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Creating Digital Product Passports for Bio-based materials

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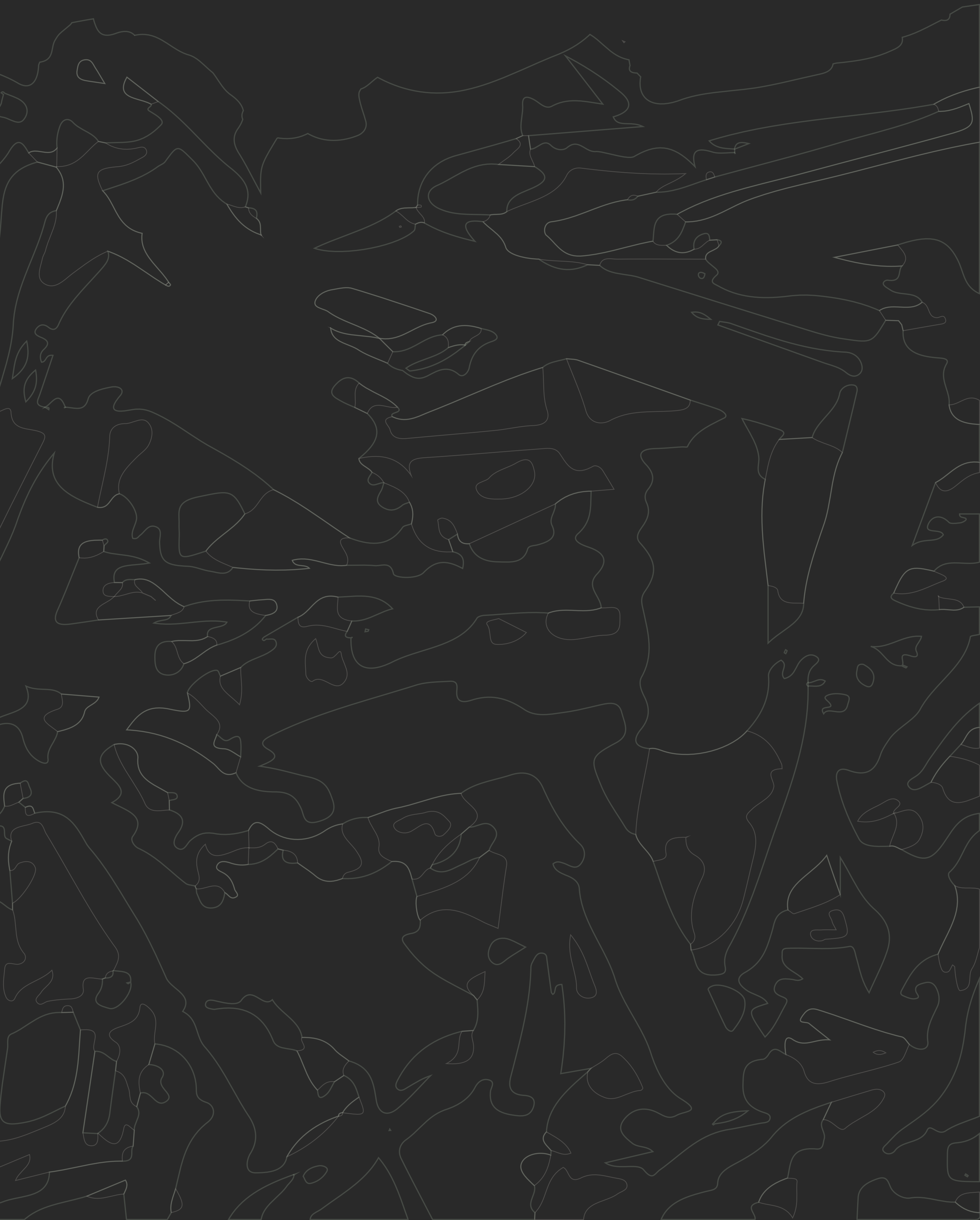
CREATING DIGITAL PRODUCT PASSPORTS FOR BIO-BASED MATERIALS



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ABSTRACT

The construction industry is under increasing pressure to reduce its environmental impact by adopting low-carbon materials and circular economy strategies. Bio-based materials such as Hempcrete offer regenerative alternatives to conventional products through carbon sequestration and renewable sourcing. Yet, their implementation remains limited by fragmented data, inconsistent performance assessment, and the absence of standardized digital documentation. At the same time, the transition toward circular practices depends on transparent and interoperable data frameworks that enable informed material decisions.

This thesis addresses these challenges by exploring how Digital Product Passports (DPPs), integrated within Building Information Modeling (BIM), can improve data accessibility and support circular approaches in construction specifically for bio-based materials. It develops a BIM-based DPP proof of concept for Hempcrete to inform future frameworks for reliability, traceability, and broader adoption of bio-based materials.

The study follows three phases: (1) a literature review on bio-based materials, Life Cycle Assessment (LCA), Circular Economy principles, and Digital Product Passports to establish the theoretical framework; (2) a review of two case studies to gather data on Hempcrete's performance, LCA, and circular strategies; and (3) the development of a BIM-based DPP prototype with semantic layers.

Results indicate that current BIM standards require custom property sets and supplementary ontological definitions to accommodate circularity data and the specific characteristics of hempcrete effectively. The developed prototype successfully centralized material-level and element-level lifecycle information, demonstrating a qualitative improvement in data accessibility compared to conventional documentation workflows, which do not support linked datasets, semantic structuring, or traceable identifier management. Validation processes also revealed where data transfer breaks down, including issues with parameter mapping, unit handling, naming conventions, and GUID tracking, confirming that limited software interoperability and persistent semantic inconsistencies remain significant barriers to scalability.

The developed prototype successfully organizes Hempcrete-related data into an accessible and updatable format, demonstrating how digital tools can bridge the gap between sustainability research and practical implementation within the built environment. The research concludes by proposing a standardized data template and supporting ontology for bio-based materials, providing a replicable digital infrastructure that can guide future DPP development and contribute to the decarbonization of the built environment.

DEDICATION

To my mother, father, sister and grandma whose strength and love made every step possible.

To my uncle and aunt, for inspiring me more than you'll ever know. I wouldn't be here without you.

To the rest of my family, who have always been there with unwavering support.

And to my chosen family, in Colombia and in Torino, for walking beside me through every challenge and every joy.

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My heartfelt thanks go to my best friend and editor, who generously provided her professional skills to elevate this humble thesis far beyond what I could have achieved alone.

STATEMENT ON THE USE OF AI TOOLS

AI tools were used in this thesis to support specific tasks related to writing, visualization, coding, and data processing. ChatGPT was used to improve redaction and clarity, to refine the structure of the text, and to ensure consistency with predefined writing rules concerning conciseness, avoidance of repetition, and the use of third person. It was also used as a problem-solving tool to address technical or conceptual questions that arose during the research process.

Gemini Nano was used to generate a limited number of images and graphs when visual material was needed to support the explanation of concepts.

The mock-up visualization that required programming knowledge beyond the author's skills were produced with Google AI Studio, which assisted in generating and adapting code for interface.

The AI agent integrated in Visual Studio was used to understand, correct, and improve the Python scripts required for the methodological process. It also supported the generation and refinement of graphs derived from those scripts.

All AI outputs were reviewed, validated, and edited by the author to ensure accuracy, methodological coherence, and academic integrity.

INTRODUCTION

The construction sector is one of the largest contributors to global greenhouse gas emissions and resource depletion. Embodied carbon emissions, associated with the manufacturing, transport, and end-of-life stages of materials, account for approximately 11% of global greenhouse gas emissions (Adams et al., 2019), while the sector consumes nearly 30% of all raw materials worldwide (Bilal et al., 2020). Traditional materials such as concrete and steel require high energy inputs, generate significant emissions, and produce waste streams that are difficult to recover or reuse. Transitioning to low-carbon and carbon-storing construction practices could significantly reduce these impacts and contribute to climate mitigation by 2100 (Steyn et al., 2025). Achieving this shift requires the implementation of circular strategies, including reuse, extended use cycles, and resource-efficient design, to reduce dependence on virgin material extraction. This transition aligns with the European Climate Law, enforced in July 2021 as part of the European Green Deal, which legally commits Europe to achieving net-zero greenhouse gas emissions by 2050 and a 55% reduction by 2030 compared to 1990 levels (European Commission, 2021).

Bio-based materials are increasingly offering viable alternatives to conventional construction products due to their renewable origin, low embodied carbon, and compatibility with circular economy principles. Some of these materials also provide carbon-sequestration potential, contributing to further reductions in greenhouse gas emissions. Adebowale and

Agumba (2023) note that “bio-based materials in construction not only aid in reducing greenhouse gas emissions associated with traditional building materials but also enhance social well-being by creating healthier built environments.”

Among these, hempcrete stands out as the focus of this research. Characterized by its low embodied carbon, carbon-sequestration potential, and renewable origin, Hempcrete is a bio-composite made from hemp hurds or shives mixed with a lime-based binder. It combines structural lightness with strong thermal and hygroscopic performance, providing natural insulation and effective moisture regulation (Steyn et al., 2025). Hempcrete also offers high vapor permeability, acoustic comfort, and resistance to mold growth, contributing to healthier and more durable building envelopes (Steyn et al., 2025). In addition to its environmental advantages, it can be locally sourced and easily recycled or repurposed, aligning with circular economy principles and supporting regional bio-based value chains.

Despite these advantages, the adoption of hempcrete and other bio-based materials remains limited. A major barrier is the lack of consistent, accessible, and reliable information on their properties, life cycle performance, and end-of-life pathways. This results partly from the biological variability of these materials and the inconsistent accounting of their environmental impacts across different LCAs (Mikulļnas and ąeduikytļ, 2025). For example, materials such as timber and hemp store carbon during growth, yet their overall performance and emissions profiles vary according to regional conditions, agricultural practices, and sourcing methods (Alsani et al., 2023).

Stakeholders across the construction sector face persistent challenges in comparing materials, evaluating long-term durability, and incorporating circular strategies within building projects. The absence of standardized data structures, certification schemes, and clear evaluation frameworks limits their ability to make evidence-based design decisions. These gaps also complicate material approval and insurance processes, discouraging designers and developers from selecting bio-based options. Combined with high upfront costs and limited market incentives, these conditions continue to hinder the broader adoption of bio-based materials (Schmidt et al., 2021 as cited in Mikulļnas and ąeduikytļ, 2025).

These challenges highlight the need for a coherent framework that enables the consistent capture, structuring, and exchange of material data throughout the construction process. Such a framework is essential to ensure that information about performance, environmental impact, and end-of-life potential can be systematically recorded and accessed by all stakeholders. Within this context, Digital Product Passports (DPPs) have emerged as a potential mechanism to organize and communicate this information in a standardized and interoperable format. A DPP functions as a comprehensive record of a material's life cycle, encompassing stages from raw material sourcing to manufacturing, use, reuse, or recycling. By providing detailed and verifiable data, DPPs can enhance transparency, traceability, and accountability across the value chain (Kim et al., 2024). When integrated within Building Information Modeling (BIM) environments, these passports allow designers, contractors, and regulators to access continuously updated datasets that support informed decisions on resource use, waste management, and material recovery (Kim et al., 2024).

While DPPs are gaining attention in research and policy frameworks, their practical implementation in the construction sector remains at an early stage. A milestone in this development was the Buildings as Material Banks (BAMB) project, which demonstrated how material passports and reversible design strategies can support resource recovery and circularity within the built environment. However, despite such advances, the sector continues to face barriers to widespread DPP adoption. Da Trindade et al. (2020) highlight that the lack of technological know-how remains a major obstacle to achieving sustainability in construction.

Current efforts to integrate DPPs across construction products are hindered by the absence of standardized data formats, limited interoperability with BIM platforms, and insufficient technical information on material behavior. Although BIM methodologies are well established in both research and practice, few applications combine these tools within a decision-support framework that informs design and material selection (Figueiredo et al., 2021). These barriers limit the implementation of circular economy strategies such as component reuse, material traceability, and closed-loop resource management.

Hempcrete exemplifies two main challenges in advancing sustainable construction. The first is the limited availability of long-term performance data and clear documentation of its circularity pathways. Despite its promising environmental properties, uncertainties remain regarding its durability, maintenance requirements, and behavior under different climatic or operational conditions. The second challenge concerns the absence of frameworks that make material information easily accessible and interoperable across life cycle stages. This limitation affects not only bio-based materials but most construction products, restricting stakeholders' ability to evaluate options, compare impacts, and integrate circular strategies into design and construction processes.

To address these issues, this thesis develops a prototype BIM-integrated Digital Product Passport (DPP) for a hempcrete-based material. By structuring and digitizing material information, the research seeks to enhance data reliability, improve information exchange among stakeholders, and facilitate the identification of circular economy opportunities. As Mikulļnas and ąeduikytļ (2025) note, documenting material properties, origins, and environmental impacts enables reuse and enhances traceability across the construction life cycle. Linking such passports to digital platforms could support real-time material tracking, fostering greater transparency and trust within the industry.

Through a case study analysis of hempcrete materials, the research assesses the structural, environmental, and safety performance of a selected bio-based wall cassette. Considering the entire product life cycle, the study explores the role of BIM as an enabler for identifying key data points and integrating information on material sourcing, manufacturing, assembly, use cycles, and end-of-life strategies. The work contributes to ongoing European discussions on DPPs as part of sustainable construction regulation and provides a concrete example of how such tools could be applied to bio-based materials.

This thesis is organized into five chapters. Chapter 1 presents the background and literature review covering bio-based materials, hempcrete properties, life cycle assessment methods, circular economy principles, and the emerging framework of digital material passports. Chapter 2 examines two case studies: a reference project by Natural Building Systems (NBS) and the selected Shotlander hemp block, which serves as the basis for prototype development. Chapter 3 describes the methodology used to collect data, design the DPP prototype, and evaluate its functionality. Chapter 4 reports the results of the study, including the developed prototype and its implementation within BIM. Chapter 5 discusses the findings, explores circularity strategies, and offers recommendations for future research and industry adoption. It also reflects on how the thesis and the developed prototype might inform future frameworks for Digital Product Passports of bio-based materials, emphasizing the roles of key stakeholders such as governmental bodies, carbon-offsetting organizations, designers, and developers.

CHAPTER 1

BACKGROUND AND LITERATURE REVIEW

This literature review provides the theoretical foundation for the thesis by analyzing four interrelated areas of interest: bio-based materials in construction, with a focus on hempcrete; LCAs of bio-based materials; circular economy strategies for construction; and material passports. These four areas specify the main dimensions of the research, from material to construction scale, while showing how LCA and circular economy strategies enable broader adoption of bio-based materials.

The review of the state of the art was performed using specialized search engines such as Scopus, EBSCO, and Google Scholar. The various studies were selected based on three key criteria: (1) relevance, determined by keywords, abstracts, and the applicability of the research within the architecture, engineering, and construction (AEC) industry; (2) date of publication-preferably works published from the year 2020 and onwards, with a greater preference for works from 2024 and 2025; and (3) language-only those studies published in the English language. These criteria ensured that the review embedded the most current developments and findings. The resultant literature provides a structured overview of key advances, challenges, and developments in the subject matter at hand and forms the basis for the analytical framework.

BIO-BASED MATERIALS

The construction industry is increasingly trying to reduce its environmental footprint, particularly the carbon intensity associated with conventional materials. Bio-based materials, derived from renewable biological sources offer a promising alternative toward more sustainable and circular building practices (Pedgley, Rognoli, & Karana, 2021). They generally present lower carbon footprints, reduced resource depletion, and decreased greenhouse gas emissions, while also lessening dependence on finite resources, and offering potential biodegradability at end-of-life (Ahmad, Jaiswal, McCormack, & Byrne, 2024), which aligns with global sustainability objectives, including the United Nations Sustainable Development Goals (SDGs 9 - Industry, innovation and Infrastructure; 12 - Responsible consuption and production; 13 - Climate action; and 15 Life on land) (United Nations, 2015). However, their adoption remains limited, due to persistent challenges such as insufficient data on long-term durability, lack of standardized performance criteria, and barriers to large-scale manufacturing (Dams, et al., 2023).

1.1.1 Definition

According to the European Committee for Standardization, Technical Committee 411 (CEN/TC 411), bio-based products are wholly or partly derived from renewable biological raw materials (biomass) such as plants, trees, or other organic sources. They are characterized by their bio-based carbon content and their capacity to replace fossil-based products while meeting end-use performance requirements at competitive costs. Their long-term potential relies on contributing to product cycles that minimize greenhouse gas emissions and environmental impacts through reduced waste, energy consumption, and water use (European Commission, 2007).

Within this category, bio-composites represent a specific group of materials in which at least one constituent originates from natural resources. When both the matrix and reinforcement are derived from biomass, the material can be considered a fully bio-based bio-composites (Vilaplana, Strömberg, & Karlsson, 2010). These composites, which may or may not be biodegradable or compostable, are produced from renewable sources such as plants, algae, animals, and agricultural by-products (Arias, 2025). This definition remains prevalent in recent literature and forms the basis for how bio-composites are understood in this work.

Additionally, a bio-composite can be considered sustainable when its life cycle performance, from raw material extraction to end-of-life management, demonstrates reduced environmental impact. According to Vilaplana et al., (2010) a bio-composite can be considered sustainable when:

Renewable and/or recycled resources are utilized for their manufacture;

The extraction, synthetic, modification, and processing operations are benign, energy- and cost-effective; No hazardous environmental or toxicological effects arise during any stage of their life cycle by emissions of degradation compounds, additives or fillers;

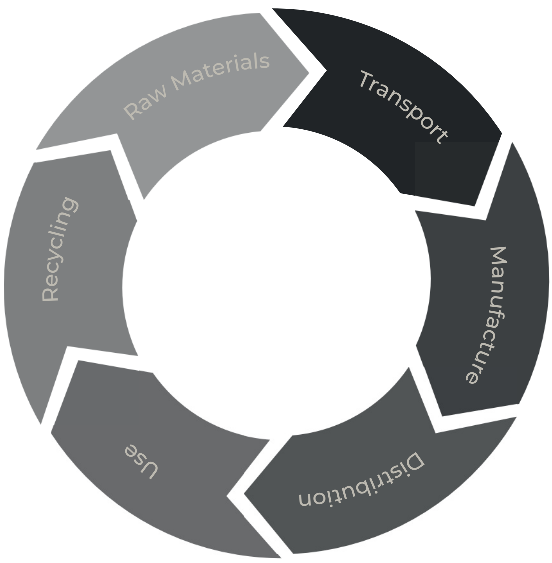

Figure 1. *Material life cycle of bio-based composites.*
Note. Created by author.

Their end-of-life strategies (recycling, composting, and incineration) are effectively considered and implemented to guarantee the return of the material and energetic value back to the cycles.

In some studies, the production of natural fiber-based composites showed to require significantly less energy than conventional synthetic composites, approximately 17% less energy (Banik, Dey, & Sastry, 2017), making them potentially more resource-efficient. Agricultural crops such as straw and natural fibers are particularly attractive as raw materials due to their abundance, low cost, recyclability, biodegradability, and favorable thermal properties (Ahmad et al., 2024). These qualities position bio-composites as key candidates for advancing circular and low-impact construction practices, provided that performance and durability requirements are also met. For this research, these aspects highlight not only the technical potential of bio-based composites, but also the need to document and evaluate their performance systematically.

1.1.2 Properties for construction

Bio-composites encompass a range of building materials such as hemp-lime composites, mycelium-based panels, straw bales, wood-fiber boards, cellulose insulation, sheep's wool, and bio-resin–reinforced natural fibers. Their thermal, acoustic, moisture, and mechanical performance depends on composition, manufacturing method, and application.

A key advantage of many bio-composites is their thermal insulation capacity. Hemp-based composites, for instance, typically show thermal conductivities between 0.08 and 0.2 W/(m·K), placing them among the most effective low-density insulating materials (Brzyski, et al., 2020). Experimental data from the LEC project report U-values as low as 0.119 W/m²·K for sheep's wool insulation in timber frame walls, 0.135–0.175 W/m²·K for cellulose in timber and steel frames, 0.162 W/m²·K for mycelium combined with CLT walls, and 0.224 W/m²·K for wood fiber insulation with CLT (Dams, et al., 2025). These values depend on wall thickness but indicate that bio-composites can meet or exceed energy-efficiency targets when properly integrated into building envelopes.

In addition to their thermal properties, many bio-based materials demonstrate effective acoustic absorption and moisture buffering, contributing to indoor comfort by regulating humidity and reducing the risk of condensation (Wendołowicz, et al., 2024). However, they also present draw backs such as limited moisture resistance, fiber/matrix incompatibility, supply logistic issues, flammability, complex processing, and highly variability in fiber properties (Andrew & Dhakal, 2022). Overall, these properties highlight both the potential and the limitations of these materials. Their ability to combine low thermal conductivity with moisture regulation enhances building performance, yet mechanical limitations, inconsistent production standards, and limited performance data continue to hinder wider adoption (Dams, et al., 2023).

1.1.3 Importance in construction sector

Potential as carbon reservoir

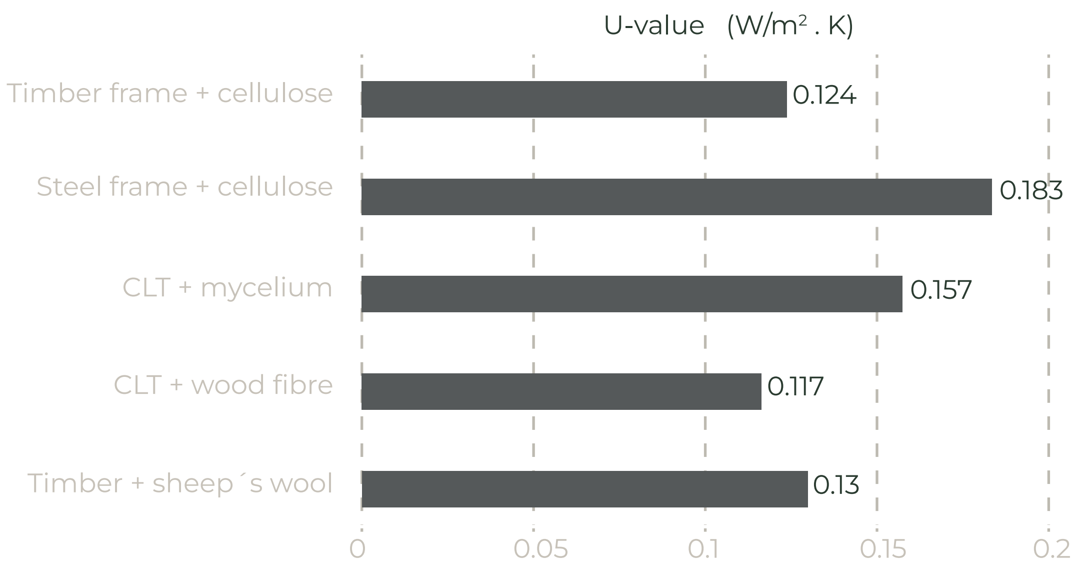

Figure 2. *Comparison of theoretical U-values for wall panels.*
Note. Created by author (Adapted from Dams et al., 2025).

Recent studies on global material flows reveal an unprecedented acceleration in material extraction and consumption since the early 21st century (Krausmann et al., 2018). This is not a short-lived spike: the trend that emerged around 2002 has persisted for over two decades, reflected in the parallel increase of waste generation and greenhouse gas emissions. Humanity has deposited or emitted an estimated 2,500 Gt of material waste into the global environment since 1900, remarkably, 28% of this occurred between 2002 and 2015 alone (Krausmann et al., 2018).

Projections indicate that between 2015 and 2050, the global population will grow by 34%, while the demand for crops will rise by 44%, forage by 95%, fossil energy carriers by 90%, and building-stock materials by nearly 194% (Krausmann et al., 2018). This translates into the extraction of 1,000 Gt of biomass and 4,100 Gt of fossil and mineral resources within just 35 years.

Building on these projections, Krausmann et al. (2018) estimated that such developments could increase cumulative CO_2 emissions by 53% reaching 542 Gt. This would exceed the remaining global carbon budget consistent with a 50% probability of limiting warming to 2 °C by approximately 30–132% (IPCC, 2014).

To realign the construction sector with climate goals, its annual emissions must fall by at least 16% by 2030 (IEA, 2019). Improving material efficiency alone could reduce future building material demand by 26% (Roijen et al., 2025). Moreover, construction materials offer an additional advantage: because they remain in use for decades, they can serve as long-term carbon reservoirs, delaying the release of sequestered greenhouse gases.

Recent scenarios illustrate the scale of change required. Measures such as replacing 10% of aggregate with carbonate-based aggregate, substituting 15% of brick with biomass fibers, fully transitioning to bio-based plastics, using bio-oil–based asphalt, and replacing 6–15% of cement with bio-char fillers by 2045–2090 could be sufficient to meet median targets for 1.5 °C and 2 °C pathways (Roijen et al., 2025). These findings make clear that transforming material systems is not optional but indispensable. Bio-based materials must be understood as more than an ecological alternative, but as an active tool for carbon storage and emissions reduction within the construction sector.

Challenges and opportunities

Despite their potential to store carbon and reduce environmental impacts, bio-based materials face several barriers to large-scale adoption in the construction sector. These challenges can be grouped into four categories: economic competitiveness, technical performance, validation and certification, and socio-cultural acceptance.

Economic barriers are significant, as competitive pricing of conventional materials continues to limit the market entry of bio-based alternatives, as does the lack of established value chain for their large-scale production and distribution (Roijen et al., 2025). Overcoming these systemic issues requires both market incentives and coordinated policy support.

From a technical standpoint, researchers emphasize that sustainable bio-composites must remain structurally and functionally reliable while using environmentally benign synthesis and modification processes (Vilaplana et al., 2010). Ensuring appropriate end of life strategies, such as recycling, composting, or energy recovery through incineration, is equally critical. However, these goals are difficult to achieve because bio-polymeric matrices and natural reinforcements often degrade or lose performance under thermal processing, limiting recyclability (Vilaplana et al., 2010). Validation and certification also present major challenges, as existing construction standards are primarily designed for conventional materials and rarely accommodate the specific characteristics of bio-based products.

Addressing these issues calls for more comprehensive life-cycle assessments to clarify environmental impacts from production to disposal. Collaborative efforts among researchers, industry stakeholders, and policymakers are critical to drive innovation and establish the standards required for widespread adoption (Zhao et al., 2020 As cited by Arias, 2025).

Beyond technical and economic consideration, opportunities for bio-based materials also depend on social and experimental dimensions. Materials that evoke empathy for natural environments or create new sensory experiences, can also add value (Sayuti & Ahmed-Kristensen, 2020). Yet incorporating such subjective qualities into material selection remains challenging because they are highly context-dependent (Arias, 2025). This highlights the need to move beyond conventional decision-making frameworks that prioritize cost and performance.

Emerging concepts such as material biography, which link a material's functional properties with its cultural, historical, and environmental narratives, offer new ways to frame material identity and foster broader acceptance of sustainable options (Rognoli et al., 2022) Similarly, decision-making tools that integrate visual rating scales, cost indicators, and detailed material comparisons, can help non-specialists understand trade-offs and benefits more effectively (Arias, 2025). Improving usability, communication, and cultural relevance is just as essential as advancing technical performance.

This thesis builds on that premise by investigating how Digital Product Passports can serve as a framework to communicate material properties, life-cycle performance, and circularity potential, supporting informed decision-making for bio-based materials in construction.

HEMPCRETE

Hempcrete is a bio-composite material composed of the woody core of the hemp plant (shiv) mixed with a lime-based binder. Due to its comparatively low ecological footprint across its life cycle, it has gained increasing attention in both academic research and industrial production (Steyn et al., 2025). The material embodies the main opportunities and challenges of bio-based construction (Dams, et al., 2023), making it an ideal case study for exploring how performance, usability, and circularity can position hempcrete as a viable alternative to conventional building materials, even when used as a non-load-bearing, non-structural component (Asghari & Memari, 2024).

1.2.1 Biological Background

The hemp plant

Hemp is the generic term for the fiber and grain derived from Cannabis sativa, a plant characterized by its low levels of tetrahydrocannabinol (THC), the primary psychoactive compound in marijuana (The AGRICOLA group, 2008). It is one of the oldest cultivated crops, with evidence of use spanning over 5,000 years. However, production declined in the twentieth century when it became a forbidden crop. Hemp cultivation briefly revived during the Second World War, and today active seed-breeding programs continue in only a few European countries.

Known for its versatility and rapid growth, hemp can reach heights of one to five meters within a cropping cycle of just 90–120 days (Steyn et al., 2025). As a dicotyledonous angiosperm, its anatomical structure comprises a root system; stalk, leaves, and flowers. The stalk is the primary source of industrial fiber, and consists of six distinct layers: starting from the innermost pith surrounding the hollow core, followed outward by the xylem, cambium, phloem (or parenchyma), cortex, and the outermost epidermis. Within this stalk, two main components are of industrial significance: the bast (long, strong fibers) and the hurd/shiv (woody core), each serving different applications (Steyn et al., 2025).

Figure 3. *Structure of the hemp plant.*
Note. Created by autor (adapted from Steyn et al., 2025).

This study focuses on the hurd, also referred to as the primary xylem or woody core, located inside the vascular cambium of the stem. These short fibers, typically no longer than 0.5 mm (Bócsa & Karus, 1998), occur in bundles mixed with the bast, of 10 to 40 cells running longitudinally from root to tip. Chemically, the hurd is composed primarily of cellulose, hemicellulose, and lignin, which together comprise the properties essential for composite applications.

Cellulose, which represents approximately 44–55% of hemp hurd, gives tensile strength and contributes to hempcrete's insulating capacity due to its porosity. Hemicellulose (16–18%) binds the fibers and aids in moisture regulation, while lignin (4–28%) provides compressive strength and resistance to decay, while extractives influence color, odor, and durability. (Asghari & Memari, 2024)

In recent years, the industrial value of hemp hurd has increased due to its high absorbency, low dust production, thermal insulation, and antibacterial properties, making it an increasingly attractive material for bio-composites (The AGRICOLA group, 2008).

Lime-based binder

The binder plays a crucial role in hemp composite production, determining both the mechanical and environmental performance of the composite. As Hirst (2013) explains, "Binders create a connective matrix between the shiv particles whilst also providing fire and fungal protection. Once hardened in the composite material, the binder matrix also provides the primary load path through which compressive stresses can be transmitted"

Lime, derived from quarried limestone (naturally occurring calcium carbonate, $CaCO_3$), is widely used as a binder in hempcrete due to its compatibility with hemp particles, broad availability, and comparatively low emissions during manufacturing (Asghari & Memari, 2024). To be used as a binder, limestone must undergo calcination in a kiln, transforming $CaCO_3$ into calcium oxide (CaO), commonly known as quicklime, while releasing CO_2 (Steyn et al., 2025).

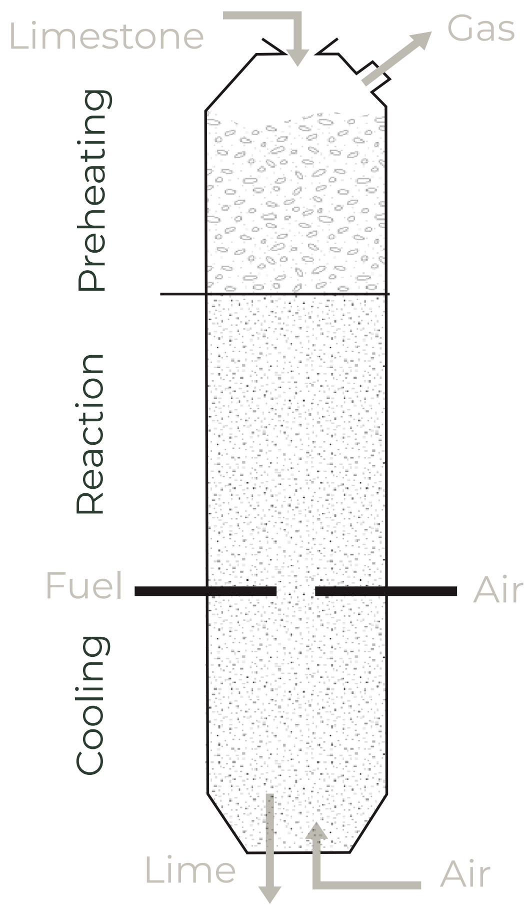

Figure 4. *Schematic of normal shaft kiln for limestone calcination.*

Note. Created by autor (adapted from Hertz et al., 2015).

In hempcrete production, different lime-based binders may be employed, including hydrated lime and hydraulic lime. As summarized in the comprehensive review by Steyn et al. (2025), hydrated lime is produced by slaking quicklime (adding controlled amounts of water to induce an exothermic reaction) resulting in calcium hydroxide ($Ca(OH)_2$). Because hydrated lime hardens by absorbing CO_2 from the air, it is referred to as an "air lime" (Stanwix & Sparrow, 2014 as cited by Steyn et al., 2025). When applied in hempcrete, mortar, or plaster, carbonation occurs: atmospheric CO_2 is absorbed into the binder, converting $Ca(OH)_2$ back into $CaCO_3$ and completing the "lime cycle" (Hirst, 2013) This uptake of CO_2 partially offsets the emissions generated during lime decomposition.

Hydraulic lime, by contrast, sets through a chemical reaction with water in addition to carbonation. Its hydraulic properties allow thick hempcrete layers to gain strength more rapidly (Magwood, 2016 as cited by Steyn et al., 2025). Natural hydraulic lime (NHL) is produced by firing and slaking clay-bearing or siliceous limestone, yielding dicalcium silicate (Ca_2SiO_4) and calcium hydroxide ($Ca(OH)_2$) as primary mineral phases. When NHL reacts with water, hydration produces calcium silicate hydrates (C–S–H), providing early strength, while simultaneous carbonation converts $Ca(OH)_2$ to $CaCO_3$. NHL production occurs at lower firing temperatures (≈900–1100 °C) than Portland clinker formation (1450 °C), resulting in reduced CO_2 emissions and less environmental impact from mortar preparation (Asghari & Memari, 2024).

Although lime-based binders are most commonly used in hempcrete, alternative binders can be incorporated to enhance compressive strength. Examples include gypsum, magnesium hydroxide, and pozzolanic materials (Asghari & Memari, 2024).

1.2.2 Cultivation and Harvest

Industrial hemp is a fast-growing annual crop capable of producing high yields across a wide range of climates. According to The AGRICOLA group, (2008), cultivars typically reach heights between 2 and 4.5 m; seed cultivars are shorter and stockier, while fiber cultivars are taller and slenderer. Under favorable conditions, hemp completes its cropping cycle in 90–120 days, with fiber-only applications allowing harvest as early as 60–90 days after seeding. It is among the fastest-growing biomasses, producing approximately 6-10 tons per acre annually.

Well adapted to temperate regions, hemp requires minimal fertilization, irrigation, or plant protection products (Malabadi et al., 2023). Its dense canopy naturally suppresses weeds, and the crop demonstrates resistance to fungi and rodents, reducing or eliminating the need for herbicides (Hirst, 2013). When hemp is included in crop rotation, it can disrupt traditional disease cycles and provide favorable conditions for subsequent winter crops.

Following cultivation, hemp undergoes several processing stages before it can be used in bio-composites. Based primarily on the works of Ingrao et al. (2015), Steyn et al. (2025), and Malabadi et al. (2023), the process begins with seedbed preparation through plowing to a depth of 30–35 cm followed by rotary harrowing. Once mature, the stalks are cut and collected using conventional balers and arranged in windrows for dew retting. Retting, essential for loosening fiber bundles, can be performed by immersion in water for about 8–14 days or naturally in the field for 2–3 weeks, where microbial degradation separates the bast fibers from the woody core.

After retting, the stalks are scratched and decorticated to fragment woody core and separate, producing the cellulose aggregates used in hempcrete. The hurds are then cut into lengths ranging from 6 to 25 mm to meet construction specifications.

Although hemp generates large quantities of biomass, only around 30% consists of the long fibers traditionally used for textiles, leaving approximately 60% as stalk or shiv (Ingrao, et al., 2015). This surplus material often goes underutilized and may even be burned, resulting in both waste and lost economic value. Farmers also face uncertainty in securing consistent markets for their crops. While hemp is often promoted as having “30,000 uses,” industrial processors usually specialize in one single application, limiting broader valorization (Chloe Donovan from NBS, personal communication, 19 September 2025). These challenges highlight the need for integrated processing strategies that enhance resource efficiency and economic viability in hemp production.

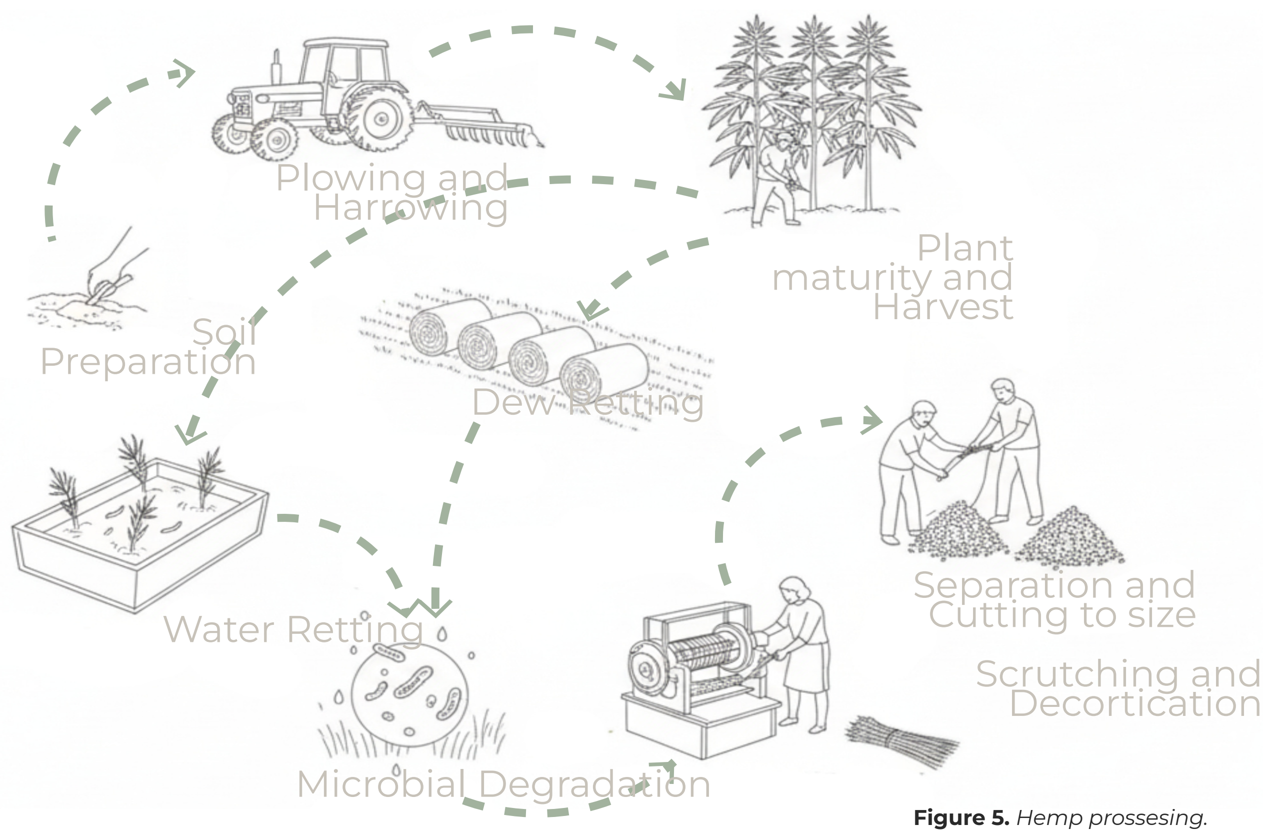

Figure 5. *Hemp prossesing.*
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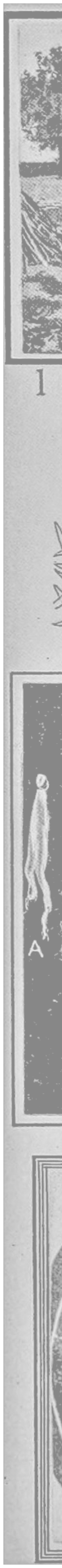

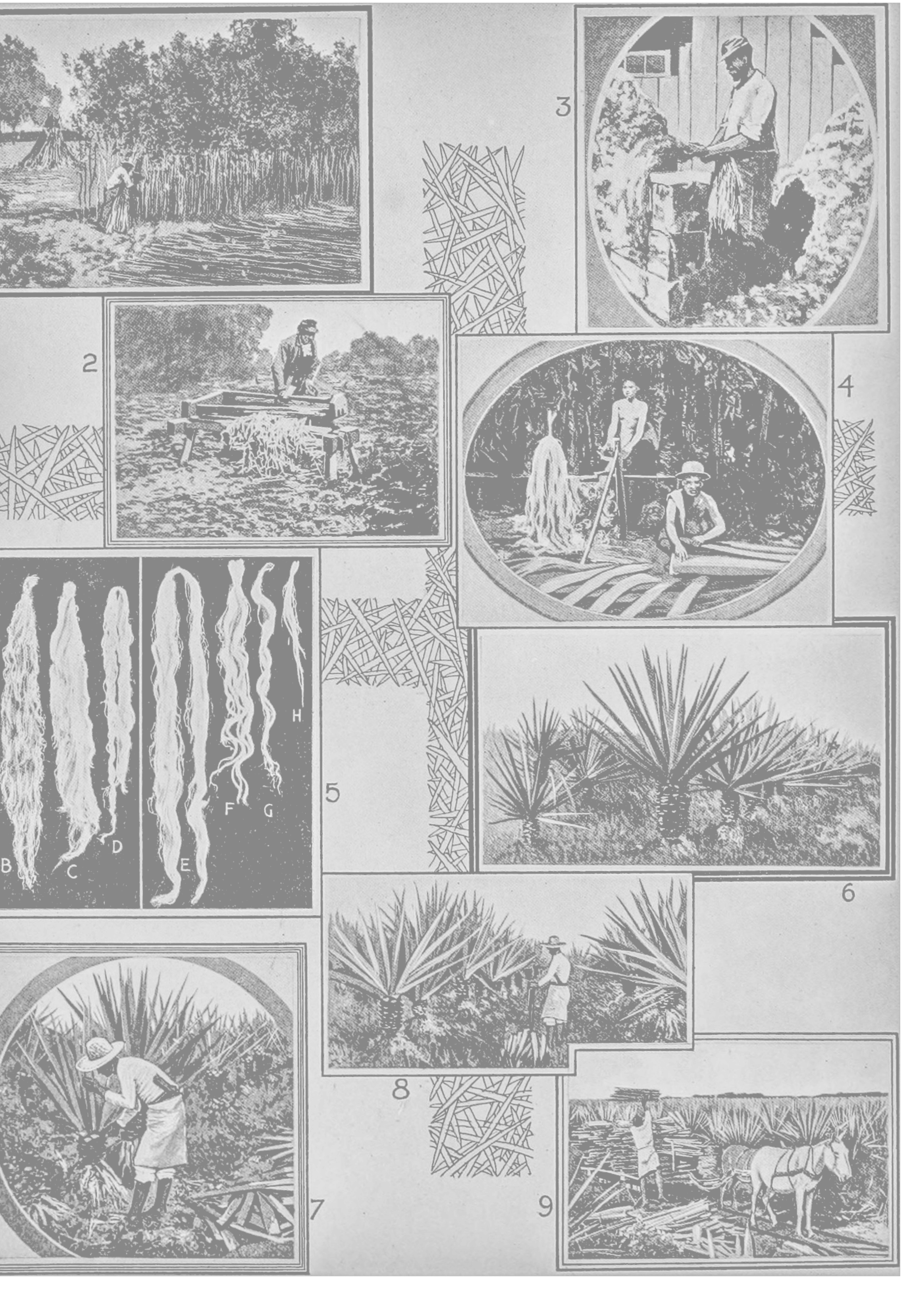
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1.2.3 Technical Properties

Structural

Density

Density is one of the properties that sets hempcrete apart from conventional materials like Portland cement concrete, which typically has a consistent density of around 2400 kg/m³. In contrast, the density of hempcrete is highly variable due to the lightweight, porous nature of hemp shives (Barbhuiya & Das, 2022). The material density depends on several factors, including shive size and porosity, binder content, compaction energy, and water content. Finer shives and higher binder content generally increase density (Pantawee et al., 2017). In-situ compaction is also essential, as hemp shives do not self-compact and may otherwise leave voids, compromising material performance (Jami et al., 2019).

According to Magwood, (2016 as reviewed in Steyn et al., 2025), very light mixes (150–200 kg/m³) are used for loose-fill insulation, where structural properties are not required, while roof insulation typically require densities between 200–250 kg/m³ (Asghari & Memari, 2024). Wall applications vary depending on the construction method: spray-applied hempcrete generally achieves 200–250 kg/m³, whereas cast-in-place reach 400–500 kg/m³, with typical hemp-to-binder ratios around 1:2 (Yadav & Saini, 2022). Higher-density formulations, ranging from 350–500 kg/m³ (Steyn et al., 2025) to 600-1000 kg/m³ when using maximum binder proportions (Yadav & Saini, 2022), are suitable for floors and sub-slab insulation, where greater compressive strength is required. Hirst (2013), identifies 220–330 kg/m³ as an optimal range for wall applications, offering a balance between insulation and structural performance.

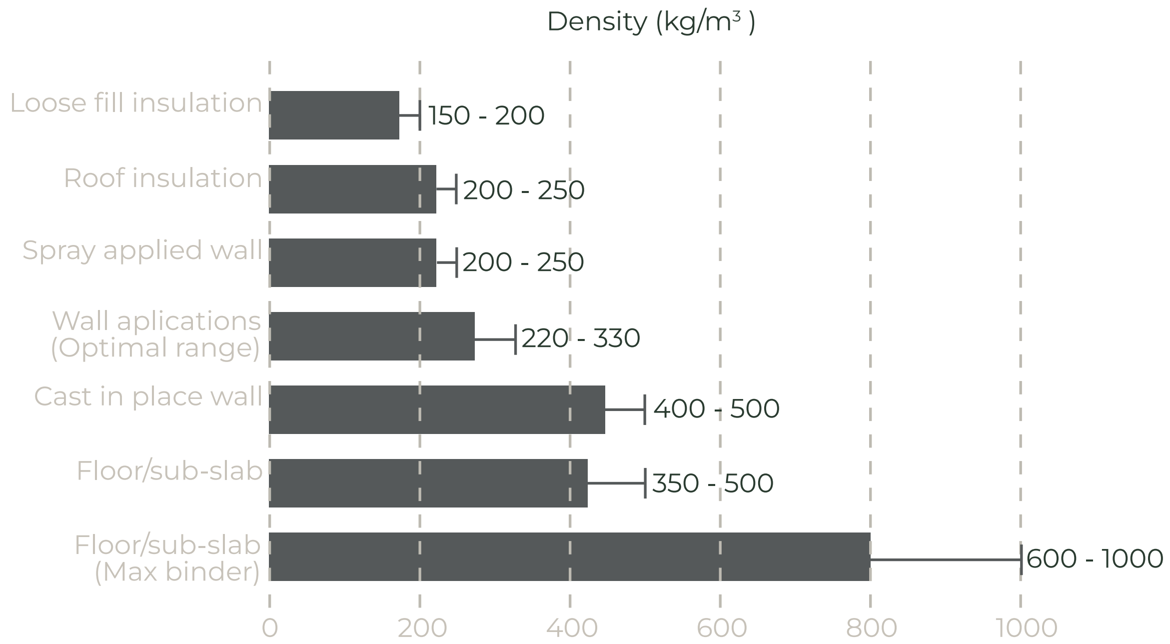


Figure 6. *Density of hemp-based materials.*
Note. Created by author(adapted from Steyn et al., 2025).

Compressive Strength

Hempcrete has low compressive strength and is therefore is considered a non-load-bearing material. Its highly porosity and the relatively weak adhesion between hemp shives and lime-based binder, account for its limited mechanical performance compared to conventional concrete (Steyn et al., 2025; Malabadi et al., 2023). Instead of failing by brittle fracture, hempcrete deforms gradually under load, as the hemp particles compress and exhibit elastic-like behavior (Asghari & Memari, 2024).

Reported compressive strengths by Steyn et al. (2025) and Asghari & Memari (2024), vary widely depending on mix formulation and curing conditions. Typical lime-based mixes range from 0.06 to 0.8 MPa, averaging around 0.25 MPa, with varied blends rising from 0.02–0.04 MPa at five days to 0.29–0.41 MPa after one year. Optimized or higher-density formulations reach 0.65-1.9 MPa, while Magnesium hydroxide ($Mg(OH)_2$)) based binders can achieve values near 2 MPa. Compared with other bio-based composites, hempcrete (≈0.48 MPa) performs better than rice husk (≈0.33 MPa) or sunflower bark (≈0.22–0.33 MPa) but remains below straw-based composites (≈3–4 MPa).

The maximum compressive strength of hempcrete rarely exceeds 3.5 MPa, far below structural concrete´s typical 17 MPa threshold (Asghari & Memari, 2024). Despite this limitation, its flexibility, energy absorption, and ductility make it suitable for non-load-bearing applications, particularly in building envelopes valued for their thermal, acoustic, and hygroscopic performance.

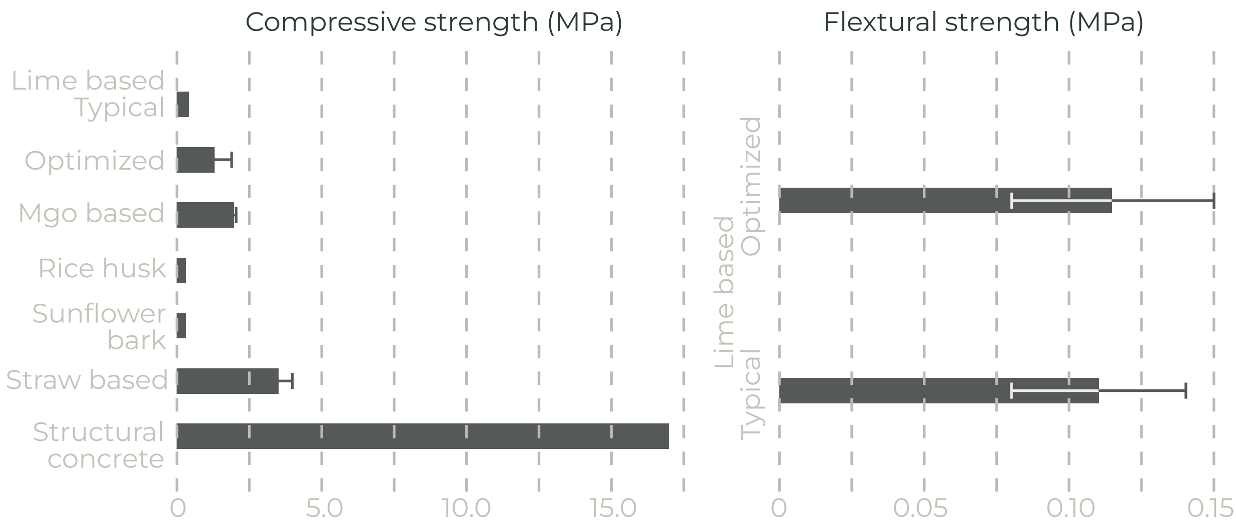


Figure 7. Compressive and flextural strenght of hemp-based materials.
Note. Created by author(adapted from Steyn et al., 2025).

Flexural strength

The flexural strength of hempcrete depends on the type and quantity of binder, the proportion and physical characteristics of hemp shives, and the degree of compaction during production (Brzyski, et al., 2020). Reported values typically range between of 0.08 to 0.15 MPa. (Steyn et al., 2025; Brzyski, et al., 2020). For example, lime–hemp composites with 20% hemp shives and densities around 600 kg/m³ achieve values between 0.08 and 0.141 MPa.

However, durability studies indicate flexural strength decreases when subjected to cyclic wetting and drying, over time (Sassoni et al., 2015). Medium-density hempcrete (≈640 kg/m³) can lose nearly 49% of its flexural strength under accelerated aging conditions, while high-density specimens (≈1210 kg/m³) showed minimal reductions of about 6%, suggesting that greater density improves long-term performance.

Non-structural

Acoustic

According to Vontetsianou (2023), the acoustic performance of hempcrete results from its micro- and macro-porous structure. While the proportion of hemp shives influences absorption, the binder type often plays an even stronger influence on acoustic behavior, particularly when comparing clay and lime-based hempcrete formulations (Steyn et al., 2025). Lime-pozzolan binders improve acoustic absorption compared to more hydraulic binders (Vontetsianou, 2023), while hemp–clay mixtures, due to their denser binder, provide higher air resistance (Asghari & Memari, 2024). Specimens with smaller hemp shives and produced with smaller hemp shives and lime-pozzolanic binders also perform better acoustically. Surface permeability and texture further influence the sound absorption coefficient, which can range between 0.3 and 0.9 depending on formulation and frequency (Asghari, et al., 2024; Steyn et al., 2025).

Wall thickness is another key variable in acoustics. Panels under 20 cm thickness exhibit absorption peaks at lower and mid frequencies (below 400 Hz and 1200 Hz, respectively), while thicker walls shift performance toward lover frequencies (Kinnane et al., 2016). Environmental exposure and aging may also influence long-term acoustic stability. Some studies reported no significant difference in specimens subjected to wetting and drying cycles, as the resulting changes in porosity and density were not substantial enough to alter sound absorption, whereas others observe reductions in performance due to lime-induced mineralization of hemp pores caused by slaked lime diffusion (Steyn et al., 2025). Unrendered hempcrete walls can absorb 40–50% of incident sound, with average noise reduction coefficients (NRC) near 0.69, outperforming many conventional materials (Kinnane et al., 2016).

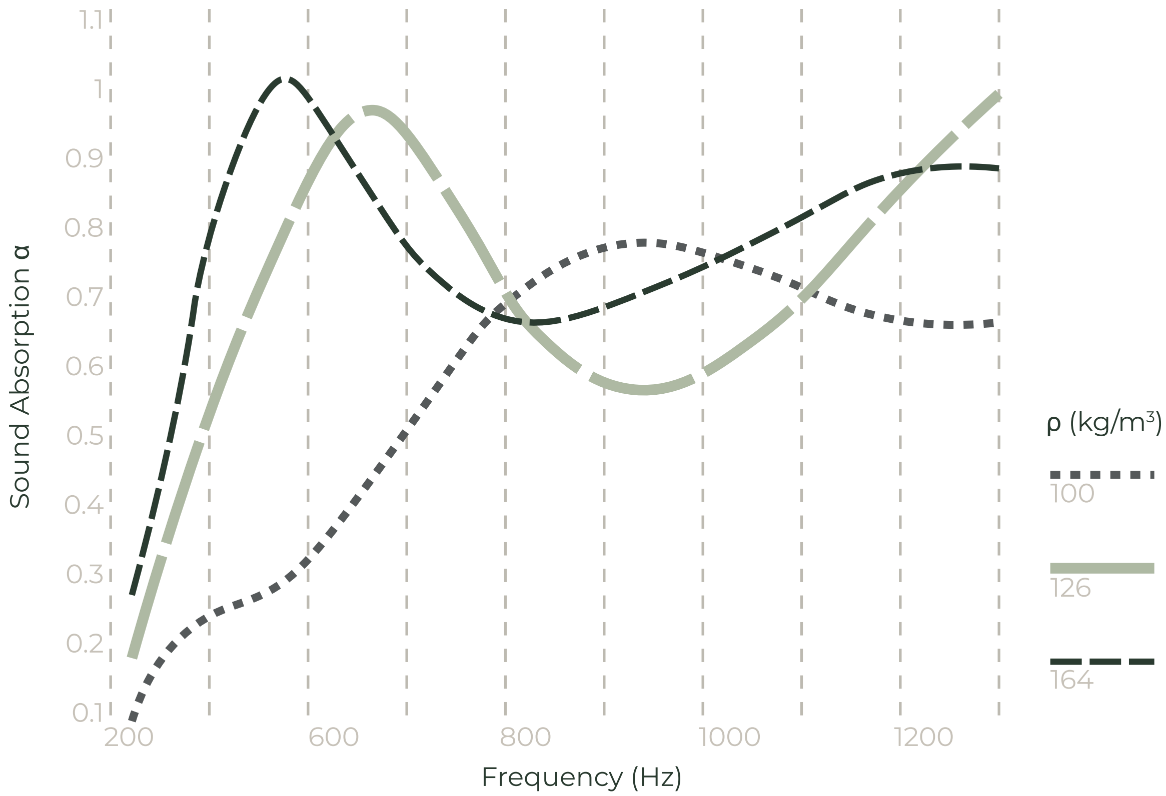


Figure 8. *Sound absoption characteristics of loose hemp shiv, for different levels of compaction.*
Note. Created by author(adapted from Kinnane et al., 2016).

