?CodeNameM ?ClassificationCodeM where { ?Building a bot:Building. ?Building dpp:hasClassificationCode ?CodeName. ?CodeName dpp:hasClassificationCode ?ClassificationCode. ?Element a dpp:Element. ?Element dpp:hasClassificationCode ?CodeNameE. ?CodeNameE dpp:hasClassificationCode ?ClassificationCodeE. ?Product a dpp:product. ?Product dpp:hasClassificationCode ?CodeNameP. ?CodeNameP dpp:hasClassificationCode ?ClassificationCodeP.

		?Material a dpp:material. ?Material dpp:hasClassificationCode ?CodeNameM. ?CodeNameM dpp:hasClassificationCode ?ClassificationCodeM. } limit 100 Zo krijg je de code van gebouw, element, product en materiaal
Q11a	What elements contain the material cement?	select ?Element ?Product ?Material ?Name where { ?Element a dpp:Element. ?Element dpp:hasProduct ?Product. ?Product a dpp:product. ?Product dpp:hasMaterial ?Material. ?Material a dpp:material. ?Material rdfs:hasName ?Name. FILTER (?Name = 'Cement') } limit 100
Q12a	What is the recycling potential and reusability potential of concrete?	select ?Product ?Name ?CircPropSet ?Recycling ?RecyclingPotential ?Reuse ?ReusabilityPotential where { ?Product a dpp:product. ?Product rdfs:hasName ?Name. ?Product dpp:hasCircularityPropertySet ?CircPropSet. ?CircPropSet dpp:hasRecyclingPotential ?Recycling. ?Recycling dpp:hasRecyclingPotential ?RecyclingPotential. ?CircPropSet dpp:hasReusabilityPotential ?Reuse. ?Reuse dpp:hasReusabilityPotential ?ReusabilityPotential. FILTER (?Name = 'Concrete mixture') } limit 100
Q13a	What is the recommended future function of the products containing the material polyisocyanurate?	select ?Product ?Material ?Name ?CircPropSet ?FutureFunction ?Function where { ?Product a dpp:product. ?Product dpp:hasMaterial ?Material. ?Material rdfs:hasName ?Name. ?Material dpp:hasCircularityPropertySet ?CircPropSet. ?CircPropSet dpp:hasFutureFunction ?FutureFunction. ?FutureFunction dpp:hasFutureFunction ?Function.

		FILTER (?Name = 'Polyisocyanuraat') } limit 100
Q14a	What is the nen2767 code of the walls?	select ?Element ?Name ?ClassCode ?Code where { ?Element a dpp:Element. ?Element rdfs:hasName ?Name. ?Element dpp:hasClassificationCode ?ClassCode. ?ClassCode dpp:hasClassificationCode ?Code. # FILTER (?Name = 'Basic wall prefab')
Q15a	What is the GUID of the concrete wall?	select ?Element ?Name ?GUID where { ?Element a dpp:Element. ?Element rdfs:hasName ?Name. ?Element props:hasCompressedGuid ?GUID FILTER (?Name = 'Basic wall prefab') } limit 100

Table 2p: Queries Competency Questions Sustainability advisor

Competency questions sustainability advisor		Explanation
Q1c	Where is the building located?	select ?Building ?Address where { ?Building a bot:Building. ?Building props:ProjectAddress ?Address. } limit 100

Q2b	Who are the manufacturers of the products?	select ?Product ?Name ?Manufacturer ?ManufacturerName where {
		
		?Product a dpp:product.
		?Product rdfs:hasName ?Name.
		?Product bmp:hasManufacturer ?Manufacturer.
		?Manufacturer bmp:hasManufacturerName ?ManufacturerName.
		}