1.2.4 Thermal Performance

Thermal performance distinguishes hempcrete from conventional construction materials. Reported thermal conductivity values range between 0.051 W/mK and 0.22 W/mK, significantly lower than those of concrete (0.51–2.2 W/mK) and brick (0.426–0.62 W/mK) (Steyn et al., 2025). Density strongly influences thermal performance: low-density mixes (around 290–310 kg/m³) exhibit 8–13% lower conductivity than denser counterparts (320–336 kg/m³), and an increase from 300 kg/m³ to 500 kg/m³ can raise conductivity by approximately 54%, (Steyn et al., 2025).

Higher hemp content and reduced lime generally improve insulating performance, while binder type and additives also affect performance. Metakaolin slightly increases thermal conductivity (≈0.5%), Fluidized Bed Combustion (FBC) fly ash by around 6%, whereas crushed brick reduces it to around 0.093 W/mK at 318 kg/m³ (Janowska-Renkas et al., 2025). Natural hydraulic lime (NHL) mixes typically have lower densities and thermal conductivities (≈ 0.091 W/mK), though increasing the NHL proportion raises conductivity (Steyn et al., 2025).

The characteristics of the hemp shives and production method further influence performance. Finer shives increase thermal conductivity due to denser packing, while thicker ones reduce density and enhance insulation (Brzyski, et al., 2020). High compaction reduces porosity and can raise conductivity by up to 68%, whereas delignification treatments may lower it by up to 32%. Thermal behavior is also anisotropic, with conductivity increasing by up to 30% when heat flows perpendicular to the compaction direction (Steyn et al., 2025).

Also, hempcrete exhibits high thermal mass and specific heat capacity (typically 1200–1600 J/kgK, up to 2062 J/kgK), allowing it to absorb, store, and gradually release heat, thereby stabilizing indoor temperatures and reducing energy demands for heating and cooling (Asghari & Memari, 2024). These properties yield measurable performance gains: hempcrete envelopes reduce overheating hours by 21.7% in Vancouver's temperate climate and 26.9% in Toronto's more extreme one, while also improving winter insulation (Steyn et al., 2025). In warmer climates such as France, its thermal inertia helps mitigate heat wave effects (Asghari & Memari, 2024).

1.2.5 Carbon Sequestration

In their review, Steyn et al., (2025) established that the carbon sequestration potential is a defining feature of the environmental performance of hempcrete. The material captures and stores atmospheric CO_2 through two complementary mechanisms: by the significant absorption of CO_2 during cultivation through photosynthesis, fixing between 1.5 and 2.1 kg CO_2e/kg hemp shives (Malabadi et al., 2023). and by continuing this process after incorporation into construction through carbonation, a process where atmospheric CO_2 reacts with calcium hydroxide, $Ca(OH)_2$, in the binder to form calcium carbonate, $CaCO_3$, thereby storing carbon in the hardened matrix. (Asghari & Memari, 2024). Depending on composition and curing conditions, the binder sequesters an additional 0.25 to 0.57 kg CO_2 per kilogram of material, offsetting emissions from lime production.

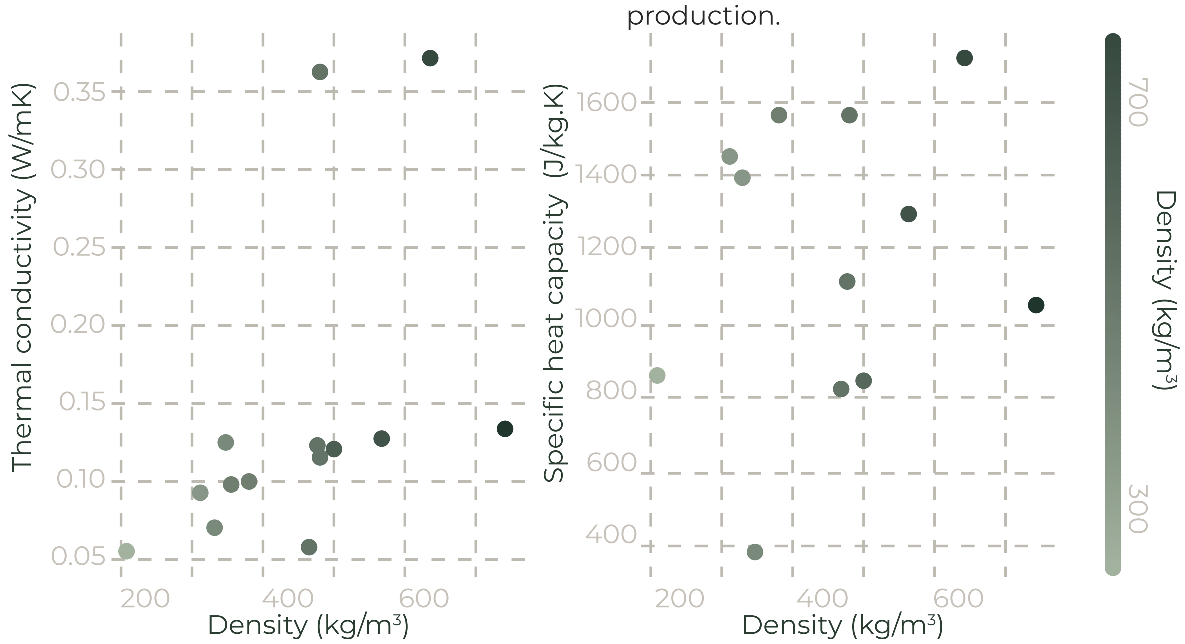


Figure 9. *Thermal performance of hemp-based materials.*
Note. Created by author (adapted from Dams et al., 2025).

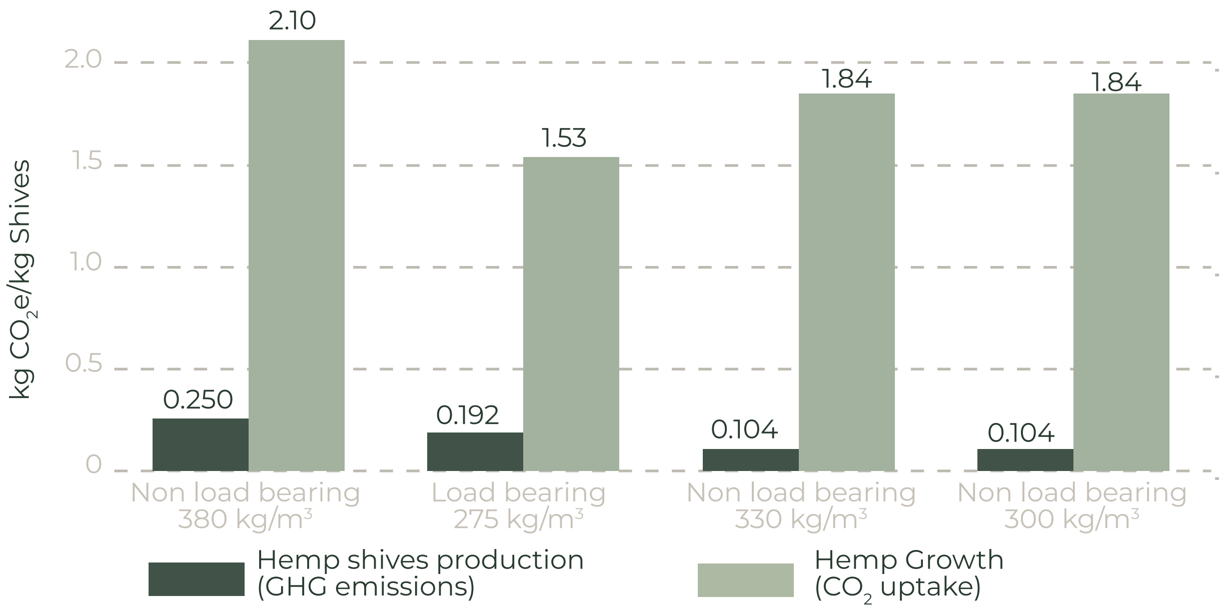


Figure 10. *Carbon sequestration potential of hemp-based materials.*
Note. Created by author(adapted from Dams et al., 2025).

Combined, these mechanisms enable hempcrete to achieve net negative emissions ranging from −0.3 to −1.0 kg CO_2 per kilogram of material (Asghari & Memari, 2024). At the building scale, hempcrete walls can store up to 82.7 kg CO_2e per square meter (Ip & Miller, 2012). Hirst (2013) demonstrated that mixes with higher water content achieved sequestration rates of about 19%, compared with 9% for drier formulations, indicating that mix composition strongly influences carbonation efficiency.

End-of-life management further determines whether sequestered carbon remains stored. Recycling or repurposing hempcrete, as crushed material for compost, backfill, or soil improvement, can preserve most of the captured carbon, while incineration or uncontrolled decomposition would release it (Hemp Carbon Standard, 2025). Comparative LCAs show that hempcrete achieves a net carbon balance approximately 10% better than autoclaved aerated concrete (AAC), with up to 17% lower embodied energy in non-load-bearing applications (Florentin et al., 2017). Conventional materials reach similar operational energy performance only through extensive insulation, which substantially increases embodied emissions (Essaghouri & Li, 2023).

However, sequestration results vary with hemp variety, cultivation methods, and climatic conditions (Bouyer, 2008; Hirst, 2013). The carbonation rate also depends on binder chemistry, porosity, render thickness, and exposure time, and remains difficult to quantify precisely. Further research is needed to assess sequestration across different agricultural sources and to examine material behavior during degradation and recycling at end of life.

1.2.6 Durability

Durability is essential to evaluate hempcrete's long-term performance and reliability. As with most bio-based composites, its behavior over time is influenced by factors such as moisture exposure, mechanical stress, thermal variation, and biological activity. Understanding how hempcrete responds to these conditions is essential for ensuring reliability, user safety, and material longevity.

Resistance to moisture

Hemp particles are hygroscopic, tending to absorb water vapor, while the high porosity of hemp shives further contributes to water uptake (Pantawee et al., 2017). This moisture sensitivity is one of hempcrete's main drawbacks, as excessive water retention can lead to swelling, bio-decay, and mechanical degradation (Malabadi, Kolkar, & Chalannavar, 2023).

The moisture performance of hempcrete is strongly influenced by the choice of binder. Natural hydraulic lime enhances vapor permeability while reducing liquid water absorption, thereby lowering the risk of bio-decay compared to aerated lime binders (Walker, 2013 as cited by (Steyn et al., 2025). Magnesium oxide (MgO) cements also show potential for lightweight composites due to their alkaline nature, which improves the interaction between the binder and hemp shives (Stevulova et al., 2015; Steyn et al., 2025). Additionally, alkaline pre-treatment of shives with sodium hydroxide (NaOH) can significantly reduce their hydrophilicity.

xperimental studies report variable water absorption rates depending on treatment methods. Specimens treated with aluminum sulphate ($Al_2(SO_4)_3$) and calcium hydroxide ($Ca(OH)_2$) show absorption levels between 14.5% and 16.5% (Pantawee et al., 2017). Despite these improvements, hempcrete remains highly absorbent and must be protected from prolonged dampness through adequate ventilation and proper detailing to prevent bio-decay, salt crystallization, and freeze–thaw damage (Bevan & Woolley, 2008, as cited in Steyn et al., 2025; Yadav & Saini, 2022).

Shrinkage

According to Murphy et al., 2010 as reviewed by Steyn et al. (2025), hempcrete undergoes significant volumetric shrinkage during its drying and curing phase, specially within the first ten days after casting. This shrinkage occurs as excess mixing water evaporates and the binder undergoes chemical transformations such as hydration and carbonation. Due to its lightweight and highly porous structure, the shrinkage is generally uniform, preventing the formation of large or visible cracks despite the overall reduction in volume.

The type of binder used plays a more decisive role in shrinkage behavior than the proportion of hemp shives. Hydrated lime binders, which rely solely on carbonation for hardening, retain moisture longer and typically produce greater shrinkage because of their higher water-to-binder ratio. In contrast, pre-formulated mixes or natural hydraulic lime (NHL) binders undergo partial hydraulic setting reactions that stabilize the material earlier, reducing overall shrinkage (Murphy et al., 2010, as cited in Steyn et al., 2025).

Long term performance

According performance tests conducted out by Delannoy, et al. (2019), hempcrete under stable environmental conditions, 50 % relative humidity and 20 °C over a two-year period, demonstrates excellent dimensional and functional stability. Its thermal, acoustic, hydric, and mechanical properties remain largely unchanged, as do its microstructure and binder composition.

The mechanical response of hempcrete under accelerated aging is less consistent across studies. While some researchers report negligible variations (Delannoy, et al., 2019), others observe reductions of up to 51 % in compressive strength and 61 % in flexural or tensile strength (Steyn et al., 2025). These discrepancies are closely related to the density of the specimens, with higher-density hempcrete generally exhibiting greater resistance to strength loss (Sassoni et al., 2015).

Despite these variations, hempcrete is broadly recognized for its long-term durability (Asghari & Memari, 2024). Its service life is estimated at around 100 years, with progressive hardening and increased rigidity over time due to ongoing carbonation of the lime binder (Malabadi et al., 2023).

Resistance to Pests

Hempcrete demonstrates intrinsic resistance to insects, mold, and microbial attack, a property largely attributed to the alkaline nature of lime-based binders (Asghari & Memari, 2024). With a pH typically above 10, the lime matrix creates an inhospitable environment for fungi, bacteria, and insects, acting as a natural preservative for hemp shives.

Fire resistance

Hempcrete exhibits favorable fire-resistant properties, making it one of the most promising material for modern insulation applications, where fire safety has become a major area of research interest. Tests conducted by Janowska-Renkas et al. (2025) indicate that hempcrete does not ignite, produces minimal smoke, and releases no flaming droplets during combustion, achieving high ratings for smoke evaluation (usually between classes C and B according to EN 13501-1). Its heat release rate (HRR) and total heat release (THR) are significantly lower than those of conventional building materials, demonstrating a reduced potential for fire spread (Asghari & Memari, 2024). Fire resistance can be further improved through the addition of mineral modifiers such as fly ash from fluidized bed combustion (FBC) and metakaolin (Janowska-Renkas et al., 2025).

Self-healing

Hempcrete exhibits self-healing capacity driven by the continuous carbonation of its lime binder. As calcium hydroxide ($Ca(OH)_2$) within the matrix reacts with atmospheric CO_2, calcium carbonate ($CaCO_3$) precipitates within micro-cracks and pores, gradually sealing them over time (Janowska-Renkas et al., 2025). This natural process enhances the airtightness, reduces water permeability, and limits the migration of aggressive ions that could compromise durability.

The interfacial transition zone (ITZ) between the hemp particles and the lime paste is critical to durability. A dense and well-developed ITZ improves the mechanical integrity, reducing micro-crack formation and propagation according to (Janowska-Renkas et al., 2025). Optimizing binder composition, mix design, and curing conditions further enhances ITZ quality, ensuring that carbonation-induced sealing occurs on the matrix.

1.2.7 Standard and Building codes

Construction standards, together with the progressive development of hempcrete building guidelines (including the former French RP2C rules and their updated 2024 professional standards led by Construire en Chanvre) have been crucial in advancing hempcrete's acceptance within mainstream construction (Steyn et al., 2025 & Construire en Chanvre, 2024). Although testing protocols exist for individual constituents, there remains a lack of recognized national or international standards specifically focused on test procedures. This gap limits certification, market confidence, and large-scale implementation (Janowska-Renkas et al., 2025).

Hempcrete products must nonetheless comply with local and national building codes governing fire safety, structural integrity, and thermal and acoustic performance. For example, environmental performance is assessed under international such as ISO 14040 and ISO 14044, which define the framework for life cycle assessments (LCAs). Similarly, ASTM D6007-02 provides a method for measuring volatile organic compound (VOC) emissions, which is relevant when assessing indoor air quality impacts of hemp fiberboard and related products. In Europe, EN 15804 defines the product category rules for environmental product declarations (EPDs), ensuring hempcrete and relates bio-based products are documented consistently across life cycle stages.

LIFE CYCLE ASSESSMENT

Life Cycle Assessment (LCA) is a standardized methodology for evaluating the environmental performance of products, processes, and services across all stages of their life cycle, as defines by ISO 14040. It enables the identification and quantification of environmental impacts, providing a scientific basis for improving sustainability strategies. In the construction sector, LCA serves as a key tool for assessing the performance of bio-based materials and supporting designers and decision-makers in reducing carbon emissions and resource consumption.

1.3.1 Definition

Life Cycle Assessment (LCA) is a "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO 14040 and ISO 14044)

LCA provides a framework for comparing products, processes, or services across multiple environmental categories, with particular emphasis on Global Warming Potential (GWP), which measures the contribution of greenhouse gases to climate change in kilograms of CO_2 equivalent. The carbon footprint, closely related to GWP, is especially significant in the case of bio-based materials, as it considers not only emissions but also the potential for carbon sequestration (Araujo, Caldas, Hasparyk, & Filho, 2025). Embodied energy (EE), which accounts for the energy required to produce and process a material, and operational energy (OE), which reflects the energy consumed during its use phase, are also key indicators assessed within LCA studies. Other impact categories often considered include acidification potential (AP), eutrophication potential (EP), ozone depletion potential (ODP), photochemical ozone creation potential (POCP), as well as water scarcity and land use impacts.

The system boundary and the functional unit are essential components in structuring an LCA. The system boundary defines the extent of the analysis and determines which life cycle stages are included, ranging from cradle-to-gate (raw material extraction to the factory gate), gate-to-gate, cradle-to-grave (covering the entire lifespan including end-of-life), or gate-to-grave. The functional unit provides a quantified description of the product's primary function and serves as the reference for comparison across systems. In construction-related studies, it is often defined as one square meter of a wall system or one kilogram of material.

According to ISO 14040/44, the LCA methodology consists of four interconnected phases. The first phase, goal and scope definition, establishes main parameters of the study, including the functional unit, system boundaries, assumptions, limitations, and the selected impact categories. The second phase, life cycle inventory (LCI), involves collecting and quantifying all relevant input and output data, such as raw material use, energy consumption, emissions, and waste flows. The third phase, life cycle impact assessment (LCIA), translates inventory data into potential environmental impacts using established assessment methods and characterization factors. Finally, the interpretation phase synthesizes the results in relation to the defined goals, identifying key findings, limitations, and uncertainties, and may include sensitivity analyses to ensure robustness and reliability. (International Organization for Standardization, 2006).

The primary role of LCA is to reveal how materials and systems perform their life cycles, highlighting opportunities to reduce waste, extend service life, and improve reuse or recycling pathways. LCAs also provide a foundation for developing Digital Product Passports (DPPs), ensuring that their environmental performance is transparently documented and integrated into strategies that support material circularity.

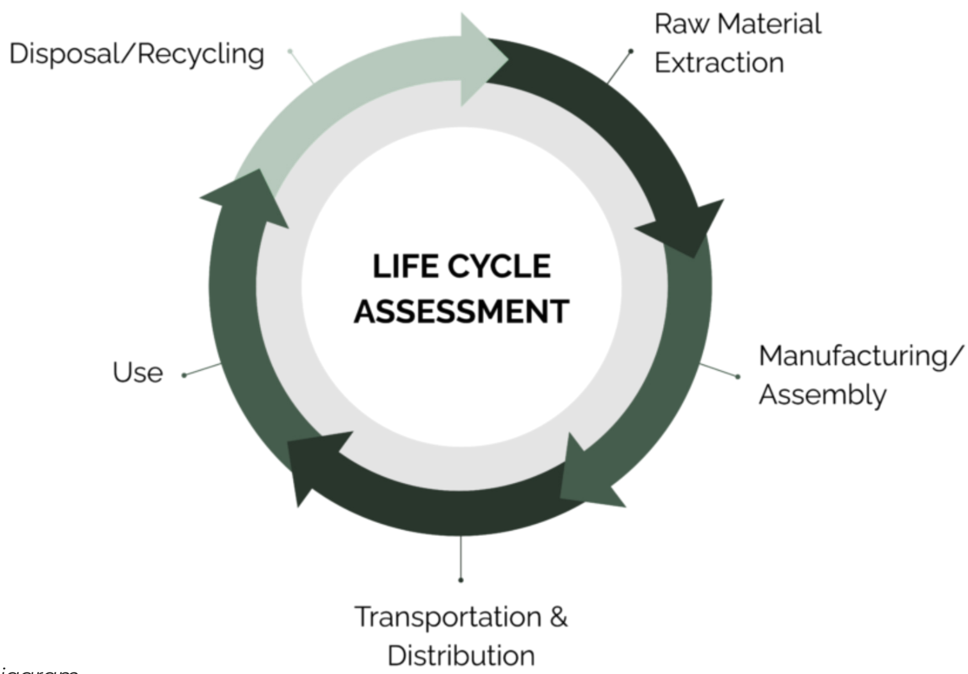


Figure 11. *LCA diagram.*
Note. Reprinted from Life Cycle Assessment Explained, by M. Eckelman & S. Nunberg, 2023, Sustainability Tools in Cultural Heritage. https://stich.culturalheritage.org/life-cycle-assessment-explained/.

1.3.2 Regulation

At the international level, ISO 14040 and ISO 14044 establish the principles, framework, and requirements for conducting LCAs. These standards define goals and scopes, LCI, LCIA, and interpretation phases (International Organization for Standardization, 2006). They also acknowledge that assumptions made during an LCA, such as system boundaries, data sources, and selected impact categories, introduce degree of subjectivity. Therefore, comparisons between different LCA studies are only valid if conducted under identical assumptions and contexts, which must be explicitly stated. Importantly, ISO standards caution against reducing LCA results to a single aggregated score, as this can obscure trade-offs bewteen impact categories.

Complementary standards such as ISO 14041, 14042, and 14043 provide additional methodological detail for specific LCA phases. ISO 15686-5 expands the scope of sustainability assessment through Life Cycle Costing (LCC), while ISO 14001 defines requirements for environmental management systems, enabling manufacturers to demonstrate compliance beyond product-level evaluations (Hemp Carbon Standard, 2025).

ISO 21930 establishes the international framework for assesing the sustainability of construction products and defines the structure that Environmental Product Declarations (EPDs) must follow. However, this standard has been criticized for its mandatory static “−1/+1” treatment of biogenic carbon, which ignores the temporal benefits of carbon sequestration that may lead to counterproductive design strategies from a climate perspective (Chilton, Arehart, & Hinkle, 2025).

At the European level, EN 15804 serves as the Core Product Category Rule (PCR) for construction products, harmonizing LCA methodologies and supporting broader EU sustainability objectives. It provides the basis for EPDs in the construction sector and applies a modular approach to life cycle stages: A1–A5 for production and construction processes, B for use, C for end-of-life, and D for benefits beyond the system boundary. EN 15978 complements EN 15804 by assesing the environmental performance of buildings as a whole, enabling a more systemic evaluation of construction practices.

Industry groups such as the U.S. Hemp Building Association (USHBA) and the International Hemp Building Association (IHBA) lobby for favorable regulation, promote the benefits of bio-based construction materials, and support related research with the aim to incentivize the adoption of environmentally friendly bio-based materials, or equally, control the use of traditional, high-emission materials (Chilton, Arehart, & Hinkle, 2025).

A persistent challenge in LCA and EPD regualtion lies in how existing standards require climate impact to be calculated and reported. As a result, many EPDs fail to provide realistic carbon footprint data for informed climate decision-making. As emphasized by an industry leader at the Material Matters 2025 conference in London, EPDs have, in many cases become a procedural formality: clients seldom engage with them in detail, and without standardized points of comparison, they offer limited insight into a product's true environmental performance. This limits their capacity to function as effective tools for guiding material choices in the construction sector.

1.3.3 Methods

There are different methodological approaches to Life Cycle Assessment (LCA) that have been developed to address diverse research objectives and decision-making contexts in construction. On one hand, attributional LCA describes the physical flows to and from a product system and its subsystems, typically using average data while excluding marginal effects (Ip & Miller, 2012). It provides a descriptive account of the environmental profile of a product or process under current conditions but does not capture potential changes resulting from alternative decisions. By contrast, on the other hand, consequential LCA examines the environmental consequences of a given decision by incorporating marginal data to assess those changes (Ip & Miller, 2012). This approach is particularly relevant for evaluating long-term systemic impacts but is often more data-intensive.

Standard "static" LCAs are widely applied but have notable limitations, especially regarding the treatment of biogenic carbon in bio-based materials. These models typically follow one of two approaches: the "0/0" method, which excludes biogenic carbon entirely, or the "−1/+1" method, which assumes that all biogenic carbon stored during the production stage is re-emitted at the end of the life cycle (Chilton et al., 2025). Both approaches oversimplify the temporal dynamics of carbon sequestration and release, potentially leading to misleading conclusions about the climate performance of bio-based materials. To address this, dynamic LCA methodologies have been proposed. By incorporating time-dependent inventories and characterization factors, dynamic LCA accounts for the timing of emissions and sequestration, offering a more accurate representation of climate impacts and a stronger basis for material comparison and decisions in constructino (Chilton et al., 2025).

Lastly, Life Cycle Sustainability Assessment (LCSA) provides an interdisciplinary framework that evaluates environmental, social, and economic dimensions simultaneously (Figueiredo et al., 2021). LCSA integrates three complementary methodologies: Environmental Life Cycle Assessment (LCA), Social Life Cycle Assessment (S-LCA), and Life Cycle Costing (LCC). Although LCSA remains less developed than traditional environmental LCA due to challenges in data availability and methodological consistency, its emergence reflects a broader effort to enhance life cycle methodologies and integrate additional dimensions of sustainability assessment.

1.3.4 LCA of Hempcrete

Several academic studies have conducted LCAs of hemp-based construction materials, revealing considerable variation in their results. These differences arise from variations in study scope, selected functional units, system boundaries, geographic contexts, and the specific LCA methodologies applied. Such methodological choices strongly influence the reported indicators, meaning that direct comparison of results across studies can be misleading unless differences are explicitly identified and normalized.

For the purposes of this thesis, the review of existing LCAs serves to establish the state of art and highlight the extensive researcg already conducted on LCAs of hemp-based materials. Six representative LCA studies of hemp-based products were selected, covering different material types, climatic conditions, and methodological approaches. This comparative baseline enables Digital Product Passport (DPP) to position the case-study material within a broader research and practice context, highlight methodological sensitivities and promote transparency.

When these six studies are compared, expressed as net GWP per square meter hempcrete wall, the values vary from highly

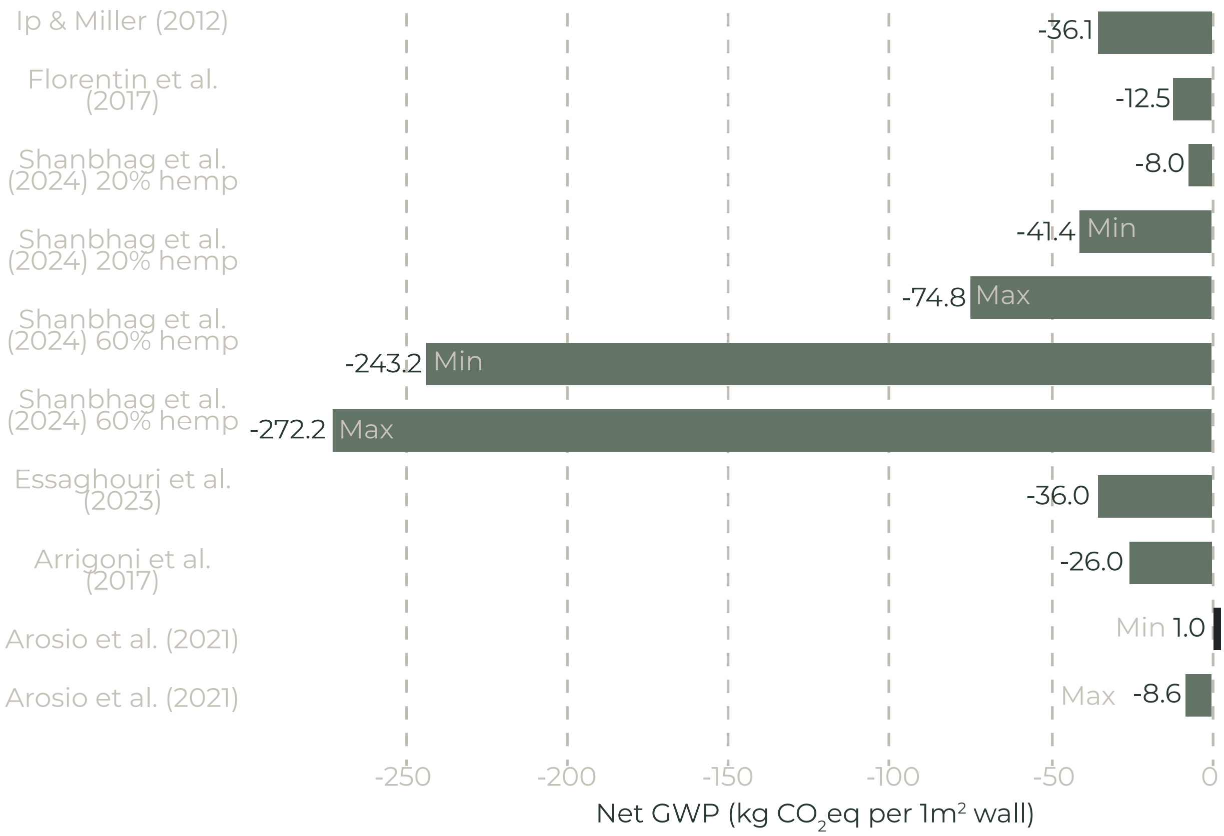


Figure 12. *Comparison of theoretical U-values for wall panels.*
Note. Created by author (Adapted from Dams et al., 2025).

Study (year) - type	Location	LCA type	Thickness (cm)	Net GWP normalized (kg CO_2-eq per 1 m² wall)	Key notes
Essaghouri, Mao & Li (2023) In-situ hempcrete	Marrakech, Morocco (hot semi-arid)	LCA: pre-use + use	30	**−36.05** (embodied carbon) ~19% hemp by wet mass	Derived from −9.88 t CO_2 for 274.06 m² of wall Hemp equivalent to ~38% of dry constituents
Arrigoni et al. (2017) Prefabricated hemp blocks	Northern Italy (temperate)	Attributional LCA, cradle-to-use (use carbonation)	25	**−26.01** (after full carbonation) ~25% hemp by wet mass	Experimental carbonation Hemp equivalent to ~43% of dry constituents
Arosio, Moletti & Dotelli (2022) Prefabricated hemp blocks	Italy	Attributional LCA, EN15804 A1–A5 + B1 (use carbonation)	20	**+0.99** to **−8.63** (net range) ~18% hemp by wet mass	Results sensitive to transport, carbonation depth , and 60-year service life Hemp equivalent to ~33% of dry constituents
Ip & Miller (2012) In-situ hemp-lime	UK (temperate)	Attributional LCA, cradle-to-gate	30	**−36.08** (includes sequestration & lime re-carbonation) ~20% hemp by wet mass	Excludes operational and end-of-life phases Hemp equivalent to ~40% of dry constituents
Florentin et al. (2017) Cast hempcrete (apartment scale)	Israel (arid)	LCA/LCEA/ $LCCO_2A$; pre-use + use discussed	22	**−12.5** (embodied carbon) **+937.5** (operational) ~15–20% hemp by wet mass	Approximation from −1 t CO_2 per apartment / 80 m² walls 25–35% hemp dry mass (% not reported but mix stated to follow recommended ratios from Allin, 2012)
Shanbhag, Dixit & Sideris (2024) Mix design study	USA (Kentucky, variable)	Process-based hybrid LCA, cradle-to-gate	30	10% hemp **−7.95** 20% hemp ≈ **−41.4 to −74.8** 60% hemp ≈ **−243.2 to −272.2**	Results adjusted to 1 m² × 0.3 m wall from original funtional unit (1ft³)

Table 1. *Summary of Life Cycle Assessment (LCA) results for hempcrete wall systems, normalized to 1 m² of wall area.*

Note 1. Created by author (Adapted from Essaghouri, Mao & Li (2023); Arrigoni et al. (2017); Arosio, Moletti & Dotelli (2022) Ip & Miller (2012); Florentin et al. (2017); Shanbhag, Dixit & Sideris (2024)).

Note 2. Most studies (five of the six reviewed) already reported results using 1 m² of wall as the functional unit, although the original wall thickness varies between 20 and 30 cm. For comparability, all values were normalized to 1 m² of wall. A mass-based functional unit (1 kg of material) was not adopted because density also varies significantly across studies, and the assessment focuses on hempcrete as a wall system rather than as a bulk material.

negative to almost neutral, reflecting both methodological and contextual aspects. The most favorable outcome is reported by Shanbhag, Dixit, & Sideris (2024) with a 60% hemp mix in the United States for extremely high carbon sequestration rates: -243 to -272 kg CO_2e/m^2. On a much smaller but still significant scale, comparable balances around -36 kg CO_2e/m^2 were provided by Essaghouri, Mao, & Li (2023) in Morocco and Ip & Miller (2012) in the United Kingdom, demonstrating that in-situ hempcrete can be a solid carbon sink across diferent climates.

Prefabricated systems perform not as well. Arrigoni, et al. (2017) in Italy report results ranging from −12.1 to −26.0 kg CO_2e/m^2 depending on carbonation assumptions, while Arosio, Moletti, & Dotelli (2022) find an almost neutral balance (≈ +1 kg CO_2e/m^2) largely due to transport burdens and conservative treatment of carbonation. At the building scale, Florentin et al. (2017) in Israel, show that even though hempcrete walls may have embodied emissions of approximately -12.5 kg CO_2e/m^2, this is easily outweighed by operational energy emissions in a hot-arid climate.

Overall, this comparison shows that under favorable boundary conditions, hempcrete provides a consistent net climate benefit. However, results still remain very sensitive to binder proportion, carbonation modeling, geographic context, and the inclusion or exclusion of the use stage.

1.3.5 Challenges

Data availability

Although environmental impact databases are relatively advanced, they remain incomplete in terms of geographical coverage, process specificity, and representativeness. In contrast, databases addressing social and economic impacts are far less developed, limitating the applicability of the LCSA (Figueiredo et al., 2021). The lack of reliable datasets, particualrly for the production phase, constrains holistic material evaluation. For example, in the case of hemp-lime walls in the United Kingdom, data accuracy was limited because construction companies do not typically record

LCA-relevant information, forcing researches to approximate energy use based on mannufacturer-supplied data (Ip & Miller, 2012).

Methodological inconsistencies

Standard carbon accounting practices often underestimate the contribution of fast-growing biogenic materials by ignoring the temporal dynamics of carbon uptake and release. This static treatment reduces complex climate ***dynamics*** to simplified assumptions, often labeling materials as “carbon-neutral” without reflecting their actual climate impact (Chilton et al., 2025). The disposal or recycling of hemp-based building products has also a decisive impact on overall results, as decomposition or incineration releases the carbon stored during the use back into the atmosphere. Failure to properly account for the end-of-life scenarios introduces inaccuracies and risks double counting, particularly when carbon is allocated across interconnected product systems (Hoxha, et al., 2020).

Comparability

LCA studies differ widely in assumptions and methodological choices, making direct comparison challenging (International Organization for Standardization, 2006). Key variations include the definition of the functional unit (like 1 m^2 wall versus 1 m^3 material), system boundaries (cradle-to-gate versus cradle-to-grave), and the time horizons. Material properties such as wall thickness, density, coating, and U-value also vary across studies, as do construction methods, whether hempcrete is cast in place, sprayed, or used as prefabricated blocks (Arrigoni, et al., 2017). Differences in binder-to-hemp ratios, crop yields, transport distances, and carbonation assumptions further complicate meaningful comparison (Essaghouri et al., 2023). As a result, the existing literature remains fragmented, with results highly context-dependent and difficult to generalize.

CIRCULAR ECONOMY

The circular economy (CE) is central to the transition toward sustainable construction, aiming to minimize waste and extend material life through reuse and regeneration. In this context, bio-based materials play a key role as renewable, low-carbon alternatives capable of storing carbon. However, challenges such as durability, certification, and end-of-life management remain. Integrating digital tools like Building Information Modeling (BIM) supports circular design by enabling material tracking and facilitating reuse.

1.4.1 Definition

Acording to (Ellen MacArthur Foundation, 2021) "The circular economy is a system where materials never become waste and nature is regenerated. In a circular economy, products and materials are kept in circulation through processes like maintenance, reuse, refurbishment, remanufacture, recycling, and composting. The circular economy tackles climate change and other global challenges, like biodiversity loss, waste, and pollution, by decoupling economic activity from the consumption of finite resources"

Principles

The Circular Economy is grounded in three core principles (Ellen MacArthur Foundation, 2021):

1. Eliminate waste and pollution: Design products to minimize waste from the outset, emphasizing durability, repairability, and recyclability while avoiding harmful substances.
2. Circulate products and materials: Extend product lifespan through maintenance, reuse, refurbishment, and recycling, prioritizing closed-loop systems that retain maximum material value.
3. Regenerate nature: Restore ecosystems and natural resources by using renewable energy and supporting regenerative production practices.

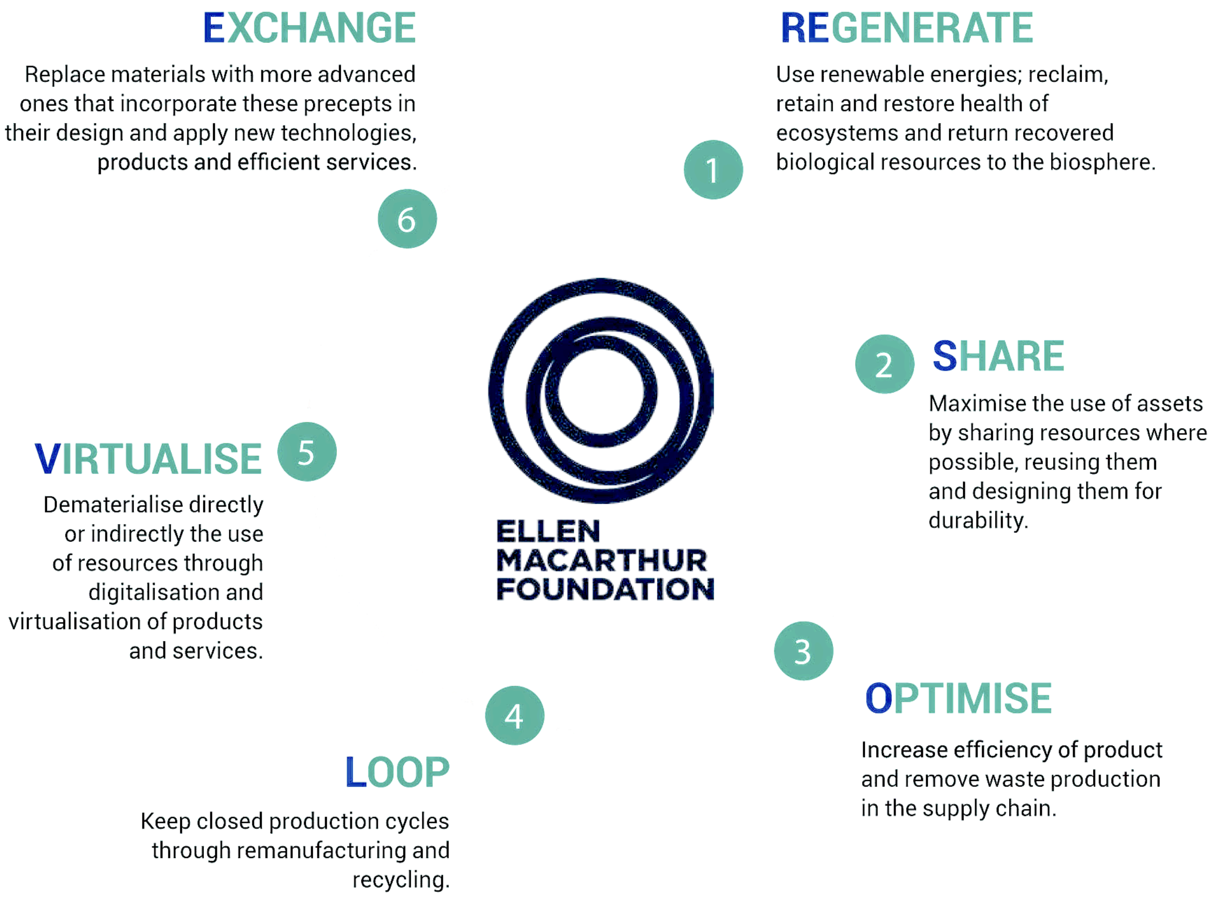


Figure 13. *The six principles of the circular economy as defined by the Ellen MacArthur Foundation.*
Note. Reprinted from Circular Economy: The 6 Principles, Ellen MacArthur Foundation. https://ellenmacarthurfoundation.org.

Additional design-oriented principles are proposed by the Circular Design Guidelines (Bajare, et al., 2025):

1. Foster collaboration: Encourage cooperation among industry, government, research, and communities to drive innovation and implement circular solutions.
2. Adopt a system perspective: Integrate all life cycle stages, with particular attention to end-of-life management.
3. Leverage digital technologies: Use tools such as IoT, data analytics, and blockchain to optimize resources, improve efficiency, and ensure transparency.

Sustainability vs Circularity

While sustainability and circularity share common concerns about technological, industrial, and consumption practices (Giarma, et al., 2025), they are not interchangeable. Sustainability is broadly defined by the triple bottom line of people, planet, and economy (Brundtland Report, 1987), whereas the Circular Economy focuses specifically on resource flows and material cycles (Giarma, et al., 2025).

Geissdoerfer et al. (2017) describe three possible relationships between sustainability and circularity: (1) Circular economy as a condition for sustainability, (2) a mutually beneficial relationship, or (3) a potential trade-off. Early CE studies often emphasized environmental improvements while overlooking social aspects, sometimes resultng in higher emissions from recycling processes than from new production. Achieveing balance therefore requires implementing CE within a broader sustainability framework to prevent rebound effects and ensure environmental, economic, and social coherence (Puma, et al., 2025; Santos, et al., 2025).

Circular materials

Circular materials are those designed with embedded circularity principles that enable them to be reused, repurposed, retrofitted, or recycled as a last resort. Rather than focusing solely on post-use processes such as collection or reprocessing, circular materials integrate strategies for durability, adaptability, and recovery from the design stage, extending their lifespan and reducing the need for virgin resources. (Pineda-Martos, et al., 2025) These materials are essential to achieving a circular economy by transforming traditional linear material flows into regenerative, closed-loop systems within the built environment.

The intrinsic circularity of materials can be explained as designing a set of high-quality, interchangeable building blocks for a growing city. Each block must be durable (long lifespan) and non-toxic (safe composition). Intrinsic circularity refers to the material's ability to be easily separated, identified through traceability systems, and reintegrated into new applications without losing its mechanical or aesthetic performance, ensuring that no component becomes waste.

In construction, circular materials can be grouped into three main categories according to their source and contribution to resource loops. Bio-based materials belong to the biological cycle and are derived wholly or partly from renewable sources such as hemp, straw, timber, flax, cork, or agricultural residues. They can also valorize waste streams, like rice husks, cassava peels, or cotton waste, into new construction products, offering both carbon storage and regenerative potential (Santos, et al., 2025).

Recycled and recovered materials belong to the technical cycle and originate from reclaimed resources such as metals, plastics, and concrete. Examples include recycled steel, copper, and recycled concrete aggregates (RCA), as well as waste-based composites and bricks made from demolition rubble or industrial by-products (Santos, et al., 2025). These materials reduce extraction of virgin resources and enable continuous material circulation at high value.

Finally, innovative and low/zero-carbon materials are engineered to actively contribute to circularity by extending durability or capturing carbon. Examples include biochar and emerging bio-mineralized or self-healing concretes. Advanced materials such as aerogels and nanocomposites also enhance strength and lifespan, supporting long-term material efficiency. (Pineda-Martos, et al., 2025).

Circular bioeconomy

The circular bioeconomy combines CE principles with the use of bio-based materials and processes to foster sustainability, resource efficiency, and climate change mitigation (Parlato & Pezzuolo, 2024) Its main strategies include:

- Valorization of Waste: Incorporating agricultural residues, municipal biowaste, and industrial by-products in applications such as bioenergy and construction, thus reducing emissions coming from poor disposal (Parlato & Pezzuolo, 2024; Le et al., 2025).
- Regeneration of Natural Systems: Design for bio-based materials to return safely to the biosphere through composting or anaerobic digestion, beneficial for soil health, ocean ecosystems, and carbon sequestration (Santos, et al., 2025; Mikulenas & Šeduikyte, 2025).
- Dual Benefits: Bio-based materials substitute non-renewable resources while storing biogenic carbon, reducing embodied emissions and contributing to climate resilience (Le et al., 2025; Mikulenas & Šeduikyte, 2025).

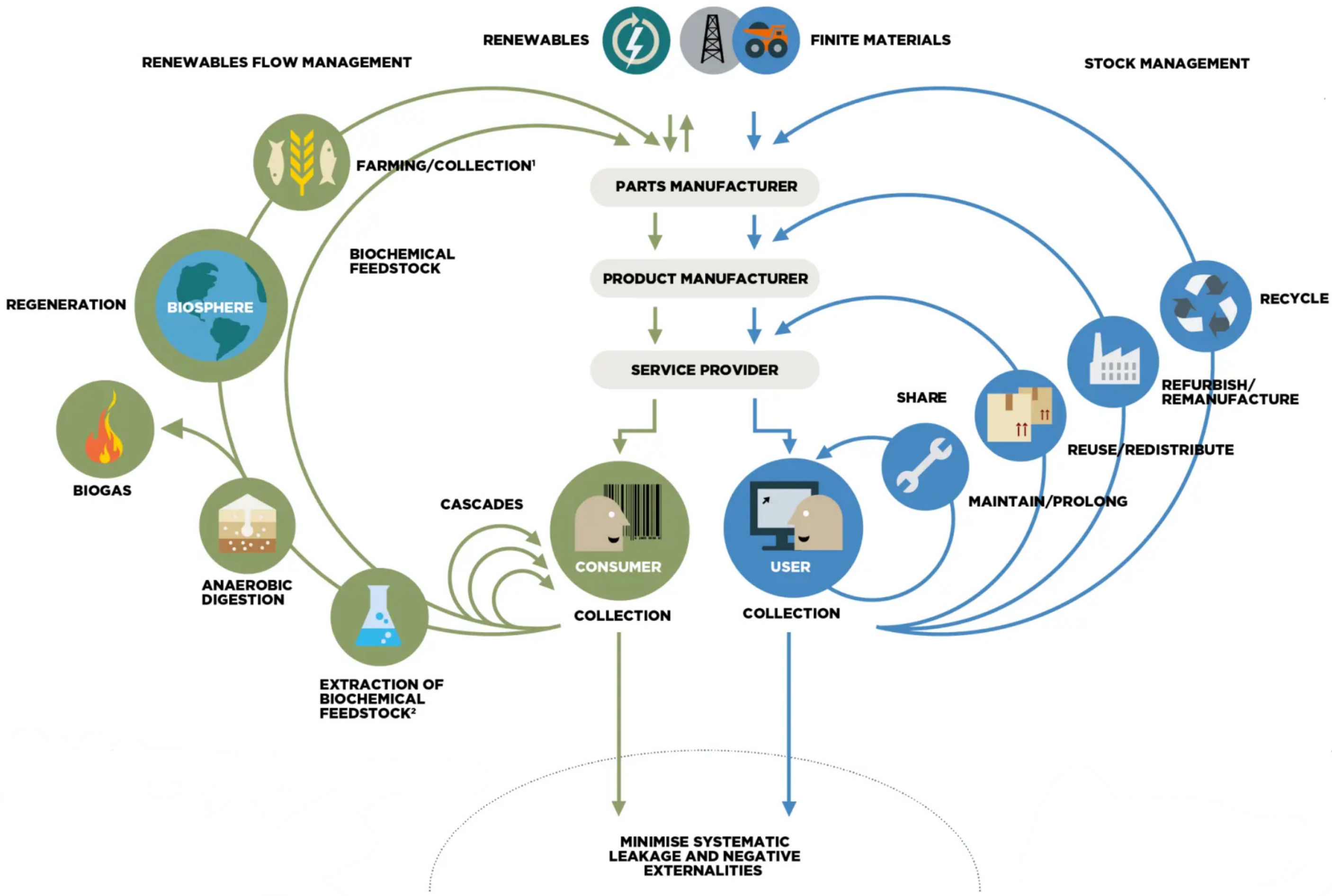


Figure 14. *Circular Economy Systems Diagram.*
Note. Reprinted from Ellen MacArthur Foundation, 2019. https://ellenmacarthurfoundation.org.

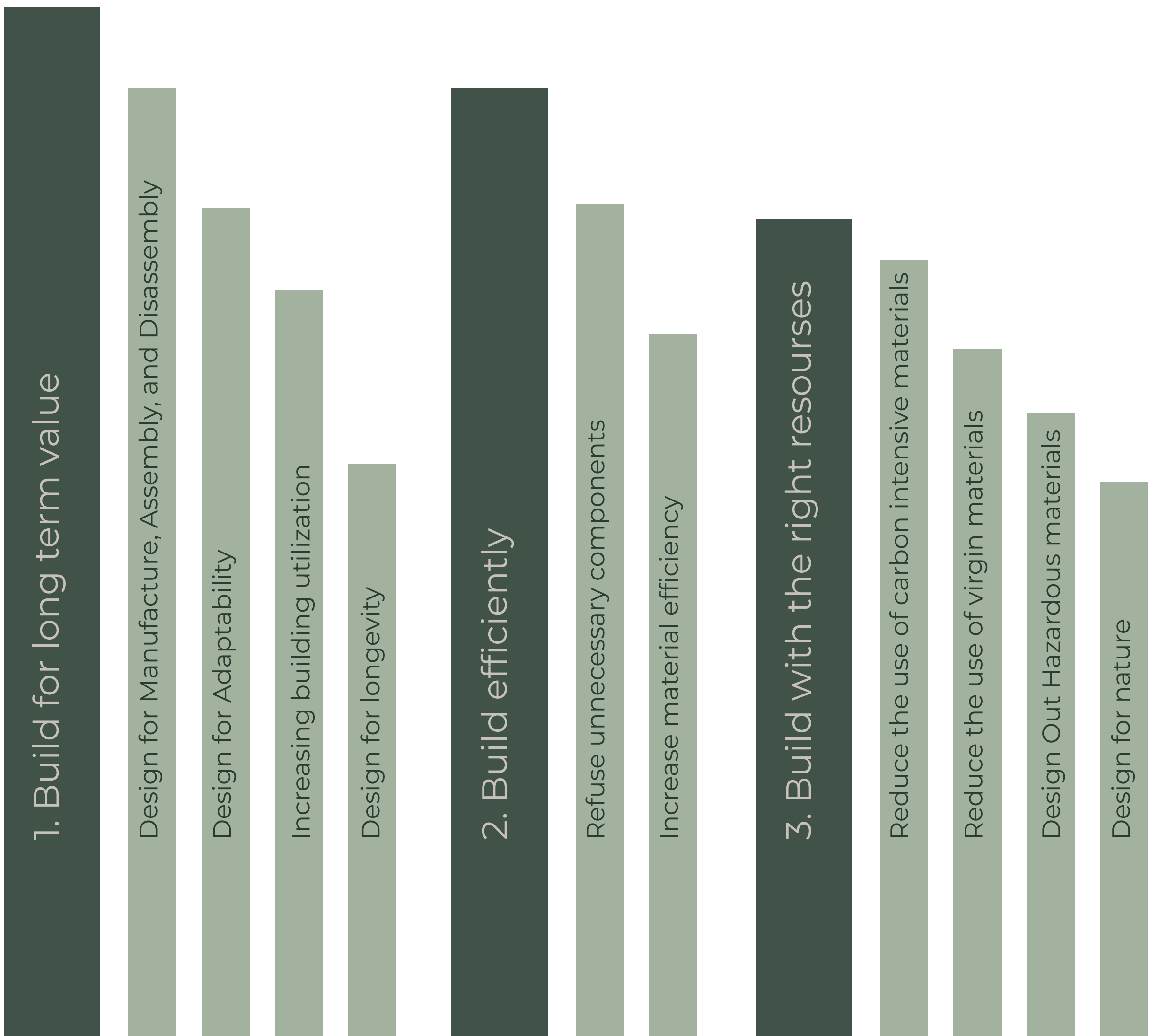
1.4.2 CE strategies for Bio-based materials

CE strategies are integral to the development and implemaenttion of bio-based materials, as they help mitigate the environmental impact of conventional construction, maximize the carbon storage protential of renewable resourses, and adress the industry challenges associated with emerging materials. Within a CE framework, bio based materials are conceived to eliminate waste at the end aend of a building´s life, as panels and components are designed for disassembly and reuse (Natural Building Systems, 2024).

Arup, in collaboration with the Ellen MacArthur Foundation (2021), developed the Circular Buildings Toolkit, which translates CE principles into a set prioritized strategies for building projects. These strategies infrom decision-making across the entire building lifecycle. For this thesis, the most relevant strategies are outlined below:

• Design for Adaptability (DfA)

The ISO 21929 standard defines adaptability as the ability to “change so as to fit the requirements of new circumstances.” It



includes physical modifications such as refurbishment, reconfiguration, expansion, or repurposing (Tsoka & Tsikaloudaki, 2025). DfA requires proactive design thinking to anticipate end-of-life scenarios and future uses, reducing the need for demolition or major interventions. Key actions include increasing convertibility and enabling multiple potential uses.

- Design for Manufacture, Assembly, and Disassembly (DfMA/DfD)

DfMA integrates the principles of efficient manufacturing and simplified on-site assembly, aiming to minimize waste, optimize labor, and improve quality. DfD extends this approach to the end-of-life phase, ensuring that components can be safely recovered for reuse, recycling, or refurbishment. According to ISO 20887, seven design principles guide DfD: accesibility, independence, simplicity, standardization, avoidance of unnecessary treatments, support for reuse models, and safety during disassembly. Prefabricated and modular construction systems are strong enablers of both approaches. Key actions include using reversible connections, standardizing component interfaces, and ensuring visibility and accessibility for future dismantling.

- Increase material efficiency

They aim to minimize material use while meeting performance requirements by avoiding oversized elements, employing hybrid or composite systems, and using prefabrication to reduce onsite waste. Key actions include minimizing waste during both production and construction through off-site fabrication of structural and envelope components.

- Reduce the use of virgin materials

Prioritize reclaimed components, recycled products, and rapidly renewable bio-based materials such as engineered timber and bio-composites.

- Reduce the use of carbon intensive materials

Embodied carbon often represents over half of a building's life-cycle emissions. Reducing cement and steel use, setting early carbon targets, and selecting suppliers with recycled inputs and clean energy are key actions

1.4.3 Regulations

Circular Economy Action Plan (CEAP)

Adopted by the European Commission in 2015 and updated in 2020, the CEAP has significantly influenced the growing interest in bio-based materials for construction (Mikulenas & Šeduikyte, 2025). It establishes a comprehensive framework covering the entire product life cycle, from production and consumption to waste management and secondary raw material markets (European Commission, 2020).

The 2020 update broadened the original scope, positioning circularity as both an environmental and economic priority. It focusses on four key areas: The progress in 'sustainable products' through the 'Ecodesign Sustainable Products Regulations,' 'supporting consumers in responsible and well-informed choices,' 'sectorial actions in seven important sectors like 'construction and buildings,' and 'reducing 'waste through 'Extended Producer Responsibilities' and 'new reduction objectives' (World Business Council for Sustainable Development, 2020).

The construction sector is identified as particularly resource-intensive and crucial for emissions reduction. The CEAP supports this through the Strategy for a Sustainable Built Environment, wich emphasizes life cycle assessment, recycled content requirements, material recovery targets, and building adaptability (Feizollahbeigi et al., 2025). This strategy, reinforced by the European Union Green Deal's Renovation Wave initiative, promotes circular renovation practices and extended material lifespans (European Comission, 2020), creating new opportunities for integrating bio-based materials into sustainable construction construction.

Energy Performance of Buildings Directive (EPBD)

The Energy Performance of Buildings Directive (EPBD) is a key policy instrument of the EU to improve building energy performance and reduce greenhouse gas (GHG) emissions, targeting a zero-emission building stock by 2050 (European Union, 2024). The latest revision, Directive (EU) 2024/1275, effective since May 28, 2024, introduces stronger requirements for both new and existing buildings. It sets ambitious renovation targets and establishes Zero-emission buildings (ZEBs) as the new standard, requiring very high energy performance, minimal energy demand, and near-zero operational carbon emissions (European Union, 2024).

By 2026, Member States must develop National Building Renovation Plans outlining strategies to reduce operational energy use and GHG emissions. The Directive also introduces Minimum Energy Performance Standards (MEPS), to renovate the worst-performing buildings and defines clear trajectories for residential and non-residential sectors. Its expanded scope now includes whole-life-cycle emissions, covering materials production, transport, construction, replacement, and end-of-life management, with life-cycle GHG data gradually integrate into Energy Performance Certificates (EPCs).

Beyond energy efficiency, the EPBD promotes digitalization and circularity through tools such as Digital Building Logbooks (DBLs), Building Renovation Passports (BRPs), and Smart Readiness Indicators (SRI) to improve performance tracking and planning (European Union, 2024). Importantly, it links energy and material efficiency by encouraging modular, industrialized, and circular design solutions, as well as the use of bio-based building materials (CBBMs) (Le et al., 2025).

Waste Framework Directive (WFD)

The WFD (Directive 2008/98/EC) establishes the core legal framework for waste management in the EU and supports the transition toward CE. It aims to protect human health and the environment by reducing the negative impacts of waste generation and improving resource efficiency throughout product and material life cycles (European Union, 2008). The directive sets a mandatory 70% recovery target for construction and demolition waste (CDW) by 2020, including reuse, recycling, and material recovery such as backfilling (Giarma et al., 2025).

At its core, the WFD defines the five-step waste hierarchy, prevention, preparation for reuse, recycling, other recovery (including energy recovery), and disposal as a last resort; and introduces key principles such as the polluter-pays principle, life-cycle thinking, and clear classifications for waste, hazardous waste, by-products, and end-of-waste criteria. Together, these measures establish a consistent framework for determining when materials can safely and effectively re-enter the economy.

EU Taxonomy Regulation

The EU Taxonomy Regulation (Regulation (EU) 2020/852) provides a common framework for defining and guiding environmentally sustainable economic activities, forming a cornerstone of the EU´s sustainable finance agenda. Its goal is to direct investments toward activities that support the transition to a sustainable economy while preventing greenwashing and reducing market fragmentation. The regulation sets out four key conditions: an activity must substantially contribute to at least one environmental objective, do no significant harm to others, comply with minimum social safeguards, and meet the technical screening criteria set by the Commission (European Union, 2020).

Within this framework, new building projects must demonstrate significant reductions in energy use and adherence to Do No Significant Harm (DNSH) principles across areas such as resource efficiency, water management, and climate adaptation (Feizollahbeigi et al., 2025). By establishing clear, science-based thresholds and life-cycle criteria, the EU

Taxonomy helps investors, developers, and policymakers prioritize actions that reduce environmental impacts and promote circularity in the built environment.

Eco-design for Sustainable Products Regulation (ESPR)

The Ecodesign for Sustainable Products Regulation (ESPR), in force since 18 July 2024, is a cornerstone of the European Commission's strategy to make sustainable products the standard across the internal market. As a major outcome of the 2020 CEAP, the ESPR expands the earlier Ecodesign Directive (2009/125/EC), once limited to energy-related products, to nearly all physical products. By embedding requirements for durability, repairability, recyclability, energy performance, and material efficiency, the regulation recognized that up to 80% of a product's environmental impacts are determined at the design phase. This principle is particularly relevant to this thesis, as it highlights how design and material specification directly influence circularity and life-cycle performance by reducing premature obsolescence and increasing product longevity.

The ESPR introduces several foundational instruments, most notably the Digital Product Passport (DPP), a mandatory digital identity providing traceable information on product composition, origin, repairability, and life cycle impacts, to be implemented by 2026. It also promotes the use of Life Cycle Assessment (LCA) methodologies, such as Product Environmental Footprint (PEF), to inform product standards, and establishes mandatory Green Public Procurement (GPP) rules to direct public spending toward sustainable materials and products.

Ministerial Decree No. 152/2024 (End of waste)

Adopted under Article 184-ter of Legislative Decree No. 152/2006, this regulation defines the criteria under which inert construction and demolition waste (C&DW) and other mineral-based inert wastes cease to be classified as waste following recovery operations. It promotes selective demolition practices to enable safe removal of hazardous substances and to support the reuse and recycling of high-quality aggregates.

This decree established that aggregates recovered, according to specific technical, environmental, and health criteria, could re-enter the market as secondary raw materials, in so far as existing product standards were met. It is consistent with the EU Waste Framework Directive 2008/98/EC, and underlines the principle of monitoring and verification that ensures recovered materials cause no adverse environmental or health impacts.

1.4.4 Challenges

Despite its potential, the transition to CE in construction, particularly through the adoption of circular bio-based building materials (CBBMs), faces presistent systemic challenges:

Economic barriers

High upfront costs remain one of the main obstacles, reinforcing the perception that sustainable options are inherently expensive (Dams et al., 2023). The lack of financial incentives often makes conventional materials appear more competitive, while limited life cycle assessments at the building scale restrict evidence of long-term savings (Le et al., 2025). Short-term decision-making further prioritizes immediate costs over potential life cycle benefits.

Institutional and regulatory barriers

Certification and accreditation processes for new materials are lengthy and costly, discouraging market entry (Parlato & Pezzuolo, 2024). The absence of standardized performance metrics and fragmented regulatory frameworks across regions also impedes large-scale implementation (Mikulļnas & ąeduikytļ, 2025).

Technical and infrastructure barriers

In many regions, recycling and material recovery systems are underdeveloped, limiting the capacity to sort, redistribute, and ensure the quality of recovered materials (Tavares et al., 2025). This weakens the circular supply chain needed for bio-based and recycled construction products.

Knowledge and awareness barriers

A general lack of understanding of CE principles and CBBMs persists across the construction sector (Puma et al., 2025). Limited access to reliable data and collaboration platforms hinders knowledge transfer, while the gap between research and industrial practice prevents innovation from reaching market readiness (Dams et al., 2023).

MATERIAL PASSPORTS

Material Passports (MPs) are defined by the Building As a Material Banks (BAMB project, 2020) initiative as "sets of data describing defined characteristics of materials in products that give them value for present use, recovery, and reuse". MPs provide essential information to extend material lifespans, enable reversible design, and support high-value recovery. Although initially developed for technical materials, MPs are equally relevant for bio-based construction materials, whose variability, durability, and end-of-life strategies require careful documentation to ensure their safe and effective reintegration into natural or technical cycles (Emmenegger, 2024).

In this thesis, the term Material Passports is used in a broader sense that includes Digital Product Passports (DPPs), both of which have been referenced in earlier sections. DPPs represent the digital and regulatory evolution of MPs, formalized under the European Ecodesign for Sustainable Products Regulation. In essence, MPs define the material and product data structure, while DPPs provide the digital infrastructure and interoperability needed to exchange this information across platforms.

1.5.1 Definition

Material Passports (MPs) are instruments designed to record critical information about products, materials, and building components in order to facilitate their reuse, recycling, or safe return to biological cycles (Waterman & Circuit, 2023). They reframe materials as valuable resources rather than waste streams, positionning buildings as storage banks of future resources. According to the BAMB project (2020), by collecting standardized data on material composition and performance, MPs enable informed design decisions, facilitate recovery, and encourage circular business models. The term is sometimes used alongside “Resourse Passports” or “Recycling Passports,” although these are distinct concepts and should not be used interchangeably.

The information contained within MPs can be broadly classified as qualitative or quantitative. Qualitative data include material and technical information such as quality, compliance with standards, recommended assembly methods and BIM-based quantity takeoffs designed to minimize waste. They also cover safety information, like storage guidelines and the use of appropriate personal protective equipment (PPE) to ensure worker safety, as well as circularity guidance on sustainable material management, reuse and recycling (Waterman & Circuit, 2023).

Quantitative data focus on measurable sustainability indicators used to assess the performance of materials and building systems. Such would include deconstructability and recovery scores, which provide an evaluation of potential reusability and recyclability, and environmental metrics that assess life cycle impacts like global warming potential, acidification potential, and energy intensity (Atta et al., 2021).

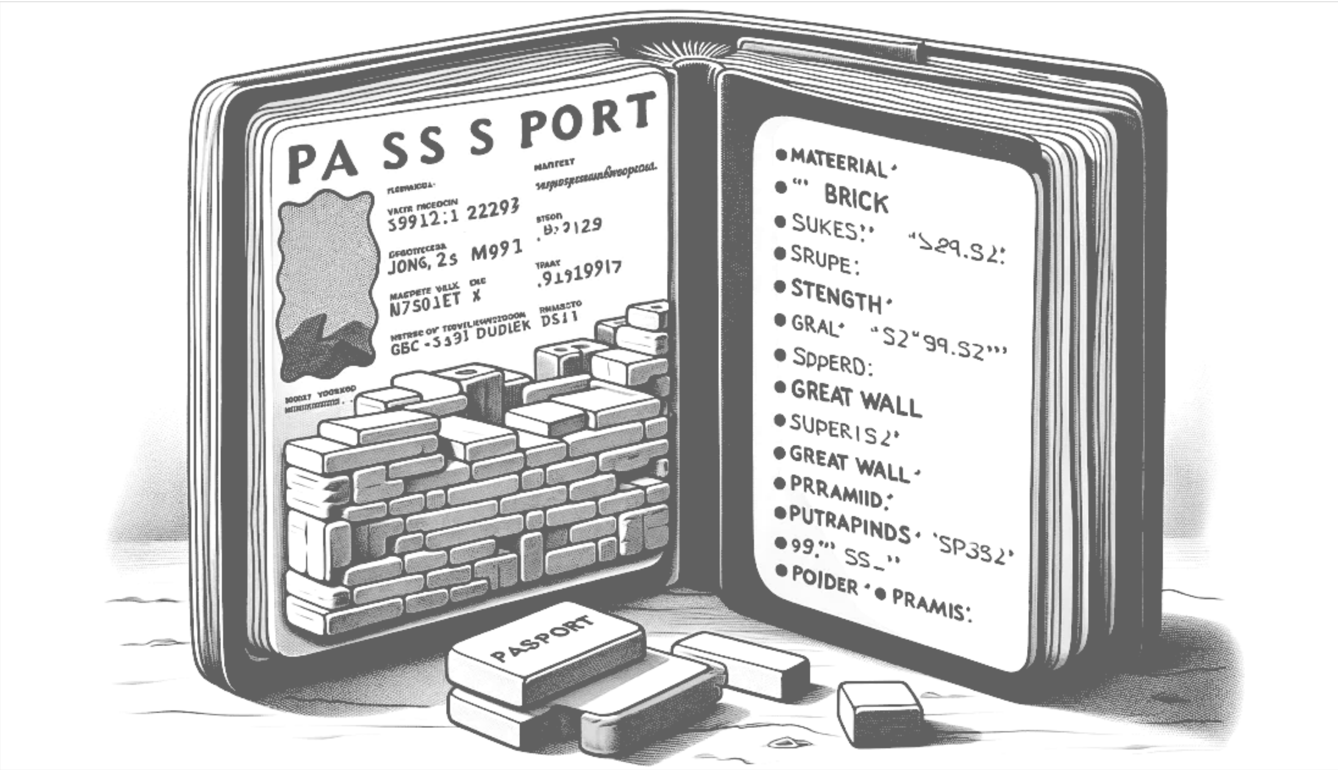


Figure 15. *Illustration of a digital product passport concept.*
Note. Reprinted from The role of open APIs in material passports, by 2050 Materials, 2025, https://2050-materials.com/blog/the-role-of-open-apis-in-material-passports/.

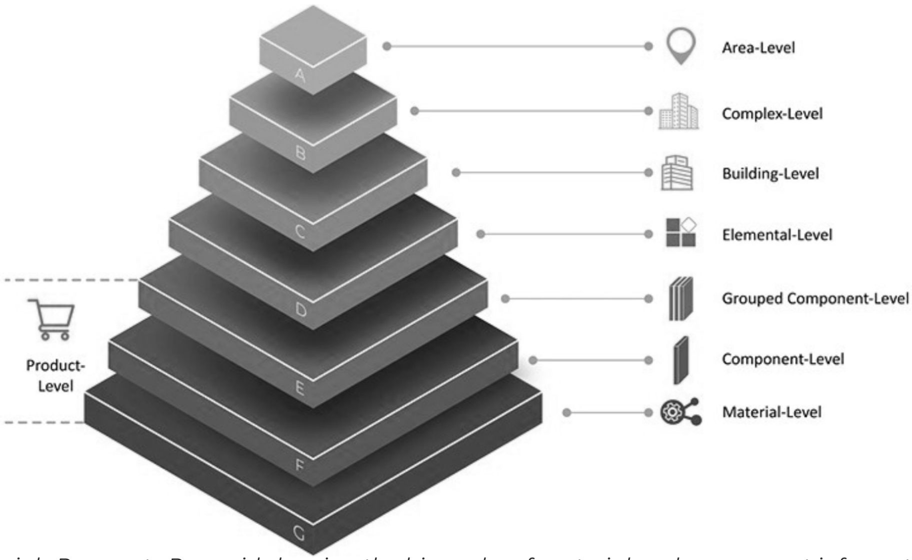


Figure 16. *Materials Passports Pyramid showing the hierarchy of material and component information levels.*
Note. Reprinted from Waterman & Circuit (2023)

Hierarchical levels

According to Waterman & Circuit (2023) and Bosma (2024), MPs can be developed at several hierarchical levels. These follow a pyramid structure where higher levels provide aggregated data from the lower levels. Therefore, these vary from individual materials to entire building portfolios.

The focus of this thesis is on the product and component level passports, which document products traded by manufacturers before their incorporation into a building and the parts forming a component. Other levels include the material, grouped component, elemental, building, portfolio, and area levels, each progressively broadening the scope of analysis.

Regulations

While MPs have primarily emerged from architectural and research initiatives, DPPs represent their formal regulatory counterpart at the European level. Within this context, the Ecodesign for Sustainable Products Regulation (ESPR) positions DPPs as a central mechanism to promote resource efficiency, support "green growth," and contribute to net-zero emission targets (Redeker et al., 2024).

The EU has already announced the mandatory implementation of DPPs, beginning with industrial and electric vehicle batteries in January 2026, with gradual expansion to additional product categories (Jung et al., 2024). In the construction sector, regulatory compliance is further guided by the revised Construction Products Regulation (CPR), which specifies both content and technical requirements for DPPs applicable to construction products (buildingSMART, 2024). Importantly, the CPR takes precedence over the ESPR where sector-specific details are provided, while the ESPR continues to apply when it offers more comprehensive provisions (Abedi et al., 2024).

Benefits

According to a review of recent literature (Abedi et al., 2024; Emmenegger, 2024; Waterman & Circuit, 2023), MPs provide multiple advantages:

1 *Sustainability and Circularity:* Promote resource efficiency and waste reduction, turning waste into valuable resources.

2 *Transparency and Traceability:* Allow tracking and tracing products from their origin to end-of-life.

3 *Improved Decision-Making:* Provide essential information for making sustainable choices, helping designers evaluate building alternatives and supporting urban mining and material exchange.

4 *Regulatory Compliance:* Help construction companies comply with environmental regulations and future EU policies like the ESPR.

5 *Efficiency:* Automate various assessments such as embodied carbon assessment, circularity performance reporting, and the creation of disassembly manuals.

1.5.2 Digital Product passports

The terms Material Passport (MP) and Digital Product Passport (DPP) are often used interchangeably, as both refer to digital datasets that provide certified identities for products by linking them to their life cycle information (Capelleveen et al., 2023). However, while MPs originated in the construction sector and mainly focus on end-of-life management, DPPs encompass a broader regulatory framework, covering all physical goods placed on the market throughout their entire lifespan (Bosma, 2024). In this sense, DPPs can be seen as the evolution of MPs, functioning as universal traceability tools that connect products, materials, and stakeholders across value chains.

Beyond being repositories of data, DPPs serve as certified digital identities, ensuring that product information is accurate, complete, and verifiable (Emmenegger, 2024). Each passport corresponds to an individual product instance rather than a series, significantly improving traceability. In practice, DPPs can be informative, instructive, corrective, or predictive; providing guidance on maintenance, identifying issues, or anticipating performance trends to optimize resource use (Psarommatis & May, 2023).

Data carriers

Data carriers are physical media that link physical products to their corresponding digital passports, enabling easy access to infromation and data systems (buildingSMART, 2024). Common identifiers include QR codes, RFID tags, NFC tags, and DataMatrix codes, which provide unique, immutable links ensuring consistent tracking across platforms. Some carriers are connected to Verifiable Credentials (VCs) for claims validation, while emerging approaches, such as Non-Fungible Tokens (NFTs) and Physical Backed Tokens (PBTs), offer decentralized solutions for product identity and ownership (Emmenegger, 2024).

The data accessed via these carriers must be structured, unambiguous, and machine-readable, and interoperable, ideally referencing standardized frameworks such as the buildingSMART Data Dictionary (bSDD). Because storage capacity is limited, carriers typically store only a pointer or Unique Resource Identifier (URI) directing users to external databases or registries. Increasingly, this information is hosted in decentralized systems like distributed storage providers or blockchain-based ledgers, which enhance data security, transparency, and permanence (Emmenegger, 2024).

Requirements

The main requirements for Digital Product Passports (DPPs) were first outlined by Jansen et al., further refined by Buchholz and Lützkendorf, and later consolidated by Emmenegger (2024). These build upon the quality framework defined in ISO/IEC 25010:2011, which classifies software and system attributes, and are broadly applicable across sectors, including construction. Together, these studies define the current DPP requirements as follows:

1. Accessibility: Permanent access to passport data must be ensured, with appropriate access control and authorization mechanisms.

2. Functional Suitability: The system must address sector-specific needs, support circular economy goals, and maintain product quality and safety.

3. Security and IP Protection: Data must remain immutable, verifiable, and compliant, with control retained by the data owner.

4. Interoperability: Information must be exchangeable across organizations through shared semantics and standardized data formats.

5. Modularity: Systems should be designed for scalability and international use, allowing updates and expansions without disrupting existing structures.

6. Legal Obligations: DPPs must meet regulatory obligations under frameworks such as the Ecodesign for Sustainable Products Regulation (ESPR) and the General Data Protection Regulation (GDPR).

Other general attributes, such as availability, portability, and non-redundancy, are implicit within system-level quality requirements but can be excluded from early prototypes due to practical limitations.

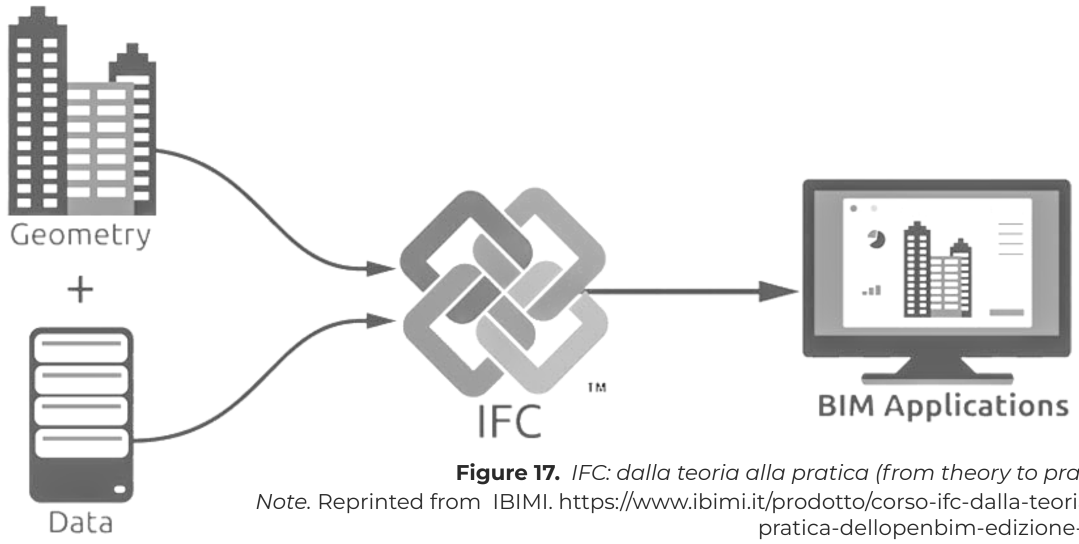


Figure 17. *IFC: dalla teoria alla pratica (from theory to practice).*
Note. Reprinted from IBIMI. https://www.ibimi.it/prodotto/corso-ifc-dalla-teoria-alla-pratica-dellopenbim-edizione-2025/.

1.5.3 BIM integration

Building Information Modelling (BIM) provides a robust framework for generating DPPs, allowing them to function as design optimization and inventory tools (Bosma, 2024). Its capacity to digitally represent the physical and functional characteristics of building components enables comprehensive data management across a project's life cycle (Waterman & Circuit, 2023). Platforms such as Madaster demonstrate this potential by registering building materials, calculating circularity, assessing material value, and managing material flows (Madaster, 2023).

BIM's ability to store, share, and update detailed information on materials and components makes it an effective foundation for DPPs, supporting the narrowing, slowing, closing, and regenerating of resource loops (Bosma, 2024). Furthermore, as noted by Waterman and Circuit (2023), BIM allows the inclusion of circularity and contractor data, data-carrier information, and product-level passport identifiers, enabling the automated generation of DPPs while improving accuracy and efficiency.

OpenBIM and IFC

OpenBIM is a collaborative approach to Building Information Modelling that uses open standards and workflows to ensure interoperability across different software platforms in the Architecture, Engineering, and Construction (AEC) industry (Waterman & Circuit, 2023; Bosma, 2024). Maintained by buildingSMART (2024), these standards enable seamless data exchange and effective collaboration among stakeholders, making OpenBIM fundamental for integrating Digital Product Passports (DPPs) into BIM workflows and ensuring consistent access to data throughout a project's lifecycle.

A core standard within OpenBIM is the Industry Foundation Classes (IFC), which facilitate information exchange across design, construction, and operation phases (Waterman & Circuit, 2023). IFC provides a common data model for describing building elements and their relationships, supporting both standardization and project-specific flexibility. Within this framework, entities such as IfcProduct (representing objects and their components) and IfcMaterial (defining the materials that compose them) are especially relevant. Together, they allow DPPs to describe and share material properties in a structured, interoperable format across systems.

Ontology networks

An ontology network represents a structured and interconnected collection of formal models designed to define, organize, and assign meaning to data within a specific domain. Rather than a single, monolithic ontology, this approach emphasizes modularity, extensibility, and flexibility to accommodate evolving requirements, legislation, and standards, particularly in complex and dynamic environments like the circular economy (Jansen, et al., 2024).

An ontology is a "formal, explicit specification of a shared conceptualization". Its primary goal is to foster a common understanding of the structure and meaning of information among people or software agents (Bosma, 2024). Ontologies define data semantically, enabling machines to interpret information based on provided definitions.

A typical ontology network for Digital Product Passports (DPPs), as outlined by Redeker et al. (2024), consists of four key modules:

1. Core concepts, defining the DPP, its related products, and information categories.

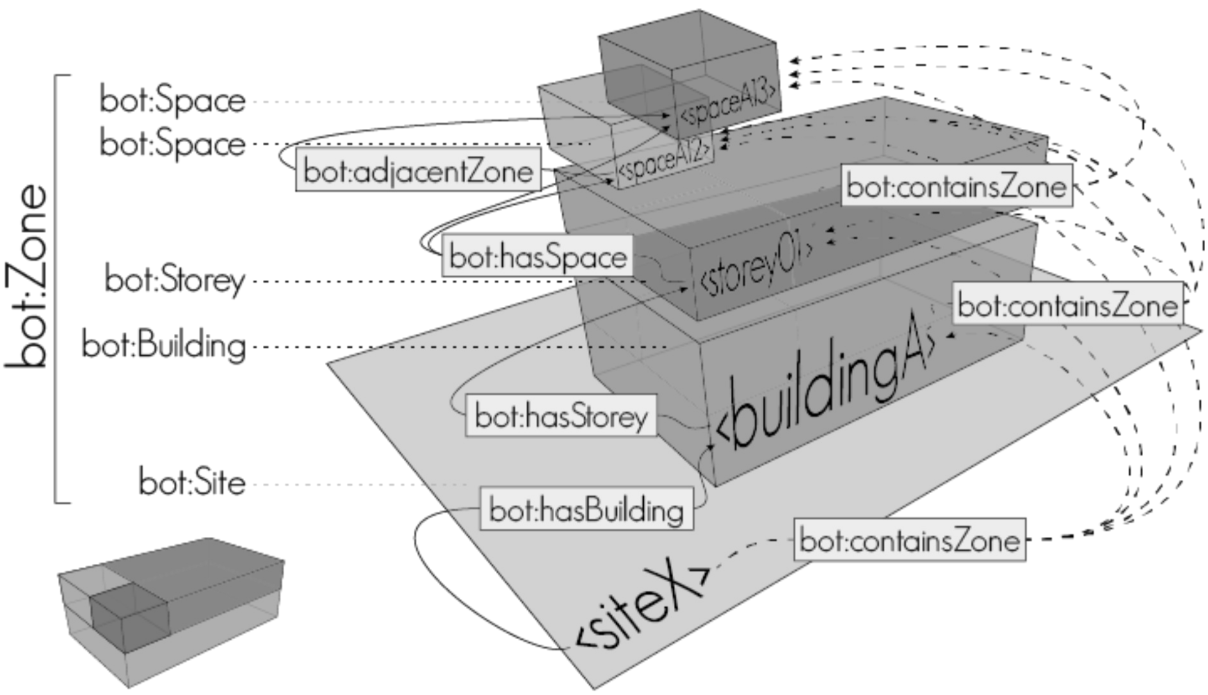


Figure 18. *Building topology ontology.*
Note. Reprinted from W3C (2021). https://w3c-lbd-cg.github.io/bot/.

2. Information modules, describing data types such as characteristics, values, units, and attached documents (like repair or disassembly guides).

3. Composition information, explaining product–component relationships and circularity aspects such as SubstanceOfConcern.

4. Provenance modules, ensuring data integrity by tracking origins, responsible actors, and timestamps.

To ensure interoperability, these networks often reuse existing ontologies rather than creating new ones (Bosma, 2024). Common examples include:

- BOT (Building Topology Ontology): defines building hierarchy (site, building, storey, space).
- BMP (Building Material Performance): gives semantic meaning to material performance data.
- LOCN (ISA Core Location Vocabulary): standardizes geographic and address data.
- QUDT: represents quantities, units, and dimensions consistently.
- PROV: traces data provenance and modification history.
- MPO (Material Passport Ontology): emerging framework for structuring material passport data.
- CAMO (Circular Materials and Activities Ontology): classifies materials, products, and activities within circular economy contexts.

Validation

Validation ensures the accuracy, integrity, and compliance of DPP data throughout the product lifecycle, which is essential for stakeholder trust (Bosma, 2024; Emmenegger, 2024). The lack of standardized formats makes robust validation critical to avoid data misinterpretation and to enhance material reuse and recycling.

- A structured validation process typically combines rule-checking systems, blockchain technology, and comparative studies.
- Rule-checking systems, as developed by Eastman et al. (2009) and refined by Pauwels et al. (2017) involve four steps: defining validation rules, preparing the model, executing checks, and generating reports. These rules verify data completeness, prevent duplication, ensure correct data types, and confirm that values fall within expected boundaries (Lee et al., 2016).
- Blockchain technology, a decentralized and immutable ledger, strengthens data provenance and integrity through cryptography, peer-to-peer networks, and consensus mechanisms, ensuring traceable and tamper-proof DPP records (Kim et al., 2024; Abedi et al., 2024).
- Comparative studies validate quantitative indicators by benchmarking sustainability parameters across datasets, as demonstrated in DPP frameworks (Atta et al., 2021; Honic et al., 2019).

1.5.4 Previous studies

Several studies and research papers have explored the practical implementation of DPPs. Five of these studies were examined in greater detail to obtain useful insights:

Digitizing material passport for sustainable construction projects using BIM (Atta, Bakhoum, & Marzouk, 2021)

Purpose

The study aimed to develop a structured methodology for generating digital Material Passports (MPs) through Building Information Modeling (BIM). Its goal was to facilitate the evaluation of sustainability and circularity indicators at different building lifecycle stages and to demonstrate how BIM can serve as a decision-support tool for sustainable design and resource management.

Method

The methodology was organized in three main stages.

1. *Definition of data categories: MPs were divided into qualitative and quantitative data groups, including material properties, environmental indicators, and circularity parameters such as deconstructability and recovery scores.*
2. *Digital integration: The researchers used Autodesk Revit, creating shared parameters and custom scripts in Dynamo to link and automate data extraction.*
3. *Validation and application: The framework was tested on two case studies (a conventional and a modular building) to assess data reliability and the practical value of the digital passports.*

Results

The resulting system automatically calculated key performance indicators (recovery, deconstructability, and environmental scores) directly from BIM data. It generated sustainability reports and visualized performance variations among different building *elements. The case studies confirmed that MPs can support early design optimization, improve data consistency, and provide reliable information for circular material management throughout a building's lifecycle.*

Challenges

- *Data availability and reliability: The methodology relied on the accessibility of detailed environmental data for each material, such as embodied carbon or recyclability potential. However, this information is not uniformly available across manufacturers or regions, which limits the comparability of results and the precision of sustainability assessments.*
- *Interoperability constraints: The workflow required manual data inputs and lacked full compatibility with external databases and existing Life Cycle Assessment (LCA) tools. This restricted scalability made it difficult to integrate with broader digital ecosystems or national product databases.*
- *Economic and temporal limitations: The study emphasized the need to incorporate dynamic economic data to evaluate cost-benefit relationships between circular and conventional materials. Furthermore, once generated, the MPs were static; the authors highlighted the importance of developing systems capable of continuous updates to reflect maintenance, replacement, or reuse activities over time.*

Concept for a BIM-based Material Passport for buildings (Honic, Kovacic, & Rechberger, 2019)

Purpose

The study aimed to develop a systematic concept for integrating Material Passports (MPs) into Building Information Modeling (BIM) workflows, enabling the extraction, management, and evaluation of material data across different design and construction stages. The authors sought to create a framework that could facilitate circular construction by improving material traceability, reuse potential, and data accessibility throughout the building lifecycle.

Method

The research proposed a multi-phase methodology structured around the progression of BIM models through distinct development stages:

1. *Conceptual Design (MPa): The MP functions as an early analytical tool to compare design variants based on recycling, reuse potential, and environmental impacts. Correct geometric modeling and classification of BIM elements are essential at this stage.*
2. *Preliminary Design (MPb): The passport becomes more refined, integrating material-specific data such as types, volumes, and thicknesses to optimize circularity and environmental performance.*
3. *Tendering Stage (MPc): The MP provides detailed quantitative data for procurement and contractual validation, ensuring traceability and alignment between design specifications and sourced materials.*
4. *Final Documentation / Handover (MPd): The completed MP acts as a comprehensive material inventory, serving as the foundation for a secondary raw materials cadaster and supporting future reuse or recycling.*

Results

The study produced a proof-of-concept framework demonstrating how BIM can serve as both a database and decision-support tool for material management. It highlighted the feasibility of embedding MP-related data directly into BIM objects, thereby linking environmental and circularity parameters with design elements. The authors illustrated that, when properly structured, this integration enables automatic calculation of material quantities, assessment of recyclability, and visualization of circular potential across the building model.

Challenges

- *Data standardization and interoperability: The proposed workflow relied on accurate classification and consistent data entry across BIM platforms, which is not always achievable due to the lack of standardized data schemas and interoperability between software environments.*
- *Lifecycle data gaps: The framework depended on environmental and material data that are often incomplete, particularly regarding end-of-life processes and reuse pathways. The study underscored the need for more comprehensive databases to capture real-world material flows and conditions.*
- *Automation and scalability: Although the concept proved effective at the prototype scale, the generation of MPs remained partly manual, limiting automation and large-scale application. The authors emphasized that future developments should enable dynamic updates and integration with external databases to maintain data accuracy throughout the building lifecycle.*
- *Practical implementation barriers: The transition from conceptual frameworks to real construction practice was identified as a significant challenge. The study noted that for widespread adoption, regulatory alignment, data exchange protocols, and clearer definitions of responsibility among stakeholders are required.*

From Material Passports to Digital Product Passports Creating and validating Linked Data-Based Digital Product Passports for the AEC industry (Bosma, 2024)

Purpose

The study aimed to develop and validate a Linked Data-based framework for Digital Product Passports (DPPs) tailored to the Architecture, Engineering, and Construction (AEC) industry. Building upon previous work on Material Passports (MPs), the research sought to formalize how product-level data can be structured, interlinked, and validated to enhance traceability, interoperability, and circular material management across the built environment.

Method

The research followed a multi-layered approach combining theoretical modeling, ontology development, and prototype validation:

1. *Ontology Development: A modular semantic framework was created to structure DPP data, including modules for core product descriptions, composition information, provenance tracking, and lifecycle data.*
2. *Integration with BIM and IFC Standards: The framework linked DPPs to existing BIM workflows through Industry Foundation Classes (IFC), enabling data to flow between design models and digital passports.*
3. *Validation Process: A rule-based validation system was implemented using RDF (Resource Description Framework) models to check data consistency, completeness, and interoperability. Test cases were applied to sample product data to assess accuracy and robustness.*

Results

The study resulted in a conceptual and technical model for interoperable DPPs capable of linking product information across *software environments and lifecycle phases. The proposed ontology connected materials, products, and lifecycle indicators under a unified structure compatible with international standards such as ISO/IEC 25010 and the Ecodesign for Sustainable Products Regulation (ESPR). Validation through rule-checking demonstrated that automated reasoning could identify missing or inconsistent data, supporting higher data quality and trust. The research concluded that Linked Data technologies provide a scalable foundation for future DPP implementation in construction, bridging the gap between product-level and building-level information systems.*

Challenges

- *Lack of standardization and regulatory clarity: Despite growing policy, the absence of finalized EU-level standards for DPP implementation, particularly regarding data structure, access control, and interoperability, creates uncertainty for the AEC sector. This lack of uniformity hinders full adoption and cross-platform integration.*
- *Complexity of data management: Managing DPPs across multiple lifecycle phases requires sophisticated systems capable of handling large, dynamic datasets. The study noted that maintaining data integrity and version control remains a challenge, especially when multiple stakeholders interact with the same dataset.*
- *Automation and industry adoption barriers: The transition from research prototypes to operational systems demands substantial investment in digital infrastructure, stakeholder training, and integration with existing BIM workflows. Without strong industry-wide coordination, DPPs risk remaining fragmented or limited to pilot-scale applications.*
- *Semantic and technical interoperability: Although the Linked Data approach improves interoperability conceptually, practical integration between ontologies (like Building Topology Ontology, Material Passport Ontology, and Circular Materials and Activities Ontology) still requires extensive alignment. Ensuring compatibility across tools and jurisdictions remains an ongoing technical challenge.*

Design, Implementation, and Analysis of Decentralized Product Passport Systems for Circular Construction (Emmenegger, 2024)

Purpose

This study aimed to define the technical architecture, data requirements, and implementation challenges of Digital Product Passports (DPPs) for the built environment. It sought to identify how DPPs could enhance material traceability, compliance with European regulations, and circularity in the construction sector. The author positioned DPPs as an evolution of Material Passports (MPs), expanding their scope beyond buildings to include all physical products within the construction supply chain.

Method

The research followed a framework development and validation methodology, structured in three main parts:

1. *Regulatory and Policy Review: The study analyzed the requirements of the European Ecodesign for Sustainable Products Regulation (ESPR), Circular Economy Action Plan (CEAP), and Construction Products Regulation (CPR) to identify mandatory DPP data fields and governance models.*
2. *System Architecture Design: A conceptual architecture was developed for DPPs, incorporating distributed data storage, interoperability layers, and data carriers such as QR codes, RFID, and blockchain-backed identifiers.*
3. *Implementation Evaluation: The framework was assessed through use cases simulating product data exchange between manufacturers, designers, and contractors. Evaluation criteria included accessibility, interoperability, security, and compliance with ISO/IEC 25010 quality attributes.*

Results

The study produced a comprehensive reference architecture for DPPs in construction, structured around four key components: data sources, data carriers, system interfaces, and governance mechanisms. It proposed that DPPs act as certified digital identities for products, enabling reliable lifecycle tracking and information exchange. The model also demonstrated how emerging technologies such as blockchain and decentralized data storage could ensure data integrity, provenance, and immutability. The results confirmed the potential of DPPs to enhance regulatory compliance, transparency, and circular economy integration within the construction sector.

Challenges

- *Fragmented data ecosystems: The study highlighted that construction data remains scattered across manufacturers, suppliers, and contractors, with inconsistent formats and metadata quality. This fragmentation limits interoperability and complicates the creation of unified product datasets.*
- *Governance and data ownership: Questions regarding data ownership, control, and access rights were identified as critical barriers. Without clear governance models, DPPs risk being either overly centralized (limiting accessibility) or too decentralized (compromising accountability).*
- *Technological constraints: While blockchain and distributed ledger technologies improve data trust, they are resource-intensive and not yet fully aligned with the energy efficiency goals of sustainable construction. Their integration into large-scale DPP systems remains experimental.*
- *Implementation readiness: The research concluded that most organizations lack the digital maturity, standardization frameworks, and technical expertise necessary to adopt DPPs. The author emphasized the need for phased implementation strategies and pilot programs to bridge this readiness gap.*

Material passport for Modular Construction (Yilmaz, Hutton, Valsaladas, Donovan, Zvirgzda, Charlson, Heaton, Suc & Ahmed-Kristensen, 2024)

Purpose

This study focused on the development and demonstration of a Material Passport (MP) testbed tailored to the modular construction sector. Supported by the Engineering and Physical Science Research Council (EPSRC), it aimed to explore how digital material tracking tools could enhance interoperability, data transparency, and circularity across modular building supply chains.

Method

The MP testbed was designed from stakeholder-defined user stories and data requirements collected through workshops involving a sustainable product manufacturer (Natural Building Systems), a software provider (Madaster), and a standards organization (GS1).

Developed using Unity 3D™, the testbed imported and replicated the Building Information Model (BIM) of a modular house to demonstrate real-time visualization and data linkage. The system was also connected to external material databases and web services, enabling interoperability between BIM and product-level data platforms.

Results

The resulting prototype demonstrated the potential of MPs to serve as interactive data environments that consolidate product, component, and building-level information. The testbed allowed users to visualize material attributes, trace their lifecycle, and access environmental performance data. It also identified functional requirements for multi-user access, standardized data structures, *and integration protocols with systems such as ERP (Enterprise Resource Planning) and BIM platforms.*

Challenges

- *Connectivity and Interoperability: Linking stakeholders, technologies, and terminologies emerged as a major obstacle. The MP needs to integrate seamlessly with existing digital ecosystems to connect asset owners at the building level with component producers at the manufacturing level.*
- *Transparency and Trustworthiness: Concerns were raised over the accuracy and source of embedded data, aggravated by the lack of formal data schemes or validation mechanisms. The study emphasized the need for verified and standardized data exchange, potentially through frameworks like GS1.*
- *Accessibility and User Differentiation: The testbed revealed that stakeholders require role-specific information views—for example, regulators, asset managers, and manufacturers each need tailored access to distinct data categories.*
- *Fragmentation and Identifier Proliferation: The multiplicity of identifiers (IFC codes, GUIDs, RFID tags, and circular passport IDs) creates confusion and inefficiency. The study proposed the establishment of a centralized identification standard, possibly managed by organizations such as GS1, to ensure global consistency.*

Future directions

The authors recommended advancing toward an unified data scheme and standardizing data exchange protocols to improve interoperability. They also proposed automating the workflow to streamline updates and reduce manual input. While recognizing the potential role of regulation, the study cautioned that premature enforcement could stifle innovation. Instead, it suggested a research-led, iterative development process supported by organizations like buildingSMART to clarify DPP data requirements and ontology structures before formal integration into BIM.

1.5.5 Available DPP tools

Several private initiatives have developed digital platforms that provide Material Passport (MP) or Digital Product Passport (DPP) solutions for the construction industry. Among the most established are Circuland, Madaster, Concular, and Upcyclea, which offer commercial systems for material tracking, lifecycle assessment, and circular design integration. Information about each platform has been drawn directly from their official websites.

Although these platforms demonstrate significant progress in enabling circular data management, they remain proprietary systems that operate with distinct data templates and interoperability limitations, preventing standardized data exchange across platforms. Their primary focus is on generating business opportunities rather than establishing open, verifiable data frameworks:

Circuland

Circuland provides a digital platform for managing building materials throughout their life cycles, emphasizing traceability, carbon footprint reduction, and circular design integration. It enables structured data collection for materials and products, links this information to BIM environments, and supports Life Cycle Assessment (LCA) to enhance material reuse potential and carbon transparencv.

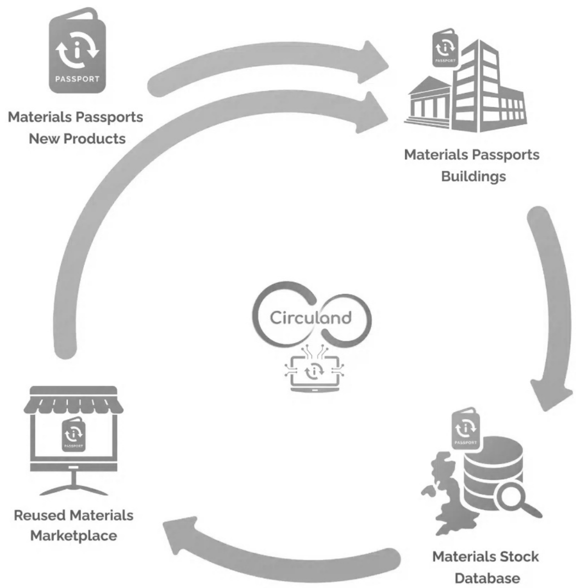


Figure 19. *Circuland.*
Note. Reprinted from Envolve global (2025). https://envolveglobal.org/envolvexl-portfolio/circuland/.

Madaster

Madaster, often referred to as a "cadastre for materials," offers digital material passports that assign each building a unique material identity. The platform records material quantities, qualities, and reuse potential while calculating a circularity index that measures a building's circular performance. Madaster uses a cloud-based system to store and update building data, enabling long-term traceability.

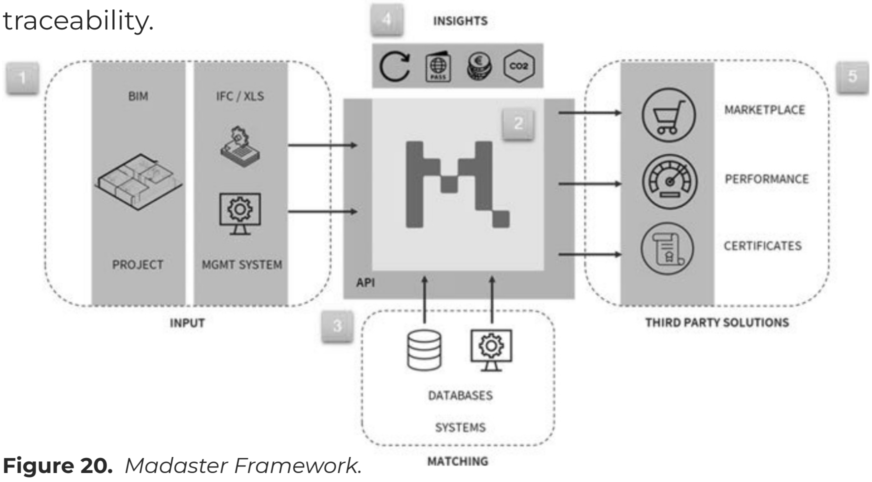


Figure 20. *Madaster Framework.*
Note. Reprinted from Madaster (2023). https://madaster.com/.

Concular

Concular operates as a marketplace for circular construction, linking deconstruction projects with new developments. Its platform facilitates material recovery, matching, and resale through detailed material passports that include data on product specifications, condition, and potential reuse. By connecting demolition projects with designers and developers, it promotes reuse logistics and resource efficiency across the construction value chain.

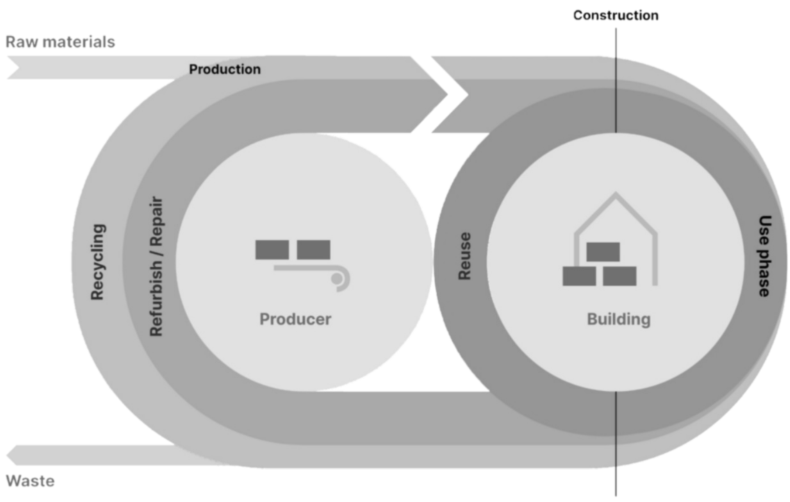


Figure 21. *CE in der Baubranche (the construction industry).*
Note. Reprinted from Concular (2025). https://concular.de/circular-economy-in-der-baubranche/.

Upcyclea

Upcyclea provides a platform for digital passports of products and buildings, closely aligned with the Cradle-to-Cradle (C2C) certification framework. It supports the creation of digital passports that integrate environmental and economic circularity assessments, offering databases of reusable materials and products. Upcyclea's system encourages design for circularity by embedding C2C principles directly into the digital passport data model.

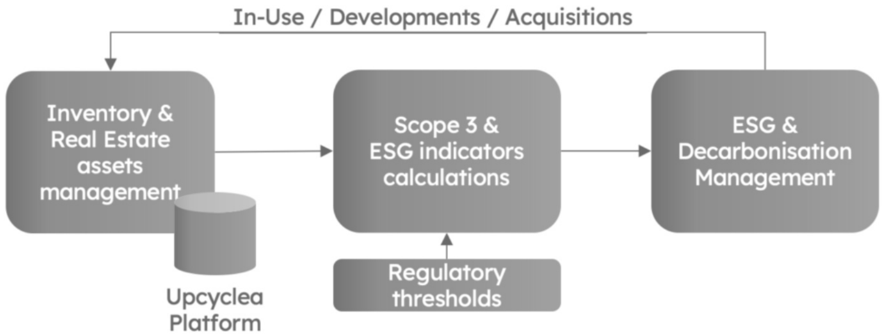


Figure 22. *Upcyclea framework.*
Note. Reprinted from Upcyclea. https://upcyclea.com/en/platform/.

2050 Materials

Although 2050 Materials is a privately owned platform, it does not currently develop Material Passports (MPs) or Digital Product Passports (DPPs). However, the company has expressed interest in frameworks and interoperability standards for DPP development. 2050 Materials is a data-driven platform designed to simplify access to, comparison of, and specification of sustainable construction materials. According to information obtained directly from the company, it hosts over 30,000 building products with data on embodied carbon, water use, end-of-life performance, health indicators, and circularity metrics. The platform supports side-by-side comparison, Whole Life Cycle Assessment (WLCA) reporting, and API integration with external software, such as RIB CostX, to make carbon data accessible during design and cost estimation.

In an interview with the co-founder, the company described its mission to act as a centralized, standardized data source for the construction sector. It compiles verified information from Environmental Product Declarations (EPDs), Cradle-to-Cradle (C2C) certifications, and health product declarations, licensing this data to software developers and construction firms building carbon or DPP solutions. To ensure data credibility, each dataset references its verification source, prioritizing third-party verified and EN 15804-compliant data.

The co-funder emphasized that market demand and ESG reporting requirements currently drive transparency more than regulation, suggesting that financial incentives could accelerate adoption. His long-term vision is for carbon and circularity data to be seamlessly integrated into design workflows, allowing real-time decision-making without extra cost.

Regarding bio-based materials, 2050 Materials identifies few data gaps but notes practical barriers such as insurer hesitancy and the need for specialized contractors. The platform aims to increase visibility and confidence in bio-based materials like hempcrete through evidence-based case studies.

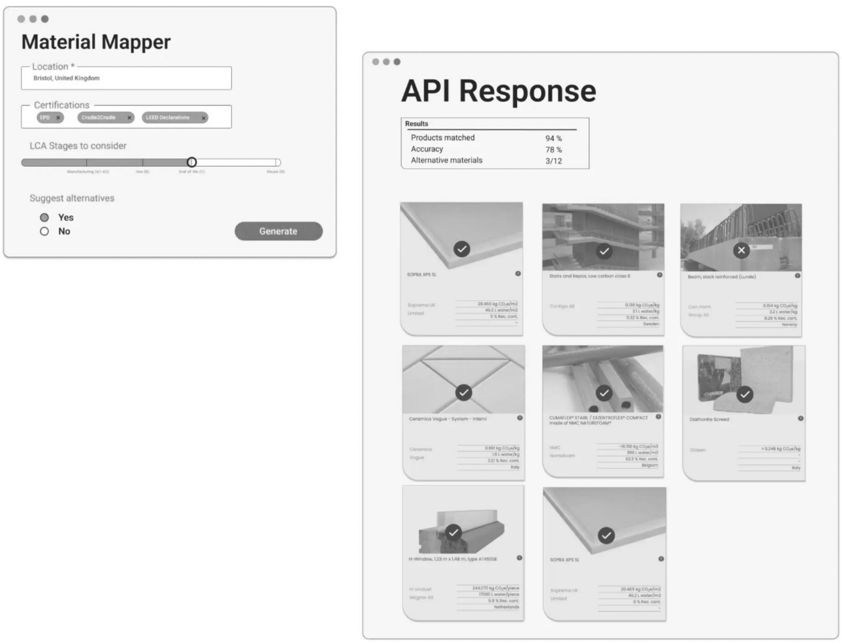


Figure 23. *2050 materials API response.*
Note. Reprinted from 2050 materials (2025). https://2050-materials.com/wp-content/uploads/2024/04/api_response.

1.5.6 General Challenges

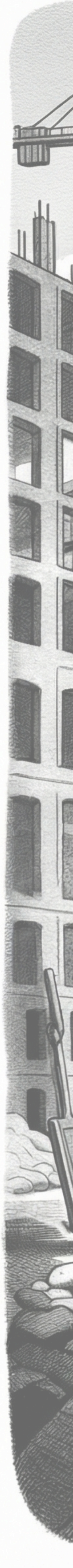
A crucial challenge for DPPs is the absence of universal standards and interoperability frameworks (Psarommatis & May, 2023). Current initiatives are fragmented across industries, using heterogeneous data formats, inconsistent taxonomies, and incompatible identification systems (GS1 barcodes vs. blockchain-based identifiers) (Datta, 2024). In the construction sector, this fragmentation is exacerbated by the lack of common standards for representing product-level information in BIM, which limits integration between design models and passport systems.

Data management and technological limitations also constrain DPP implementation. Collecting and maintaining lifecycle data from manufacturind to end-of-life is resource-intensive and costly (Abedi, Saari, & Hakola, 2024). Current BIM tools have limited capacity to host DPP-specific parameters, and linking material or product-level information often requires additional conversion (Waterman & Circuit, 2023).

Further obstacles stem from data privacy and stakeholder engagement. Many firms percive DPPs as administratively burdensome or commercially risky, fearing the disclosure of sensitive product information (Capelleveen et al., 2023). The absence of clear governance structures and defined responsibilities across value chains reinforces this resistance and slows adoption (Abedi et al., 2024).

From an economic standpoint, the initial setup and data registration costs remain high, particularly for small and medium-sized enterprises (SMEs). While the long-term benefits of DPPs are collective, the short-term costs often fall on manufacturers and data providers (Psarommatis & May, 2023; Capelleveen et al., 2023).

Finally, bio-based introduce additional complexity. Existing ontology frameworks, such as BiOnto (shared terminology and ontology for the bioeconomy & bioproducts space by BIOVOICES project), do not adequately represent the multifaceted requirements for biobased products, leaving no suitable semantic backbone for ensuring interoperability and accurate representation of bio-based materials in digital systems (Datta, 2024). This highlights an important research opportunity: the development of BIM-integrated DPP methodologies capable of accurately representing and managing data for bio-based construction materials within circular economy frameworks.




PASSPORT

GOALS, OBJECTIVE AND RESEARCH QUESTION

1.6.1 Objective

The main objective of this thesis is to develop a BIM-based Digital Product Passport (DPP) proof of concept for hempcrete, a bio-based construction material, in order to inform future frameworks for data accessibility and reliability, support Circular Economy strategies, and contribute to the wider adoption of bio-based materials in construction.

1.6.2 Goals

To achieve this objective, the research follows five specific goals:

- Establish a comparative framework for assessing hempcrete by organizing and synthesizing existing lifecycle and performance data from the literature.
- Place the hempcrete blocks provided by the collaborating company into this framework, identifying their lifecycle stages, performance indicators, and potential for circular application.
- Analyze and compare an already existing hemp-based product case study to extract insights relevant to DPP creation, with particular attention to end-of-life strategies.
- Identify gaps and opportunities revealed through the comparison, highlighting underdeveloped aspects in current hempcrete DPP approaches.
- Develop and prototype a BIM-integrated DPP capable of organizing, updating, and communicating lifecycle, performance, and circularity data.

1.6.3 Research question

How can the development of a BIM-based Digital Product Passport (DPP) contribute to a future framework that enhances the circularity of bio-based construction materials on a hemp-based case study?

CHAPTER 2

CASE STUDY OVERVIEW

To bridge the theoretical framework of bio-based materials, circular economy strategies, and Digital Product Passports with practical applications, this section examines selected case studies, one as a reference case and another one as a research case, of companies actively developing and implementing these materials. The aim is to ground the research in real-world practices, identifying both the opportunities and challenges faced by producers of sustainable bio-composite materials and their path into digitalization.

NATURAL BUILDING SYSTEMS (NBS)

The first case study, considered as the reference case, focuses on NBS, which provides an example of how innovative manufacturers design for adaptability, demountability, and reuse. Their work provides critical insights into how bio-based materials can be integrated as a regenerative approach to building. The information presented in the following section was obtained from the company's official website and from an interview conducted with Managing Director Chloe Donovan on 19 September 2025 during a visit to their facilities.

2.1.1 Overview of the NBS approach

NBS is a UK-based company founded with the mission to move away from conventional, extractive construction practices and develop building systems that are regenerative, circular, and scalable. Its work centers on the use of industrial hemp as a regenerative material, integrating it within modular, reusable components. The initiative emerged from the founder's interest in hemp cultivation and the recognition that hemp shiv, which represents around 60% of the plant's biomass, was treated as waste despite its valuable hygroscopic and insulating properties.

The company's early development combined agricultural innovation with construction expertise. Collaboration between the founder, who had a background in material experimentation, and the technical director, experienced in real estate and development, led to the creation of the ADEPT® Modular System, a reusable panel system based on hemp and timber designed for adaptability, circularity, and low-carbon performance.

NBS operates with a multidisciplinary team of architects, engineers, and material scientists. Since its establishment, it has focused on research and development, prototyping, and testing, aiming to provide climate-positive alternatives to traditional building systems by combining regenerative materials with digital tools for traceability and lifecycle optimization.