Q3b	What materials does the building contain?	select ?Material ?Name where {
		
		?Material a dpp:material.
		?Material rdfs:hasName ?Name.
		}

Q4b	What are the dimensions of the elements and products?	select ?ElementName ?ValueLenghtEL ?ValueWidthEL ?ValueHeightEL ?ProductName ?ValueLenghtPR ?ValueWidthPR ?ValueHeightPR where { ?Element a dpp:Element. ?Element rdfs:label ?ElementName. ?Element dpp:hasLength ?LenghtEL. ?LenghtEL qudt:quantityValue ?ValueLenghtEL. ?Element dpp:hasWidth ?WidthEL. ?WidthEL qudt:quantityValue ?ValueWidthEL. ?Element dpp:hasHeight ?HeightEL. ?HeightEL qudt:quantityValue ?ValueHeightEL. ?Element dpp:hasProduct ?Product. ?Product rdfs:hasName ?ProductName. ?Element dpp:hasLength ?LenghtPR. ?LenghtPR qudt:quantityValue ?ValueLenghtPR. ?Element dpp:hasWidth ?WidthPR.

		?WidthPR qudt:quantityValue ?ValueWidthPR. ?Element dpp:hasHeight ?HeightPR. ?HeightPR qudt:quantityValue ?ValueHeightPR. } Op deze manier queried alleen de producten behorend bij de elementen. Wanneer je alle producten wilt zien als je selectie elementen hebt dan moeten deze los van elkaar gequeried worden

Q5b	What is the density of all materials in the building?	select ?Material ?Name ?Density where {
		
		?Material a dpp:material.
		?Material rdfs:hasName ?Name.
		?Material rdfs:hasDensity ?Density.
		
		}

Q6b	What is the remaining life expectancy of the elements/products/materials	select ?MName ?MDate ?MServicelife ?PName ?PDate ?PServicelife ?EName ?EDate ?EServicelife where {
		
		?Material a dpp:material.
		?Material rdfs:hasName ?MName.
		?Material prov:hasCompletionDate ?MDate.
		?Material dpp:hasServicelife ?MServicelife.
		?Product a dpp:product.
		?Product rdfs:hasName ?PName.
		?Product prov:hasCompletionDate ?PDate.
		?Product dpp:hasServicelife ?PServicelife.
		?Element a dpp:Element.
		?Element rdfs:hasName ?EName.
		?Element prov:hasCompletionDate ?EDate.
		?Element dpp:hasServicelife ?EServicelife.
		
		}
		De datum dat deze geïnstalleerd of gemaakt is en dan plus levensduur erbovenop zelf uitrekenen

Q7b	What is the recycling and reusability potential of the materials/products?	
Q8b	Can the elements/products/materials be disassembled?	select ?MName ?MDescription ?MPotential where {

		?Material a dpp:material.
		?Material rdfs:hasName ?MName.
		?Material dpp:hasCircularityPropertySet ?MCircPropSet.
		?MCircPropSet dpp:hasReusabilityPotential ?MRe.
		?MRe dpp:hasDisassemblyPotential ?MDis.
		?MDis dpp:hasDescription ?MDescription.
		?MDis dpp:hasDisassemblyPotential ?MPotential.
		
		select ?PName ?PDescription ?PPotential where {
		
		?Product a dpp:product.
		?Product rdfs:hasName ?PName.
		?Product dpp:hasCircularityPropertySet ?PCircPropSet.
		?PCircPropSet dpp:hasReusabilityPotential ?PRe.
		?PRe dpp:hasDisassemblyPotential ?PDis.
		?PDis dpp:hasDescription ?PDescription.
		?PDis dpp:hasDisassemblyPotential ?PPotential.
		
		}
		
		Element level kan niet gequeries worden nu want die info is niet toegevoegd in de documenten nu.

Q9b	What products contain secondary material?	select ?Product ?Name ?Manufacturer ?ManufacturerName where {
		
		?Product a dpp:product.
		?Product rdfs:hasName ?Name.
		?Product bmp:hasManufacturer ?Manufacturer.
		?Manufacturer bmp:hasManufacturerName ?ManufacturerName.
		}

Q10b	Which materials in the building are critical?	select ?Name ?Critical where { ?Material a dpp:material. ?Material rdfs:hasName ?Name.