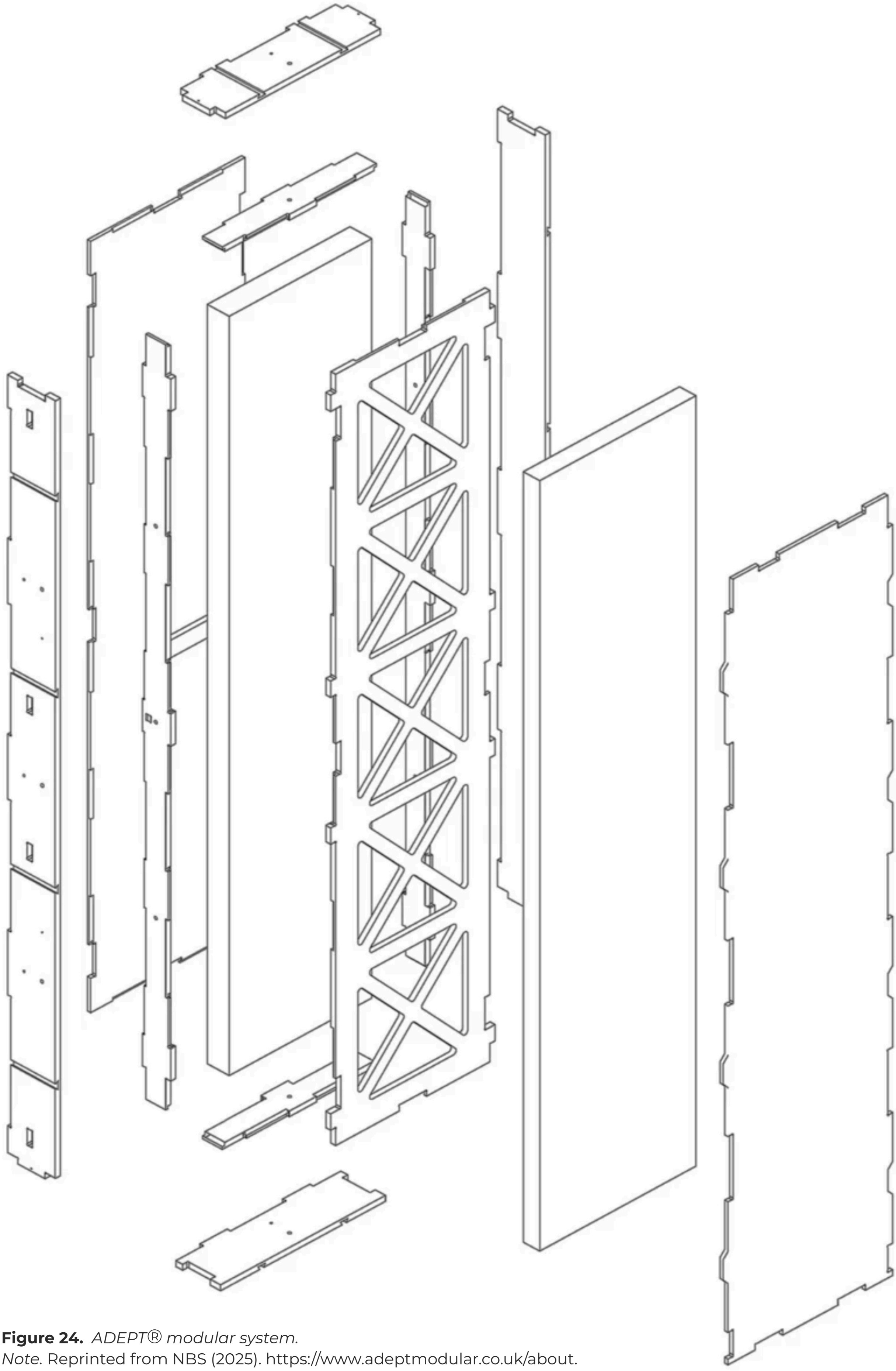


Figure 24. *ADEPT® modular system.*
Note. Reprinted from NBS (2025). https://www.adeptmodular.co.uk/about.

2.1.2 Technical Information

The Modular System

The ADEPT® Modular System is a precision-engineered construction method composed of demountable components for walls, floors, and roofs. The panels, typically 175 mm thick, 600 mm wide, and up to 2400 mm high, are lightweight (under 60 kg) and can be assembled quickly on-site. Buildings of up to three stories can be constructed without additional structural support, as the panels are self-supporting.

Material Composition and Performance

At the core of each panel is Hempsil, an insulating composite derived from hemp shiv. This bio-based material provides moisture regulation, breathability, and thermal stability, maintaining healthy humidity levels for occupants and the building envelope.

Design for Disassembly

Each component in the system is designed for reversibility. Panels can be demounted, reconfigured, and reused without generating waste, supporting adaptive building lifecycles. This kit-of-parts logic reflects a commitment to design for disassembly (DfD) and zero-waste principles.

Manufacturing Process

Production follows lean and digital manufacturing workflows. Components are fabricated in controlled environments using CAD/CAM and CNC systems, achieving up to 85% pre-manufactured value (PMV - % of a project's construction value created off-site through prefabrication or modular methods.). These processes ensure precision, reduce material loss, and facilitate consistent quality.

Hemp Supply Chain

Hemp cultivation underpins the ADEPT® system. As a short-cycle carbon capture crop, hemp sequesters approximately 11 tons of carbon per hectare annually—more than twice the rate of commercial forestry. However, NBS currently relies on French-grown hemp due to its superior quality and the UK's limited processing capacity. This dependency illustrates the absence of local decortication facilities and the broader infrastructural gap that constrains the scalability of regenerative supply chains.

Logistics and Circularity

System logistics prioritize efficiency and reuse. Panels can be flat-stacked for transport, lowering emissions and costs. Future development aims to establish regional manufacturing hubs near cultivation sites, aligning production with local resources. At the end of a building's life, panels can be dismantled and reintegrated through buy-back or return schemes, reinforcing closed-loop material cycles and extending product lifespan.

2.1.3 DPP implementation challenges

NBS integrates Digital Product Passports (DPPs) and RFID tagging into its manufacturing process to enable traceability, maintenance, and reuse of components. These digital records are linked to each panel, providing material and performance data throughout the product lifecycle. However, the implementation of these tools reveals several challenges.

1. *Data management remains a major limitation. Current processes require manual export and import of BIM data (GUID codes, RFID identifiers, product IDs), increasing administrative workload and the risk of human error. On-site data linking between physical tags and digital models is also inefficient, limiting scalability.*
2. *Platform fragmentation poses additional barriers. NBS collaborates with platforms such as Circuland and 2050 Materials, as well as academic partners like the University of Exeter, but each system operates with distinct identifiers and data structures. The lack of interoperability leads to duplicated effort and inconsistent datasets. Moreover, data ownership models that assign control to clients restrict long-term access, raising concerns about the continuity of information if platforms cease operation.*
3. *Verification and comparability issues further complicate implementation. The cost of Environmental Product Declaration (EPD) verification, around EUR 17000 per product, creates financial barriers, while existing LCA benchmarks fail to account for the higher performance of circular systems, resulting in misleading comparisons.*
4. *Systemic and market factors hinder widespread adoption. Investors and developers often prioritize short-term costs over long-term adaptability, while regulations and corporate reporting practices allow limited transparency on embodied emissions (Scope 3). This discourages circular innovators from fully leveraging digital transparency tools.*

2.1.4 Insights

Integrating Material and Digital Circularity.

NBS illustrates how bio-based materials can effectively be combined with digital traceability to enable circular construction. The integration of hemp-based components with RFID-enabled product passports provides a clear precedent for linking physical and digital layers in building systems. This approach strengthens accountability, enables reuse, and reduces the risk of stranded assets, key functions that define an effective Digital Product Passport.

End-of-Life and Design for Reuse

In the case of the ADEPT® system, strong end-of-life strategies are represented through reversible design, modular assembly, and buy-back schemes. These set conditions under which product data remains valuable beyond the first life cycle. For future DPP development, this suggests that end-of-life data should not be treated as an afterthought but rather as a continuous, traceable dimension embedded from the design stage.

Identified Gaps

The experience of NBS indicates several factors that need further reflection in the development of Digital Product Passports for bio-based materials: current processes still rely on manual data handling, fragmented digital platforms, and proprietary ownership models. These conditions emphasize the need to reflect on how DPP systems could become more open, automated, and unified, ensuring that data remains accessible and interoperable across tools and stakeholders.

HEMPSTONE (HANFSTEIN): SCHÖNTHALER

The second case study (the research case used to develop the DPP) focuses on Schönthaler, an example of how traditional manufacturers can evolve towards sustainable innovation while maintaining industrial scalability and strong regional identity. Their work is an ideal basis to study how bio-based materials can be integrated into construction supply chains and evaluated for their circular potential through tools such as Digital Product Passports. The information presented in the following section was obtained through ongoing online communication with construction consultant Werner Schönthaler, as well as from the technical sheets and Environmental Product Declaration provided by the company, and from the material's official online page.

2.2.1 Overview of the Schönthaler approach

Schönthaler is a family-run company based in Eyrs (Oris), South Tyrol, Italy, with nearly sixty years of experience in producing prefabricated building components and concrete-based materials. Since its foundation in 1964, the company has evolved from a local concrete manufacturer into an established producer of structural and architectural elements for residential and industrial construction. Over successive generations, Schönthaler has maintained a consistent focus on craftsmanship, material precision, and process optimization.

In recent years, growing environmental awareness and stricter European regulations on embodied carbon have prompted the company to redirect its *innovation toward low-impact and regenerative materials. Since 2015, it has developed a specialized line of hemp-lime bricks and complementary materials such as hemp plasters and bio-based mortars. This shift represents both a technological and philosophical departure from conventional construction: it replaces resource-intensive processes with renewable, carbon-sequestering alternatives.*

The company's hemp-lime bricks embody a symbiosis between industrial hemp and natural lime, merging one of the oldest cultivated plants with one of the oldest building materials. This combination results in a material that is carbon-negative, moisture-regulating, and fully recyclable. As Schönthaler continues to refine its environmental strategies, its products present an opportunity to explore how Digital Product Passports (DPPs) could document and enhance the material's lifecycle transparency, supporting future reuse and integration within circular construction frameworks.

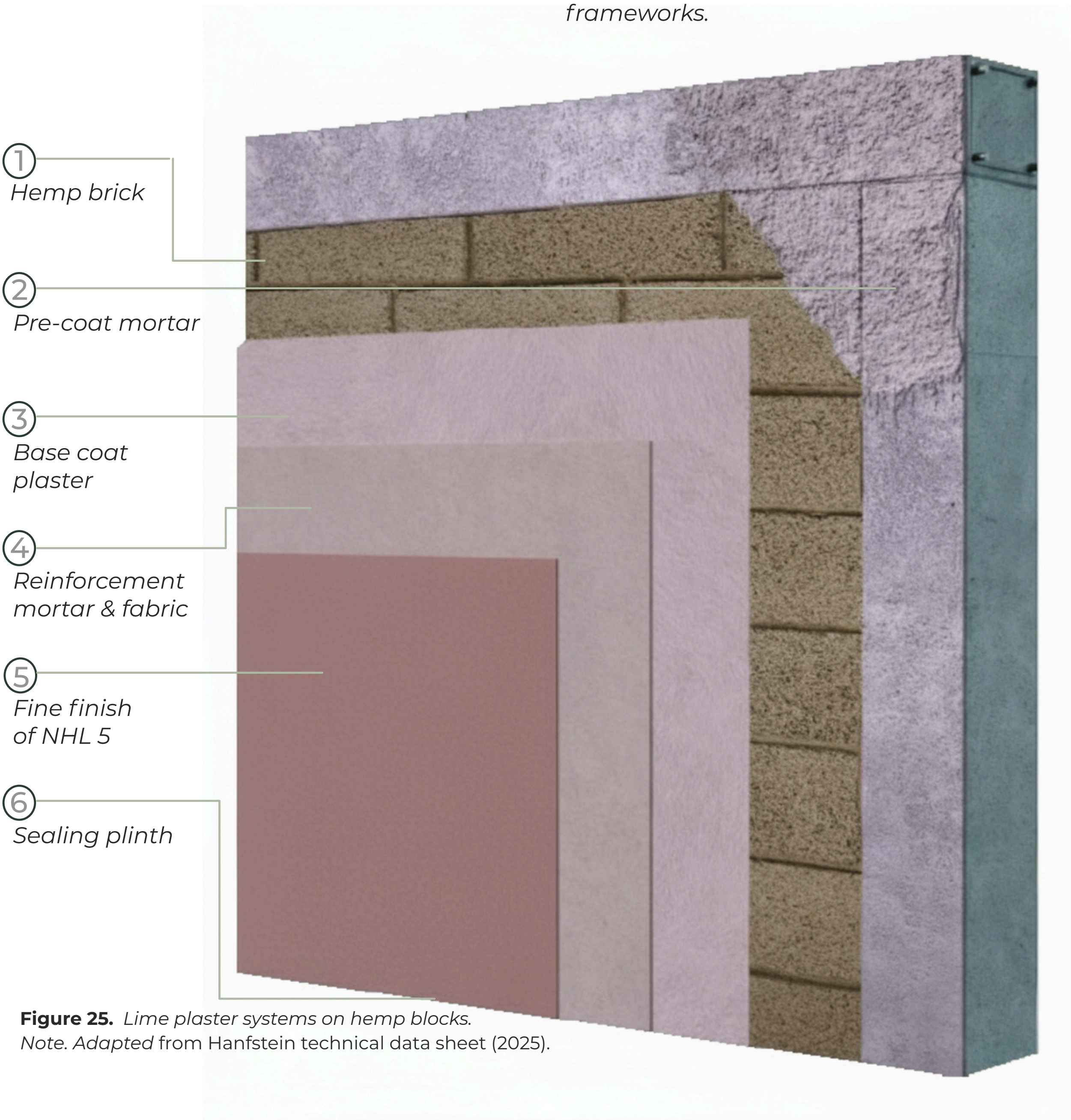


Figure 25. *Lime plaster systems on hemp blocks.*
Note. Adapted from Hanfstein technical data sheet (2025).

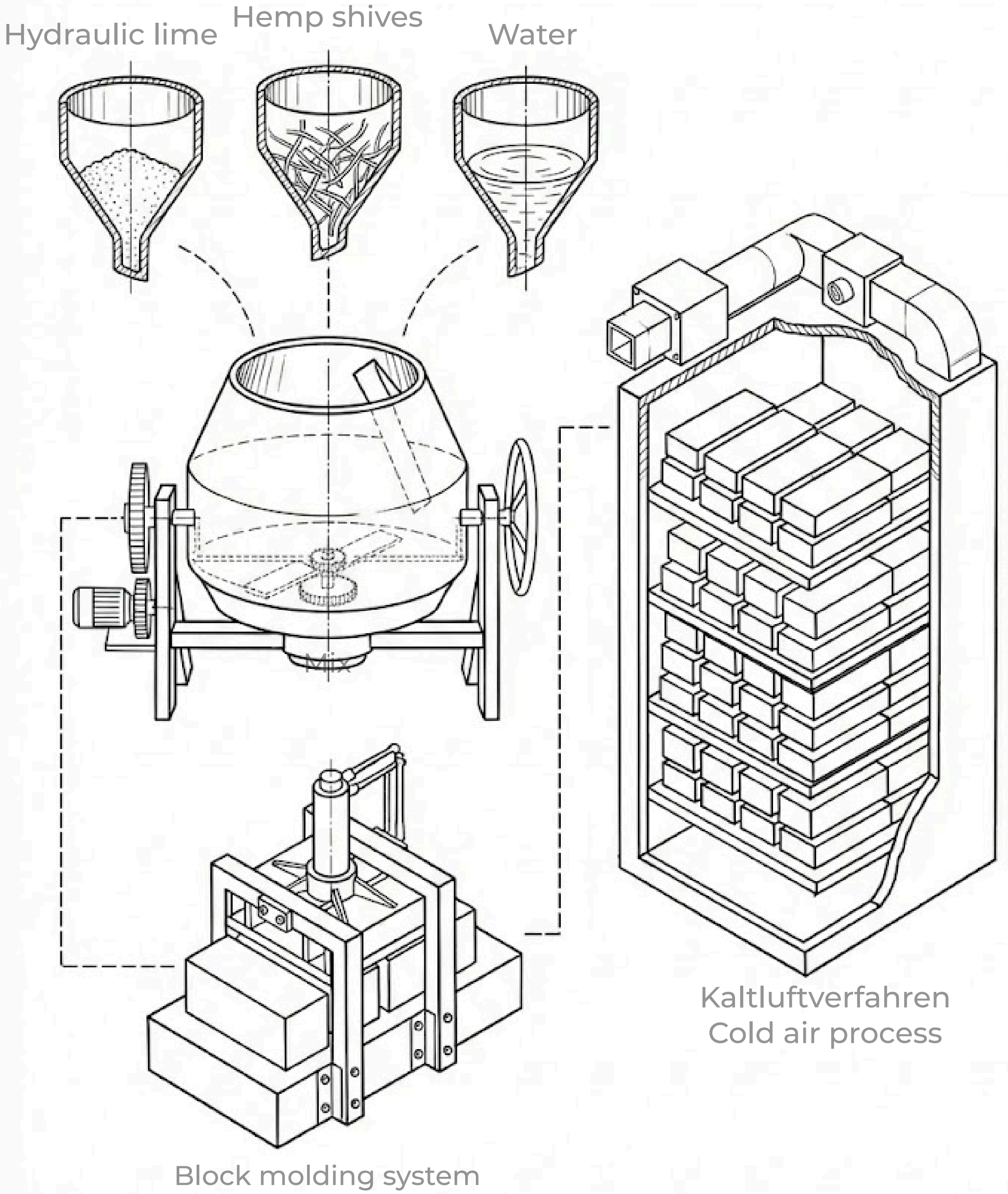


Figure 26. *Hansfstein production process.*
Note. Created by author with Gemini Nano.

2.2.2 Technical Information

Material Composition and Manufacturing Process

Schönthaler's Hanf-Kalk-Ziegel (hemp-lime bricks) are produced at the Schönthaler Betonsteinwerk in Eyrs (Oris), South Tyrol, using a process that combines raw material preparation, mechanical forming, and a cold-air curing method. The system is designed to minimize energy consumption, eliminate wastewater, and integrate carbon sequestration directly into the material's chemistry.

The two main raw materials are hemp shives (Hanfschäben) and a calcareous mineral binder. The shives are sourced regionally from Northern Italy, Austria, Switzerland, or France, depending on seasonal availability, reducing transport distances and emissions. This regional sourcing aligns with Schönthaler's strategy to strengthen local bio-based supply chains.

The mineral binder is a cement-free, lime-based mixture (CaO) combined with minor mineral additives. For every kilogram of hemp-lime brick, the mix includes approximately 0.471 kg of hydraulic lime, 0.357 kg of hemp shives (with about 15% moisture content), and 0.514 liters of drinking water. Once mixed, the material is poured into a concrete block molding system, pressed into shape, and air-dried at ambient temperature in a controlled cold-air process (Kaltluftverfahren). This method eliminates the need for kiln curing or heat input, drastically lowering energy demand.

The production process is powered entirely by the company's photovoltaic system, and all equipment operates under a uniform electricity allocation, whether producing concrete or hemp-based units. No thermal energy or process water is consumed, and production residues are reintroduced into subsequent batches. After air curing, the blocks are palletized and secured using reusable polyethylene bands, reflecting the company's attention to minimizing waste at every stage.

At the end of its service life, the bricks can be fully composted or reused. Crushed hemp-lime blocks (Zerkleinerte Hanfsteine) can be reintegrated into new production batches at up to 15% recycled content without quality loss, closing the material loop and reinforcing the company's cradle-to-cradle approach.

General Material Properties

Schönthaler produces hemp bricks in various dimensions:

Wall Thickness (cm)	Dimensions (L x W x H in cm)	Pieces/m²	Pieces/m³
8	8 x 50 x 20	9.5	111
12	12 x 55 x 20	8.6	71
15	15 x 50 x 20	9.5	67
20	20 x 55 x 20	8.6	45
24	24 x 55 x 20	9.9	41
30	30 x 55 x 20	8.6	30
38	38 x 55 x 20	8.6	24
44	44 x 55 x 20	8.6	21
Full brick (Vollziegel)	6 x 22 x 11	-	500

Table 2. *Schönthaler Hanfsteins dimentions.*
Note. Created by author (Adapted from Hanfstein technical data sheet, 2025)

- *Composition:* Made from 20–55% hemp shives and 45–80% lime-based mineral binder, entirely free of cement and petrochemical additives.
- *Density (Dry):* 310–360 kg/m³, regardless of wall thickness.
- *Density (Equilibrium Humidity):* 390–450 kg/m³, depending on environmental moisture.
- *Expected Service Life:* Approximately 100 years, consistent with standard masonry lifespans.
- *Thermal Conductivity (λ):* 0.07 W/(m·K), consistent across wall thicknesses.
- *Heat Transfer Coefficient (U-value):* Varies with wall thickness.
- *Specific Heat Capacity:* 1,870 J/(kg·K), allowing high thermal mass and phase shifts up to 24.5 hours.
- *Phase Shift:* The time delay for heat transfer through the wall, which is critical for summer cooling, increases significantly with thickness.
- *Sound Insulation (Rw):* 12 cm wall *with* plaster = 41 dB and 38 cm wall with plaster =48 dB.

Wall Thickness (cm)	U-value [W/(m²K)]	Phase Shift (Hours)
8	0.76	3:09
12	0.53	5:53
15	0.43	-
20	0.33	12:06
24	0.28	14:48
30	0.22	18:13
38	0.18	24:30
44	0.15	-

Table 3. *Schönthaler Hanfsteins U-value and phase shift.*
Note. Created by author (Adapted from Hanfstein technical data sheet, 2025)

- *Sound Attenuation Index:* R w(C; Ctr) = 43 (-1; -2) db According to: NF ENISO 140-1 (1997), NF EN 20140-3 (1995) (for a 300 mm hemp-brick wall with 5 mm internal and 15 mm external plaster).
- *Compressive Strength:* 0.5 MPa, adequate for non-load-bearing infill masonry.
- *Shear Strength:* 0.12 MPa.
- *Load-Bearing Role:* Used primarily as infill masonry in timber, steel, or concrete frames; not suitable for primary load-bearing structures.
- *Recommended Wall Height:* Up to 7 m, depending on wall thickness and wind load conditions.
- *Water Vapour Diffusion Resistance (μ):* Wet state = 3.0–3.8 and Dry state = 4.0–4.3.
- *Water Vapour Absorption Resistance:* 19 g/m²·v·h, indicating strong moisture buffering and vapour permeability.
- *Moisture Buffer Value (MBV):* 2.35 [m2.%HR)] which is described as an excellent value characterizing the material's ability to moderate air humidity changes.
- *Hygrothermal Behaviour:* Highly capillary-active and diffusion-open, supporting balanced indoor humidity and preventing condensation.
- *Fire Classification:* Euroclass B, s1, d0 (flame-retardant).
- *EI (Integrity and Insulation time EN 13501-2):* Unplastered 12 cm wall = EI 45 min, 30 cm plastered wall = EI 240 min.
- *Biological Resistance:* Naturally resistant to mold, insects, and rodents due to lime alkalinity and open-pore structure.

Environmental Performance (EPD Summary)

- *LCA Methodology:* Conducted in accordance with ISO 14025 and EN 15804+A2 standards using the Ecoinvent v3.11 database and SimaPro 10.2 software.
- *EPD Type:* “Cradle to grave” with options (Modules A1–A3, A4–A5, B1, C1–C4, and D).
- *Functional Unit:* 1 m^3 of hemp brick with two density variations:
- 405 kg/m^3 (dry weight 335 kg/m^3)
- 430 kg/m^3 (dry weight 360 kg/m^3)
- *Boundaries:* Includes raw material extraction (hemp cultivation and lime production), manufacturing, packaging, transport, installation, use phase (including carbonation), and end-of-life processing (energy recovery and recycling credits).
- Manufactured using renewable electricity from Schönthaler’s own 215.5 kWp photovoltaic system, generating approximately 230 MWh/ year.
- Hemp shives store approximately 0.15 kg C/kg, equivalent to 0.55 kg CO_2 eq/kg of material during use.
- The resulting Global Warming Potential (GWP total) for 1 m^3 of hemp brick (405 kg/m^3 density) is –38.9 kg CO_2 eq, indicating a net carbon-negative product.
- Breakdown of GWP (405 kg/m^3 density):

A*1–A3 (production):* –38.9 kg CO_2 eq

A4 (transport): +21.8 kg CO_2 eq

B1 (Carbonation): -8.29 kg CO_2 eq

C3 (end-of-life energy recovery): +220 kg CO_2 eq (represents the re-emission of previously sequestered CO_2)

D (energy substitution credits): –36.7 kg CO_2 eq

- Overall balance remains strongly negative, primarily due to biogenic carbon storage and renewable energy use.
- *Recyclability*: Up to 15% of crushed hemp stone can be reused in new production without quality loss; higher percentages are used in non-structural applications.

- *Disposal:* If not recycled, residues are suitable for energy recovery (Module C3) due to high biogenic content.
- *Circular Potential (Module D):* Credits are given for energy recovery replacing grid electricity and industrial heat from natural gas.
- *Waste and By-products:* Production waste is minimal; packaging materials (PE bands and wooden pallets) are recyclable.
- The Schönthaler hemp brick exhibits negligible human health impacts across the evaluated categories.
- In terms of indoor environmental quality, the hemp brick is emission-free *and* diffusion-open, containing no volatile organic compounds (VOCs) or synthetic resins.

Environmental Indicator	*Unit*	*A1 – A3 (Production) Result*
Global Warming Potential	kg CO_2 eq	-38.9
Acidification Potential	mol H^+ eq	9.68 E-01
Eutrophication Potential	kg P eq	7.54 E-3
Abiotic Depletion Potential (Fossil Fuels)	MJ	2.25 E+3
Total Renewable Primary Energy	MJ	2.52 E+3
Total Non-renewable Primary Energy	MJ	2.20 E+3
Net Freshwater Use	M3	6.15 E-05

Table 4. *Environmental performance indicatoprs (A1-A3).*
Note. Created by author (Adapted from EDP: Hanfsteine, by Schönthaler Bausteinwerk GmbH, 2025, Bau EPD GmbH, 2025)

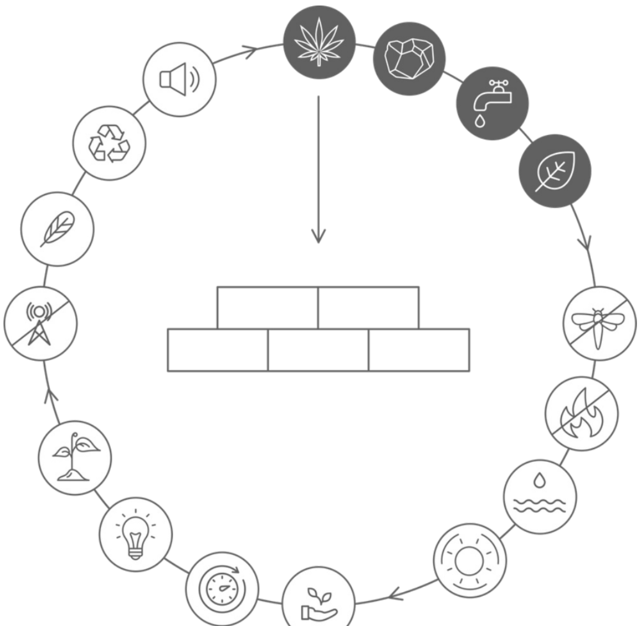


Figure 27. *Schönthaler Hanfstein benefits.*
Note. Reprinted from Schönthaler Hemp blocks Brochure.

The Schönthaler hemp brick demonstrates a distinctly carbon-negative environmental profile within the production stage (Modules A1–A3). Its life-cycle assessment shows that the biogenic CO_2 stored in hemp and the carbonation of lime during curing not only offset all process-related emissions but result in a net global warming potential of –38.9 kg CO_2 eq per m^3. The combination of locally sourced hemp shives, cement-free lime binder, and renewable electricity from photovoltaic systems further reduces reliance on fossil fuels and minimizes resource depletion.

Beyond its carbon performance, the EPD indicates low acidification, eutrophication, and fossil energy impacts, highlighting the benefits of renewable-based production and a short supply chain. Although the declared water use (47.7 m^3/m^3) is moderate, it remains within acceptable ranges for mineral-bound composites. Overall, the Schönthaler hemp brick functions not only as a high-performance insulation material but also as a carbon sink and circular construction component, embodying the principles of regenerative and low-impact building materials.

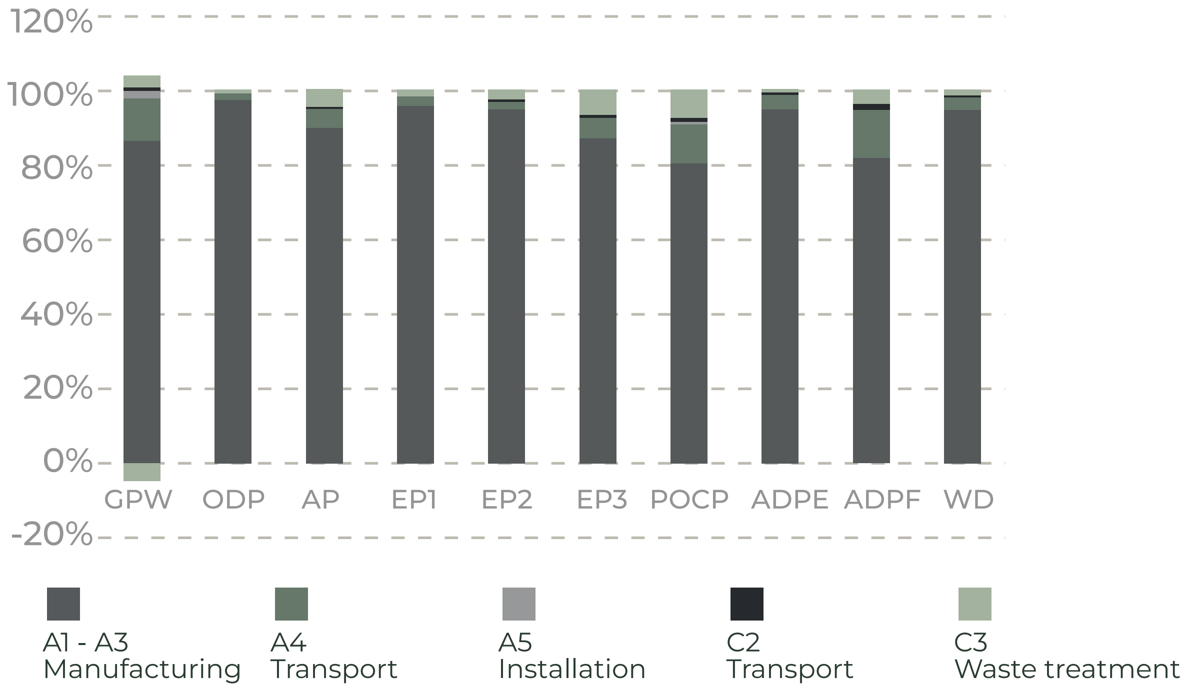


Figure 28. *Relative environmental impact of the modules under consideration: Energy recovery.*
*Note. Created by Author (*Adapted from EDP: Hanfsteine, by Schönthaler Bausteinwerk GmbH, 2025, Bau EPD GmbH, 2025)

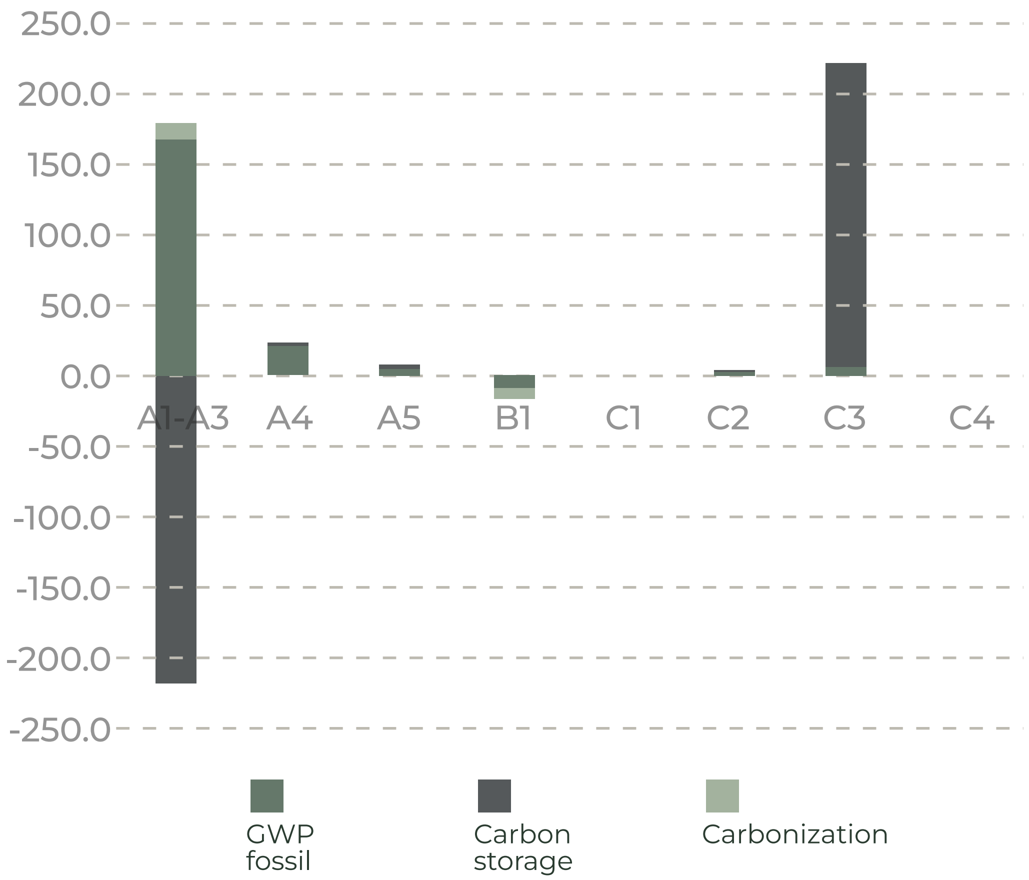


Figure 29. *Greenhouse gas balance.*
*Note. Created by Author (*Adapted from EDP: Hanfsteine, by Schönthaler Bausteinwerk GmbH, 2025, Bau EPD GmbH, 2025)

End-of-Life and Circular Scenarios

At the end of its service life, the Schönthaler hemp brick is designed for complete material recovery and reintegration within a circular production cycle. According to the EPD (Modules C1–C4 and D), the product's dismantling and treatment processes are simple and energy-efficient due to the absence of synthetic binders and the use of pure lime-based mortar. The demolition stage (C1) requires minimal mechanical effort, and no hazardous residues are produced

The material can be mechanically crushed and sieved using standard wood-chip shredders. The light fraction—a mix of hemp shives and lime binder—can be reintroduced into new production batches, allowing up to 15% recycled content without loss of quality. Higher percentages can be reused for non-structural applications such as loose-fill insulation or internal partitions. The heavier mineral residues, composed mainly of lime plaster and mortar, can be directed to construction recycling streams or potentially reused as lime raw material in industrial processes.

In the EPD's end-of-life modeling, Modules C3–C4 account for energy recovery and landfill scenarios, while Module D credits the substitution of conventional energy sources (electricity and heat from natural gas) with the energy recovered from biomass content. The EPD attributes –36.7 kg CO_2 eq/m^3 in Module D as a carbon credit for avoided emissions through energy substitution. Consequently, even when transport and disposal impacts are considered, the hemp brick maintains a net carbon-negative balance over its full life cycle.

The combination of biodegradability, reusability, and renewable content allows the Schönthaler hemp brick to function as a fully circular, low-impact construction product, aligning with European environmental targets for waste minimization and carbon neutrality in the building sector.

Phase/Scenario	*Unit*	*Result*
Transport (C2)	kg CO_2 eq	+21.8
Composting (C3.1) Biogenic carbon released during composting generates positive emissions	kg CO_2 eq	+220.0
Reuse (C3.2)	kg CO_2 eq	0.0
Energy Recovery (C4.1)	kg CO_2 eq	+0.3
Potential Benefits (D 4.1) (Energy Recovery Substitution)	kg CO_2 eq	-36.7

Table 5. *End of life phase (C-D) GWP.*
Note. Created by author (Adapted from EDP: Hanfsteine, by Schönthaler Bausteinwerk GmbH, 2025, Bau EPD GmbH, 2025)

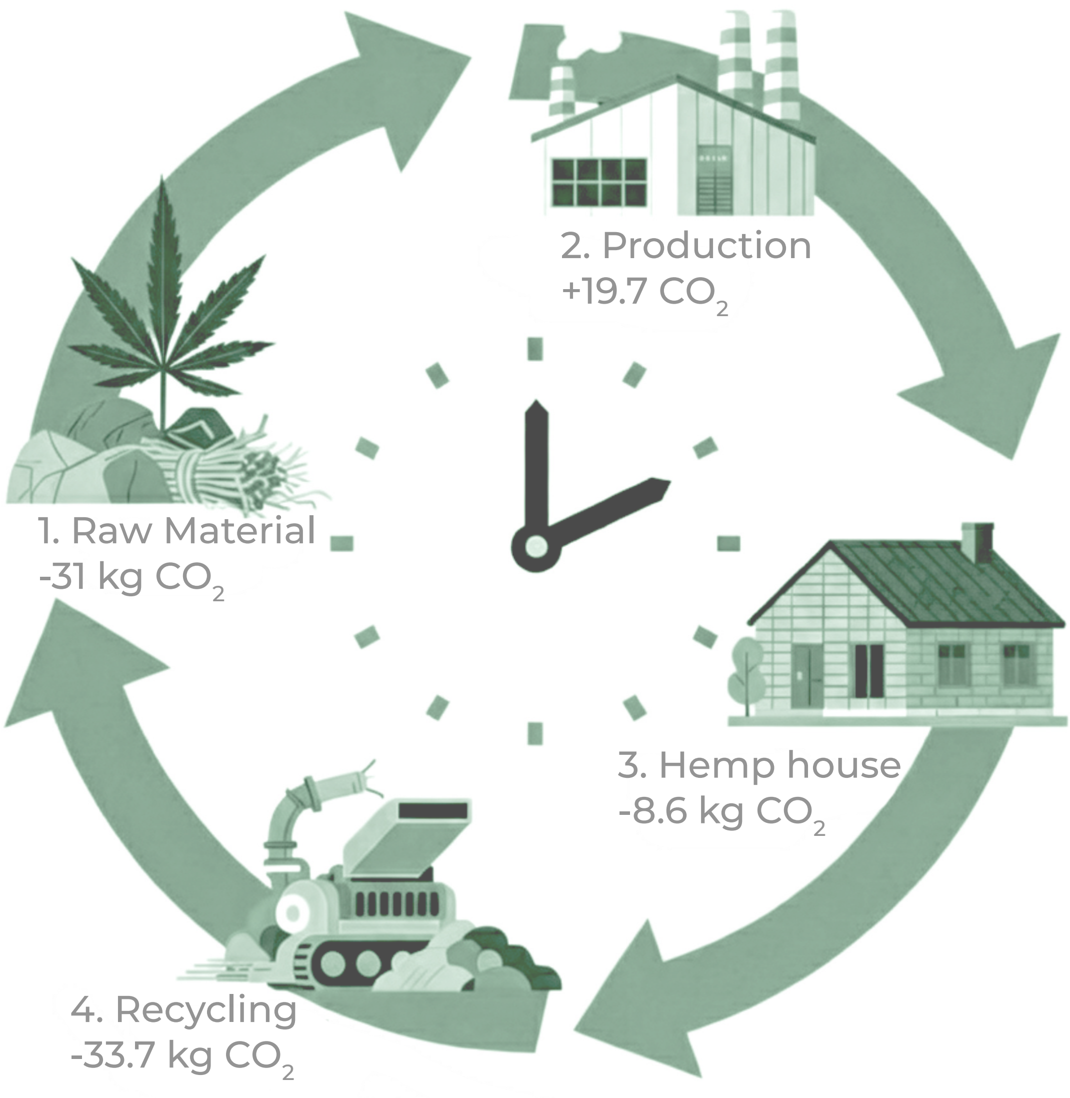


Figure 30. *Hemp brick Cycle, CO_2 savings over the life cycle.*
Note. Reprinted from Hanfstein circularity sheet by Schönthaler.

2.2.3 DPP gaps and needs

Documentation and Data Structure

- *Gap:* The available information on Schönthaler's hemp-lime bricks come from manufacturer documents such as the Environmental Product Declaration (EPD), technical data sheets, and internal reports. While these contain detailed environmental and physical performance data and is required to be updated every five years, it does not specify how data are collected, verified, or managed between revision cycles. The datasets from the EPD appear to be structured but remain static and document-based, with no integration into a dynamic or automated data management system.
- *Need:* To develop interoperable machine-readable formats linked to real-time updates for datasets by Schönthaler in order to allow the development of DPPs. This would include developing a data structure that is able to link the life-cycle monitoring/raw material inputs, process energy, emissions, and waste to databases like BIM or LCA while ensuring transparency and continuous traceability across its life.

Circularity and End-of-Life Data

- *Gap:* The company's circularity strategy gives priority to material recovery by means of crushing and reintegration of hemp-lime debris into new production batches. While this contributes to a regenerative manufacturing loop, the documentation is strictly at a material level and lacks any mechanisms for component-level traceability. There is currently no digital record linking specific batches or building components for their reuse or recovery pathways.
- *Need:* A DPP could extend Schönthaler's current closed-loop model by introducing traceable identifiers for each component, enabling modular recovery and reuse beyond the factory level. Establishing digital tracking protocols would allow information on material origin, composition, and reuse potential to accompany each unit through its life cycle, strengthening transparency in end-of-life management.

Aesthetic and Architectural Dimensions

- *Gap:* The sensory and architectural qualities of the hemp-lime brick, such as its porous surface texture, earthy color tone, and organic inclusions, are central to its material identity but remain limited in technical specifications. Existing datasets focus exclusively on quantitative performance indicators, overlooking visual, tactile, and perceptual characteristics relevant for architectural design and reuse.
- *Need:* Future DPP development should incorporate qualitative and sensory descriptors to complement physical and environmental metrics. Including parameters such as surface variation, color range, reflectance, and aging behavior would enhance design-oriented decision-making and preserve the material's aesthetic identity across reuse cycles.

CHAPTER 3

METHODOLOGY

DEFINITION OF SCOPE AND BOUNDARIES

The scope of this thesis is the development of a prototype as a proof of concept of a Digital Product Passport (DPP) for a hempcrete-based wall cassette, using Schönthaler's hemp block as the case study. The DPP will be integrated within a Building Information Modeling (BIM) environment and structured to address the needs of two key *personas*:

- Producers/manufacturer, who require verifiable documentation of product data and environmental performance; and
- Architects/designers, who need accessible, interoperable information to inform design decisions and circular strategies.

The research focuses on data integration and communication, rather than on material invention or laboratory testing. The objective is to compile, structure, and visualize existing environmental, technical, and circularity data to demonstrate how a DPP can enhance traceability, circularity and design usability for bio-based materials.

3.1.1 Boundaries and Limitations

This research is exploratory and aims to produce a conceptual and functional prototype, not a finalized industrial tool. The following boundaries apply:

1. No new material testing will be performed; all performance data are provided by the manufacturer.
2. No new LCA calculations are conducted; instead, in case theres incomplete information from the company's LCA, it will be supplemented with comparable academic data.
3. The DPP prototype will not undergo industrial-scale validation or implementation.
4. The BIM integration will demonstrate possibility and workflow compatibility, not full automation or scalability.
5. Economic, policy, and regulatory analyses of DPP implementation and frameworks are beyond the scope of this thesis.
6. Blockchain identifiers and decentralized storage are excluded, though their principles help the discussion on long-term data traceability.

PERSONA DEFINITION

Digital Product Passports (DPPs) should serve multiple stakeholders across the material life cycle by providing relevant, accessible, and comparable information. DPP should not be a static dataset but a multi-layered informational tool, where data visibility and content are tailored to the specific needs and responsibilities of different actors.

In this research, a *persona* analysis will be used to determine which information categories and levels of detail are most relevant to each group. This ensures that the DPP framework developed for the hemp-block aligns with the practical workflows and decision-making contexts of its users.

According to (Rosenberg, Stephens, & Collins-Cope, 2005) a *persona* is a description of a fictional person that represents user archetypes. This construct is an interaction design tool that was first introduced by Alan Cooper in his book "The Inmates Are Running the Asylum: Why High Tech Products Drive Us Crazy and How to Restore the Sanity". The persona represents a "typical" end user at whom the software or product is being targeted. *Personas* are generalized, fictional profiles or characters that represent distinct groups of behaviors, goals, and motivations observed during the research phase (Tu, Dong, Rau, & Zhang, 2010).

Some *personas* involved in or affected by a hemp-system include:

- Producers or manufacturers: Are responsible for manufacturing and distributing the material, and for ensuring data accuracy regarding composition, performance, and environmental impact.
- Architects or designers: They are the end-users of the DPP who rely on it to make informed material choices, compare environmental impacts, and integrate the product into digital design environments.
- Contractors and builders: Who are interested in assembly and disassembly data, logistical aspects, and safety considerations.
- End-of-life managers or users: They are concerned with reuse, recycling, or recovery information of the material.
- Researchers and policymakers: Who are engaged with the data structure for standardization, compliance, and regulatory development.

However, given the scope and technical constraints of this thesis, the DPP prototype will be developed with a focused scope on two primary persona groups:

- Producers/manufacturers
- Architects/designers

Persona analysis is an important interaction design technique intended to create a more focused product by designing the system around the user's needs (Rosenberg, Stephens, & Collins-Cope, 2005). In this research, two representative personas were developed to reflect key roles within the manufacturing process and two for the designing process. These *personas* capture the differing goals, responsibilities, and data needs:

3.2.1 Producer *persona*: Owner / Production Manager

Education: BA in Business and Construction Management

Title: General Manager/ Brand Manager

Industry: Concrete and hempcrete manufacturing

Key responsibilities: Oversees operations, logistics, and client relationships. And balances innovation with production costs and reliability.

Primary Goal: Strengthen brand credibility and market access through trusted digital documentation.

Secondary Goal: Optimize internal processes by integrating material data management.

Data needs

- *Product overview:* technical and environmental summary.
- *Production data:* updates on production volumes, energy use, and waste reduction metrics.
- *Cost and logistics data:* material quantities, transportation data, and storage requirements.
- *Certification and compliance information:* summaries of certifications, declarations, and performance labels.
- *Client-facing sustainability metrics:* simplified indicators such as carbon footprint per block or per m^2 of wall assembly.
- *Maintenance and support documentation:* instructions for handling, assembly, and end-of-life management.

3.2.2 Producer *persona*: Sustainability assessor

Education: MSc in Environmental Engineering

Title: Sustainability and Certification Manager

Industry: Manufacturing of concrete and hempcrete

Key responsibilities: Collecting and maintaining environmental data, ensuring compliance with EU and national sustainability legislation, and communicating environmental performance to clients and partners.

Primary Goal: Ensure environmental transparency and regulatory compliance through structured, verifiable data.

Secondary Goal: Use DPPs to simplify data-sharing with external stakeholders (architects, certifiers).

Data needs

- *Material composition and sourcing:* Exact information on raw materials, suppliers, and geographic origin.
- *Environmental performance indicators:* embodied carbon, energy demand, water footprint, and waste generation (aligned with EN 15804 or similar LCA standards).
- *Manufacturing process data:* energy sources, transportation distances, and emissions related to production stages.
- *Product lifespan and end-of-life data:* durability, disassembly strategies, recyclability, and biodegradation profiles.
- *Testing and certifications:* results of mechanical, thermal, and fire-resistance tests; compliance certificates.
- *Version control and traceability:* documentation of updates, data sources, and responsible actors.
- *Interoperability features:* exportable formats compatible with BIM and LCA software (.xml, .ifc, or .xls formats).

3.2.3 Architect *persona*: Technical Architect

Education: MSc in Sustainable Architecture

Title: Project Architect

- *Industry: Architecture & Sustainability Consultancy*

Key responsibilities: material selection considering performance, cost, and certification requirements; preparation of technical documentation for construction and procurement; and carrying out LCA-based comparisons while managing BIM databases.

Primary Goal: Access accurate, comparable technical and environmental data to support design and procurement decisions.

Secondary Goal: Integrate DPP data directly into BIM for seamless workflows.

Data needs

- *Technical performance data:* compressive strength, thermal conductivity, density, vapor permeability, and fire resistance.
- *Dimensional and modular information:* block dimensions, tolerances, and compatibility with standardized systems.
- *Environmental indicators:* embodied carbon (A1–A3), transport emissions (A4), and end-of-life scenarios (C1–C4).
- *Cost and sourcing information:* price per unit, availability by region, transportation distances, and lead times.
- *Documentation of lifecycle:* durability data, maintenance requirements, and replacement frequency.
- *Certification and compliance data:* Environmental Product Declarations (EPDs), CE marking, and conformity to construction standards (EN 771-3, ISO 14025).
- *Data interoperability:* structured formats compatible with BIM, IFC, or Revit family parameters for direct integration into digital models.
- *Comparability tools:* the ability to benchmark hemp blocks against conventional materials.

3.2.4 Architect *persona*: Design architect

Education: MA in Architecture and Material Culture

Title: Design Architect

Industry: Architecture Studio

Key responsibilities: Develops material-driven design concepts. Collaborates with material producers and craftsmen. Integrates environmental values through spatial and aesthetic expression.

Primary Goal: Understand the sensory, aesthetic, and narrative qualities of materials through accessible information.

Secondary Goal: Communicate material stories to clients and users in compelling, visual ways.

Data needs

- *Material narrative and origin:* documentation of where and how the hemp and lime are sourced; cultural or territorial stories tied to the material's production.
- *Visual and tactile features:* surface texture, colour variations, and how these develope over time (aging, patina, exposure).
- *Design applications:* detailing strategies and design guidelines.
- *Spatial performance:* qualitative data on acoustic comfort, humidity regulation, and thermal feel in interiors.
- *Circularity and reusability information:* how the blocks can be dismantled, reconfigured, or reintroduced into new designs.
- *Material samples and visual assets:* photographs, texture maps, or 3D models that can be used in visualizations.

3.2.5 *Persona* Data needs

To translate the qualitative *persona* insights into actionable design parameters for the Digital Product Passport (DPP), the data needs of each user group were evaluated according to their required level of detail and relevance across different information categories. This comparison aims to identify how much information each *persona* should access or prioritize.

Each category was rated on a three-level scale reflecting the degree of informational complexity and precision expected by the *persona*. High means detailed and structured data, medium means summarized or filtered data and low means minimal or qualitative information.

These categories reflect the specific priorities of each user group. Sustainability assessors depend on detailed environmental, lifecycle, and compliance data to perform accurate evaluations. Production managers require reliable economic, process, and material-origin information to support manufacturing planning and operational decisions. Technical architects need precise technical performance metrics, interoperability data, and certification details to ensure the material can be specified and integrated into building systems. Design architects benefit most from visual, contextual, and qualitative information that supports concept development and material selection during early design stages.

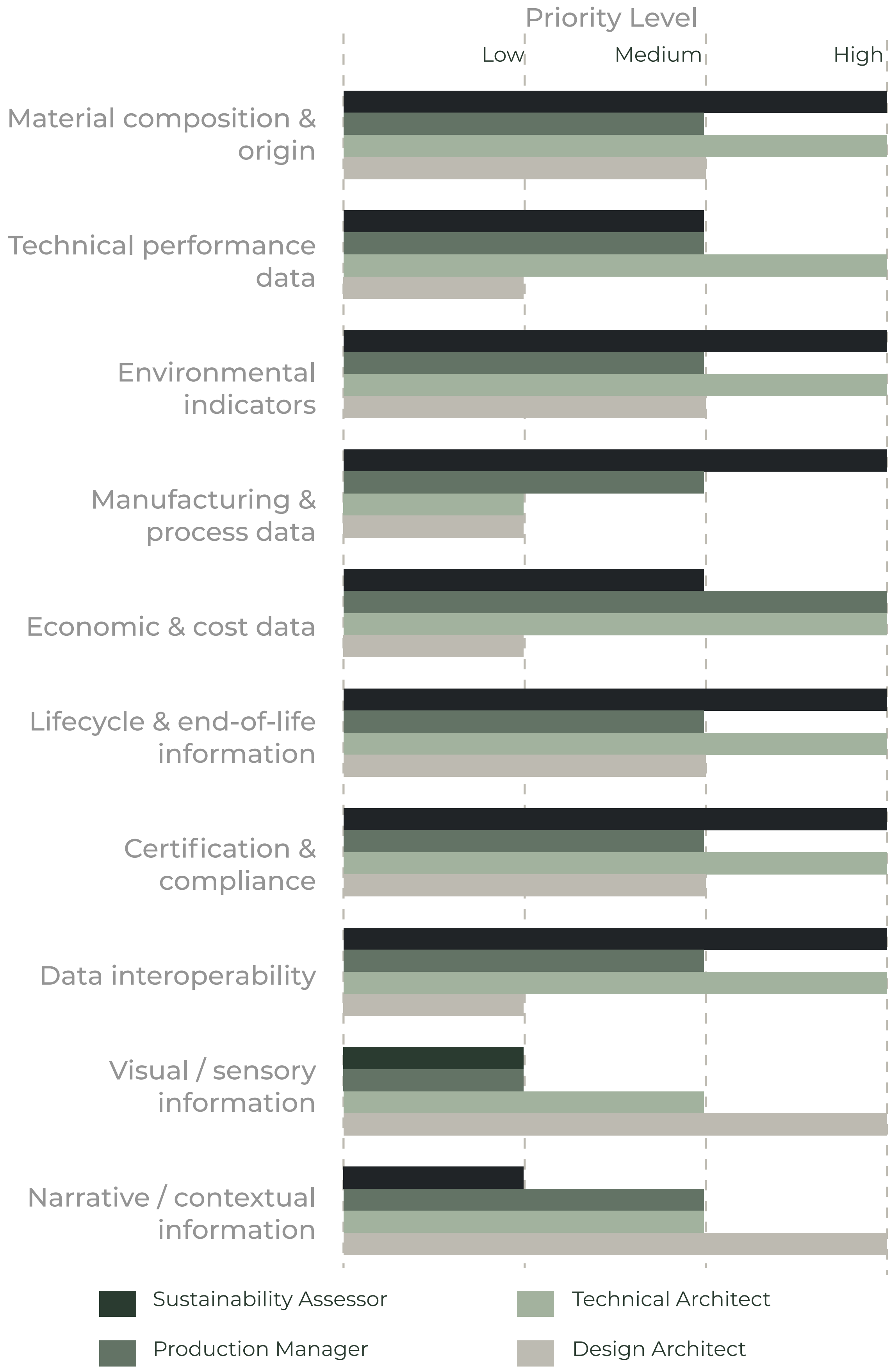


Figure 31. *Persona data needs priority level.*
Note. Created by author.

METHODOLOGICAL FRAMEWORK

This thesis proposes a hybrid methodological framework for creating and testing Digital Product Passports (DPPs) for bio-based construction materials within BIM. The framework draws from three methodologies: (Atta, Bakhoum, & Marzouk, 2021), (Bosma, 2024), and (Honic, Kovacic, & Rechberger, 2019). Each contributes specific tools or conceptual structures that have been adapted to the scope, data availability, and temporal limits of this research.

3.3.1 Information categories

The framework proposed is structured around eight main categories that integrate both qualitative and quantitative data. Each category is defined by a set of parameters drawn and adapted from (Bosma, 2024). It also expands it by adding two new dimensions: Cultural & Sensory Information and Economic & Cost Information, ensuring that the DPP responds to the needs of the personas.

Category	Parameter	Description	Data Source
1. Identification and General Information	Product Name	Name of the material	Manufacturer documentation
	Product ID	Unique identifier of the material	Certification or compliance report
	Object number	Unique BIM-generated object reference	BIM parameter
	Material Type	Category or type of material	BIM parameter
	Manufacturer	Producer of the material	Manufacturer documentation
	Distributor	Name and contact of distributor	
	Supplier	Name and contact of supplier or sub-supplier	
	Transportation Route	Typical transport routes and modes	
	Traceability ID	Unique digital ID for traceability (QR or blockchain)	
	Origin	Geographic source product	
	Version number	Passport version control	Assigned
2. Physical and Technical Properties	Material	Description of the material	Manufacturer documentation
	Component	Description of the component	
	Composition	Material composition and proportions	
	Dimensions	Dimension type (cm)	
	Height	Height of the material (mm)	BIM parameter
	Length	Length of the material (mm)	
	Width	Width of the material (mm)	
	Volume	Volume of the material(m^3)	Manufacturer documentation
	Dry density	Mass per unit volume completely oven-dried (kg/m^3)	
	Equilibrium density	Mass per unit volume on normal ambient conditions (kg/m^3)	
	Weight	Mass per unit (kg)	
	Compressive strength	Compressive resistance (MPa)	Laboratory test
	Flexural strength	Flexural resistance (MPa)	
	Thermal conductivity	λ-value (W/mK)	
	Heat transfer coefficient	u-value (W/m^2K)	
	Specific heat capacity	Heat required to raise temperature (J/kg·K)	

Category	Parameter	Description	Data Source
2. Physical and Technical Properties	Phase shift	Delay in heat transfer through material (hours)	Laboratory test
	Moisture Buffer Value	Moisture absorption/ desorption capacity of the material	
	Water vapour diffusion resistance when wet	Ability of material to allow vapor to pass through	
	Water vapour diffusion resistance when dry	Ability of material to allow vapor to pass through	
	Water vapour absorption resistance	Resistance to vapor absorption at surface	
	Standard compliance	Of relevant building or environmental standards	Certification or compliance report
3. Circularity and End-of-Life Information	Connection Type	Type of material connection (Dry interlock / bolted / screwed; Mortar / adhesive / binder-based; Cast-in-place)	Manufacturer documentation
	Connection Score	Ease of separation or reversibility score	Assigned
	Prefabrication	If product is prefabricated	Manufacturer documentation
	Prefabrication factor	Proportion of prefabricated components	Assigned
	Deconstructability score	Ease of disassembly and recovery at end of life (simplified from Atta,2021)	Calculated
	Recycling potential	% of material recyclable	Manufacturer documentation
	Reusability	If material is reusable as-is	
	Reusability potential	Likelihood of reuse without processing	
	Recovery score	Ratio of reusable, recyclable, non-toxic, uncoated elements (simplified from Atta, 2021)	Calculated
	Disassembly potential	Disassembly feasibility index	Assigned
	Disassembly instructions	Guidelines for separation or dismantling	Manufacturer documentation
	Secondary use scenarios	Possible post-use applications	
	End-of-life recommendation	Suggested disposal or reuse pathway	

Category	Parameter	Description	Data Source
4. Environmental Performance and LCA Data	EPD	Developed recent Environmental Product Declaration	Manufacturer documentation
	Link EPD	URL to Environmental Product Declaration	
	Global Warming Potential (GWP)	CO_2 equivalent per unit (All stages)	EPD
	Primary Energy Intensity (PEI) Renewable	Renewable MJ consumed during production per unit (All stages)	
	Primary Energy Intensity (PEI) Non-renewable	Non-renewable MJ consumed during production per unit (All stages)	
	Acidification Potential (AP)	SO_2 equivalent per unit (All stages)	
	Embodied carbon	Total CO_2 eq. Per kg for manufacturing (A-stage)	
	Biogenic carbon storage	CO_2 sequestered in bio-based material	
	End-of-life emissions	Emissions at disposal or biodegradation stage CO_2 eq. Per kg or m2 (C/D-stage)	
	Circularity index	Composite score combining reuse and recycling ratios	Calculated
	Normalized environmental performance	Environmental impact normalized against reference values	
	Secondary life weighting	Weighted environmental effect for second-life use	
	Environmental score	Normalized overall impact (simplified from Atta, 2021)	
5. Condition, Maintenance, and Temporal Data	Service life	Expected durability or usable lifespan	Manufacturer documentation
	Maintenance Instructions	Guidelines for maintaining the product	
	Sourcing distance	Distance of travel of sourcing for production	
	Warranty	If warranty applies	
	Warranty duration	Duration of warranty (Months)	
	Update history	Log of changes or inspections	Auto-generated (BIM)
6. Safety and Compliance	HPD	Developed recent Environmental Product Declaration	Manufacturer documentation
	Link HPD	URL to Environmental Product Declaration	

Category	Parameter	Description	Data Source
6. Safety and Compliance	Hazard classification	Identifies presence of hazardous components	Manufacturer documentation
	PM	Potential occurrence of diseases due to particulate matter emissions	
	IRP	Potential effect from human exposure to U235	
	ETP-fw	Potential Ecosystem toxicity comparator unit	
	HTP-c	Potential human toxicity comparator unit - carcinogenic effect	
	HTP-nc	Potential human toxicity comparator unit - non-carcinogenic effect	
	SQP	Potential soil quality index	
	Toxicity	Presence of harmful compounds or emissions	
	Class	Safety class according to relevant standard	Safety datasheet
	s-subclass	Specific subclass	
	d_subclass	Detailed subclass	
	Fire resistance	Fire rating or classification	Manufacturer documentation
	Coatings	Indicated if theres surface finishes or chemical treatments	
	Coatings or treatments	Surface finishes or chemical treatments	
	PPE requirements	Recommended protective equipment	
	Compliance certificates	If there are health, safety, or environmental certifications	
7. Cultural and Sensory Information	Sound Absorption Coefficient	Fraction of incident sound absorbed by the material	Laboratory test
	Sound Attenuation Index	Reduction in sound transmission through material (Rw)	
	Material perception & sensory qualities	Texture, color, smell, temperature	Direct observation
	Cultural or regional relevance	Climate suitability, agricultural value and resource availability	Literature / Regional study
	Aesthetic evolution	Material aging, architectural expression and aesthetic narratives	Literature / Expert evaluation

Category	Parameter	Description	Data Source
7. Cultural and Sensory Information	Thermal Comfort	Perceived comfort due to heat exchange with surroundings	Literature / User experience
	Hygrothermal Comfort	Perception of comfort due to indoor humidity, condensation and mold growth	
	Acoustic Comfort	Subjective perception of sound environment	
	Material Comfort	Perceived tactile and visual comfort from material properties	
	Craft or community engagement	Craft knowledge and identity and symbolism scores	Literature / Cultural study
8. Economic and Cost Information	Material unit cost	Cost per unit (kg, m^2, m^3)	Manufacturer documentation
	Assembly cost	Combined cost of labor + material per unit (kg, m^2, m^3)	
	Maintenance cost	Periodic cost for cleaning, replacement, or care	
	Economic circularity benefit	Potential cost savings from reuse or recycling	Calculated
	Replacement cost	Mid-life upgrades/ replacements	Manufacturer documentation
	Net present value	Total discounted cost/benefit over time	Calculated
	Net savings (net benefit)	Difference between options	
	Pay back period	Time to recover investment	
	Benefit-Cost ratio	PV of benefits / PV of costs	
	Lifecycle cost estimate	Sum of initial + maintenance + end-of-life cost	

Table 6. *Proposed data structure and parameter categories for a Digital Product Passport (DPP) for bio-based construction materials.*

Note 1. Created by author (Adapted from Bosma, 2024 & Waterman, 2023)

Note 2.

EPD - Environmental product declaration

HPD - Health product declaration

PM - Potential occurrence of diseases due to fine dust emissions

IRP - Potential impact from human exposure to U235 (radioactive isotope of uranium)

ETP-fw - Potential ecotoxicity impact for freshwater ecosystems

HTP-c - Potential human toxicity impact – carcinogenic effects

HTP-nc - Potential human toxicity impact – non-carcinogenic effects

SQP - Potential soil quality index

PPE - Personal protection equipment

3.3.2 Structure of information

The Digital Product Passport (DPP) will be structured around a simplified hierarchical and temporal framework derived from (Honic, Kovacic, & Rechberger, 2019). Their original methodology defines four hierarchical levels: Building → Component → Element → Material, and four temporal stages corresponding to the building lifecycle: Conceptual Design (MPa), Preliminary Design (MPb), Tendering (MPc), and Operation (MPd).

Only two hierarchical levels and two design stages are addressed in the prototype development. The DPP will operate at the Material and Element scales and within the Conceptual and Preliminary Design stages. This focused approach allows the passport to serve both architectural decision-making and material research, providing a preliminary framework for future scalability.

3.3.3 Integration with BIM

This thesis integrates the BIM-centered automation strategies from Atta et al. (2021) and the hierarchical mapping principles from Honic et al. (2019) with Bosma's (2024) approach to Linked Data and ontology design. The aim is to produce a functional, machine-readable Material/Element Digital Product Passport (DPP) while keeping the prototype workflow practical by using Excel/JSON as an intermediate exchange format and a lightweight semantic layer to enable future Linked Data conversion.

Atta et al. (2021): use of Revit shared parameters and Dynamo scripts to populate, compute and extract both qualitative and quantitative DPP fields (e.g., deconstructability and recovery indicators).

Honic et al. (2019): adapt to the hierarchical mapping (Material ↔ Element) and the use of persistent identifiers (GUIDs) so that each material passport maps to the correct element in the BIM model.

Bosma (2024): adopt the DPP "must-have" topics as canonical properties and use an ontology to define formal terms and relationships, enabling the dataset to be machine-readable and convertible to Linked Data (RDF/JSON-LD) when required.

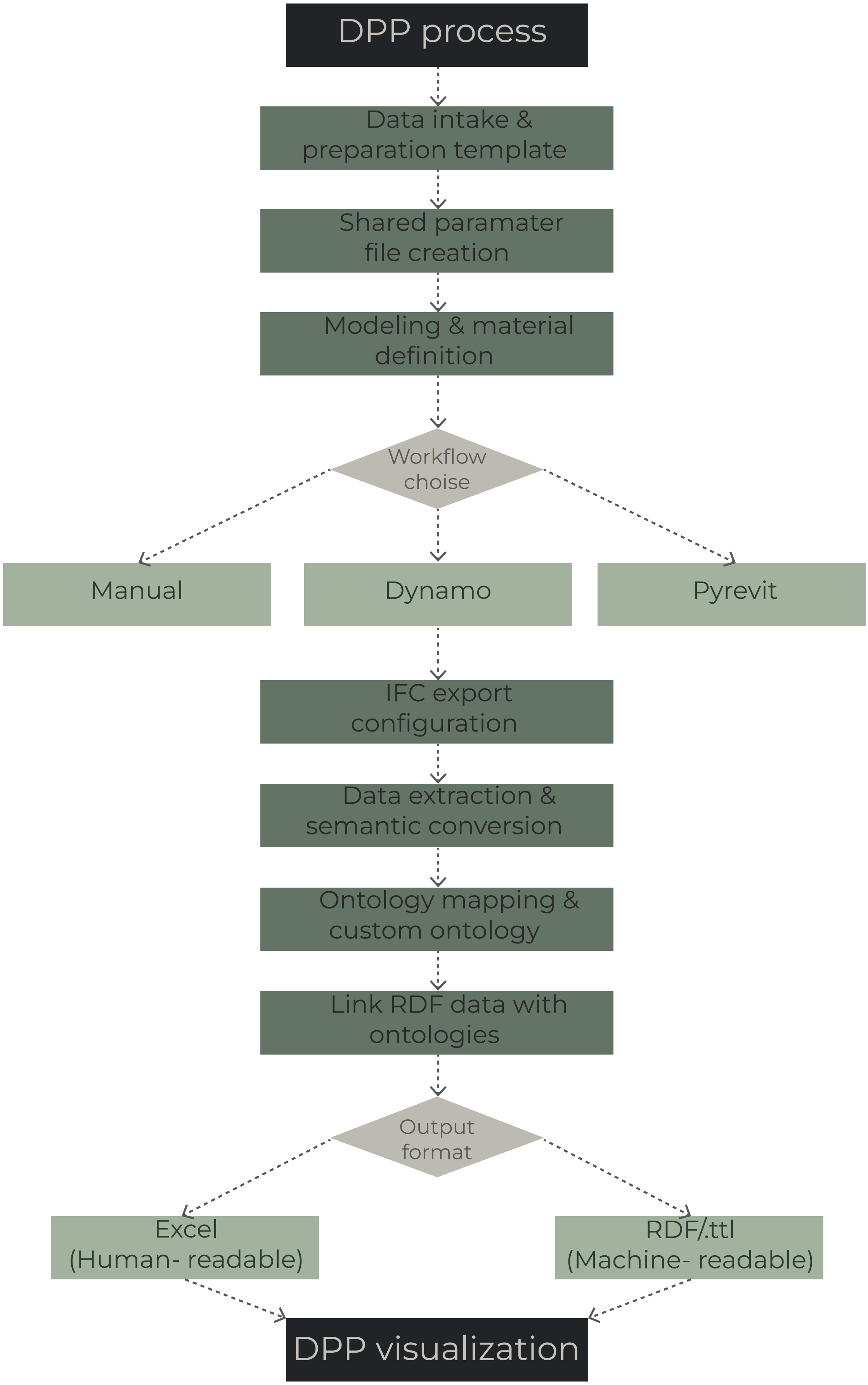


Figure 32. *Practical methodolody workflow for a DPP for bio-based materials.*
Note. Created by author.

3.3.4 Practical workflow

The process is designed to be replicable, efficient, and aligned with current digital construction practices. Autodesk Revit was selected as the main BIM environment because it is an industry leader and widely adopted across the Architecture, Engineering, and Construction (AEC) sector, ensuring relevance and interoperability.

The workflow explores different implementation methods within Revit to accommodate varying levels of technical knowledge. A manual approach is presented as the most accessible but also the slowest and least accurate. A visual programming approach using Dynamo requires more experience but allows for better automation and flexibility. A template-based method enables faster data structuring and the replication of multiple material types. Finally, a script-based workflow using PyRevit represents the most advanced and efficient option, providing high accuracy and speed, though it requires programming skills that are less common among AEC professionals.

Step 1 – Data intake and Preparation Template

After defining the relevant information categories, the first stage consisted of creating a centralized data structure to manage and access all material-related information. An Excel-based template was developed to serve as the main reference point, organizing all data fields according to the defined categories and the requirements set by Waterman and SmartBuilding. Each section in the file is interlinked, allowing to easily navigate through data sources, input values, and check dependencies between parameters.

This template functions as both a data collection tool and a starting point for the following workflow stages. It helps to extract subsets of information depending on the workflow selected (manual entry, Dynamo-based, or PyRevit scripting). In this way, the Excel file ensures consistency across different levels of technical engagement while maintaining a single source of accuracy for all DPP-related data.

Step 2 - Shared Parameter File Creation

The Shared Parameter File defines all the properties that will later be integrated into the BIM model. Within the Excel template, a dedicated sheet structures this information (listing the parameter names, data types, groups, and descriptions) serving as the reference framework for Revit parameter management.

To ensure consistency and clarity, parameters are named using a standardized convention, which facilitates the later mapping of each parameter to ontology terms. Additionally, a shared parameter file (.txt) is provided, it can be fully used or referenced in future applications. This file includes prefixes for parameter groups, following a clear hierarchical structure. For example, parameters related to data authorship are labeled as DPP_Authoring, and specific fields under this group use extended prefixes such as DPP_AUT_MaterialID.

For the manual and Dynamo-based workflows, this file acts as a guide from which each parameter group and property must be manually created within Revit's Shared Parameter Manager. This ensures alignment between the Excel data structure and the BIM environment, but it requires careful attention and time to avoid errors.

In the PyRevit workflow, this step is partially automated. The same parameter definitions are directly linked within the Python script, which generates the required parameter groups and fields automatically during execution. For this reason, the Shared Parameter File in this case is merged conceptually with the parameter definition process (detailed in Step 4), reducing manual input and ensuring consistency in naming and data types across the model.

Step 3 - Modeling and Material Definition

The third step focuses on the creation of the BIM models that host the data for the Digital Product Passport. Depending on the complexity of the material, the model can be parametric or static. In this case, since the DPP is developed at the material level, the hempcrete component is represented as a simple volumetric block.

For the manual workflow, a generic model family template was opened in Autodesk Revit. Reference planes were assigned for height, width, and length, and a solid volume was created accordingly. A new material was then defined and linked to the model. This included completing the identity information, assigning a visually accurate appearance, and adding the technical (physical) and thermal properties of hempcrete within the material editor.

The same process can be automated using Dynamo, for which a simple visual script was developed. This script automates the creation of the family, parameter setup, and material assignment, and it can be easily executed using Dynamo Player without requiring programming expertise.

For the element-level passport, a metric curtain wall panel family template was used. The hempcrete block family was loaded as a component before modelling, then placed within this wall type to construct a 1 m^2 module composed of eight blocks. This could be completed manually or through Dynamo. Since the material properties were already assigned within the block family, the modelling process focused on adjusting the module dimensions and defining the connection type through the mortar spacing. To place the module in a project environment, an exterior curtain wall was created and its horizontal and vertical grids were set to 1000 mm and 850 mm. The wall family was parametrized for height, width, and length to maintain flexibility across different design configurations.

Step – 4 Parameter Definition and Data Integration

In this step, the model is populated with the information, by linking the parameter structure defined in the Excel template with the BIM model. This process can be carried out through three different workflows depending on the desired level of automation and the technical skills available.

Manual workflow: Using the completed Excel file as a reference (containing the fields: parameter name, data, unit, instance/type, group, and formula), users manually open the parameter manager in Revit. Existing parameters are filled with the available data, and new parameters are created by selecting the corresponding shared parameters from the shared parameter file. Each parameter value or formula is then entered individually. This approach ensures full control and transparency but is time-consuming and prone to user error.

Dynamo workflow: For semi-automated integration, two separate Excel files are exported from the main dataset:

One file containing: parameter name, parameter type (instance/type), group type, and group name, used to create parameters in the model.

Another file containing: parameter name, data, and formula, used to fill the parameters with values.

These two files are used in separate Dynamo scripts that can be easily used through Dynamo Player, requiring only the proper linking of the Excel files organized according to the provided example. The scripts were built using the custom packages "Crumple" (developed by Aussie BIM Guru) and "Clockwork", which extend Dynamo's standard functionality and simplify the process. This method offers a balance between automation and accessibility for users with basic visual programming experience.

PyRevit workflow: For full automation, a Python script in PyRevit was developed. This script is configured to create and populate all shared parameters in a single process. It requires an Excel file containing the rows: shared parameter name, parameter group type, group name, instance/type, and formula. To enable PyRevit to read Excel files directly, an additional tool extension developed by Aussie BIM Guru (available through his GitHub repository) was installed. The process must be executed within a Revit project template, rather than within a family file, to ensure that all parameters are correctly registered and accessible across multiple family types. The script can be executed across multiple families simultaneously, making it the fastest and most accurate method. However, it requires basic knowledge of Python and familiarity with PyRevit's environment.

Step 5 – IFC Export Configuration

To export the BIM model to IFC format and ensure full interoperability and alignment with digital passport data structures, the IFC 4x3 schema was selected as the target format, as it provides improved support for property sets, classification systems, and material-level data management compared to previous versions.

A customised IFC export setup was developed to guarantee that the exported file contains the appropriate level of detail (LOD), the necessary parameter information, and the correct links to external data definitions. The export configuration references two key files:

The Property Set Definition File (.pset), which specifies the custom properties and their data types to be included in the IFC.

The Parameter Mapping File (.txt), which aligns the Revit shared parameters with the corresponding IFC property names and categories.

This configuration ensures that the resulting IFC file maintains both the semantic integrity and the data completeness required for Digital Product Passport generation. The exported IFC can then be verified in IFC viewers or platforms such as Navisworks, confirming that all relevant hempcrete properties, are accurately included.

At this stage, two separate IFC files are produced: one representing the material-level model (hempcrete) and another representing the element-level model (hempcrete wall). The element-level DPP functions as a container for the material passport, incorporating all its properties while progressively adding higher Levels of Development (LOD) relevant to the complete wall component. The following steps in the workflow are identical for both files.

Step 6 – Data Extraction and Semantic Conversion

Digital Product Passport (DPP). The workflow follows the approach presented in Bosma's thesis (2024) and uses the Python IFC-to-RDF conversion tool available in Bosma's public repository. The script was adapted for this thesis to remove unnecessary information from the IFC export and to retain only the attributes relevant to the selected material. The modifications and the updated script are documented in the annexes.

The adapted tool processes the IFC file and generates a TTL file, which is a type of RDF serialization format. During the conversion, the tool extracts the Global Unique Identifiers (GUIDs), geometric references, and the mapping relationships between elements and materials. It also filters out project-level information that is not required for a material-focused DPP, such as building, site, or level data. The resulting TTL file therefore contains only the information needed for semantic modeling and ontology alignment.

A structured Excel file is generated directly by the modified IFC-to-LBD exporter, together with the resulting TTL file. The exporter was adapted for this thesis so that both outputs are produced automatically in a single process, improving simplicity and consistency. The Excel file presents the relevant attributes in tabular form and supports verification of the conversion results. No manual extraction or manual data input is performed at any stage.

Together, the TTL file and the extracted Excel sheet provide a consistent and semantically structured dataset. The goal of this step is to obtain a file format that can be linked to ontologies and external data sources, ensuring that the digital model is not only geometrically defined but also semantically interpretable for its integration into the Digital Product Passport framework.

Step 7 – Ontology Mapping and Custom Ontology Development

After the IFC data is converted into a structured TTL file, the next step aligns the extracted information with defined ontologies. This process ensures that every parameter in the dataset is semantically interpretable, machine-readable, and interoperable across different platforms. For this thesis, a Python tool was developed to automatically map the TTL content to multiple ontologies. The tool uses predefined namespace references, including BOT, PROPS, DPP, BPO, BMP, QUDT, UNIT, PROV, FOAF, and Schema.org. The implementation and usage instructions are documented in the annexes.

A custom ontology was created in Protégé and added to this list of namespaces. This ontology acts as a network ontology that links the classes and properties of all selected vocabularies. Its function is to provide a unified structure that enables consistent mapping across sources, especially when several ontologies define related or overlapping concepts. The custom ontology is exported as a TTL file and is included in the repository accompanying this thesis.

This stage was carried out within an academic trial framework and does not aim to deliver a complete or standardized ontology model. Since ontology engineering is not the author's area of expertise, the process was approached experimentally in order to test feasibility and to demonstrate how BIM-derived material information can be semantically structured. The intention is to explore potential pathways rather than to validate a definitive semantic structure.

The Python tool performs multi-ontology mapping, meaning that each parameter is linked to corresponding properties or classes in several ontologies rather than a single one. This approach is essential for interoperability, because platforms and datasets rely on different vocabularies. For example, a quantity may be defined in QUDT, its material relationship in BPO, and its DPP-specific meaning in the Bosma DPP ontology. Mapping these connections ensures that the same piece of information can be understood and used consistently.

The mapping logic, the role of each ontology, and the rules used by the Python tool are explained in an accompanying md file. The combined ontology framework ensures that parameters are not treated as isolated attributes but as part of a connected semantic network. This structure allows the digital model to be linked to external data sources and to be interpreted in any system that relies on standardized web ontologies.

Step 8 – Linking RDF Data with Ontologies

The ontology mapping process from the previous step produces a new TTL file that already contains the mapped RDF representation of the dataset. This file expresses the IFC-derived data using classes and properties from several ontologies. The same mapping process can also be carried out using Protégé, which provides a more readable environment for users without expertise in semantic technologies. Both methods follow the same logic.

When using Protégé, the initial RDF file from Step 6 is opened and the selected ontologies are imported either as OWL files or through their URLs. Once imported, the classes and properties appear in the Protégé interface as structured hierarchies that can be referenced during the mapping process.

Semantic linking consists of assigning each dataset parameter to the appropriate ontology property or class. The alignment connects IFC-derived elements and attributes to their semantic equivalents. Object properties are used for relationships between entities, and data properties are used for relationships that assign values or characteristics. When a concept is not defined in any of the existing ontologies, the custom ontology is used to provide the missing definition. This ensures that every parameter has a URI reference and that its meaning can be resolved by external systems.

After the mappings are created, Protégé is used to visualize the resulting semantic graph and to verify that the relationships and definitions from the ontologies are correctly applied. The resulting mapped TTL file becomes the core semantic dataset for the Digital Product Passport, providing a machine-readable structure that supports interoperability across platforms and data sources.

It is important to note that this stage was developed within an academic trial framework and does not aim to establish a finalized or standardized semantic model. Since ontology linking is not the author's area of expertise, this process was approached experimentally to demonstrate feasibility and fulfil the methodological requirements of the thesis. The focus is on exploring how BIM-based material data could be semantically structured rather than producing a fully validated ontology model.

Step 9 – Digital Product Passport Assembly and Visualization (Final Step)

For the assembly and visualization of the Digital Product Passport (DPP) for hempcrete, the process integrates all previous stages, resulting in two complementary outputs:

A human-readable dataset, structured in Excel, which consolidates all parameters, metadata, and references.

A machine-readable dataset, structured in RDF, containing the semantic relationships and ontology links established in the earlier steps.

The Excel dataset is the reference version for data interpretation and validation. It has a section for references and value ranges, which can be used for comparability between materials or test results. This structure ensures that each data point is both documented and contextualized within known performance limits or literature-based standards.

The RDF dataset, on the other hand, serves as the interoperable version, allowing automated querying and potential integration with external platforms. Together, these two formats form the foundation of the Digital Product Passport, one enabling transparent communication of material properties to human users, and the other supporting machine-based interpretation and data exchange.

To visualize the DPP, an experimental web-based interface was generated using Gemini AI studio, an AI-driven webpage generator from google. The tool allows the DPP to be displayed interactively by feeding it with either of the final datasets (Excel / RDF). The visualization incorporates the reference and range data from the Excel file, enabling the comparison of material parameters and performance indicators in a clear, user-friendly way.

A mock-up of this interface will be presented in the Results section, along with the corresponding Gemini implementation code, to illustrate how the DPP data can be accessed and visualized across both human-readable and machine-readable layers. At this stage, the visualization also reconnects with the persona analysis developed earlier in the methodology. The interface and displayed information are adapted according to the identified user profiles, highlighting the parameters most relevant to their needs and decision-making processes.

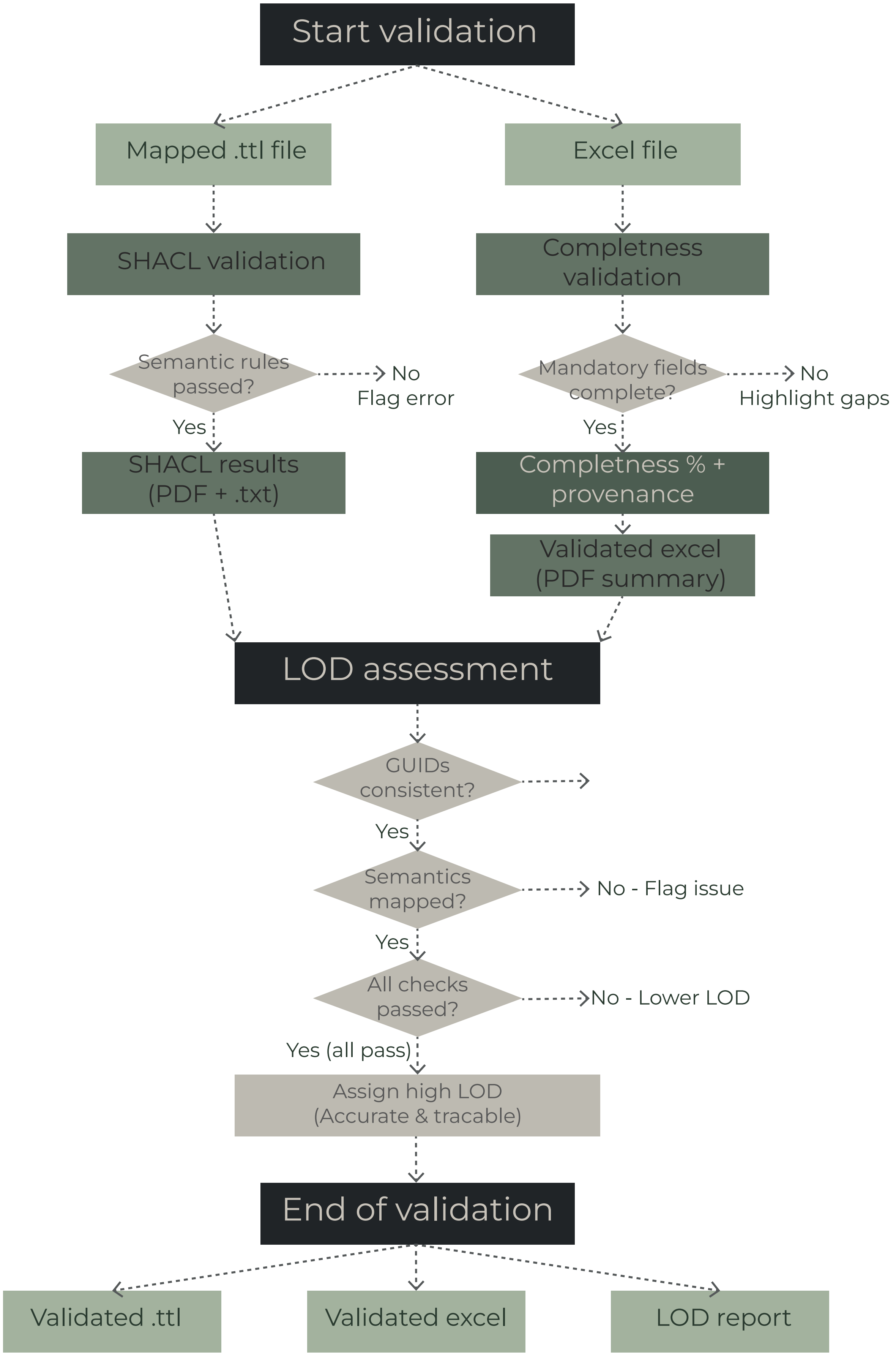


Figure 33. *Validation workflow for the RDF file and Excel dataset of a DPP.*
Note. Created by author.

3.3.5 Validation framework

The validation process verifies the quality, consistency, and semantic correctness of the Digital Product Passport data. It is carried out through two complementary methods: a SHACL-based validation of the mapped TTL file and a completeness validation of the extracted Excel dataset. Both methods are documented in the annexes, including the modifications introduced to Bosma's original SHACL shapes.

Semantic validation using SHACL

The mapped TTL file generated in the previous steps is validated using a SHACL test adapted from Bosma's thesis. The SHACL shapes were modified to reflect the structure of the custom ontology network and to ensure that every property in the TTL file is semantically defined. The test verifies that all properties resolve to valid ontology terms, that data types follow the definitions in QUDT or Schema.org, that relationships refer to existing classes, and that undefined or orphan predicates are flagged.

The validation tool outputs two files: a PDF report that summarises model conformance and a TXT file containing the detailed SHACL log. This validation is applied only to TTL files to maintain workflow simplicity, although the methodology can be extended to other RDF serialisations.

Completeness validation of the Excel dataset

The Excel file extracted from Dynamo is validated against the initial database structure. For each material or element entry, the completeness of the Digital Product Passport is calculated as the percentage of populated fields. Mandatory parameters follow the criteria defined by Bosma (2024) and by the Material Passport guidelines from Waterman and Circuit (2023) and buildingSMART (2024). Missing or incomplete values are automatically highlighted, and reference ranges within the dataset support manual enrichment when required.

In addition to assessing completeness, the validation tool records provenance information, including the name of the validator, the timestamp of the validation, and the validation method. A separate tool later merges this provenance metadata into the mapped TTL file to ensure accuracy and traceability across the workflow.

The completeness validation outputs a validated Excel file with highlighted gaps and a PDF summary presenting completeness scores for each DPP.

Level of Development (LOD) assessment

The results of both validations are used to assess the Level of Development of each Digital Product Passport. The LOD assessment reflects the accuracy, traceability, and semantic reliability of the data. This includes verifying the consistency of GUIDs between the IFC export and the semantic dataset, confirming that shared parameters were successfully mapped to ontology terms, and ensuring compliance with the defined semantic rules.

Together, these validation steps ensure that each Digital Product Passport is complete, semantically consistent, and interoperable within the data environments used throughout the workflow.

GAP ANALYSIS AND DATA ENRICHMENT

To ensure data completeness and traceability, a structured gap analysis was developed using a parameter matrix in Excel, to identify missing or incomplete data within the documentation provided by the hempcrete manufacturer.

For each parameter, the table records:

- Availability in Manufacturer Documentation (Yes/No)
- Range Availability (where multiple product variants exist)
- Primary Data Source (Technical data sheet, Environmental Product Declaration)
- Gap Identified (automatically flagged through conditional statements)
- Proposed Supplementary Source (Literature, BIM model, calculated value)
- Notes for contextual information or data verification steps.

The gap identification process was automated through logical IF statements and VLOOKUP functions, which compared the available dataset against the list of required parameters. Missing or incomplete data were highlighted and color-coded for visual clarity. A snippet of this table will be presented in the Results chapter and annexed in full for reference.

When gaps were detected, potential supplementary sources were proposed according to the data type:

- BIM parameters were used to complete missing geometric or dimensional values.
- Calculated values were derived through established formulas or range estimates.
- Academic and industry literature provided secondary data for physical and thermal performance indicators.

Following the identification phase, all data will undergo normalization to ensure unit consistency, methodological comparability, and alignment with BIM standards.

EVALUATION

The developed Digital Product Passport (DPP) was evaluated through a validation methodology that combined qualitative and technical assessments. This evaluation tried to verify the accuracy, usability, and interoperability of the DPP.

3.5.1 Qualitative validation

The qualitative validation was originally planned as consultations with relevant stakeholders, including material manufacturers, architects, and academic researchers familiar with bio-based materials and digital workflows. These consultations were intended to assess three dimensions:

- *Usability:* the clarity and accessibility of the DPP interface and data structure.
- *Relevance:* the adequacy of the parameters selected to represent the environmental and circular performance of hempcrete.
- *Applicability:* the perceived value and practicality of integrating the DPP within real design or material management processes.

Since no stakeholder feedback was received within the required timeframe, the validation was performed through a *persona*-based heuristic evaluation. This approach applied the previously defined *personas* to evaluate the DPP prototype by using a set of informed heuristics related to usability, data clarity, and circularity requirements. Although based on a hypothetical profile of users, this provided a structured assessment of how different user types would interact with the DPP and which challenges or opportunities may arise in practice.

Automated Persona-Based Heuristic Evaluation

To make this validation, an automated evaluation was implemented using a Python tool developed specifically for this thesis with the help of Visual Studio AI agent. The tool operationalised the previously defined personas and heuristics to generate a structured and repeatable assessment of the DPP.

The evaluation tool implemented a multi-method automated assessment framework integrating semantic analysis, data quality metrics, and persona-based heuristic scoring. It starts by parsing structured inputs, including personas, heuristics, TTL files, and the dataset, into internal object representations, which allow consistent processing across components. Rule-based heuristics were applied to three parts of the DPP: the user interface mock-up, the semantic data model, and the tabular dataset. For each combination of persona, heuristic, and component, the tool creates a separate assessment, for a total of 108 assessments. Each contain quantitative scoring, expressed on a scale from 0 to 100 percent based on predefined criteria, and qualitative findings derived from automated pattern detection, structural checks, and metric analysis. Results are then aggregated across personas, heuristics, and components to identify performance patterns and improvement needs. Finally, it creates actionable outputs in the form of a complete report, checklists by persona, a JSON summary, and several visualizations. This integrated approach leads to a structured and reproducible method for assessing the completeness, usability, and circularity alignment of the DPP, especially where direct, manual stakeholder consultation is not feasible.

All source files related to the evaluation tool, including the Python scripts, documentation guides, and the complete set of generated outputs, are available in the thesis repository hosted on GitHub

3.5.2 Technical validation

The technical validation focused on assessing data integrity, interoperability, and compliance with existing standards for digital material documentation:

- *Verifying* that all data entries within the DPP were internally consistent and accurately sourced from the validated dataset.
- *Testing* interoperability within BIM environments (through IFC export and property set mapping) to confirm that the passport structure could be seamlessly integrated into digital modeling workflows.
- *Comparing* the developed structure against emerging Digital Product Passport standards to ensure methodological alignment and scalability.

Dataset validation

A Python tool was developed to validate the DPP dataset. The script implemented four types of data quality checks:

- Range checks, to verify that numerical values (for example density, moisture content, and thermal properties) fell within plausible and literature-supported intervals.
- Format checks, to ensure that all entries followed predefined conventions, such as units, numeric formatting, and consistent text structure.
- Uniqueness checks, to identify duplicated parameters or repeated values that could indicate errors in data sourcing or transcription.
- Referential checks, to confirm that linked values and dependencies (for example parameters derived from other measurements) remained coherent across the dataset.

Semantic validation

A second Python tool was created to assess the mapping process between the initial dataset and the final semantic outputs. The tool compared three inputs: (1) the original list of parameters, (2) the first exported TTL file, and (3) the mapped TTL file generated after applying the custom property set mapping.

The script counted how many parameters were:

1. fully semantically mapped,
2. partially mapped, and
3. missing or unmapped.

This quantitative comparisons provides a basis for evaluating the semantic completeness of the DPP and establishing an appropriate Level of Development (LOD) for the dataset and model structure.

The feedback from these methodologies was documented and analyzed. Rather than modifying the DPP during this stage, the insights were presented as part of the Results and further discussed to inform recommendations for the future development and standardization of Digital Product Passport frameworks.

CHAPTER 4

RESULTS

OUTCOME OF GAP ANALYSIS

The objective of the gap analysis was to identify missing or incomplete data required for the creation of the Hempcrete Digital Product Passport (DPP). It compared the parameters defined during the methodology phase against information available from manufacturer documentation, certification sources, and Revit built-in parameters. This process allowed for the systematic identification of data gaps, assessment of their relevance to circularity and traceability, and proposal of supplementary sources to complete the dataset.

Parameter	In manufacturer Doc.?	Range Available?	Data Source	Gap Identified	Proposed Sup. Source
Product Name	Yes	Na	Technical data sheet 06/2025	No	
Product ID	Yes	Na	German general type approval	No	
Object number	No	Na	BIM parameter	Yes	BIM parameter
Dry density	Yes	Yes	EPD 2025	No	
Equilibrium density	Yes	Yes	EPD 2025	No	
Weight	No	No		Yes	Calculate
Compressive strength	Yes	No	Technical data sheet 06/2025	Yes	Literature
Prefabrication	Yes	Yes	Report for KBOB list	No	
Prefabrication factor	No	Yes	Range Atta et al. 2021	Yes	Assign
Disassembly instructions	Yes	No	EPD 2025	Yes	Literature
Secondary use scenarios	Yes	No	EPD 2025	Yes	Literature
End-of-life recommendation	Yes	No	EPD 2025	Yes	Literature
EPD	Yes	Yes	By manufacturer	No	
Link EPD	Yes	Na	By manufacturer	No	
Global Warming Potential (GWP)	No	No		Yes	Calculate
Warranty	Yes	Yes	By manufacturer	No	
Update history	No	Na		Yes	BIM parameter
HPD	Yes	Yes	By manufacturer	No	

Table 7. *Excerpt of Gap Analysis for Hempcrete Product Data.*

Note 1. Created by Author.

Note 2. KBOB list - Swiss national database of environmental impact values for construction materials, building elements, and energy carriers.

Following the identification of missing parameters, the dataset was completed by integrating supplementary information from BIM parameters, IFC standards, technical documentation, and available literature. When direct data were not provided by manufacturers, specific values were derived through parametric or manual calculations based on established references. This process ensured that all essential data categories were represented in a consistent and interoperable format. The resulting dataset consolidated manufacturer data with model-based attributes, providing the necessary foundation for the subsequent stages of model development and DPP structuring.

The completed dataset revealed that while most identification and general information parameters could be retrieved from manufacturer documentation and certification sources, several attributes remained dependent on the BIM modeling process. Parameters such as object number and traceability ID were intentionally left unfilled at this stage, as they are generated dynamically after model development and IFC exporting. This reflects the dual nature of the dataset, where static information (e.g., product specifications and origin) is complemented by dynamic data produced through digital workflows. Consequently, the dataset functions as a hybrid structure that integrates fixed manufacturer data with model-generated parameters.

Parameter	Data	Unit	Range	Source	Filled?
Product Name	Hempstone	NA	NA	Technical data sheet 06/2025	Yes
Product ID	Z-17.25-1299	ID	NA	German general type approval	Yes
Object number		GUID	NA	BIM parameter	No
Dry density	335	kg/m³	310-360	EPD 2025	Yes
Equilibrium density	405	kg/m³	390-450	EPD 2025	Yes
Weight	2.68	Kg	6.00 - 15.00	Calculated	Yes
Compressive strength	0.5	Mpa	0.06-0.8	Technical data sheet 06/2025 (Range by Steyn et al., 2025; Asghari & Memari, 2024)	Yes
Prefabrication	Yes	NA	Yes/No	Report for KBOB list	Yes
Prefabrication factor	1	Score	1 (Yes) - 0 (No)	Range Atta et al. 2021	Yes
Disassembly instructions	Mechanical dismantling: Crushing and Sieving for Recycling	NA	Manual dismantling; Semi-Mechanical Disassembly; Thermal Disassembly; Chemical Disassembly; Demolition; Modular Disassembly	EPD 2025 (Range by ISO 20887:2020)	Yes
Secondary use scenarios	Reused on the construction site for applications requiring increased density, such as floor material	NA	Direc reuse; Partial reuse; Reprocessing into aggregare; Soil amendment; Upcycling into thermal or acoustic insulation; Upcycling into new composites or panels; Backfilling	EPD 2025 (Range by European Commission 2020, LEVEL(s))	Yes
End-of-life recommendation	Composting and soil improvement; Disposal via incineration	NA	Biological recovery; Material recyclcing; Energy recovery; Landfill disposal	EPD 2025 (Range by EN 15804:2012 +A2:2019)	Yes
EPD	Yes	NA	Yes/No	By manufacturer	Yes
Global Warming Potential (GWP)	1.3392	kg CO_2eq. / Block	-6.6 - 3.8	Calculated from EPD (Range derived from published volumetric ranges (≈ −184 to +105 kg CO_2e/m³))	Yes
Warranty	No	NA	Yes/No	By manufacturer	Yes
Update history		Date	NA	BIM parameter	No

Table 8. *Excerpt of the Completed Dataset for the Hempcrete Product Passport.*

Note. Created by Author.

MODEL DEVELOPMET

During the model development stage, the entire dataset was converted into an interoperable structure suitable for generating the Digital Product Passport. This phase involved the creation of a workflow that enabled the connection between the source files, the BIM environment, the export of the IFC format, as well as the conversion and mapping into RDF**,** ensuring consistency between material information and its digital representation. Each component of the workflow contributed to automating data transfer and facilitating validation.

4.2.1 Excel base template

TThe Excel base template was structured to ensure that the dataset was consistent, human-readable, and ready for integration into the workflows. The sheets defining information categories, shared parameters, and group types established a clear hierarchy, consistent naming, and data-type control. This structure ensured that every value could be traced, validated, and interpreted without ambiguity. The data entry sheet applied these definitions through controlled units, ranges, and references, while additional sheets supported automated extraction for the PyRevit and Dynamo workflows. Parameter mapping aligned each property with relevant ontologies to ensure semantic interoperability during IFC export and RDF conversion. The final dataset sheet consolidated all validated information after the workflows were completed.

This structured template was essential because every subsequent step depended on a coherent and well-organized dataset. Consolidating the information at the beginning ensured alignment between data definitions, naming conventions, and parameter types across the entire workflow. This avoided inconsistencies during parameter creation, model integration, and ontology mapping, and it allowed automated processes to run reliably while reducing the risk of human error. The template therefore provided a controlled and understandable working space, even though it was not a final DPP product. It functioned as the foundation from which all validation, automation, and export steps could operate.

More importantly, the template highlighted why a formal framework for Digital Product Passports is necessary. By structuring the dataset in a consistent, traceable, and human-readable format, it became clear how manufacturers could organize their material information from the start in ways that support accuracy, interoperability, and long-term reliability. A simple tool such as Excel was sufficient to demonstrate that when information is consolidated and accessible, the creation of a DPP becomes more efficient and more scalable. Establishing this structure early is therefore not only a practical requirement of the workflow but also evidence of how standardized data practices can enable wider adoption and future scalability of DPPs for bio-based materials.

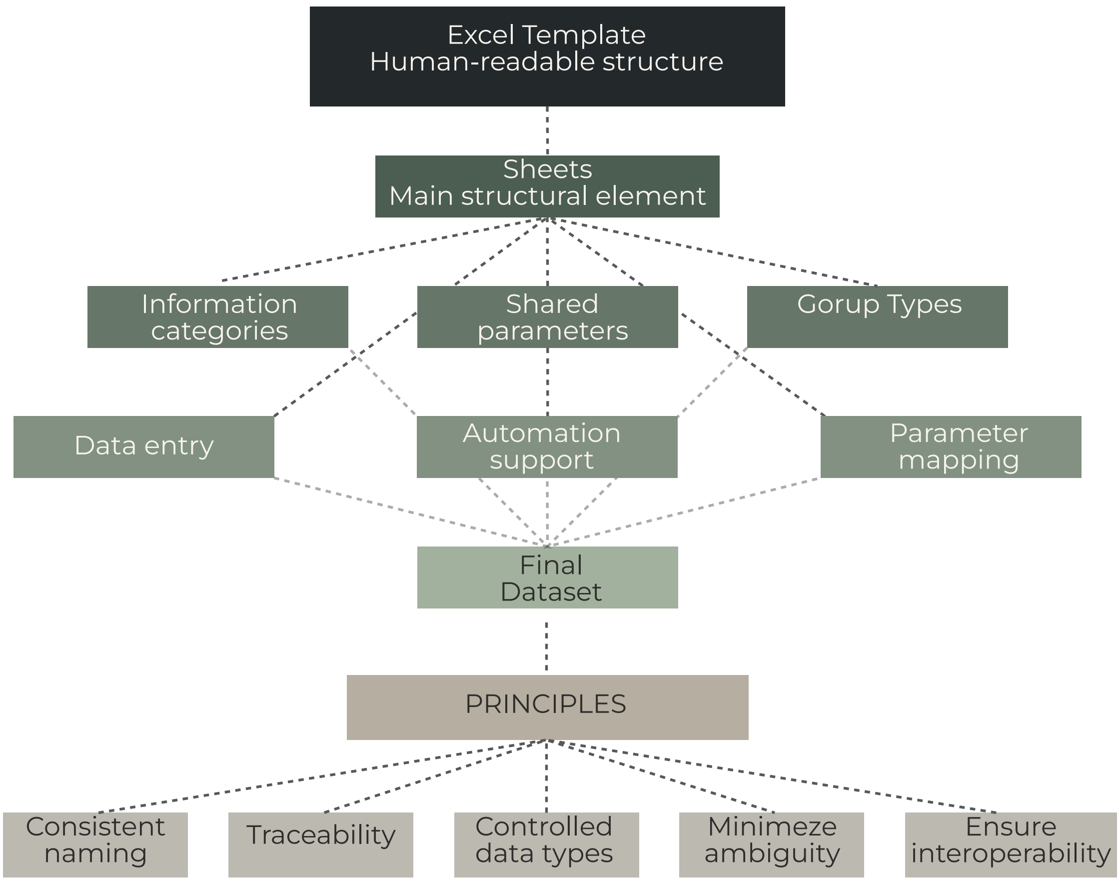
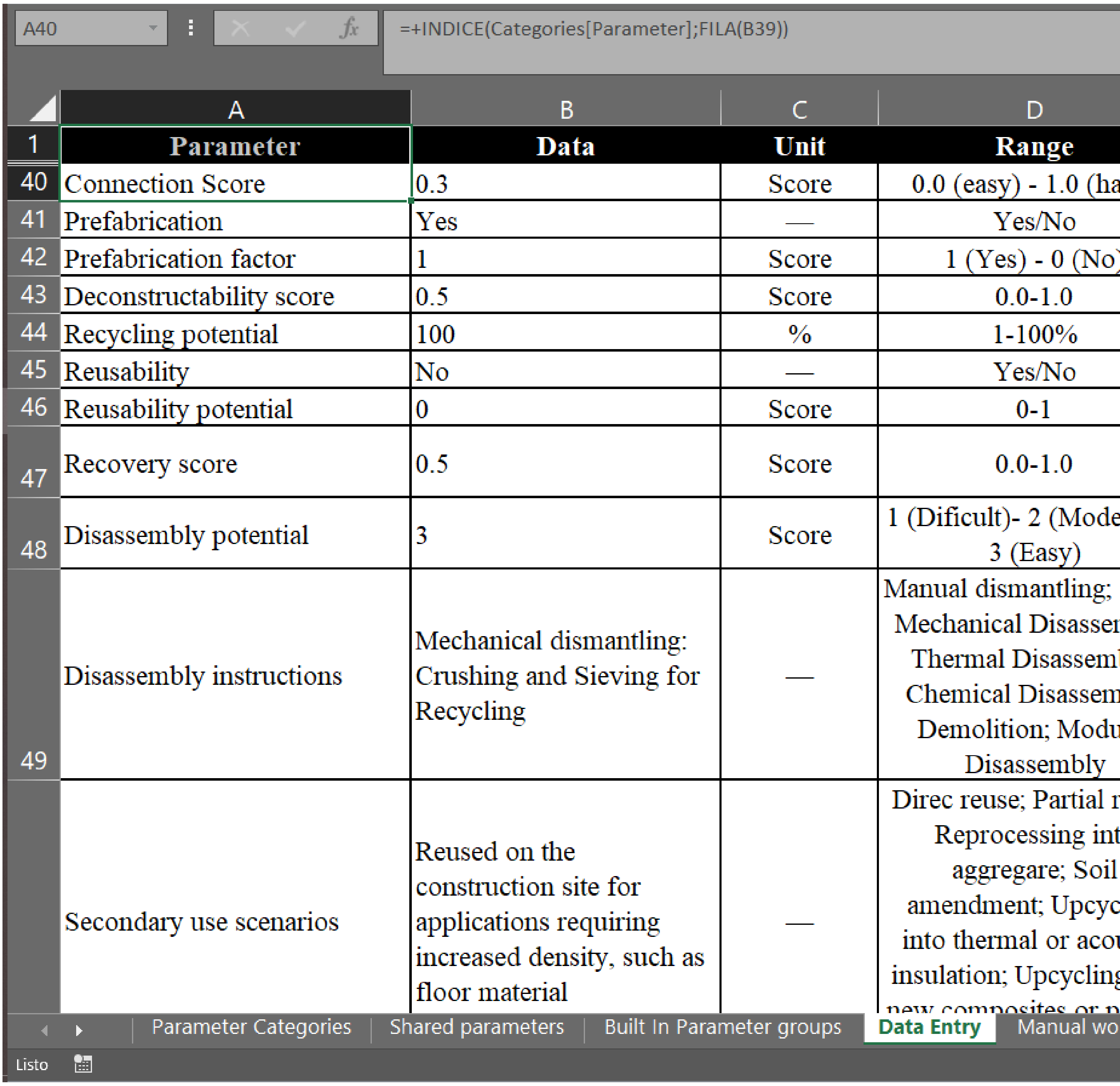


Figure 34. *Structure of Excel base tamplate.*
Note. Created by author.



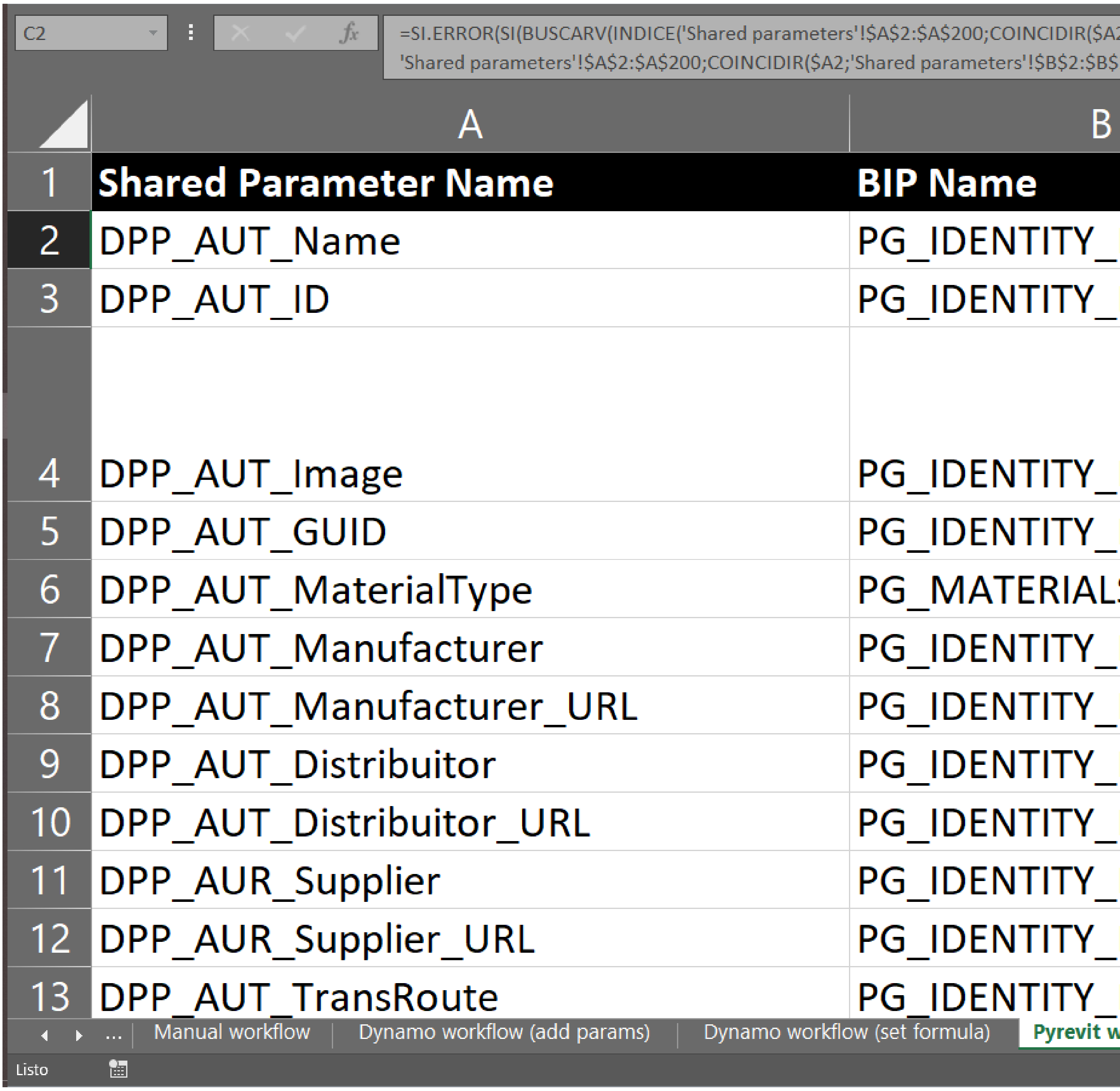
	A	B	C	D
1	**Parameter**	**Data**	**Unit**	**Range**
40	Connection Score	0.3	Score	0.0 (easy) - 1.0 (ha
41	Prefabrication	Yes	—	Yes/No
42	Prefabrication factor	1	Score	1 (Yes) - 0 (No)
43	Deconstructability score	0.5	Score	0.0-1.0
44	Recycling potential	100	%	1-100%
45	Reusability	No	—	Yes/No
46	Reusability potential	0	Score	0-1
47	Recovery score	0.5	Score	0.0-1.0
48	Disassembly potential	3	Score	1 (Dificult)- 2 (Mode 3 (Easy)
49	Disassembly instructions	Mechanical dismantling: Crushing and Sieving for Recycling	—	Manual dismantling; Mechanical Disassem Thermal Disassem Chemical Disassem Demolition; Modu Disassembly
	Secondary use scenarios	Reused on the construction site for applications requiring increased density, such as floor material	—	Direc reuse; Partial r Reprocessing int aggregare; Soil amendment; Upcyc into thermal or acou insulation; Upcycling new composites or p

Figure 35. *Screen shot of sheet for Data Entry of the Excel base tamplate.*
Note. Created by author.

	E	F
	Source	**Formulas**
rd)	Assigned	
	Report for KBOB list	
)	Range Atta et al. 2021	if(Prefabrication,1,0)
	Range Atta et al. 2021	ConnectionScore+PrefabricationFactor/2
	Technical data sheet 2017	
	EPD 2025	
	Range Atta et al. 2021	if(Reusability,1,0)
	Range Atta et al. 2021	((RecyclingPotential/100)+ReusabilityPotential+(if(Toxicity,0,1))+(if(Coatings,0,1)))/4
rate)-	Range assigned	
Semi- mbly; bly; bly; lar	EPD 2025 (Range by ISO 20887:2020)	
euse; o ling ustic g into anels;	EPD 2025 (Range by European Commission 2020, LEVEL(s))	

rkflow | Dyn ...