		?Material dpp:hasCriticality ?Critical. }

Q11b	What condition assessments have been made to the elements/products over the years?	select ?PName ?PGuid ?PAssessment where {
		
		?Product a dpp:product.
		?Product rdfs:hasName ?PName.
		?Product dpp:hasGuid ?PGuid.
		?Product dpp:hasCircularityPropertySet ?PCircPropSet.
		?PCircPropSet dpp:hasConditionAssessment ?PCondition.
		?PCondition dpp:hasConditionAssessment ?PAssessment.
		}

Table 3p: Queries Competency Questions Must-haves

	Must-have	Competency questions must-haves
Q1c	Dimensions	See question Q4b
Q2c	Weight	Included in density

Q3c	Density	What is the density of all products?
		
		select ?Name ?Density where {
		
		?Product a dpp:product.
		?Product rdfs:hasName ?Name.
		?Product rdfs:hasDensity ?Density.
		}

Q4c	Geometry	What is the geometry of all products?
		
		select ?Name ?ValueLenght ?ValueWidth ?ValueHeight where {
		
		?Product a dpp:product.
		?Product rdfs:hasName ?Name.
		?Product dpp:hasLength ?Lenght.
		?Lenght qudt:quantityValue ?ValueLenght.
		?Product dpp:hasWidth ?Width.
		?Width qudt:quantityValue ?ValueWidth.
		?Product dpp:hasHeight ?Height.
		?Height qudt:quantityValue ?ValueHeight.
		}

Q5c	Quantity	How many products are there in the building?
		
		select ?Name where {
		
		?Product a dpp:product.
		?Product rdfs:hasName ?Name.
		
		}
		Kunt dan aflezen in query tabel hoeveel resultaten

Q6c	Building location	See question Q1c
Q7c	Recycling potential	See question Q7b
Q8c	Reusability potential	See question Q7b
Q9c	Disassembly potential	See question Q6a
Q10c	Disassembly instructions	See question Q6a
Q11c	Future functions	See question Q9a
Q12c	Circularity	Combined with the above subjects
Q13c	Material composition	What is the material composition of the present products?

		select ?Name ?Material ?NameMaterial where {
		
		?Product a dpp:product.
		?Product rdfs:hasName ?Name.
		?Product dpp:hasMaterial ?Material.
		?Material rdfs:hasName ?NameMaterial.
		
		}

Q14c	Material criticality	See question Q7a
Q15c	Secondary material/product	See question Q9b
Q16c	Origin	Material level, See question Q4a

Q17c	Product name/details	What are the names and descriptions of the products?
		
		select ?Name ?Description where {
		
		?Product a dpp:product.
		?Product rdfs:hasName ?Name.
		?Product rdfs:hasDescription ?Description.
		}

Q18c	Product object nr.	What are the product's object numbers?
		
		select ?Name ?GUID ?CompressedGUID where {
		
		?Product a dpp:product.
		?Product rdfs:hasName ?Name.
		?Product dpp:hasGuid ?GUID.
		?Product props:hasCompressedGuid ?CompressedGUID.
		}

Q19c	Manufacturer article nr.	select ?PName ?MNumber where {
		
		?Product a dpp:product.
		?Product rdfs:hasName ?PName.
		?Product dpp:hasManufacturerNumber ?MNumber.
		}

Q20c	Location in building	What is the location of the products in in the building? select ?LabelStorey ?LabelSpace ?NameElement ?Name where { ?Storey a bot:Storey. ?Storey rdfs:label ?LabelStorey.

		?Storey bot:hasSpace ?Space. ?Space rdfs:label ?LabelSpace. ?Element a dpp:Element. ?Element rdfs:hasName ?NameElement. ?Element dpp:hasProduct ?Product. ?Product a dpp:product. ?Product rdfs:hasName ?Name. Can also add ID to find the specific location. This way it is described which storey, room and element

Q21c	Warranties	What are the warranties of the products?
		
		select ?Name ?Warranty where {
		
		?Product a dpp:product.
		?Product rdfs:hasName ?Name.
		?Product dpp:hasWarranty ?Warranty.
		}

Q22c	Updates	See question Q11b
Q23c	Service life	See question Q3a
Q24c	Condition assessment	See question Q11b

Q25c	Temporal information	What is the delivery date of the products?
		
		select ?Name ?CompletionDate where {
		
		?Product a dpp:product.
		?Product rdfs:hasName ?Name.
		?Product prov:hasCompletionDate ?CompletionDate
		}