Recuento: 2 125%

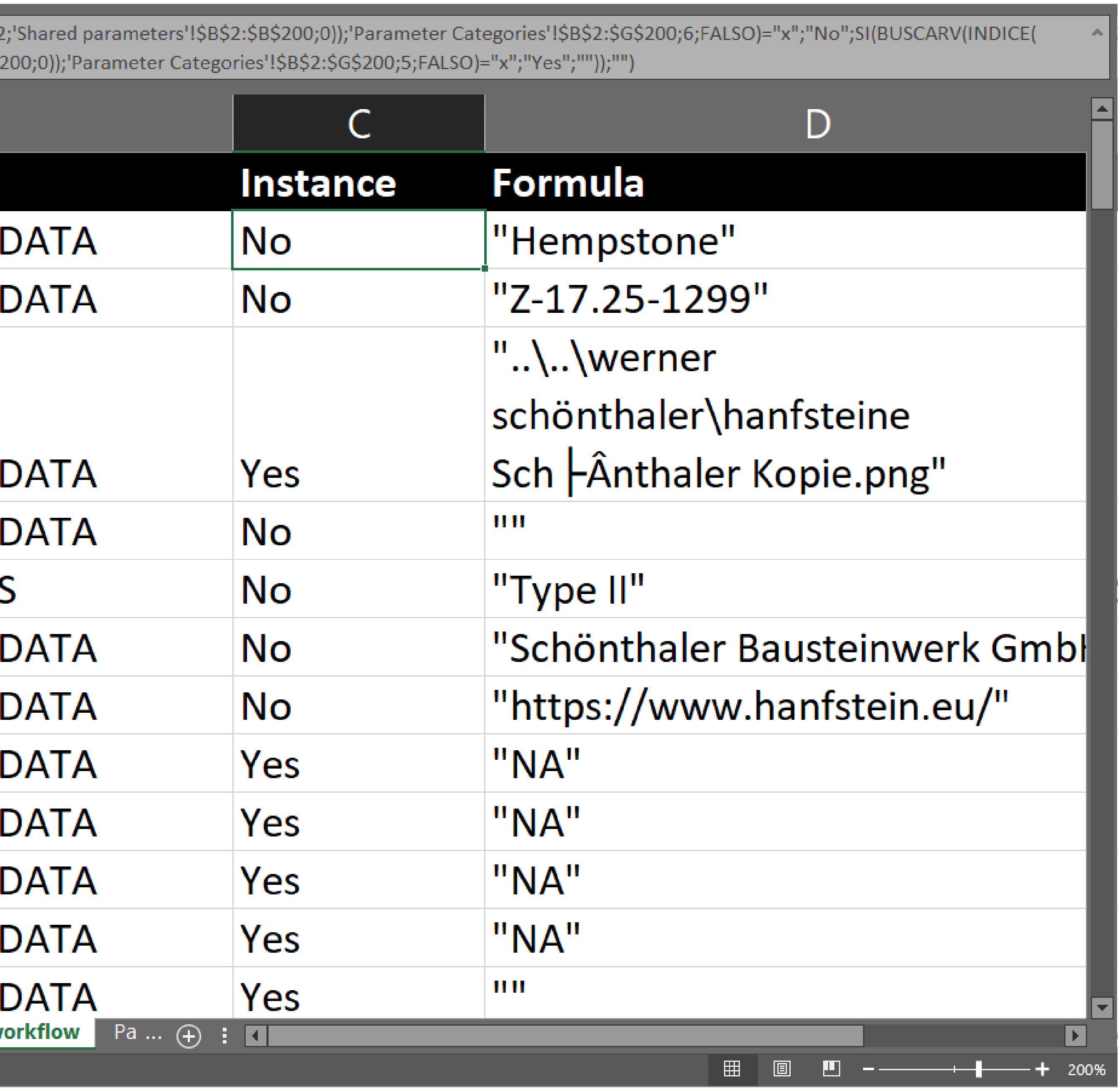

C2 =SI.ERROR(SI(BUSCARV(INDICE('Shared parameters'!$A$2:$A$200;COINCIDIR($A2 'Shared parameters'!$A$2:$A$200;COINCIDIR($A2;'Shared parameters'!$B$2:B

	A	B
1	Shared Parameter Name	BIP Name
2	DPP_AUT_Name	PG_IDENTITY_
3	DPP_AUT_ID	PG_IDENTITY_
4	DPP_AUT_Image	PG_IDENTITY_
5	DPP_AUT_GUID	PG_IDENTITY_
6	DPP_AUT_MaterialType	PG_MATERIALS
7	DPP_AUT_Manufacturer	PG_IDENTITY_
8	DPP_AUT_Manufacturer_URL	PG_IDENTITY_
9	DPP_AUT_Distribuitor	PG_IDENTITY_
10	DPP_AUT_Distribuitor_URL	PG_IDENTITY_
11	DPP_AUR_Supplier	PG_IDENTITY_
12	DPP_AUR_Supplier_URL	PG_IDENTITY_
13	DPP_AUT_TransRoute	PG_IDENTITY_

Manual workflow | Dynamo workflow (add params) | Dynamo workflow (set formula) | Pyrevit w

Listo

Figure 36. *Screen shot of sheet for the Pyrevit Workflow of theExcel base tamplate.*
Note. Created by author.



2;'Shared parameters'!$B$2:$B$200;0));'Parameter Categories'!$B$2:$G$200;6;FALSO)="x";"No";SI(BUSCARV(INDICE(
200;0));'Parameter Categories'!$B$2:$G$200;5;FALSO)="x";"Yes";""));"")

	C	D
	Instance	Formula
DATA	No	"Hempstone"
DATA	No	"Z-17.25-1299"
DATA	Yes	"..\..\werner schönthaler\hanfsteine Sch ├Ânthaler Kopie.png"
DATA	No	""
S	No	"Type II"
DATA	No	"Schönthaler Bausteinwerk GmbH
DATA	No	"https://www.hanfstein.eu/"
DATA	Yes	"NA"
DATA	Yes	"NA"
DATA	Yes	"NA"
DATA	Yes	"NA"
DATA	Yes	""

4.2.2 Dynamo scripts

The Dynamo workflows supported two main tasks: modeling automation and data population. For modeling, two scripts were developed, one for generating the Hempcrete brick and one for the wall component. Both scripts produced the required geometry and material assignments with a similar level of effort compared to the manual workflows. However, the Dynamo version allowed modifications through the visual programming interface, which provided flexibility when adjusting dimensions or testing variations.

The second set of scripts focused on parameter and formula inputs. These were more complex to develop because the workflow required improvements to the publicly available version created by Aussie BIM Guru. Error handling was added through Python nodes, and the independent execution of each step** was implemented**. Although the configuration process was more demanding than the manual workflow, the resulting automation significantly reduced input time, ensured accuracy, and produced consistent parameter values across the model.

The Dynamo workflows also showed how semi-automation can support the DPP process once the dataset is already structured. While nodes occasionally produced internal errors or required manual adjustments, the visual programming interface made it possible to inspect, correct, and refine the scripts without rebuilding them entirely. This flexibility demonstrated how practitioners can iterate on the workflow, test variations, and improve the process as their familiarity with the tool increases. For a future DPP framework, this highlights that well-prepared data enables practical automation even when the tools are imperfect, and that visual scripting environments can serve as adaptable layers that reduce repetitive work, maintain data consistency, and support ongoing updates to material information.

The final versions of the scripts, including documentation of the modifications made to the original workflows, were placed in the annexes and GitHub repository.

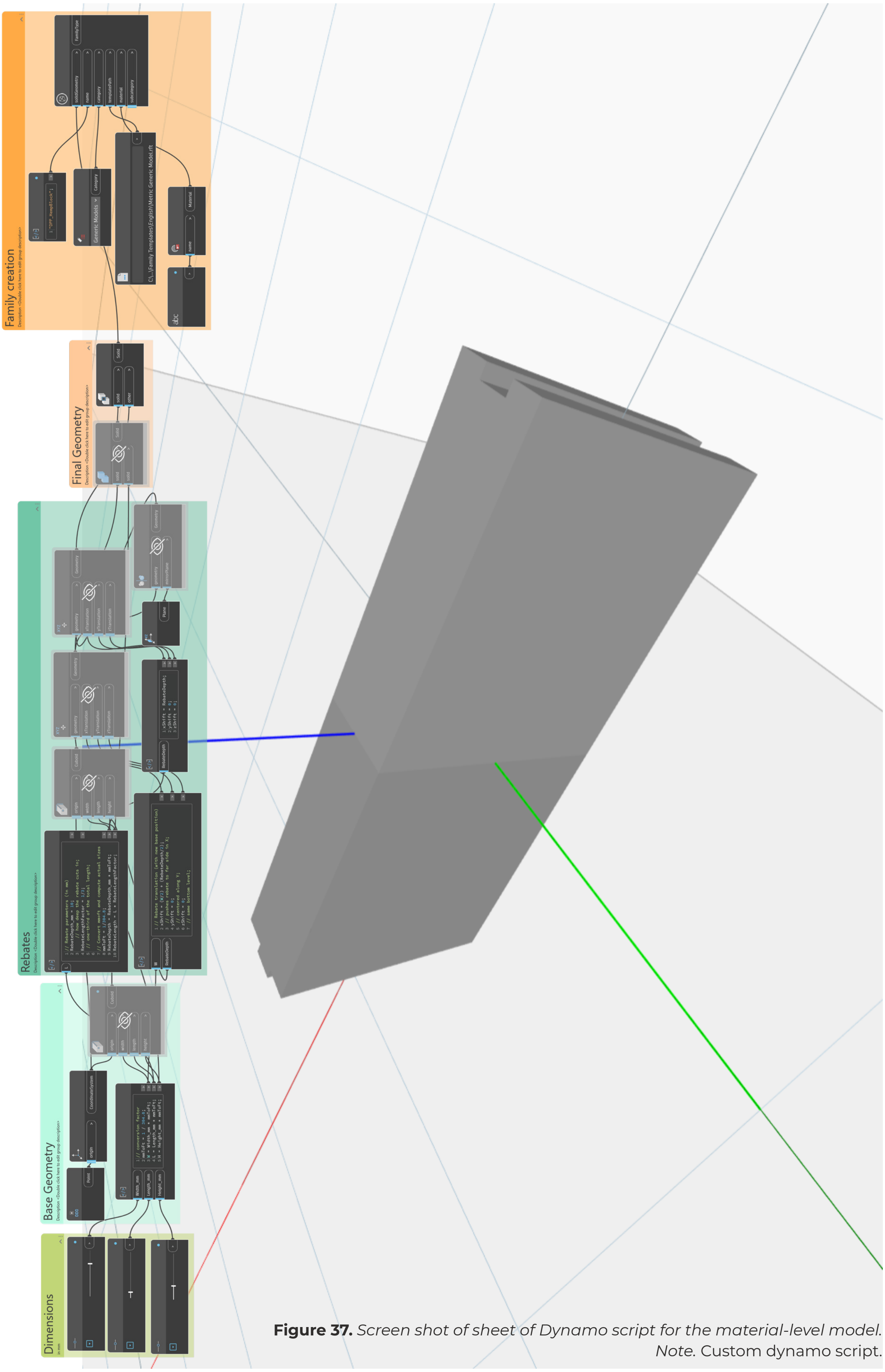


Figure 37. *Screen shot of sheet of Dynamo script for the material-level model.*
Note. Custom dynamo script.

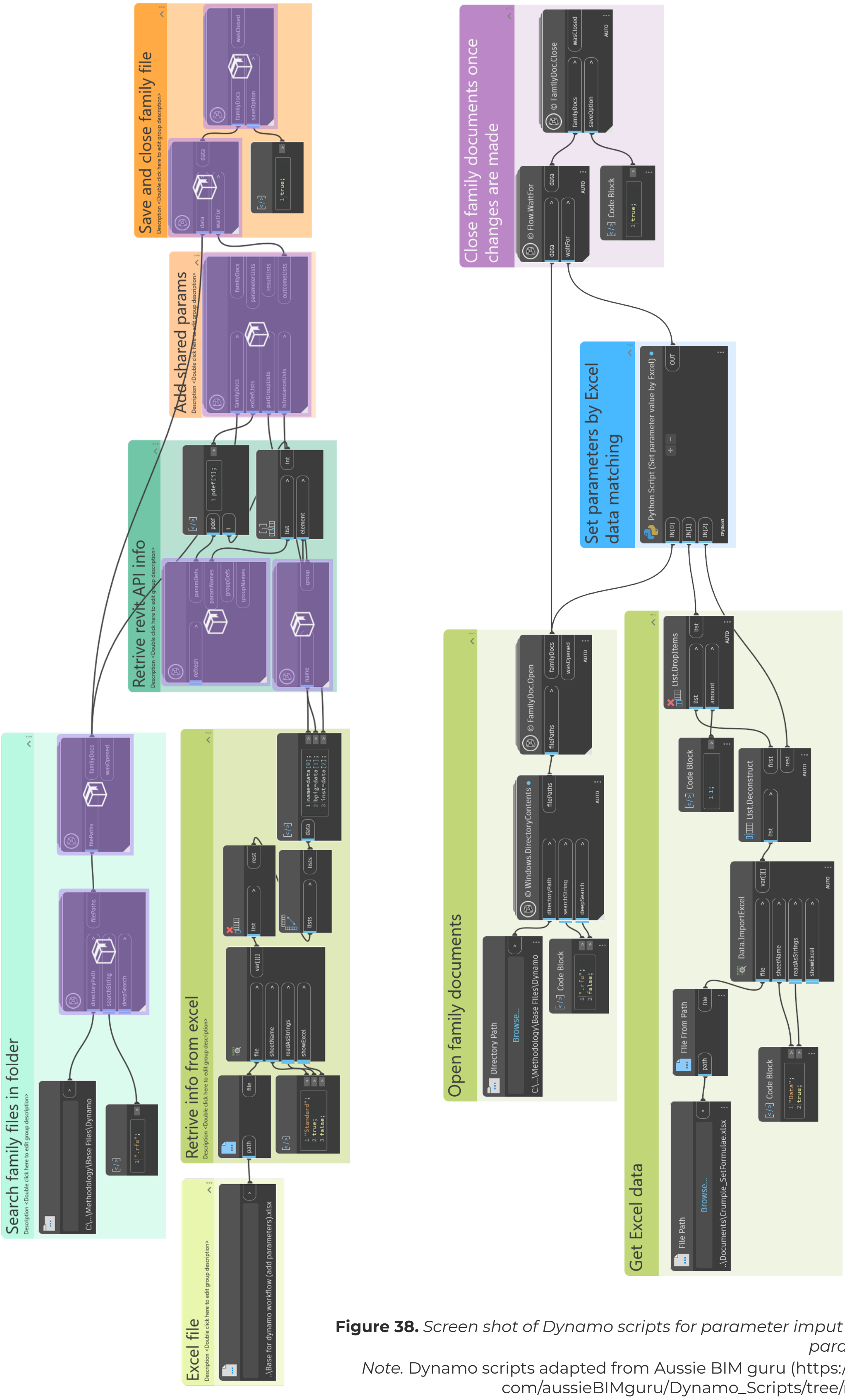


Figure 38. *Screen shot of Dynamo scripts for parameter imput and set parameters.*

Note. Dynamo scripts adapted from Aussie BIM guru (https://github.com/aussieBIMguru/Dynamo_Scripts/tree/master).

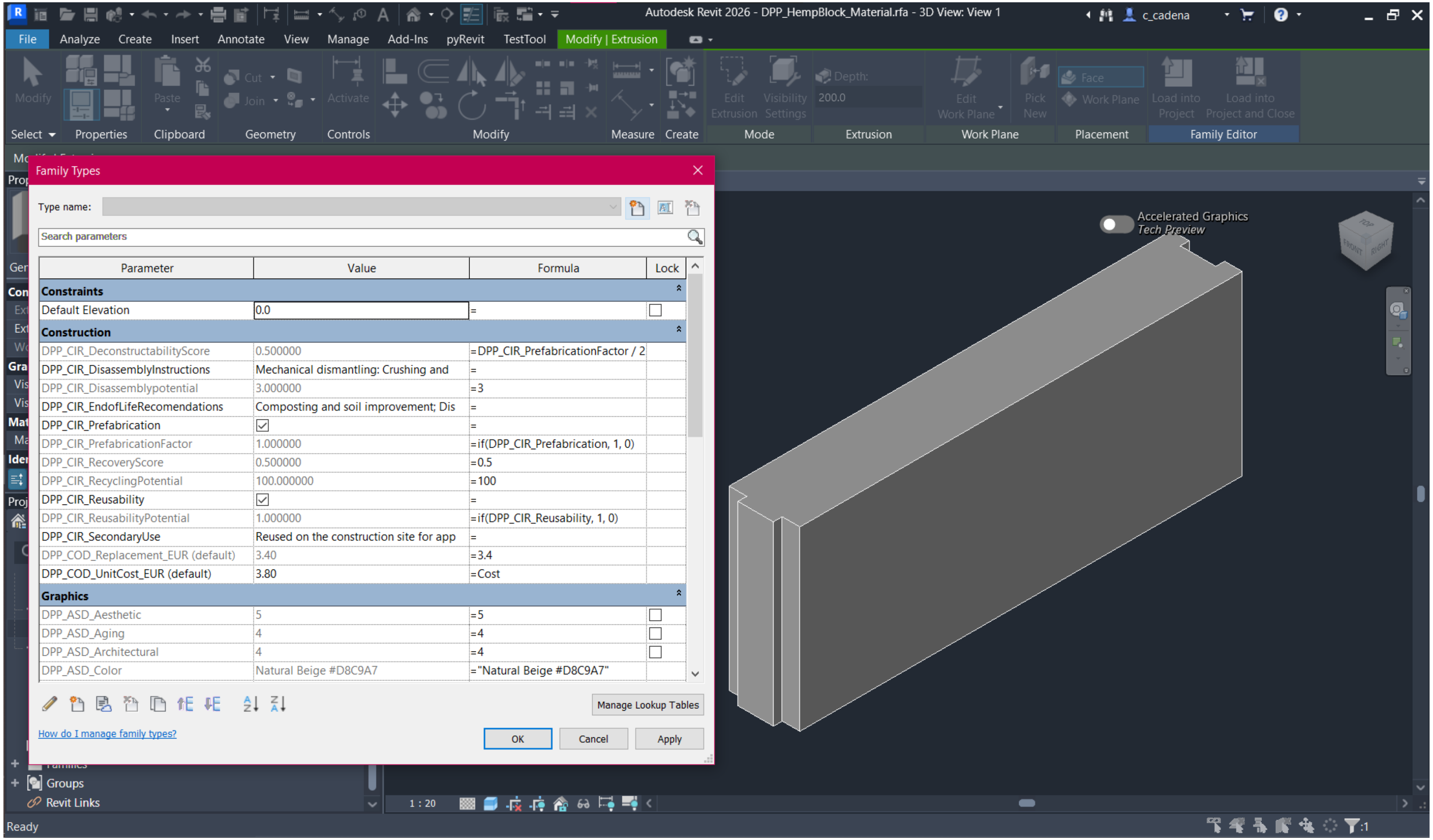


Figure 39. *Screen shot of material-level model and filled parameters in Revit.*
Note. Created by author (In Autodesk Revit).

4.2.3 Pyrevit scripts

PyRevit was used exclusively for parameter input because it provided faster execution and clearer error handling than the manual workflow. The environment offered direct feedback during execution, which supported debugging when Python knowledge was available. The workflow integrated a script originally developed by Aussie BIM Guru, but substantial modifications were required because the original version depended on a different Excel library and did not interpret the dataset correctly. The adjusted script was restructured to read values natively and ensure accurate mapping between cells and parameters.

Further updates were needed for the parameter insertion scripts to correctly read built-in parameters, manage parameter groups, and handle cases where values required conditional assignment. After these adjustments, the workflow reliably populated parameters across the model and enabled processing of multiple family files simultaneously, which reduced manual handling time and improved consistency. The same benefit was possible with Dynamo, though it required more configuration.

During execution, the PyRevit console displayed warnings for parameters that could not accept formulas or required manual assignment due to Revit's internal constraints. These issues were expected and did not affect the overall workflow. Because the script produced a clear list of affected parameters, the remaining manual corrections were limited and easy to complete. This highlighted the advantage of having a structured dataset: automation could run through all parameters, flag non-automatable cases, and reduce manual work to a small, manageable subset.

The PyRevit workflow therefore demonstrated how full automation becomes effective when parameter definitions are stable and consistently formatted. Unlike the semi-automated Dynamo scripts, PyRevit required no intermediate intervention, showing the efficiency gained when dependable naming, data types, and mapping rules are in place. This behavior illustrates how fully automated tools can support scalable DPP creation, provided that manufacturers and practitioners supply structured, interoperable information from the start.

The final scripts, along with documentation of all modifications, were included in the annexes and the GitHub repository.

```
Available worksheets in Excel file:

Sheet 1: 'Standard'

Sheet 2: 'Pyrevit workflow'

Sheet 3: 'Group parameter under'

DEBUG: Found worksheet by name:
'Standard'

DEBUG: Reading data from worksheet...

DEBUG: Rows: 87, Columns: 4

DEBUG: Reading data row by row...

DEBUG: Row 1: ['Shared Parameter
Name', 'BIP Name', 'Instance',
'Formula (optional)']

DEBUG: Successfully read 87 rows

Reading worksheet: 'Standard' (87
rows, 4 columns)

Processed 83 parameters from Excel

Processing 1 families with 83
parameters...

DEBUG: Available 'Green' attributes
in GroupTypeId: ['GreenBuilding']

Formula failed for DPP_MAT_
Composition: This parameter cannot be
assigned a formula.

Parameter name: familyParameter

Formula failed for DPP_DAT_
StandarCompliance: It is an invalid
formula string.

Parameter name: formula

Formula failed for DPP_CIR_
Prefabrication: It is an invalid
formula string.

Parameter name: formula

Formula failed for DPP_CIR_
Reusability: It is an invalid formula
string.

Parameter name: formula

Formula failed for DPP_END_EPD: It is
an invalid formula string.

Parameter name: formula

Formula failed for DPP_END_EPD_URL:
This parameter cannot be assigned a
formula.

Parameter name: familyParameter

Formula failed for DPP_TMP_Warranty:
It is an invalid formula string.

Parameter name: formula

Formula failed for DPP_SAD_HPD: This
parameter cannot be assigned a
formula.

Parameter name: familyParameter

Formula failed for DPP_SAD_Toxicity:
It is an invalid formula string.

Parameter name: formula

Formula failed for DPP_SAD_Coatings:
It is an invalid formula string.

Parameter name: formula

Formula failed for DPP_SAD_
Compliance: It is an invalid formula
string.

Parameter name: formula

Added 78/83 parameters, set 58/69
formulas

Completed: 1/1 families updated
```

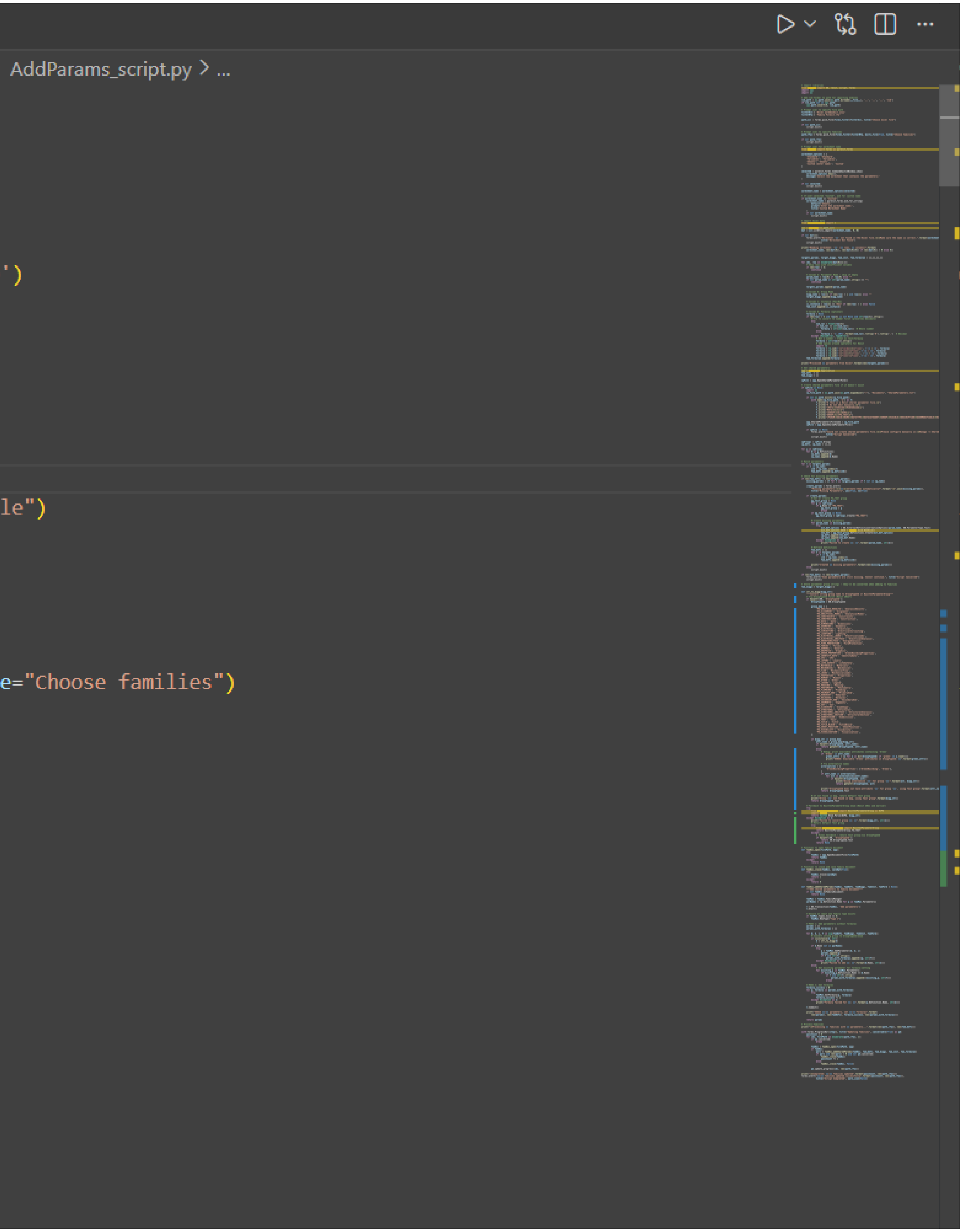
Figure 40. *Pyrevit console output for the parameter imput and paarameter filling.*
Note. From Pyrevit in Autodesk Revit console.

AddParams_script.py 9, M

Pyrevit Parameters tool > TestTool.extension > TestTool.tab > TestTool.panel > AddParams.pushbutton >

```
# Import libraries
from pyrevit import DB, revit, script, forms
import sys
import os

# Add lib folder to path for importing modules
lib_path = os.path.join(os.path.dirname(__file__), '..', '..', '..', 'lib
if lib_path not in sys.path:
    sys.path.insert(0, lib_path)

# Prompt user to specify file path
filterXcl = 'Excel workbooks|*.xlsx'
filterRfa = 'Family Files|*.rfa'

path_xcl = forms.pick_file(files_filter=filterXcl, title="Choose excel fi

if not path_xcl:
    script.exit()

# Prompt user to specify families
path_rfas = forms.pick_file(files_filter=filterRfa, multi_file=True, titl

if not path_rfas:
    script.exit()

# Prompt user for worksheet name
from pyrevit import forms as pyrevit_forms

worksheet_options = {
    'Standard': 'Standard',
    'Variables': 'Variables',
    'Sheet1': 'Sheet1',
    'Custom (enter name)': 'Custom'
}

selected = pyrevit_forms.CommandSwitchWindow.show(
    worksheet_options.keys(),
    message='Select the worksheet that contains the parameters:'
)
```

Figure 41. *Screen shot of add params button script for pyrevit in Visual Studio.*
Note. Pyrevit base script from Aussie BIM guru, and adapted in Visual Studio.


AddParams_script.py > ...
')
le")
e="Choose families")

4.2.4 IFC models and RDF files

The IFC models generated in Revit were the base input for the RDF representations required for semantic validation. This step was essential because, even though IFC is already a standardized format based on the EXPRESS schema, its structure is rigid and optimized primarily for geometric and object-based coordination rather than flexible, machine-interpretable data exchange. Digital Product Passports, however, require information that is easily queryable, shareable, linkable to external knowledge sources, and domain-interoperable. For this reason, the workflow required converting IFC into RDF, which is based on OWL and supports semantic relationships, extensibility, and direct machine interpretation.

The IFC-to-LBD converter was therefore adapted to address two limitations in the original version. First, the converter was extended to generate an additional Excel output listing all extracted IFC properties, creating a clear comparison point against the dataset structured in the Excel template. Second, the converter was reconfigured to clean the IFC file by removing unrelated project data, retaining only the elements relevant to the passport. This improved the clarity of both the RDF output and the verification process.

The resulting RDF files offered a flexible, graph-based representation of the material and component properties, enabling the alignment between parameters, ontologies, and URIs defined in the Parameter Mapping sheet. Comparing the RDF data with the Final Dataset revealed whether values, identifiers, and semantic links had been transferred correctly. The parallel Excel export also supported the detection of missing parameters, naming inconsistencies, unit mismatches, and grouping errors within the IFC structure.

This stage demonstrated why semantic conversion is necessary for DPP development: while IFC provides standardized structure, RDF enables interoperability, machine readability, and integration with broader digital ecosystems. The sequential workflow permitted data integrity at each step but also exposed the fragmentation of the current process. With further development, these steps could be consolidated into a single Python-based tool running directly inside Revit. Although this integration extends beyond the scope of this research, the results indicate that increased automation is feasible and would improve repeatability, reduce manual intervention, and support scalable DPP generation.

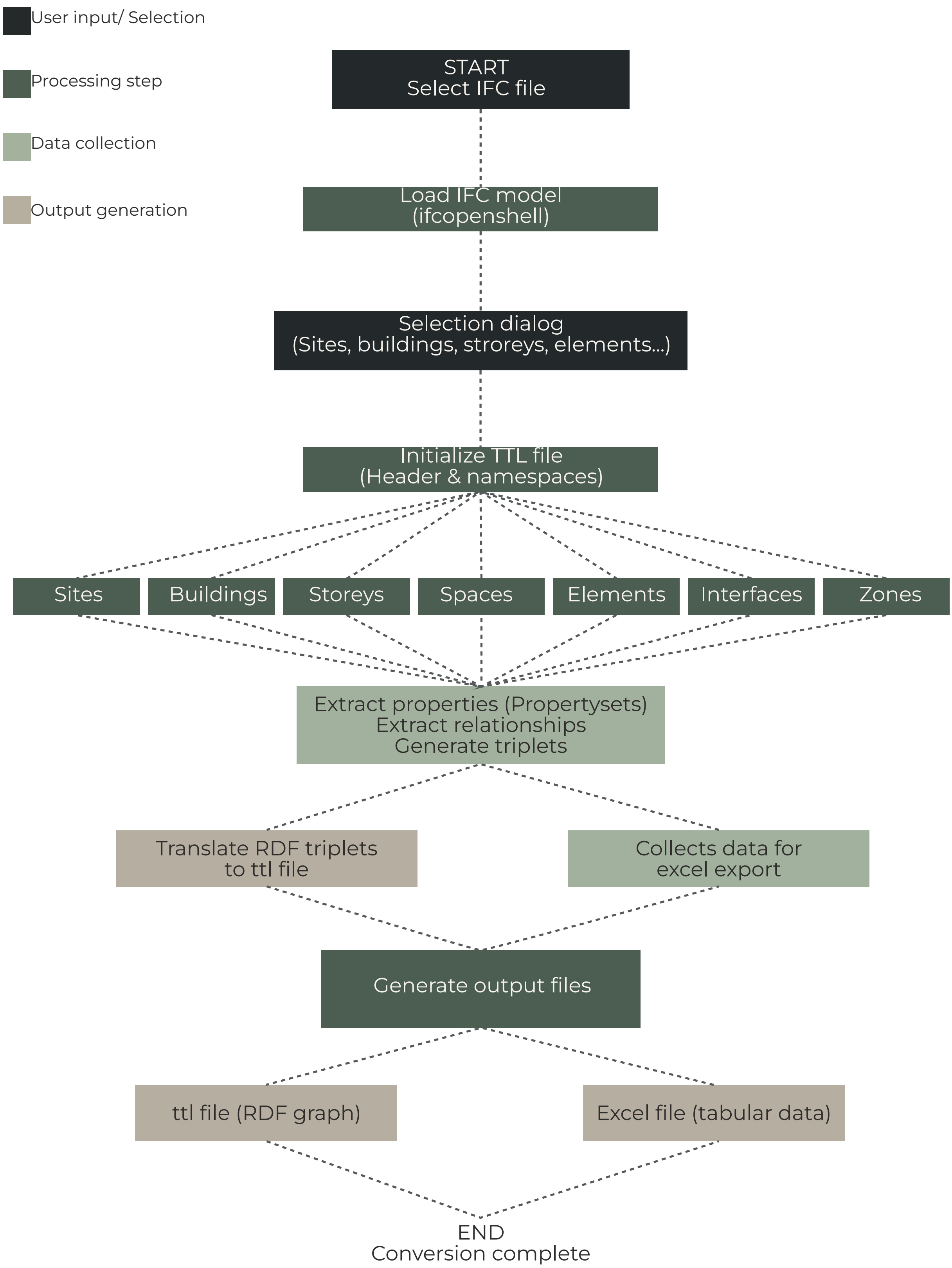


Figure 42. *Workflow of the IFC to LBD convertion python script.*
Note. Created by author (base python script by Bosma, 2024)

```
# baseURI: http://linkedbuildingdata.
net/ifc/resources20251114_132103/

@prefix inst: <http://
linkedbuildingdata.net/ifc/
resources20251114_132103/> .

@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#> .



inst: rdf:type <http://www.w3.org/
2002/07/owl#Ontology> .



inst:element_84

      a bot:Element ;

      rdfs:label "DPP_HempBlock_
Material:DPP_HempBlock_
Material:1664827"^^xsd:string ;

      bot:hasGuid
"f7c6ec25e43b4ab68533be62a885d060"^^xsd
:string ;

      props:hasCompressedGuid
"3tnkmbv3jAjeKplcAeXT1W"^^xsd:string ;

      props:Category "Generic
Models"^^xsd:string ;

      props:FamilyName "DPP_HempBlock_
Material"^^xsd:string ;

      props:Family "DPP_HempBlock_
Material"^^xsd:string ;

      props:FamilyAndType "DPP_
HempBlock_Material: DPP_HempBlock_
Material"^^xsd:string ;

      props:Type "DPP_HempBlock_
Material"^^xsd:string ;

      props:TypeId "1664811"^^xsd:
string ;

      props:DefaultElevation
"0.0"^^xsd:double ;

      props:ElevationFromLevel
"0.0"^^xsd:double ;

      props:Host "Level : L1"^^xsd:
string ;

      props:Level "L1"^^xsd:string ;

      props:MovesWithNearbyElements
"False"^^xsd:boolean ;

      props:OffsetFromHost "0.0"^^xsd:
double ;

      props:Dpp_Cir_
Deconstructabilityscore "0.5"^^xsd:
double ;

      props:Dpp_Cir_
Disassemblyinstructions "Mechanical
dismantling: Crushing and Sieving for
Recycling"^^xsd:string ;

      props:Dpp_Cir_
Disassemblypotential "3.0"^^xsd:double
;

      props:Dpp_Cir_
Endofliferecomendations "Composting and
soil improvement; Disposal via
incineration"^^xsd:string ;

      props:Dpp_Cir_Prefabrication
"True"^^xsd:boolean ;

      [...]
```

Figure 43. *Excerpt of .ttl (RDF) file of material-level IFC converted.*
Note. Created by author

Element Type	Element Name	Parameter	Value	Data Type	Unit
IfcBuildingElementProxy	DPP_HempBlock_Material:DPP_HempBlock_Material:1664827	Dpp_Cod_Repl	3.4	double	EUR
IfcBuildingElementProxy	DPP_HempBlock_Material:DPP_HempBlock_Material:1664827	Dpp_Cod_Unit	3.8	double	EUR
IfcBuildingElementProxy	DPP_HempBlock_Material:DPP_HempBlock_Material:1664827	Dpp_Dim_Heig	200.00000000000082	double	mm
IfcBuildingElementProxy	DPP_HempBlock_Material:DPP_HempBlock_Material:1664827	Dpp_Dim_Leng	80.00000000000001	double	mm
IfcBuildingElementProxy	DPP_HempBlock_Material:DPP_HempBlock_Material:1664827	Dpp_Dim_Widt	499.99999999999613	double	mm
IfcBuildingElementProxy	DPP_HempBlock_Material:DPP_HempBlock_Material:1664827	Area	0.16000000000000394	double	
IfcBuildingElementProxy	DPP_HempBlock_Material:DPP_HempBlock_Material:1664827	Volume	0.008000000000000538	double	
IfcBuildingElementProxy	DPP_HempBlock_Material:DPP_HempBlock_Material:1664827	Dpp_Sad_Fire_(	B (Very limited contribution to fire)	string	
IfcBuildingElementProxy	DPP_HempBlock_Material:DPP_HempBlock_Material:1664827	Dpp_Sad_Fire_I	d0 (No flaming droplets or particles)	string	
IfcBuildingElementProxy	DPP_HempBlock_Material:DPP_HempBlock_Material:1664827	Dpp_Sad_Fire_!	s1 (Little or no smoke)	string	
IfcBuildingElementProxy	DPP_HempBlock_Material:DPP_HempBlock_Material:1664827	Dpp_Sad_Firer	B - s1; d1	string	

Figure 44. *Excerpt of the excel file of material-level IFC converted.*
Note. Created by author

4.2.5 Ontology Network

Ontology analysis

The aim of the ontology analysis was to explore the feasibility of constructing a coherent ontology network capable of supporting a BIM-based Digital Product Passport for Hempcrete. For this purpose, four ontologies were combined in the Protégé platform: the DPP ontology by Bosma (2014), the BOT ontology, the QUDT ontology, and BioOnto from the BIOVOICES project. They were compared to understand if there was internal consistency, a degree of semantic overlap, and their potential to form an integrated network suitable for DPP information.

The integrated ontology showed that there is little interoperability between the four ontologies. Very few terms are compatible across all four ontologies, although most are compatible in pairs rather than being identical across ontologies. The most compatible relationship was between the DPP ontology and the QUDT ontology, which together represented more than half of possible semantic links. This result corresponds to the inherent role of measurable properties the DPP data structure. Moderate alignment was found between the DPP ontology and BioOnto, expected becasue of the circularity focus of the DPP ontology. However, there is little compatibility between the BOT ontology and either material or biological ontologies. This is because the BOT ontology focuses too much on architectural topology and spatial relationships and can not describe material properties with sufficient depth for product descriptions.

Although the four ontologies have a very limited overlap, this does not necessarily imply weak coverage. Instead, the distributed structure indicates that each ontology contributes different types of information that complement the others. The low number of shared concepts reflects the differenciated focus of each ontology rather than a lack of relevance. When considered together, the four ontologies provide a broad semantic base that should be capable of covering the BIM DPP parameters, even if their internal connections are limited.

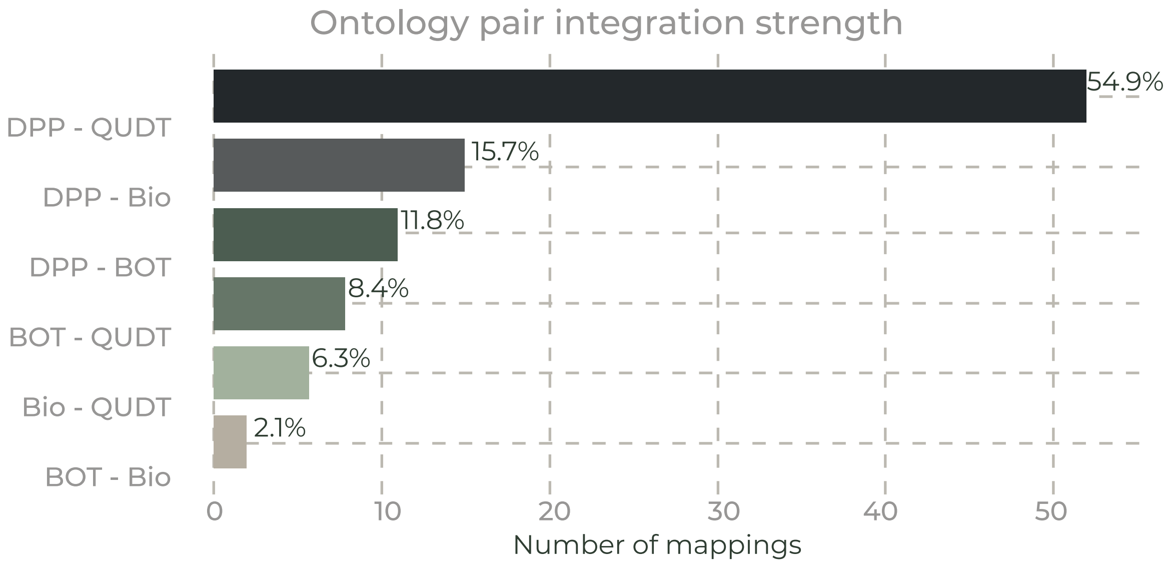


Figure 45. *Integration strength across ontology pairs.*
Note. Mapping count. Created by author with Visual Studio.

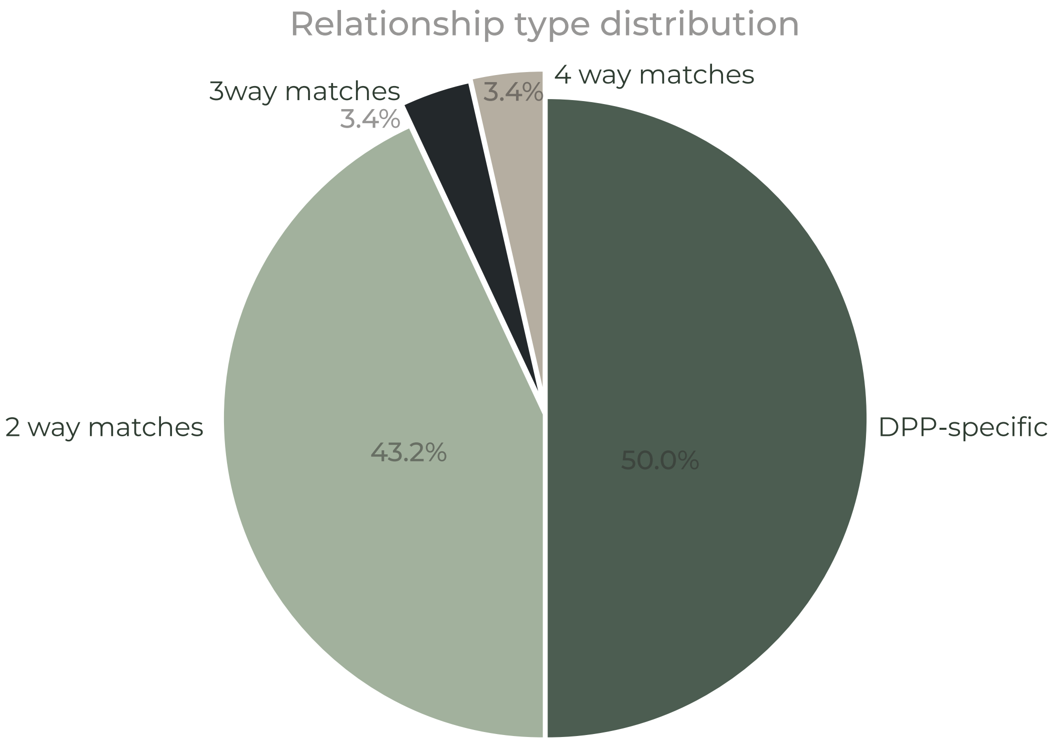


Figure 46. *Percentage distribution of relationship type.*
Note. 4-way, 3-way, 2-way matches, and DPP-specific concepts. Created by author with Visual Studio.

Mapping against paramteres

To check whether the four ontologies really provide a semantic base that could support the BIM DPP parameters, the integrated ontology was compared with the full set of 111 parameters defined for Hempcrete. This comparison made it possible to test if the limited internal connections among the ontologies restricted their practical usefulness, or if their complementary nature still allowed them to cover a significant portion of the dataset.

QUDT had the highest number of connecctions across almost all categories, indicating that measurable and quantitative descriptors make a substantial portion of the DPP dataset. The DPP ontology showed strong representation, particularly for identification, provenance, material properties, and sustainability-oriented descriptors. BioOnto made a moderate number of connections in categories involving material composition, environmental impact, health-related aspects, and sustainability, reflecting its focus on bio-based material and environmental semantics. By contrast, BOT contributed only a small number of connections, consistent with its emphasis on architectural topology rather than material-specific or lifecycle information.

At the parameter level, the number of usable connections increased across all ontology pairs, revealing that their specialized vocabularies aligned with the dataset more effectively in practice than at the conceptual level. The increase was particularly evident for QUDT, which rose from 52 to 67 links, and for BioOnto, which expanded from 15 to 25 links, demonstrating that the detailed structure of the DPP parameters related to additional relevant concepts within the ontologies. However, the combined ontology still covered only 18 of the 111 parameters, showing that several aspects remained semantically unrepresented.

This underlines the need to develop custom ontology terms, to achieve full semantic coverage of all the parameters and to extended ontology network further. While the four ontologies provide substantial and complementary support, they require targeted extensions to fully represent the complexity and specificity of a bio-based material within a BIM-based Digital Product Passport.

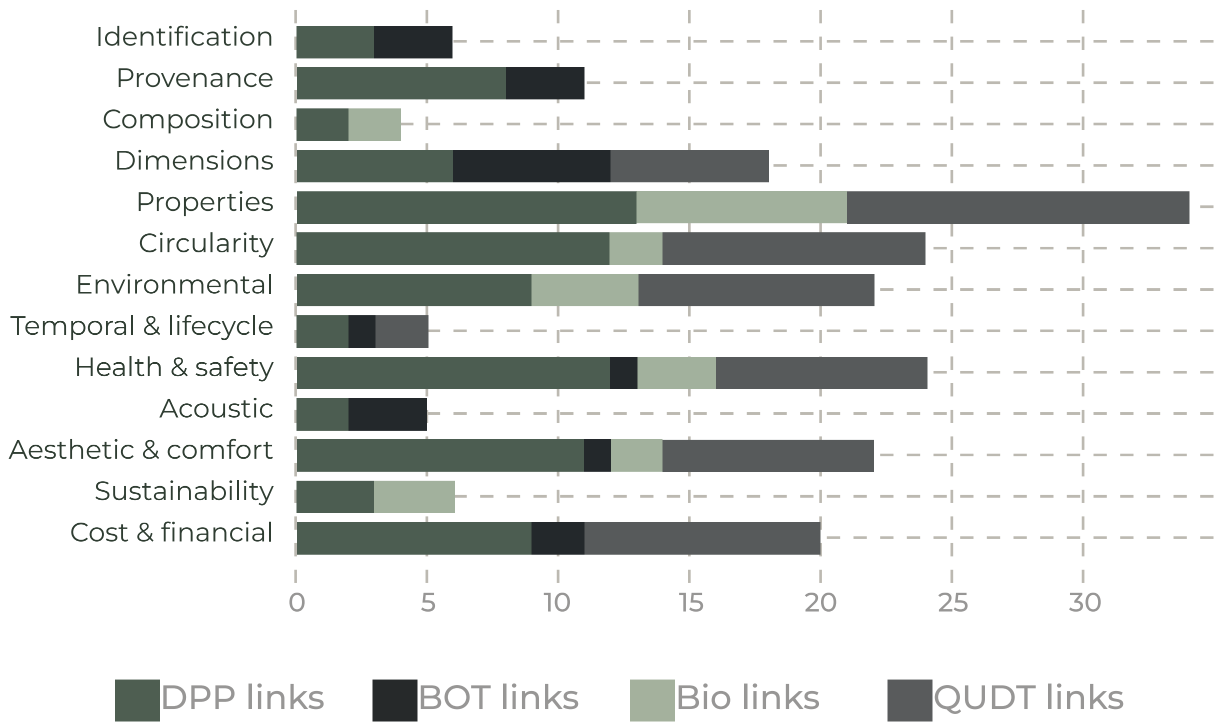


Figure 47. *Ontology integration across 13 parameter categories.*
Note. Created by author with Visual Studio.

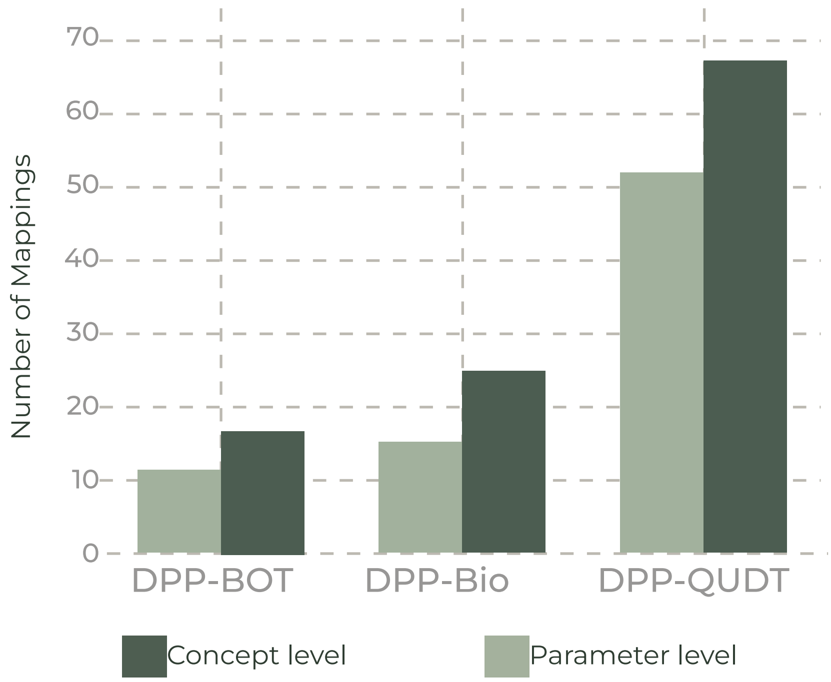


Figure 48. *Concept vs parameter level integration.*
Note. Concept to parameter level coverage growth (18→111 properties). Created by author with Visual Studio.

4.2.6 Validation reports

The validation reports were generated using a combination of Python tools, partly derived from Bosma's workflow and partly adapted for this research. These reports evaluated whether the Digital Product Passport structure was transferred correctly throughout the workflow, from the Excel dataset to the BIM model, the IFC export, and the RDF output. The reports provided two forms of validation: semantic validation based on the Turtle files, and quantitative comparison based on the Excel outputs extracted from the IFC models.

The TTL validation assessed whether the parameter values exported from Revit and converted into RDF were correctly represented according to the mapped ontologies. Both the material-level and element-level passports revealed issues related to the tracking of identification numbers, such as GUIDs, and the way these identifiers were mapped within the ontological structure. These inconsistencies indicated that the current workflow requires additional rules for managing identifiers, including strategies for linking GUIDs to stable URIs, defining parent–child relationships between elements and their materials, and aligning repeated identifiers with a consistent referencing method. This is particularly important when multiple components reference the same material dataset.

The Excel comparison provided a complementary layer of validation by checking the similarity between expected values from the Final Dataset and the values extracted from the IFC. The tool quantified how many parameters matched, based on similarity of the value and the associated units. This comparison was particularly useful for detecting deviations that were not semantic errors but inconsistencies introduced during the IFC export or parameter assignment. The results confirmed that several parameters transferred accurately, although mismatches occurred in cases involving unit conversions, nonstandard parameter names, or incomplete population of built-in fields.

Together, the validation reports demonstrated that the workflow produced functional outputs but also revealed structural limitations that must be addressed for future iterations. Full validation requires resolving identifier management, improving parameter mapping rules, and refining the IFC export to avoid unintended data loss. The reports for each passport type, including the PDF outputs of the TTL and Excel validations, were included in the annexes.

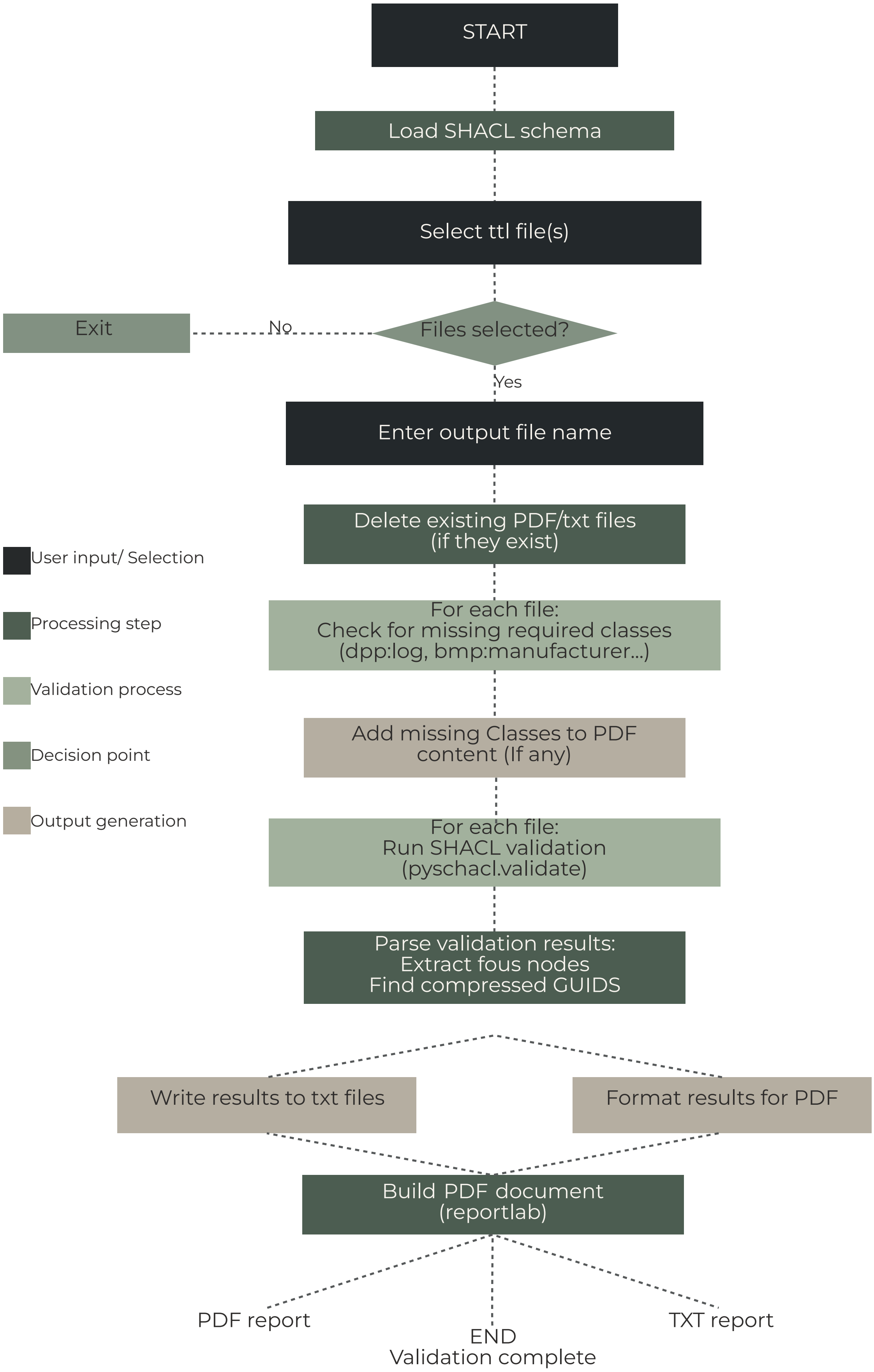


Figure 49. *Workflow of the Validation python script.*
Note. Created by author (Base python script by Bosma, 2024)

Validation Report

C:/Users/Catalina/OneDrive - Pontificia Universidad Javeriana/Desktop/THESIS/Methodology/DPP_Material/DPP_HempBlock_Material_mapped.ttl

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

----

Validation results for C:/Users/Catalina/OneDrive - Pontificia Universidad Javeriana/Desktop/THESIS/Methodology/DPP_Material/DPP_HempBlock_Material_mapped.ttl:

Validation results for C:/Users/Catalina/OneDrive - Pontificia Universidad Javeriana/Desktop/THESIS/Methodology/DPP_Material/DPP_HempBlock_Material_mapped.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:string ; sh:minCount Literal("1", datatype=xsd:integer) ; sh:minLength Literal("1", datatype=xsd:integer) ; sh:path props:hasCompressedGuid] Focus Node: Result Path: props:hasCompressedGuid Message: Less than 1 values on ->props:hasCompressedGuid

Figure 50. *PDF of the material-level TTL validation output.*
Note. Created by author.

Dataset Comparison Report

Completeness: 32.9%
(28/85 parameters matched)

Parameter	Base Value	Base Unit	Conv. Value	Conv. Unit	Status	Checks
DPP_AUT_Name	Hempstone		Hempstone		Match	OK
DPP_AUT_ID	Z-17.25-1299	ID	Z - 17.25 - 129		Value & Unit Mismatch	OK
DPP_AUT_GUID	None	GUID	3tnkmbv3jAjeKpl		Value & Unit Mismatch	OK
DPP_AUT_MaterialType	Type II		Type II		Match	Range
DPP_AUT_Manufacturer	Schönthaler Bau		Schönthaler Bau		Match	OK
DPP_AUT_Traceability	None				Missing in Converted	Missing in Converted
DPP_AUT_Origin	39020 Oris (BZ)		39021 Oris (BZ)		Value Mismatch	OK
DPP_AUT_Version	HKZ 335	No.	HKZ 335		Unit Mismatch	Range
DPP_MAT_Material	Infill masonry		Hemp-Lime		Value Mismatch	OK
DPP_MAT_Composition	Made from 20–55		Made from 20–55		Match	Range
DPP_AUT_TypeDimension	8x50x20	cm	8x50x20		Unit Mismatch	Range
DPP_DIM_Height_mm	200	mm	200.00000000000	mm	Match	OK
DPP_DIM_Width_mm	80	mm	499.99999999999	mm	Value Mismatch	Range
DPP_DIM_Length_mm	500	mm	80.000000000000	mm	Value Mismatch	Range
DPP_DIM_Volume_m3	0.008		0.008	m³	Unit Mismatch	OK
DPP_DAT_DryDensity_kgm3	335	kg/m³	335.0		Unit Mismatch	OK
DPP_DAT_EqDensity_kgm3	405	kg/m³	405.0		Unit Mismatch	OK
DPP_DAT_Weight_kg	2.68	kg	2.67	kg	Match	Range
DPP_DAT_CompressiveStrenght_Mp	0.5	MPa	0.5	MPa	Match	OK
DPP_DAT_ShearStrenght_Mpa	0.12	MPa	0.12	MPa	Match	OK
DPP_DAT_VaporDiffµ_wet	3.8	µ	3.8000000000000		Unit Mismatch	Range
DPP_DAT_VaporDiffµ_dry	4.3	µ	4.3		Unit Mismatch	Range
DPP_DAT_VaporAbsorption	19	d[g/m²vh]	19.0		Unit Mismatch	Range
DPP_DAT_StandarCompliance	Yes		True		Match	Range
DPP_CIR_Prefabrication	Yes		True		Match	Range
DPP_CIR_PrefabricationFactor	1	Score	1.0		Unit Mismatch	Range
DPP_CIR_DeconstructabilityScor	0.5	Score	0.5		Unit Mismatch	OK
DPP_CIR_RecyclingPotential	100	%	100.0		Unit Mismatch	Range

Figure 51. *PDF of the Material-level excel validation output.*
Note. Created by author.

DPP MOCK-UP

The DPP mock-up was produced using the outputs generated throughout the workflow, specifically the TTL-mapped parameter set, the structured Excel dataset, and the validation results obtained from the semantic and numerical checks. Its purpose was to provide a preliminary visualization of how the DPP for a bio-based construction material could appear within a digital database. The mock-up served only as a visual representation and did not function as a fully interactive interface.

The page was designed to reflect the information hierarchy established in the dataset, including material characteristics, physical and mechanical properties, environmental indicators, provenance information, and circularity-related attributes. The values displayed were partly real and partly illustrative. Some parameters originated from manufacturer documentation, others from literature or estimation, and several were included only to demonstrate how the structure could accommodate different types of information. This ensured that the mock-up represented the functional potential of the passport without implying full data completeness.

The mock-up also incorporated indicators showing the data source and level of accuracy. These indicators were derived from the TTL validation process conducted during the workflow and illustrated how uncertainty or validation gaps could be communicated within a passport interface. Although these indicators provided useful context, they were visual placeholders rather than functioning validation tools.

Two additional materials were included in the mock-up. These materials were not part of the evaluation and were not subjected to the validation processes described in earlier sections. They were incorporated solely to demonstrate how multiple passports could coexist in a shared environment, enabling comparison between materials and highlighting the potential advantages of bio-based solutions within a broader dataset.

The prototype also included elements such as a QR code and download buttons for the IFC file. These components were included to illustrate how digital links or file retrieval might appear in a future implementation. However, as the mock-up operated only as a static visualization, these elements were not functional. The interface itself was not part of the thesis; it served only as a conceptual aid to demonstrate how the curated and validated DPP data could be represented within a future digital system.

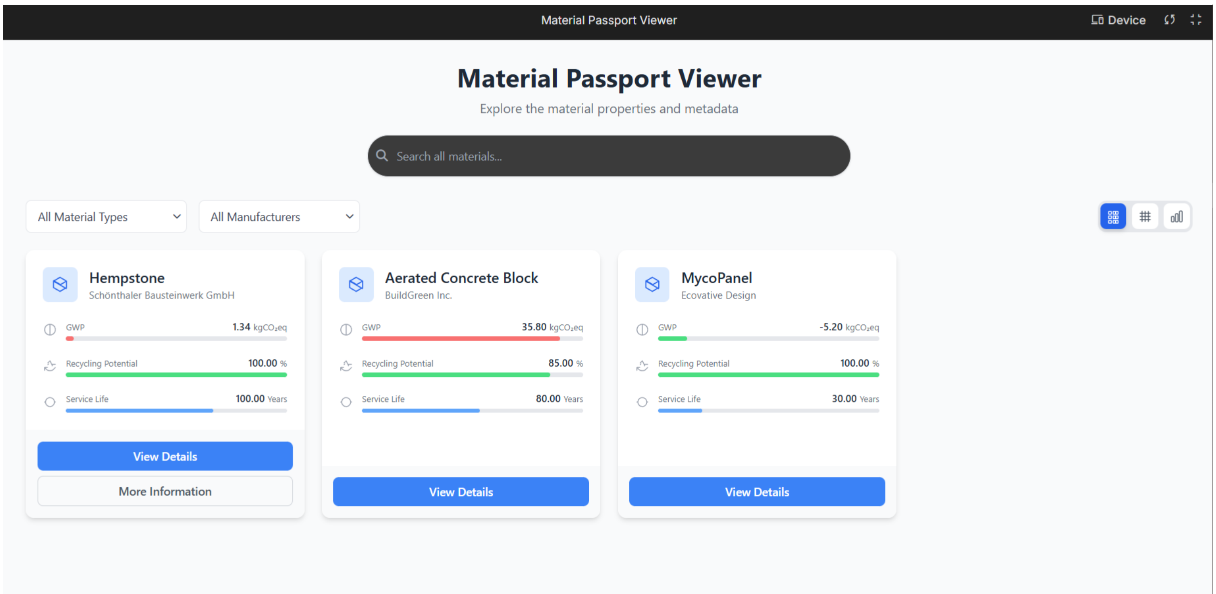


Figure 52. *Screen shot of Material Passport Viewer inital page.*
Note. Created by author with Google AI studio.

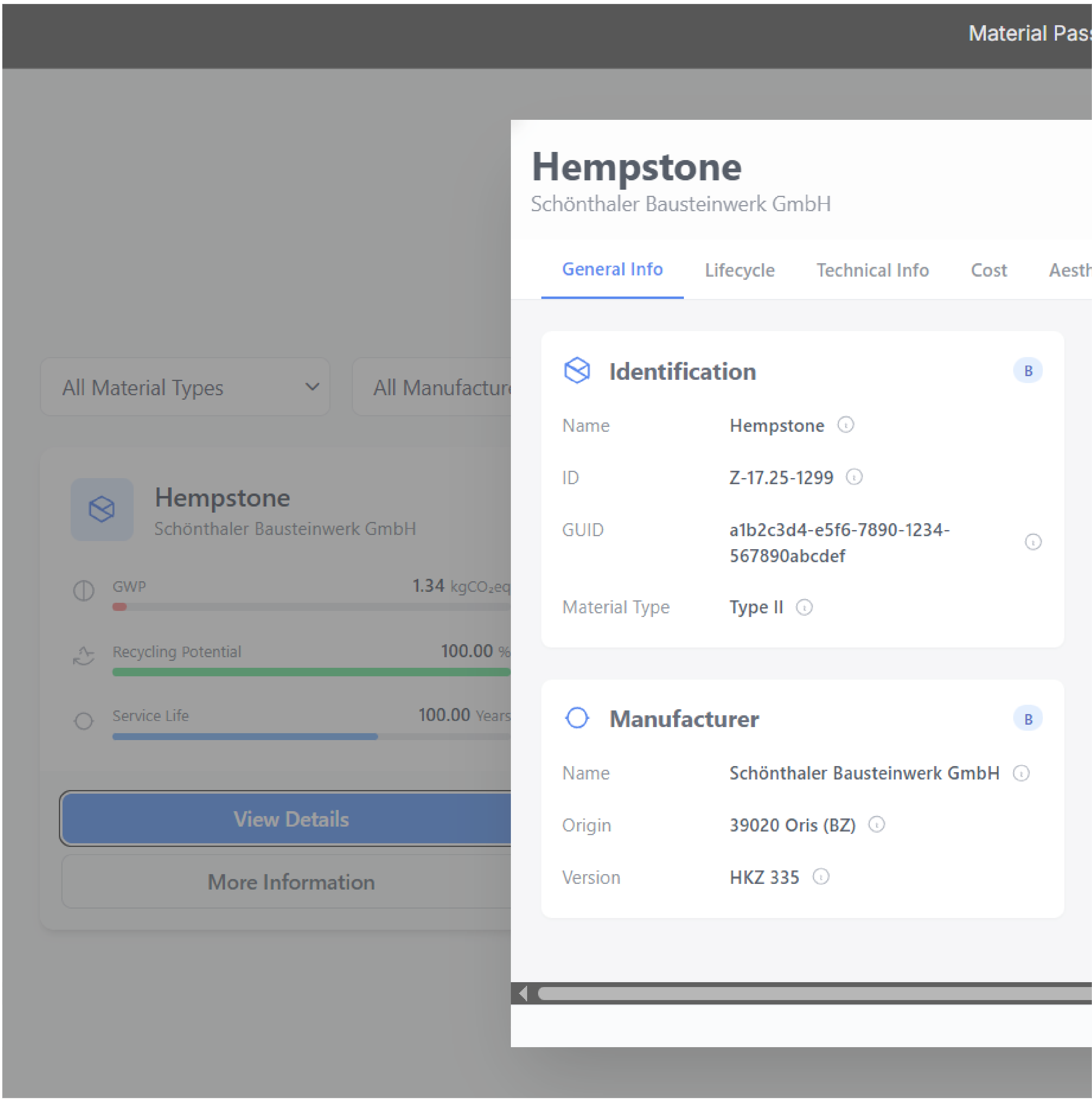
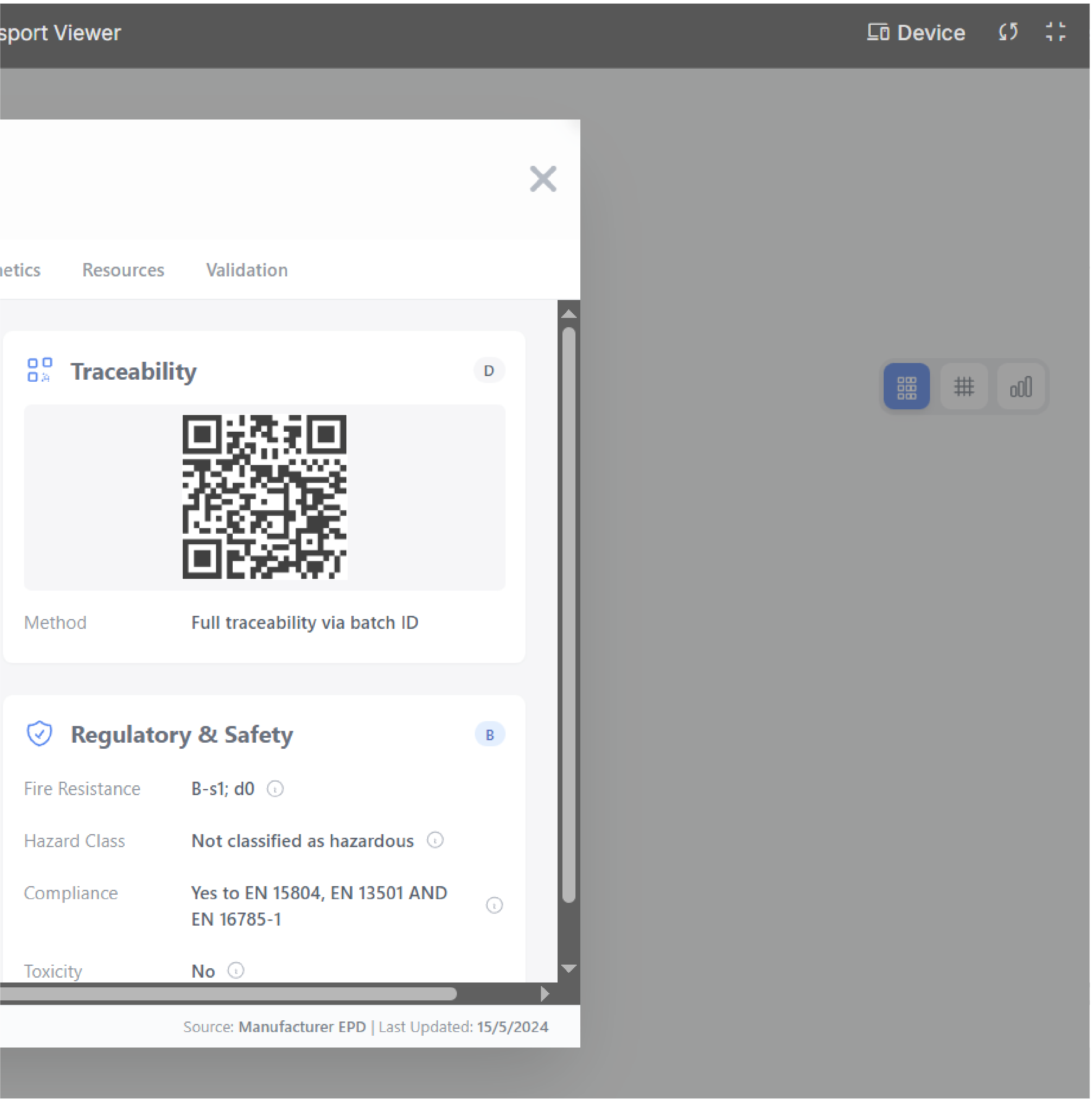


Figure 53. *Screen shot of General information tab on hempcrete DPP.*
Note. Created by author with Google AI studio.


sport Viewer
Device
etics
Resources
Validation
Traceability
D
Method
Full traceability via batch ID
Regulatory & Safety
B
Fire Resistance
B-s1; d0
Hazard Class
Not classified as hazardous
Compliance
Yes to EN 15804, EN 13501 AND EN 16785-1
Toxicity
No
Source: Manufacturer EPD | Last Updated: 15/5/2024

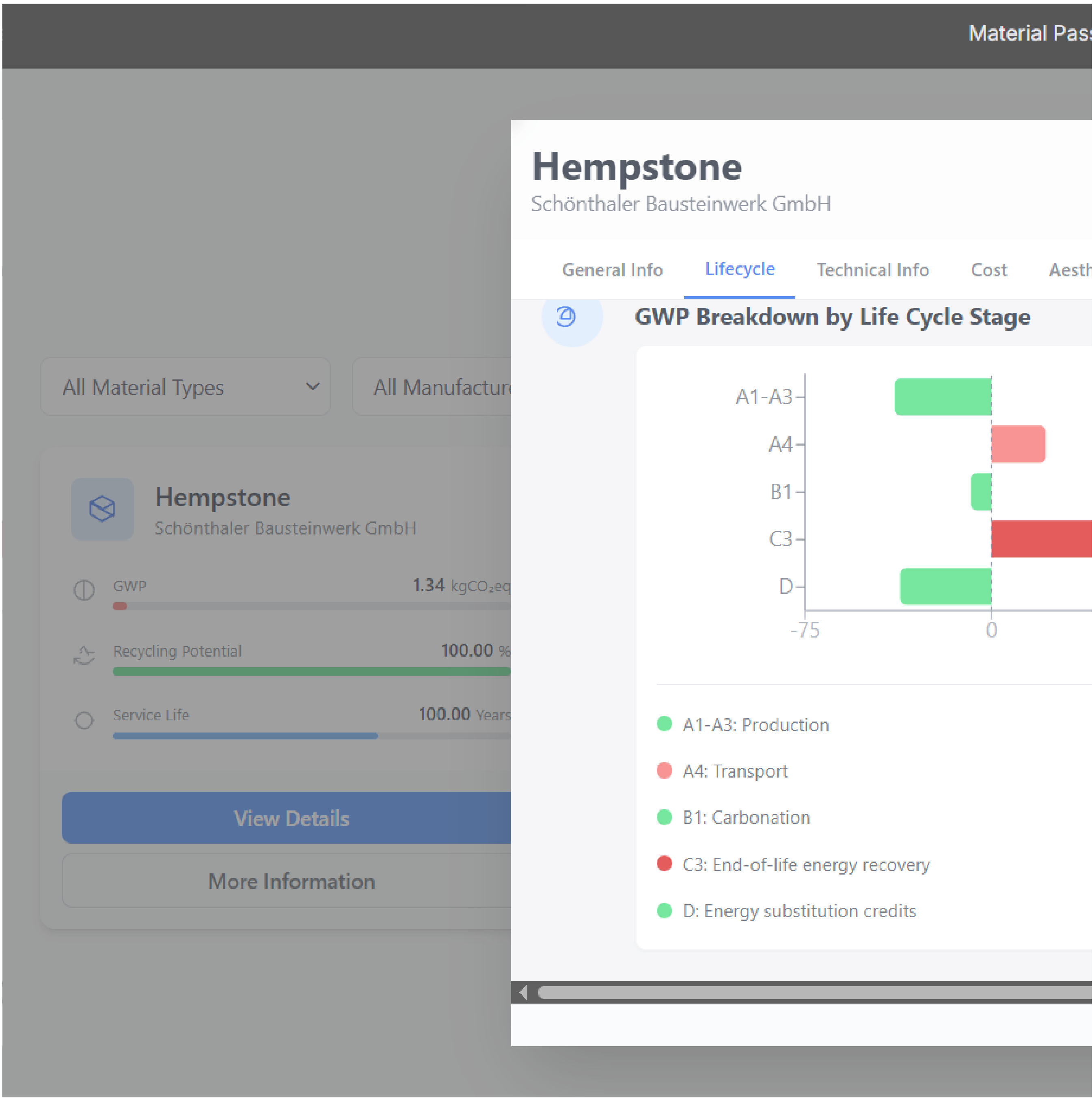
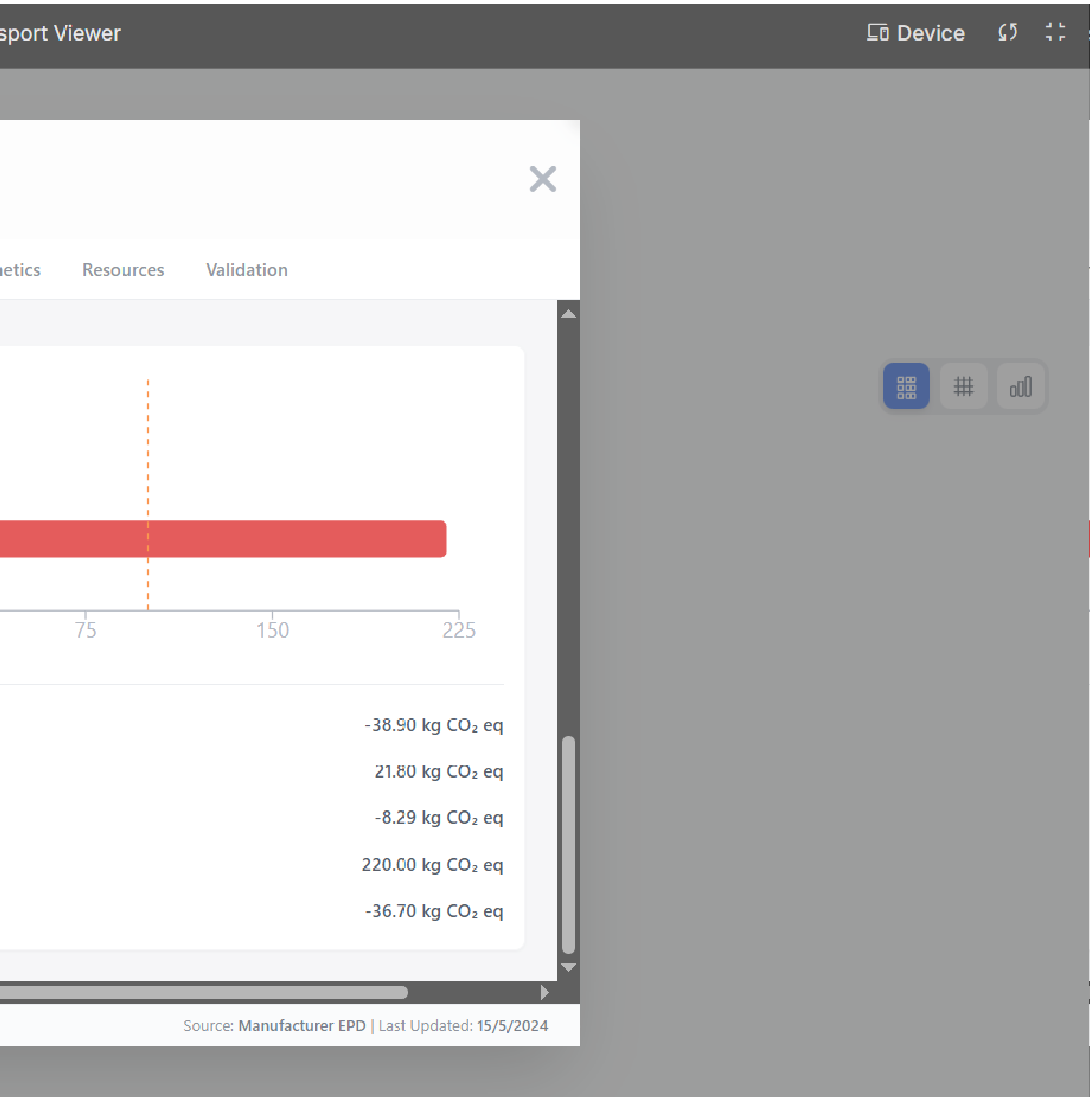


Figure 54. *Screen shot of Life cycle tab on hempcrete DPP.*
Note. Created by author with Google AI studio.


sport Viewer
Device
etics
Resources
Validation
75
150
225
-38.90 kg CO_2 eq
21.80 kg CO_2 eq
-8.29 kg CO_2 eq
220.00 kg CO_2 eq
-36.70 kg CO_2 eq
Source: Manufacturer EPD | Last Updated: 15/5/2024

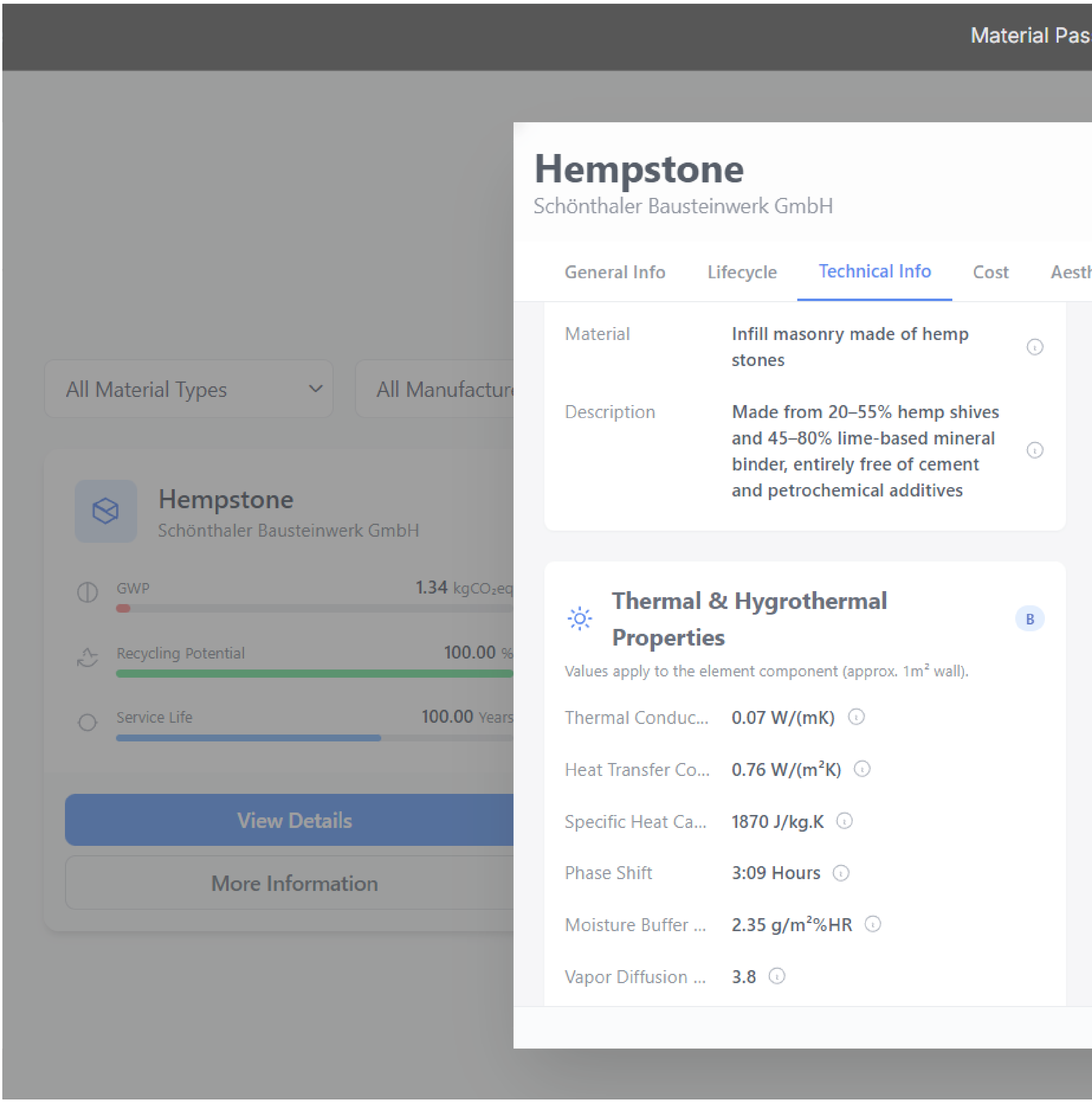
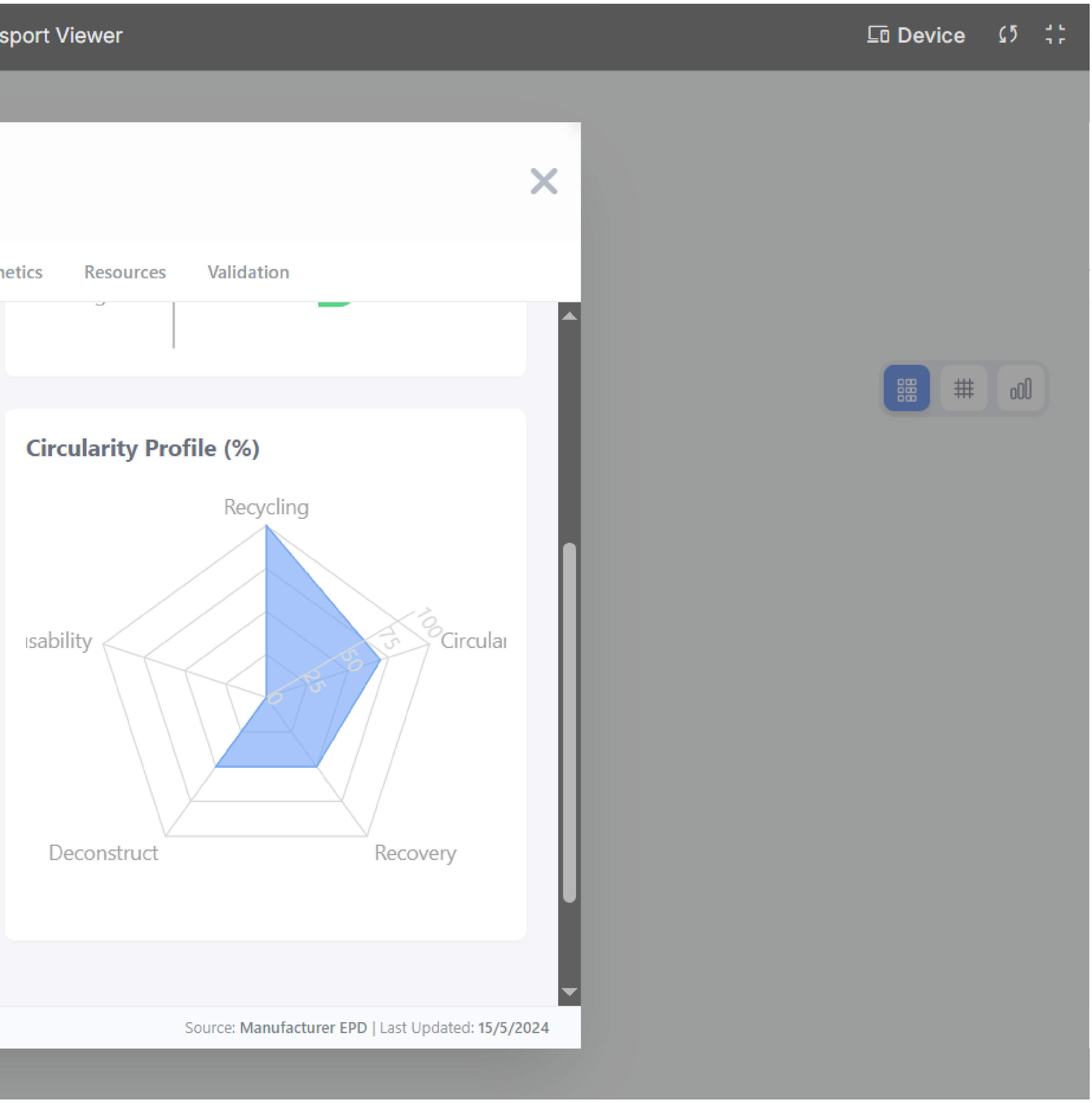


Figure 55. *Screen shot of Technical information tab on hempcrete DPP.*
Note. Created by author with Google AI studio.


sport Viewer
Device
netics
Resources
Validation
Circularity Profile (%)
Recycling
Circular
Recovery
Deconstruct
ısability
0
25
50
75
100
Source: Manufacturer EPD | Last Updated: 15/5/2024

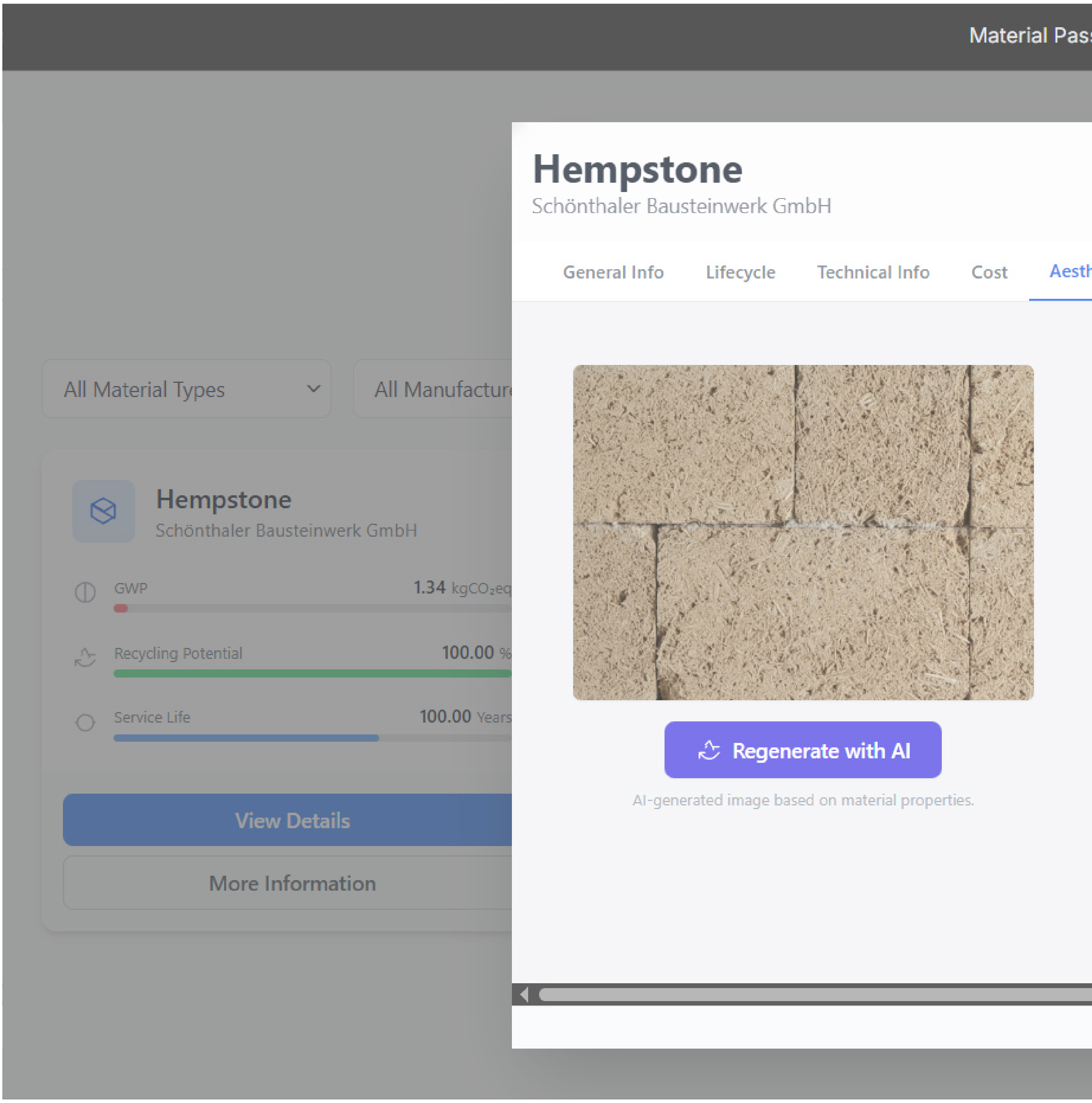
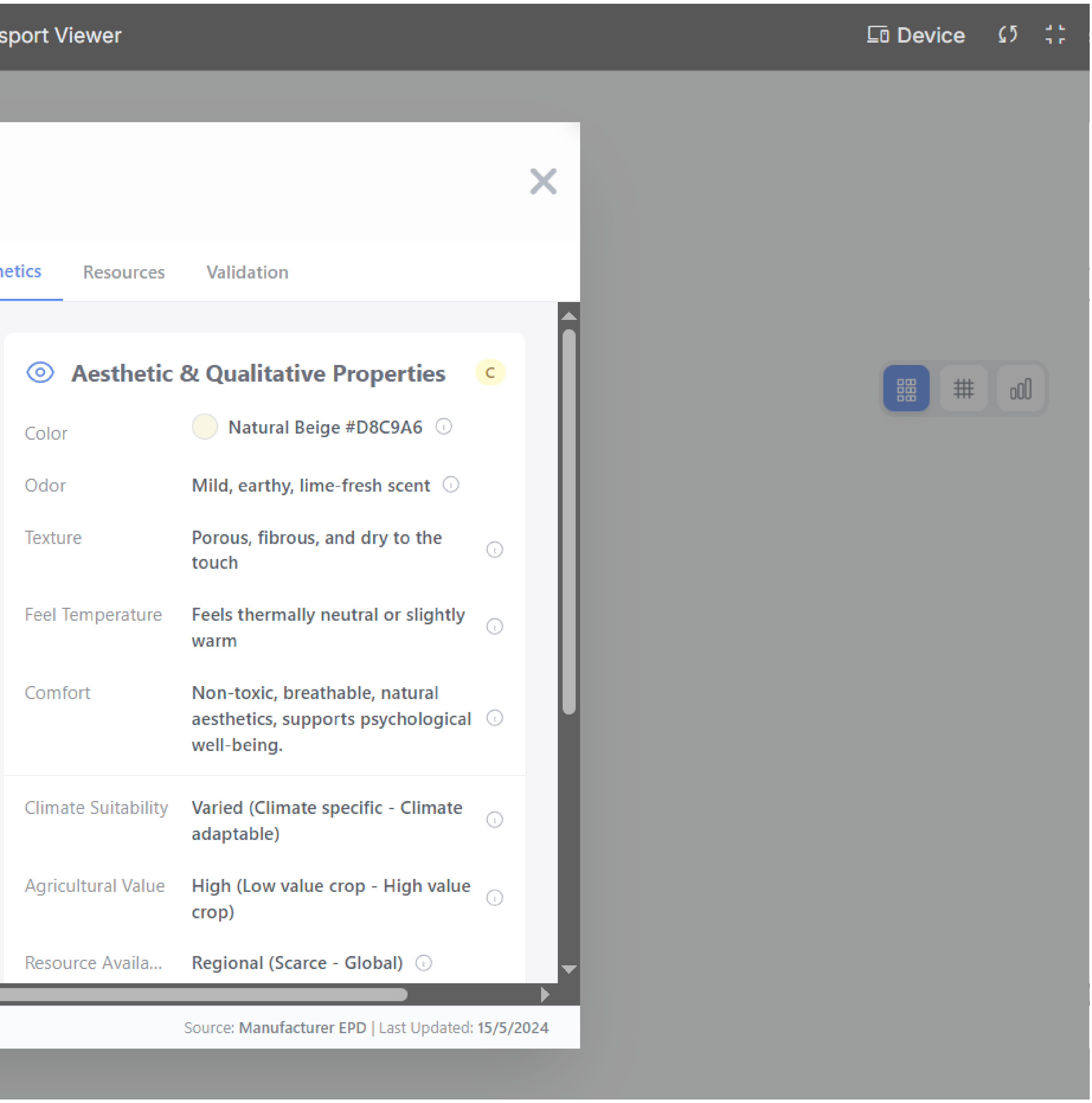


Figure 56. *Screen shot of Aesthetics tab on hempcrete DPP.*
Note. Created by author with Google AI studio.


sport Viewer
Device
etics
Resources
Validation
Aesthetic & Qualitative Properties
C
Color
Natural Beige #D8C9A6
Odor
Mild, earthy, lime-fresh scent
Texture
Porous, fibrous, and dry to the touch
Feel Temperature
Feels thermally neutral or slightly warm
Comfort
Non-toxic, breathable, natural aesthetics, supports psychological well-being.
Climate Suitability
Varied (Climate specific - Climate adaptable)
Agricultural Value
High (Low value crop - High value crop)
Resource Availa...
Regional (Scarce - Global)
Source: Manufacturer EPD | Last Updated: 15/5/2024

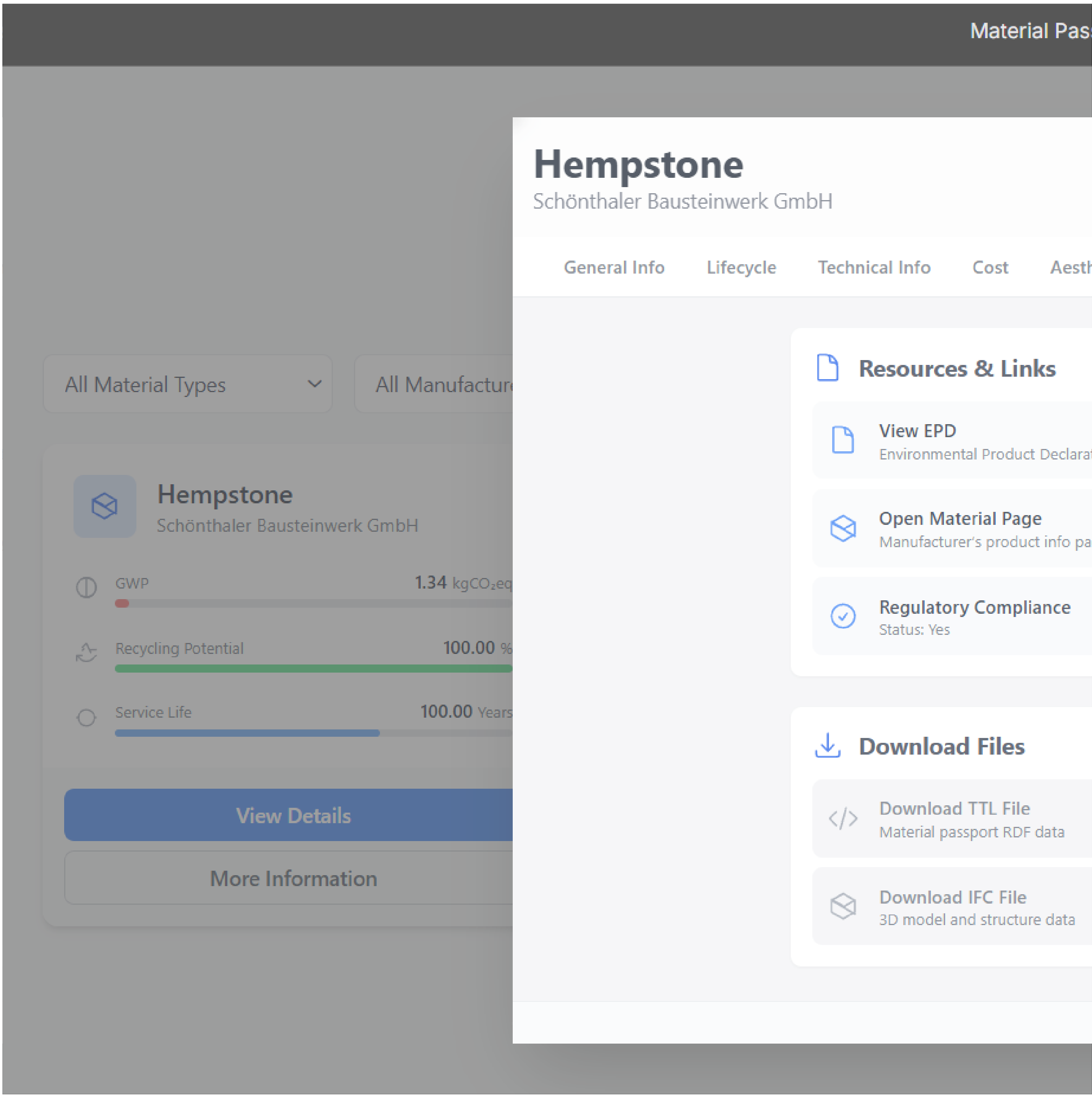
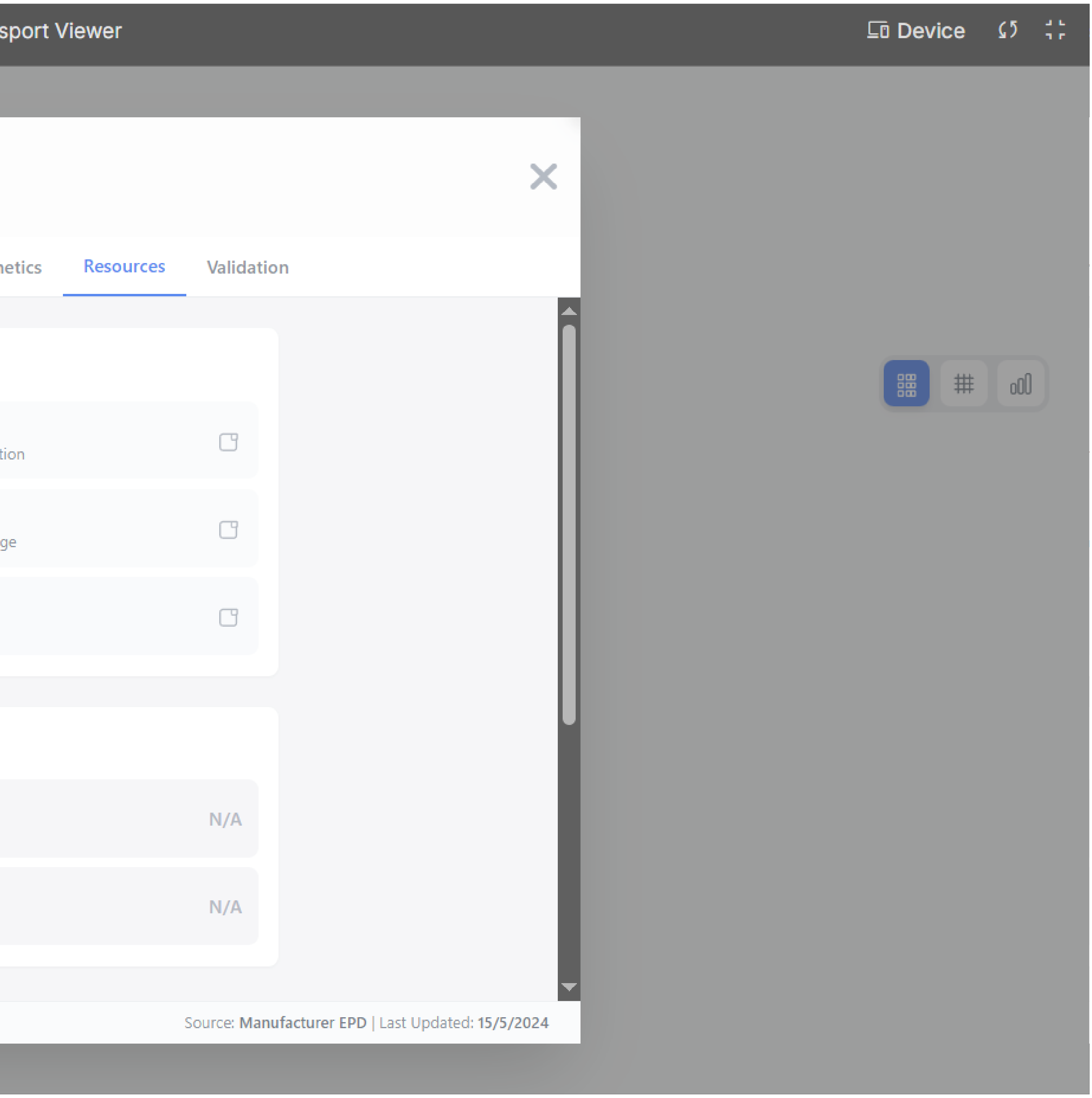


Figure 57. *Screen shot of Resourses tab on hempcrete DPP.*
Note. Created by author with Google AI studio.


sport Viewer
Device
netics
Resources
Validation
tion
ge
N/A
N/A
Source: Manufacturer EPD | Last Updated: 15/5/2024

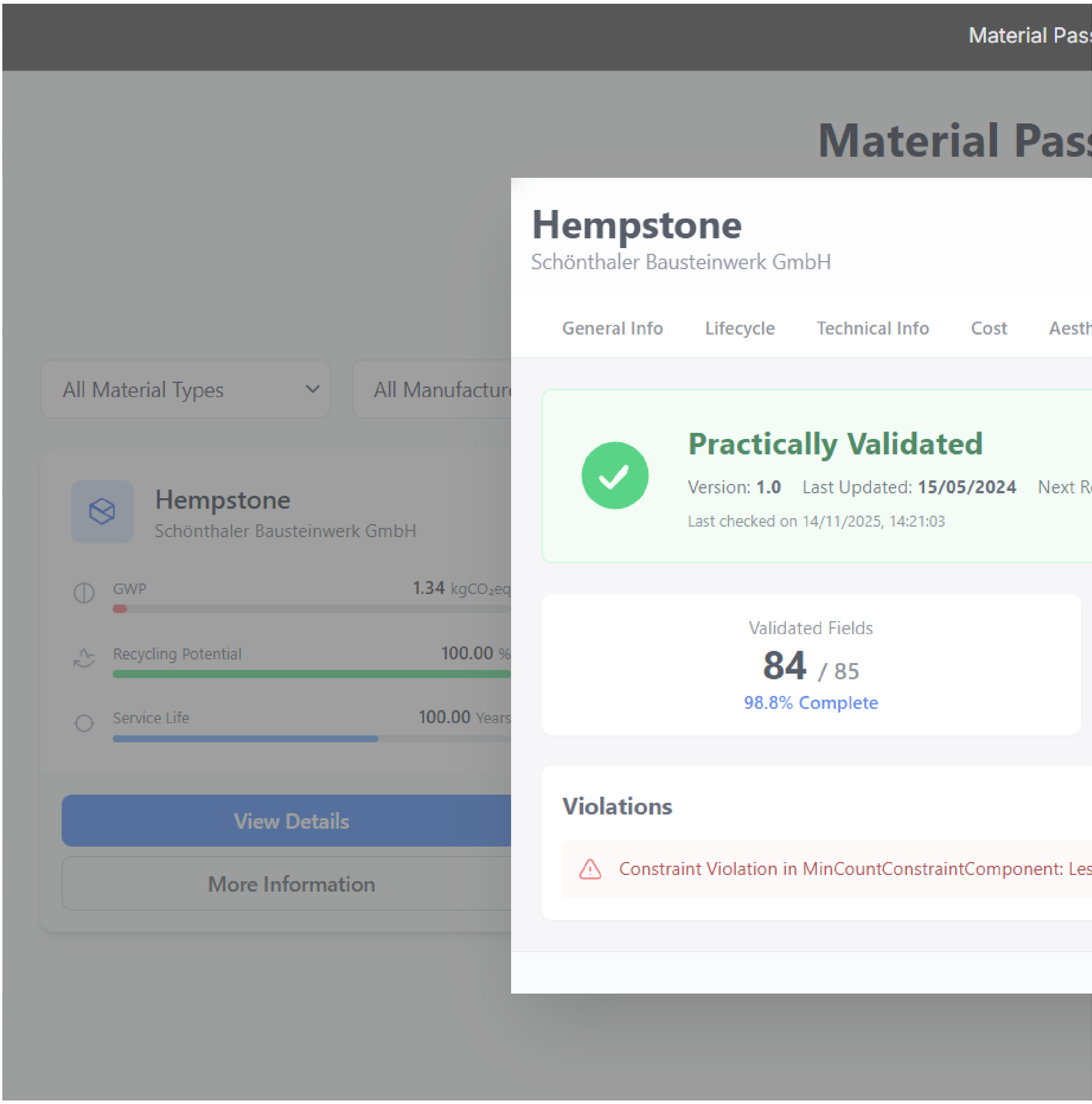
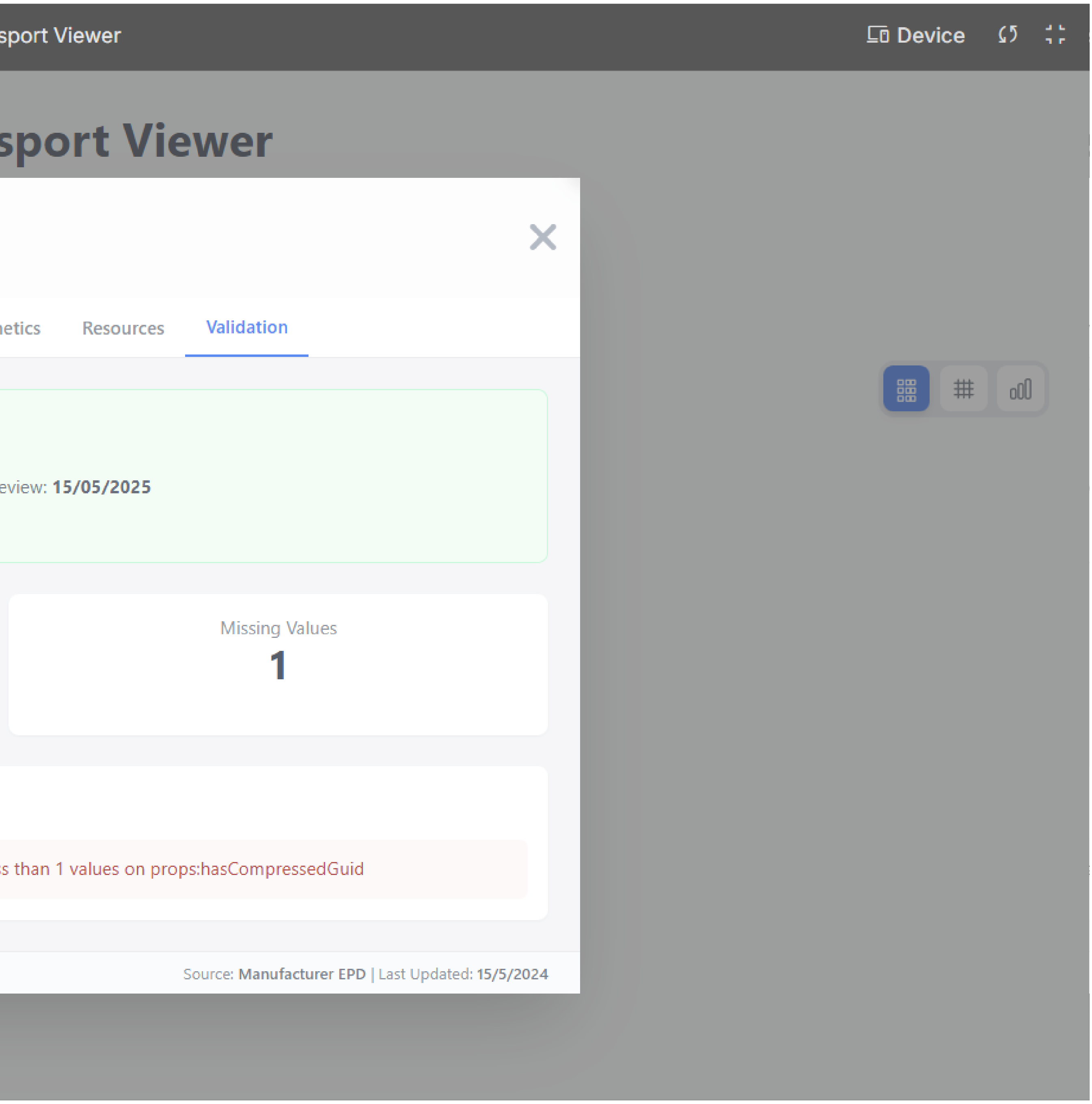


Figure 58. *Screen shot of Validation tab on hempcrete DPP.*
Note. Created by author with Google AI studio.


sport Viewer
Device
sport Viewer
etics
Resources
Validation
eview: 15/05/2025
Missing Values
1
s than 1 values on props:hasCompressedGuid
Source: Manufacturer EPD | Last Updated: 15/5/2024

EVALUATION RESULTS

The evaluation examined the Digital Product Passport for Hempcrete through qualitative and technical assessments. The qualitative analysis was carried out using a *persona*-based heuristic evaluation, where the previously defined *personas* were applied to assess usability, data clarity, and relevance. The technical analysis verified the DPP against interoperability, accessibility, and shareability criteria, supported by the Level of Development analysis and comparison with relevant standards. The structure of the DPP was not modified during this stage.

4.4.1 Qualitative validation

The qualitative validation applied a *persona*-based heuristic evaluation to assess the DPP for hempcrete. Heuristic evaluation is generally defined in usability research as a method in which evaluators use general principles, or heuristics, to identify possible problems in a system when direct user testing is not feasible. According to Friess (2025), heuristics act as established usability principles that help evaluators judge whether information is clear, consistent, and aligned with user needs.

Personas are hypothetical but specific representations of potential users that help evaluators focus on realistic goals, expectations, and constraints. Research has shown that combining personas with heuristic evaluation can lead evaluators to identify more complex, user-centred issues and use more user-focused reasoning in their assessments, even if the total number of findings remains similar to traditional heuristic evaluation (Friess, 2025).

The previously defined personas were applied to a set of selected heuristics, focusing on data clarity, relevance, consistency, and the potential usefulness of the DPP for circularity strategies. Each persona guided the evaluation from a professional perspective, ensuring that the assessment reflected the varied expectations of users who interact with bio-based materials and digital information workflows.

Heuristic	**Description**
1. Clarity of Information	Information in the DPP should be understandable. Terminology, units, and definitions should be clear and unambiguous.
2. Information Relevance	The parameters included should be meaningful for assessing the environmental, technical, and circular performance of hempcrete.
3. Consistency of Structure and Data	The DPP should maintain a coherent internal structure, with consistent data fields, naming conventions, and categorisation.
4. Accessibility of Key Information	Essential information (like composition, cost, performance indicators, sourcing, LCA values) should be easy to locate.
5. Completeness of Material Data	The DPP should provide sufficient technical and environmental information to support design, specification, and lifecycle-related decisions.
6. Transparency of Data Sources	Each parameter should clearly indicate its origin (manufacturer data, laboratory tests, literature), enabling users to assess data reliability and update needs.
7. Alignment with Circularity Requirements	The DPP should support circular workflows by including information on reuse, disassembly, biodegradation, repair options, and end-of-life strategies.
8. Compatibility with Digital Workflows	The DPP structure should support interoperability, enabling integration with BIM softwares.

Table 9. *Heuristics Used for the Qualitative Evaluation.*
Note. Created by author.

Automated Persona-Based Heuristic Evaluation

The automated persona-based heuristic evaluation provided a clear overview of how the DPP performs across data structure, information quality, and user-centred criteria. The results show that the DPP offers a strong technical basis, particularly in the organisation, completeness, and relevance of its material information. Both the dataset and the TTL files performed consistently well, which confirms that the information architecture is well structured and suitable for supporting lifecycle assessment, computational reuse, and circularity-focused workflows.

Persona-level performance followed a similar pattern. Technical and sustainability-oriented users reported higher satisfaction, which suggests that the DPP already supports roles that rely on detailed and structured information. The Design Architect persona obtained a comparatively lower score. This reflects the need for clearer access to frequently referenced parameters during early design stages, where navigation speed and information clarity are essential. The combined persona and component results confirm that most usability limitations relate to the visualization mock-up rather than the underlying dataset or semantic model.

Heuristic-level results highlight the strengths of the DPP. Completeness, relevance, consistency, and circularity alignment showed high compliance, demonstrating that the selected parameters, structural organisation, and lifecycle focus are appropriate for the intended use. These strengths indicate that the DPP is conceptually robust and already offers several of the informational capabilities needed for design and decision making.

The lowest scoring heuristic was transparency. This result requires contextual interpretation. The dataset includes source attribution and update information, and the visualization mock-up contains provenance elements. The automated evaluator could not detect these features because it analysed static screenshots rather than interactive components or embedded metadata. The transparency score therefore reflects the limitations of automated visual inspection rather than an absence of provenance in the DPP. Nonetheless, improving visibility and consistency of source information would still strengthen user trust.

Two additional areas require improvement. First, workflow compatibility. Several functions expected in digital design environments are not yet implemented, including file downloads and export options. Enhancing these elements would improve integration across BIM and assessment tools. Second, accessibility of key information. The lack of search functionality, glossary support, and simplified navigation affects the efficiency of information retrieval, particularly for design workflows.

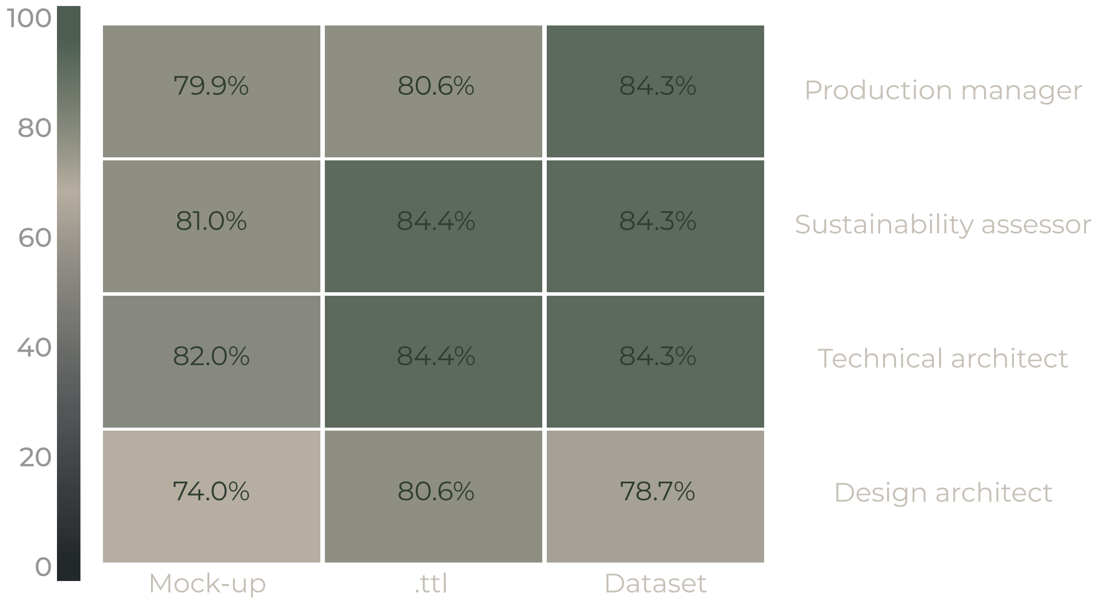


Figure 59. *Persona-component score matrix.*
Note. Created by author from python output.

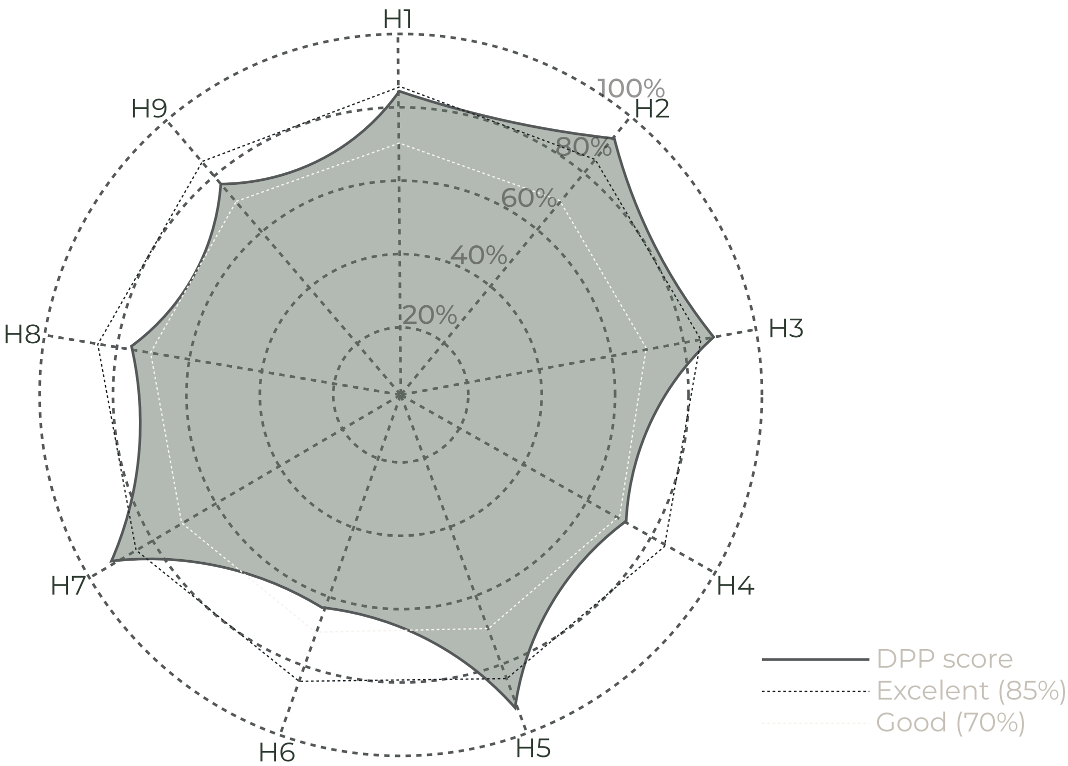


Figure 60. *Heuristic compliance radar chart.*
Note. Created by author from python output.

Overall, the results indicate that the DPP performs strongly as a structured and circularity-oriented information system. Although the automated evaluation cannot confirm the DPP's usefulness for real stakeholders, it provides valuable insight into its performance at this stage and identifies clear priorities for improvement

4.4.2 Technical validation

The technical evaluation examined the DPP through three steps. First, the exported IFC dataset was validated against the original data to detect information loss or restructuring, addressing data accuracy and shareability. Second, interoperability and accessibility were assessed by importing the IFC file into different viewers to evaluate consistency and data visibility. Third, the dataset was compared with relevant BIM and DPP standards to identify compliance and limitations. These steps provided the basis for defining the Level of Development (LOD) reached by the prototype and for identifying remaining gaps.

Dataset Validation

Dataset validation focused on interpreting the low match rate reported in the Excel comparison and understanding the causes of the detected mismatches. Although the automated comparison indicated that only a limited set of parameters matched directly, this did not reflect actual information loss. Most mismatches resulted from how parameters had been inserted and formatted inside the Revit model to comply with the API requirements. Once exported to IFC, Revit preserved this formatting, which often differed from the structure and numeric representation of the original dataset. As a result, values such as 12 in the original Excel appeared as 12.00 in the IFC-derived export. These formatting variations were expected and produced false mismatches during strict string-based comparison.

For this reason, the accuracy of the dataset was assessed through data-quality checks rather than through direct value equality. Data-type verification confirmed that numerical, string, and categorical parameters maintained appropriate formats. Range and format checks showed that values remained within expected limits for those parameters with clearly defined domains. Negative results in some checks were expected because certain parameters were intentionally left empty during insertion to confirm that the validation workflow could detect missing information. Additional negative range checks occurred in parameters without fixed numerical ranges or in complex string fields where valid ranges must be defined more precisely.

Consistency and uniqueness checks showed no contradictions or duplicated identifiers, presence checks behaved as expected given the intentional omissions, and referential-integrity verification confirmed that links between elements were preserved. When evaluated through these criteria, the transformed dataset demonstrated a high level of accuracy. The reported mismatches originated from predictable formatting behavior or intentional test conditions, not from information loss during the IFC export or Excel transformation.

The validation results also highlight the need for a more flexible data-checking approach in future DPP frameworks. Fixed string matching or rigid numerical thresholds are not suitable for BIM-based workflows, where formatting, precision, and unit expressions vary across platforms. Future frameworks should incorporate tolerance-based comparisons, adaptable range definitions, and validation rules that recognize expected behavior within BIM environments. This flexibility would improve the reliability of data verification and support more robust DPP implementations for bio-based construction materials.

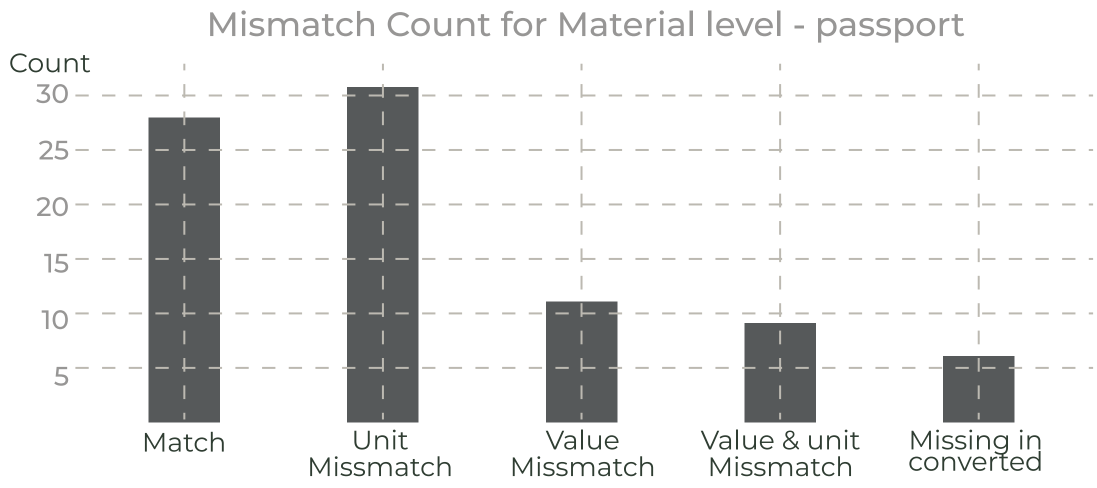


Figure 61. *Mismatch count for material-level passport from excel validation data-quality checks.*
Note. Created by author.

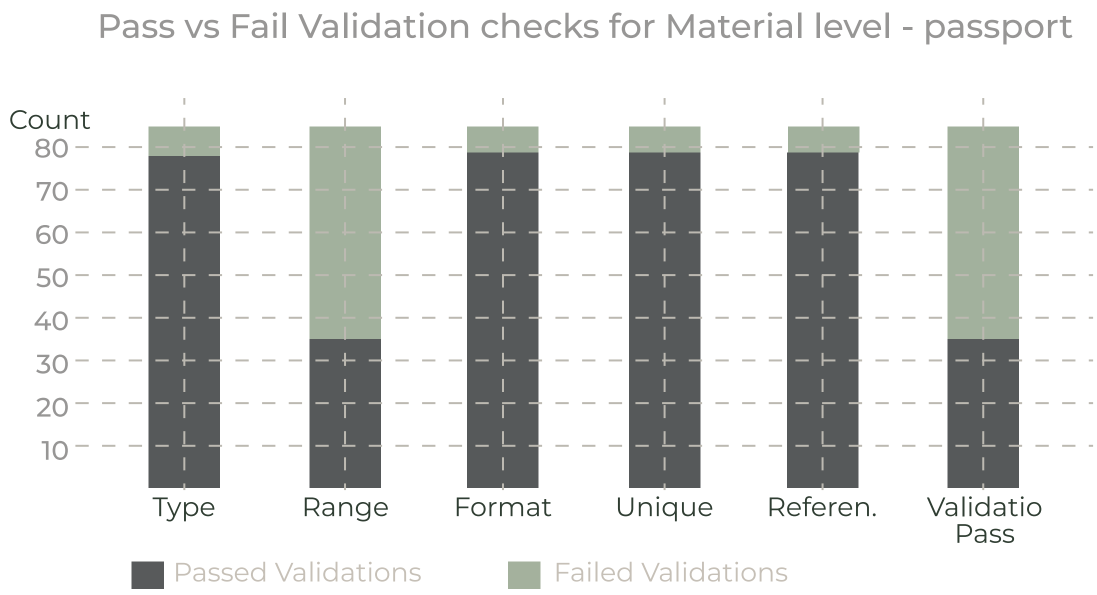


Figure 62. *Pass vs fail validation checks for material-level passport from excel validation data-quality checks.*
Note. Created by author.

Dataset Comp

Completeness: 32.9% (28

Yellow cells (Source) can be filled ma

Parameter	Base Value	Base Unit	Converted Value	Converted Unit	Value Match	Unit Match	Sta
DPP_MAT_Material	Infill masonry made of hemp stones		Hemp-Lime		NO	YES	Va Misn
DPP_MAT_Composition	Made from 20–55% hemp shives and 45–80% lime-based mineral binder, entirely free of cement and petrochemical additives		Made from 20–55% hemp shives and 45–80% lime-based mineral binder, entirely free of cement and petrochemical additives		YES	YES	Ma
DPP_AUT_TypeDimension	8x50x20	cm	8x50x20		YES	NO	Unit Mi
DPP_DIM_Height_mm	200	mm	200.0000000000008 2	mm	YES	YES	Ma
DPP_DIM_Width_mm	80	mm	499.9999999999961 3	mm	NO	YES	Va Misn
DPP_DIM_Length_mm	500	mm	80.00000000000001	mm	NO	YES	Va Misn
DPP_DIM_Volume_m3	0.008		0.008	m³	YES	NO	Unit Mi
DPP_DAT_DryDensity_kg m3	335	kg/m³	335.0		YES	NO	Unit Mi
DPP_DAT_EqDensity_kg m3	405	kg/m³	405.0		YES	NO	Unit Mi
DPP_DAT_Weight_kg	2.68	kg	2.67	kg	YES	YES	Ma
DPP_DAT_CompressiveSt renght_Mpa	0.5	MPa	0.5	MPa	YES	YES	Ma
DPP_DAT_ShearStrenght	0.12	MPa	0.12	MPa	YES	YES	Ma
DPP_DAT_VaporDiffμ_w et	3.8	μ	3.800000000000000 3		YES	NO	Unit Mi
DPP_DAT_VaporDiffμ_dr y	4.3	μ	4.3		YES	NO	Unit Mi
DPP_DAT_VaporAbsorpti on	19	d[g/m²v	19.0		YES	NO	Unit Mi
DPP_DAT_StandarCompli	Yes		True		YES	YES	Ma
DPP_CIR_Prefabrication	Yes		True		YES	YES	Ma
DPP_CIR_PrefabricationF actor	1	Score	1.0		YES	NO	Unit Mi
DPP_CIR_Deconstructabi lityScore	0.5	Score	0.5		YES	NO	Unit Mi
DPP_CIR_RecyclingPoten tial	100	%	100.0		YES	NO	Unit Mi

Figure 63. *Screen shot of Excel validation output.*
Note. Created by author.

parison Report

/85 parameters matched)

anually for data provenance tracking

tus	Validator	Date	Type OK	Range OK	Format OK	Unique OK	Referential OK	Validation Pass	Validation Issues
lue natch	CADENA	2025-11-18	YES	YES	YES	YES	YES	YES	
tch	CADENA	2025-11-18	YES	NO	YES	YES	YES	NO	Range
ismatch	CADENA	2025-11-18	YES	NO	YES	YES	YES	NO	Range
tch	CADENA	2025-11-18	YES	YES	YES	YES	YES	YES	
lue natch	CADENA	2025-11-18	YES	NO	YES	YES	YES	NO	Range
lue natch	CADENA	2025-11-18	YES	NO	YES	YES	YES	NO	Range
ismatch	CADENA	2025-11-18	YES	YES	YES	YES	YES	YES	
ismatch	CADENA	2025-11-18	YES	YES	YES	YES	YES	YES	
ismatch	CADENA	2025-11-18	YES	YES	YES	YES	YES	YES	
tch	CADENA	2025-11-18	YES	NO	YES	YES	YES	NO	Range
tch	CADENA	2025-11-18	YES	YES	YES	YES	YES	YES	
tch	CADENA	2025-11-18	YES	YES	YES	YES	YES	YES	
ismatch	CADENA	2025-11-18	YES	NO	YES	YES	YES	NO	Range
ismatch	CADENA	2025-11-18	YES	NO	YES	YES	YES	NO	Range
ismatch	CADENA	2025-11-18	YES	NO	YES	YES	YES	NO	Range
tch	CADENA	2025-11-18	YES	NO	YES	YES	YES	NO	Range
tch	CADENA	2025-11-18	YES	NO	YES	YES	YES	NO	Range
ismatch	CADENA	2025-11-18	YES	NO	YES	YES	YES	NO	Range
ismatch	CADENA	2025-11-18	YES	YES	YES	YES	YES	YES	
ismatch	CADENA	2025-11-18	YES	NO	YES	YES	YES	NO	Range

Interoperability Testing

TheThe exported IFC files were tested in Autodesk Viewer and Navisworks to verify that the DPP attributes remained readable and consistent across platforms. All custom parameters appeared in both viewers; however, some were grouped inconsistently, revealing limitations in how Autodesk Revit maps parameters during IFC export. To address this, a cleaning process was applied in the IFC-to-LBD conversion to streamline property sets and improve semantic clarity.

A comparison of the material-level and element-level DPP exports demonstrated a clear link between modelling scale and data structure. In Autodesk Viewer, the wall assembly (element file) and individual blocks (material file) each retained their own DPP attributes. In Navisworks, the layered detail was more visible but proved excessive for this example. The result emphasizes the need to tailor parameter mapping to scale in order to avoid data duplication or unnecessary complexity.

This showed that the element-level DPP is more suitable for BIM integration because it aligns with modelling logic, supports aggregation of performance indicators and costs, and connects directly to construction elements used in coordination workflows. In contrast, the material-level DPP proved more effective for semantic applications, since it produced cleaner, lighter data structures and reduced redundancy during IFC-to-LBD conversion. This distinction suggests that Digital Product Passports benefit from being deployed at different scales depending on their intended purpose, with element-level passports enabling project-level BIM operations and material-level passports supporting database performance and structured information management.

These findings inform future DPP frameworks by showing that the exported information must align with object scale and intended use. Guidance should define when attributes belong at the material-type level and when they are assigned to elements or assemblies. Establishing this hierarchy, along with export templates that filter redundancy and separate identity data, environmental indicators, and product-level characteristics, will support interoperable, lightweight, and scalable DPP workflows.

Category	Material-Level DPP	Element-Level DPP
Visibility	Directly selectable; always displayed	Not selectable as whole; only visible through components
Hierarchy	Clear at material scale	Missing; assembly not represented as single node
Information Structure	Complete but scattered across categories	Repetition of material data; no unique element attributes
Consistency	Stable across viewers	Stable across viewers
Navigation	Manageable; categories and tabs help	Fragmented; repeated per brick
Redundancy	Moderate	High, repeated in every component
Granularity	Appropriate for material identity	Too granular for small assemblies
Export Behavior	Custom Psets visible and preserved	Element-mapped Psets not exposed in viewers
Usefulness	Good for semantic work, LBD, and databases	Better for BIM workflows, aggregation, and costing
IFC–Revit Mapping	Works but disorganized (dual categories)	Mapping propagates through components but not at assembly level
Viewer Interpretation	Similar and predictable	Both platforms collapse assembly into parts
Impact on RDF	Lightweight and efficient	Repeated data increases RDF size
Suitable Phase	Early design, comparison, semantic analysis, database optimisation	Detailed design, BIM coordination, performance aggregation
Framework Requirement	Basic filtering, category cleanup	Strong hierarchical rules, selective export per scale

Table 10. *Material-level IFC va Element-level IFC performance comparison across evaluation categories.*
Note. Created by author.

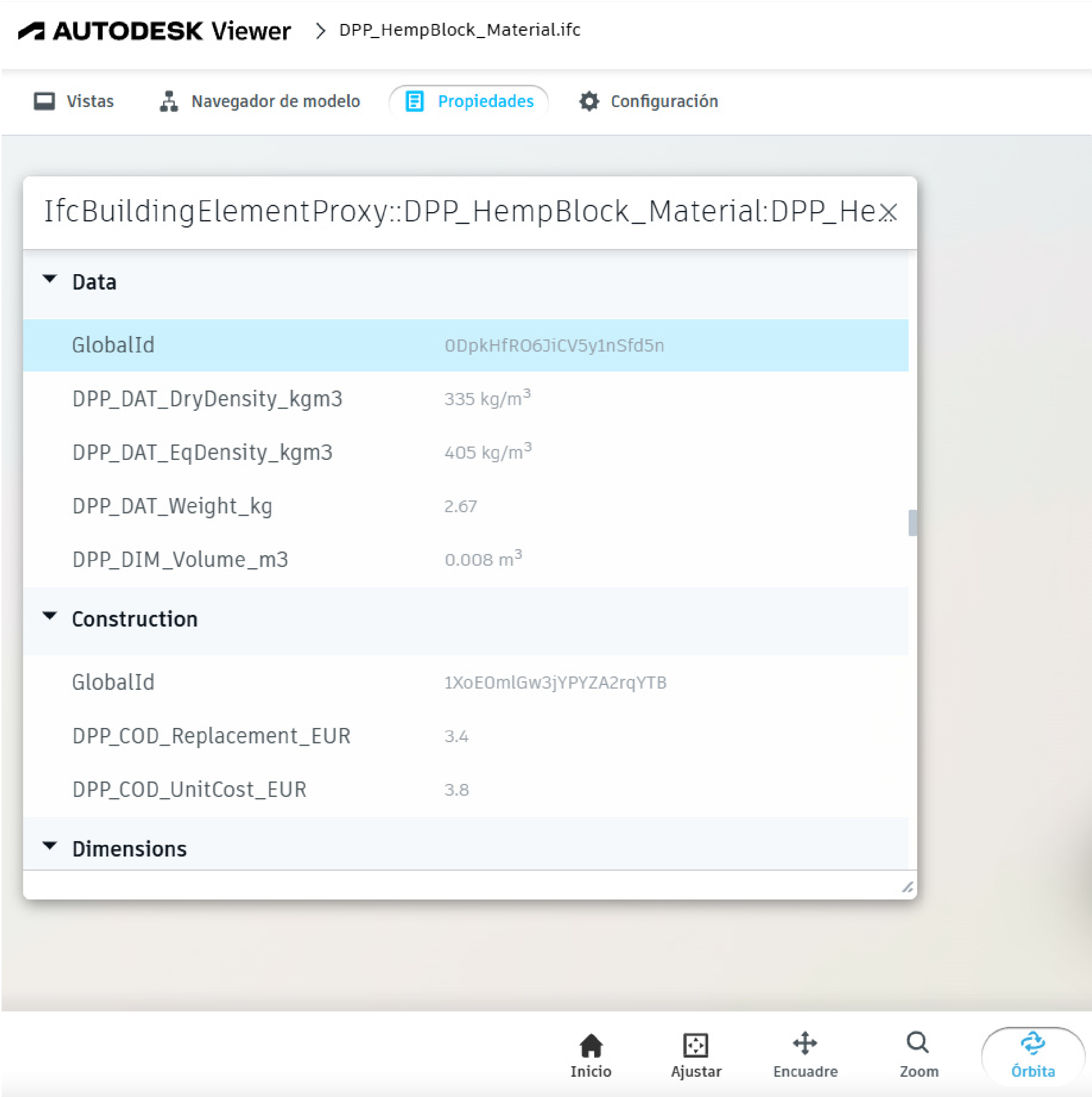
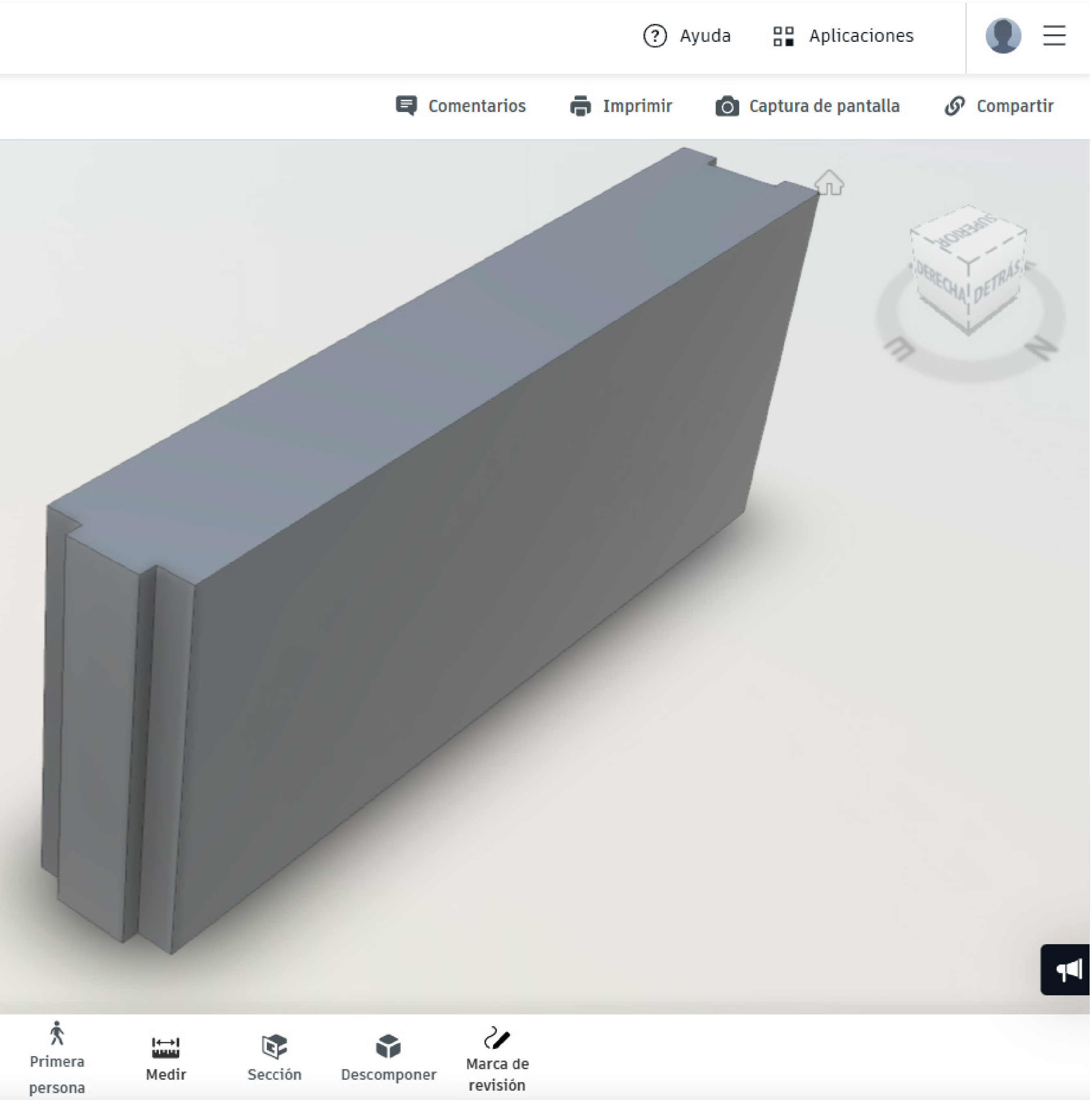


Figure 64. *Screen shot of Material-level IFC in Autodesk Viewer.*
Note. Created by author.


Ayuda
Aplicaciones
Comentarios
Imprimir
Captura de pantalla
Compartir
Primera persona
Medir
Sección
Descomponer
Marca de revisión

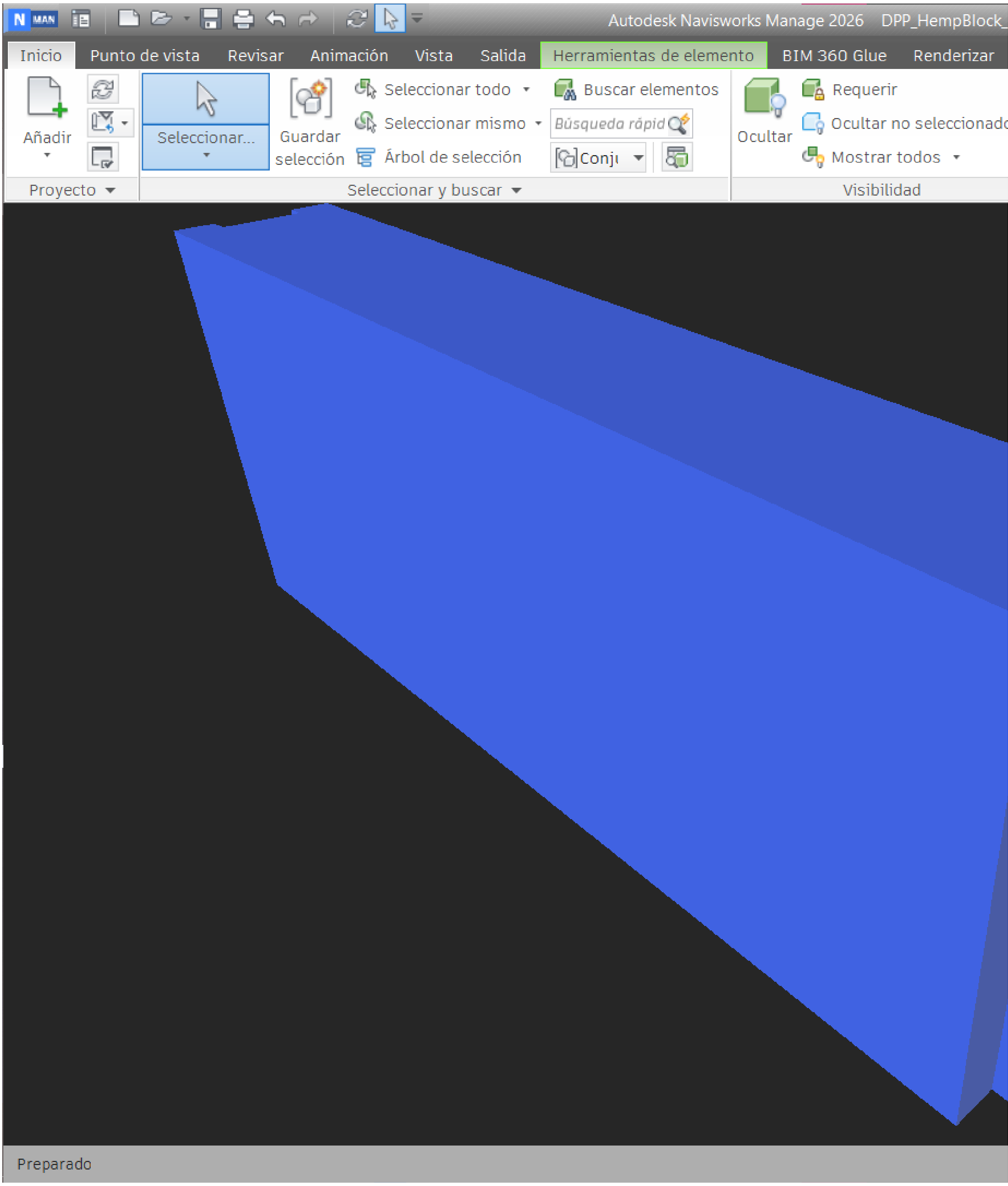
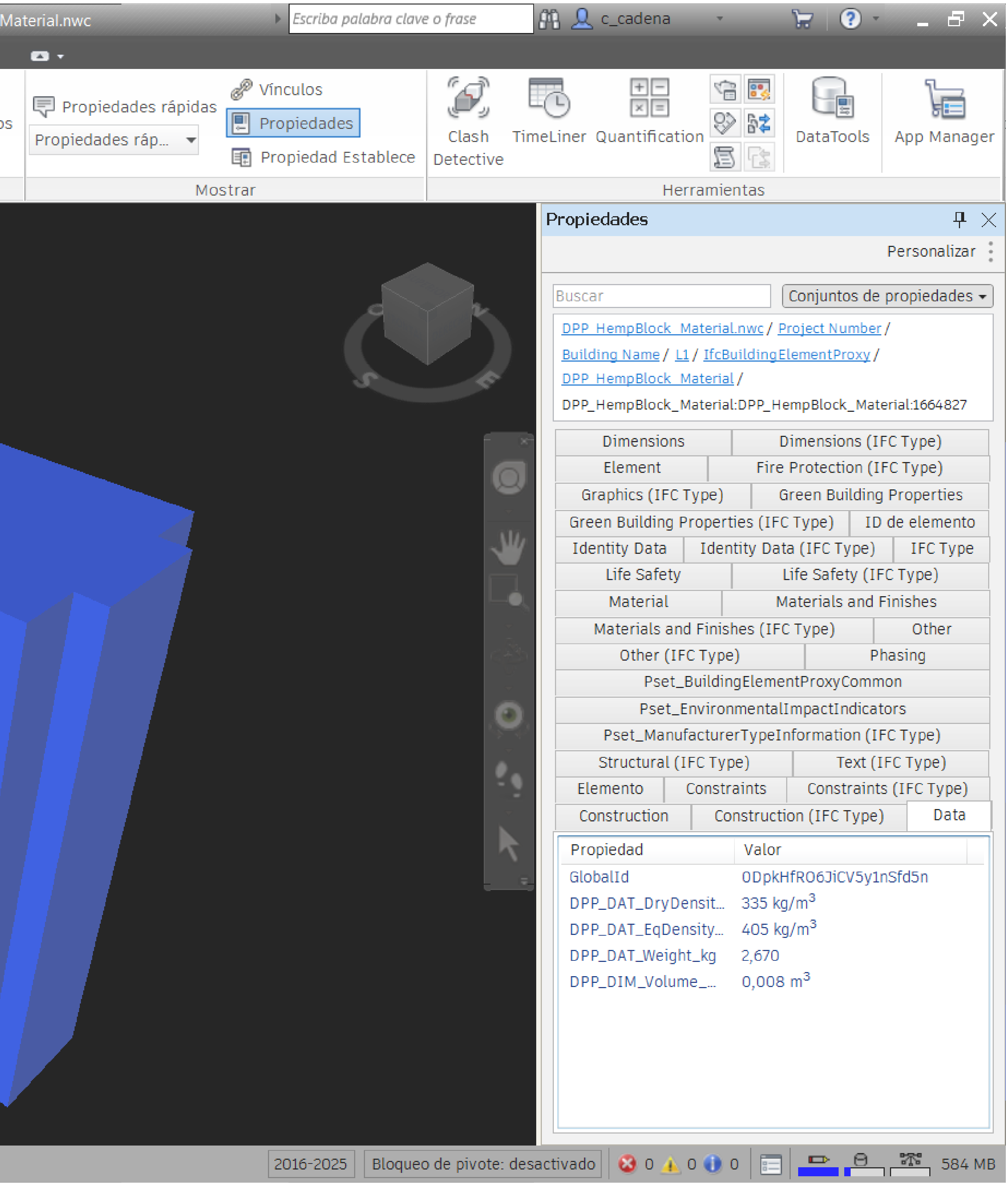


Figure 65. *Screen shot of Material-level IFC in Naviswork.*
Note. Created by author.


Material.nwc
Escriba palabra clave o frase
c_cadena
Propiedades rápidas
Vínculos
Propiedades
Propiedades ráp...
Propiedad Establece
Mostrar
Clash Detective
TimeLiner
Quantification
DataTools
App Manager
Herramientas
Propiedades
Personalizar
Buscar
Conjuntos de propiedades
DPP_HempBlock_Material.nwc / Project Number / Building Name / L1 / IfcBuildingElementProxy / DPP_HempBlock_Material /
DPP_HempBlock_Material:DPP_HempBlock_Material:1664827
Dimensions
Dimensions (IFC Type)
Element
Fire Protection (IFC Type)
Graphics (IFC Type)
Green Building Properties
Green Building Properties (IFC Type)
ID de elemento
Identity Data
Identity Data (IFC Type)
IFC Type
Life Safety
Life Safety (IFC Type)
Material
Materials and Finishes
Materials and Finishes (IFC Type)
Other
Other (IFC Type)
Phasing
Pset_BuildingElementProxyCommon
Pset_EnvironmentalImpactIndicators
Pset_ManufacturerTypeInformation (IFC Type)
Structural (IFC Type)
Text (IFC Type)
Elemento
Constraints
Constraints (IFC Type)
Construction
Construction (IFC Type)
Data
Propiedad
Valor
GlobalId
0DpkHfRO6JiCV5y1nSfd5n
DPP_DAT_DryDensit...
335 kg/m³
DPP_DAT_EqDensity...
405 kg/m³
DPP_DAT_Weight_kg
2,670
DPP_DIM_Volume_...
0,008 m³
2016-2025
Bloqueo de pivote: desactivado
584 MB

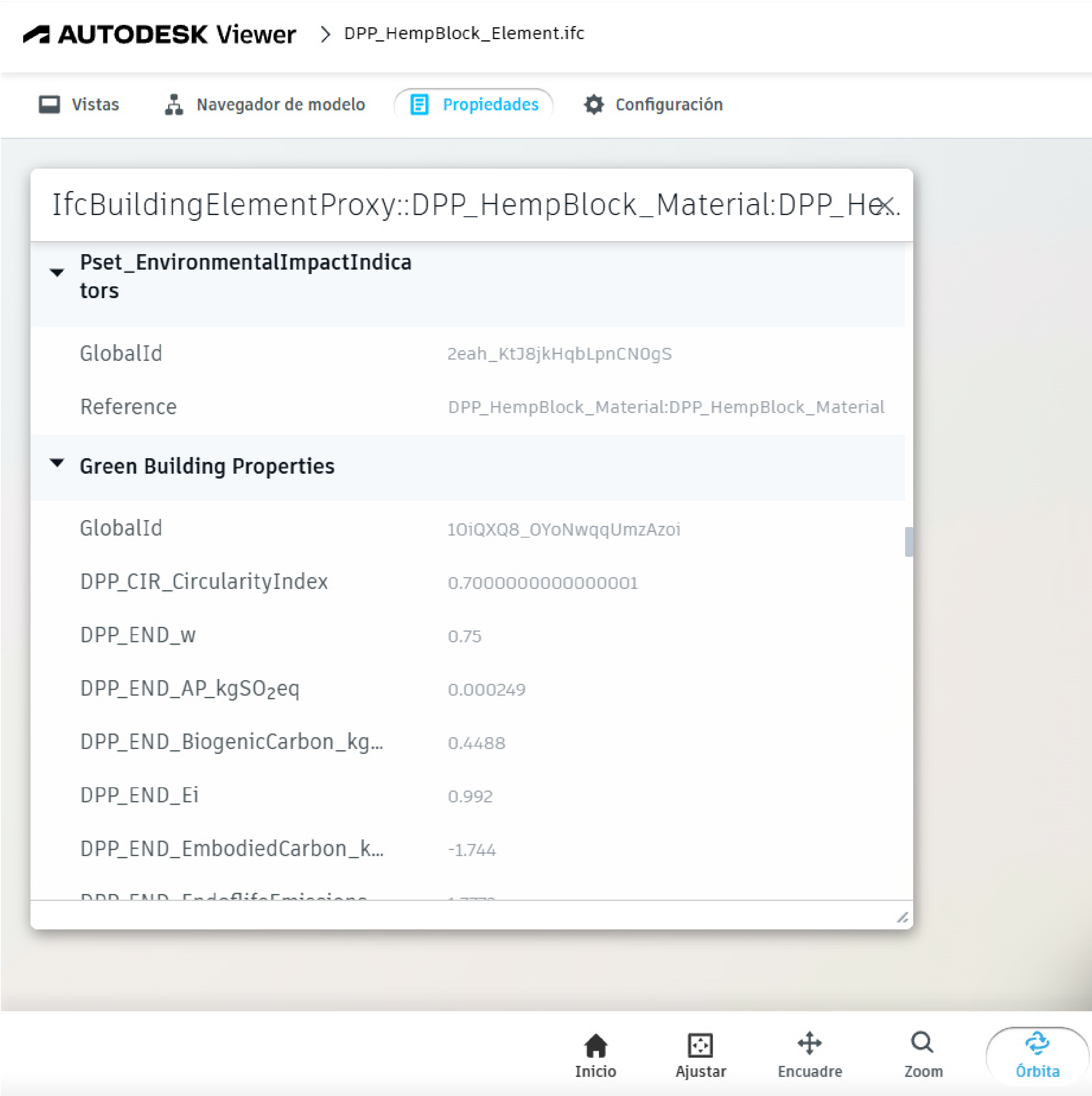
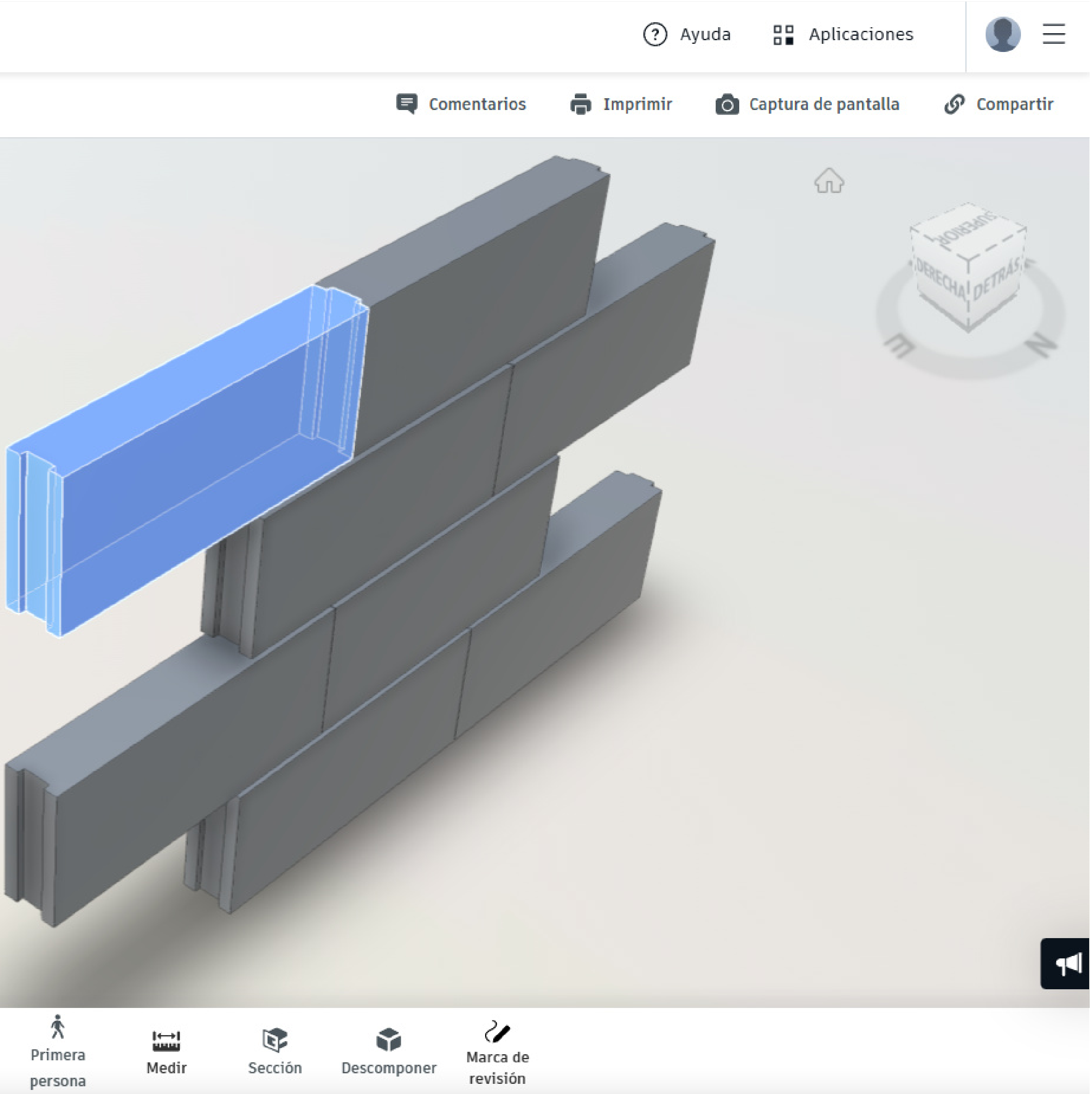


Figure 66. *Screen shot of Element-level IFC in Autodesk Viewer.*
Note. Created by author.


Ayuda
Aplicaciones
Comentarios
Imprimir
Captura de pantalla
Compartir
SUPERIOR
DERECHA
DETRÁS
E
N
Primera persona
Medir
Sección
Descomponer
Marca de revisión

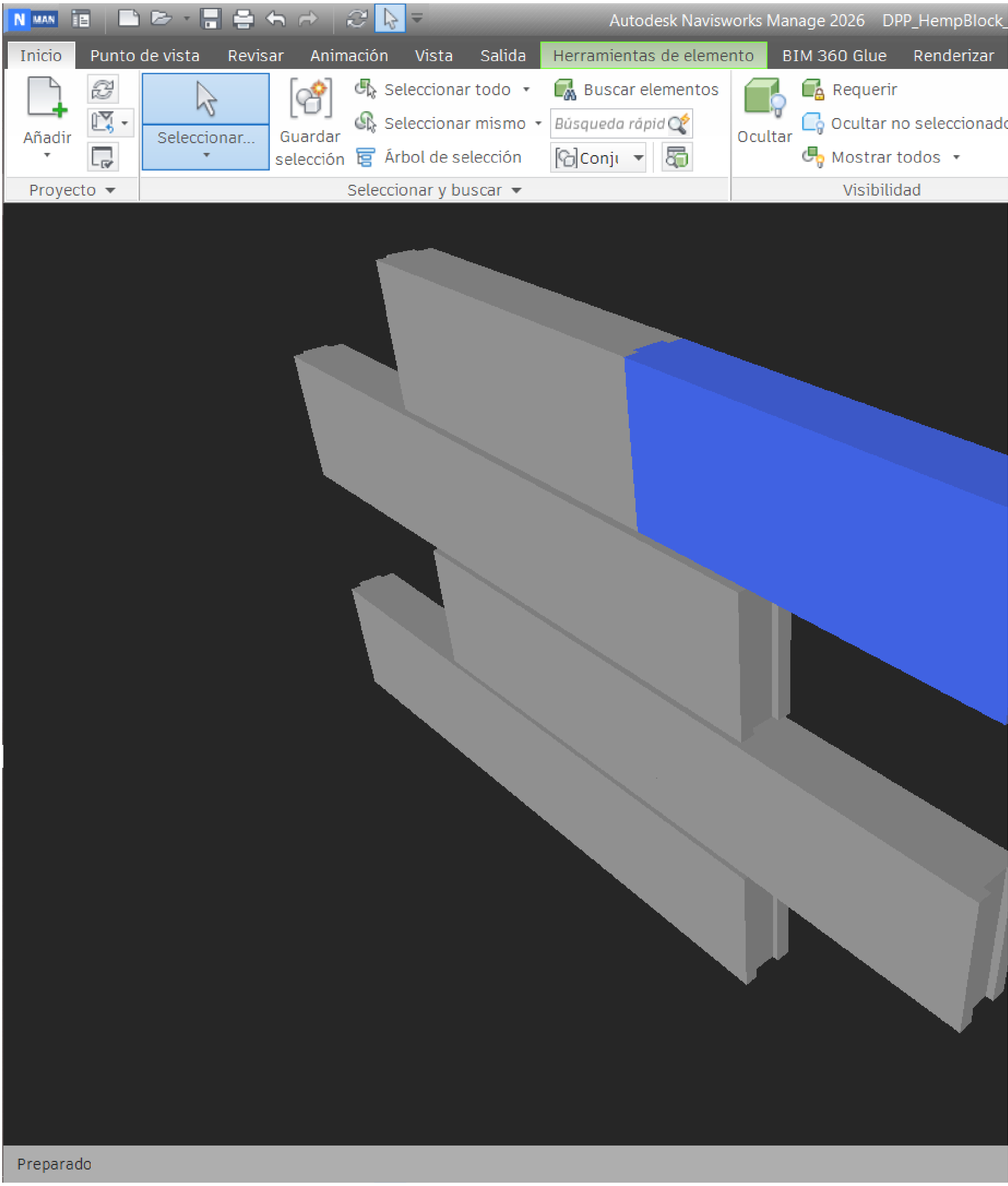
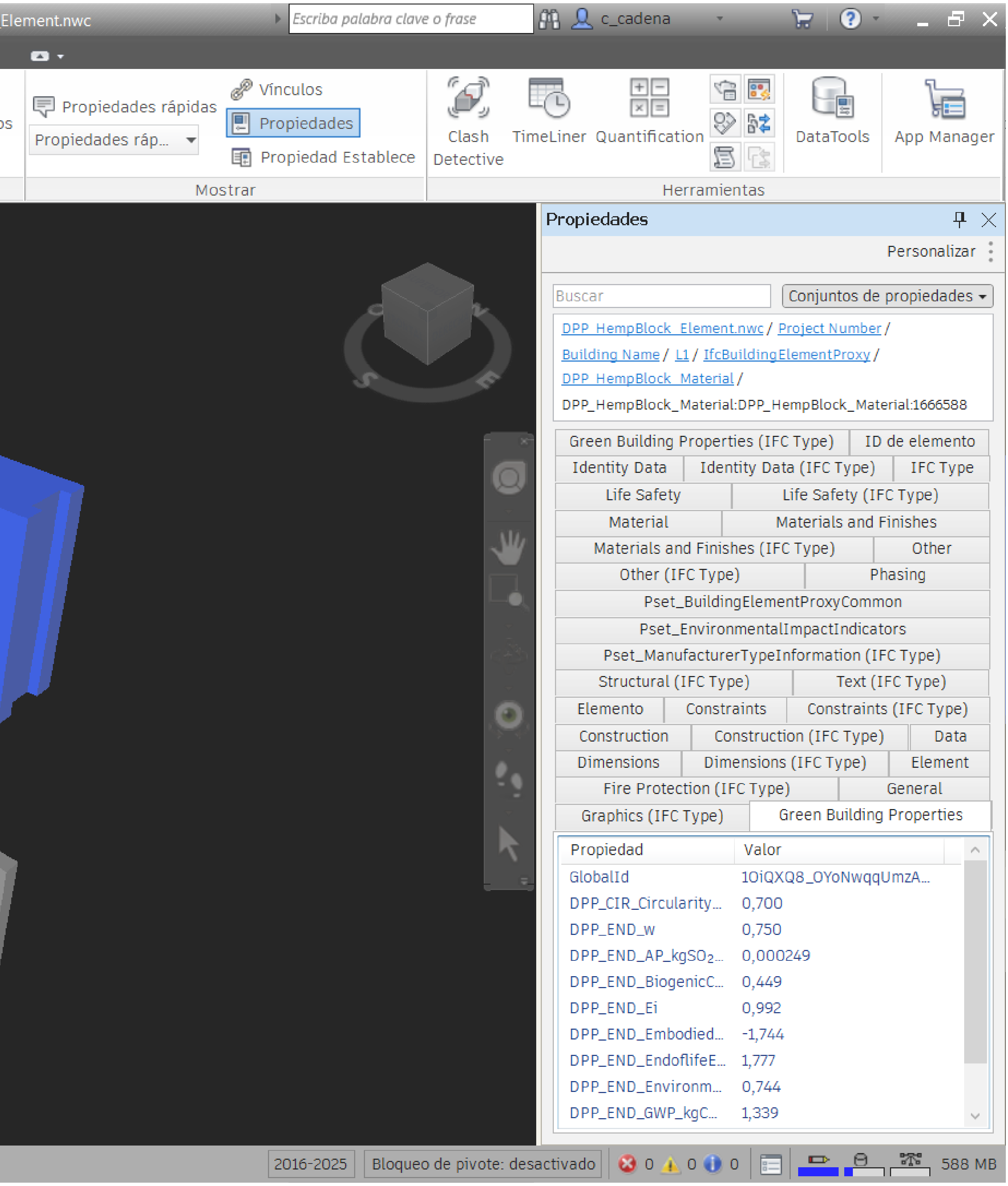


Figure 67. *Screen shot of Element-level IFC in Naviswork.*
Note. Created by author.


Element.nwc
Escriba palabra clave o frase
c_cadena
Propiedades rápidas
Vínculos
Propiedades
Propiedades ráp...
Propiedad Establece
Mostrar
Clash Detective
TimeLiner
Quantification
DataTools
App Manager
Herramientas
Propiedades
Personalizar
Buscar
Conjuntos de propiedades
DPP_HempBlock_Element.nwc / Project Number /
Building Name / L1 / IfcBuildingElementProxy /
DPP_HempBlock_Material /
DPP_HempBlock_Material:DPP_HempBlock_Material:1666588
Green Building Properties (IFC Type)
ID de elemento
Identity Data
Identity Data (IFC Type)
IFC Type
Life Safety
Life Safety (IFC Type)
Material
Materials and Finishes
Materials and Finishes (IFC Type)
Other
Other (IFC Type)
Phasing
Pset_BuildingElementProxyCommon
Pset_EnvironmentalImpactIndicators
Pset_ManufacturerTypeInformation (IFC Type)
Structural (IFC Type)
Text (IFC Type)
Elemento
Constraints
Constraints (IFC Type)
Construction
Construction (IFC Type)
Data
Dimensions
Dimensions (IFC Type)
Element
Fire Protection (IFC Type)
General
Graphics (IFC Type)
Green Building Properties
Propiedad
Valor
GlobalId
1OiQXQ8_OYoNwqqUmzA...
DPP_CIR_Circularity...
0,700
DPP_END_w
0,750
DPP_END_AP_kgSO2...
0,000249
DPP_END_BiogenicC...
0,449
DPP_END_Ei
0,992
DPP_END_Embodied...
-1,744
DPP_END_EndoflifeE...
1,777
DPP_END_Environm...
0,744
DPP_END_GWP_kgC...
1,339
2016-2025
Bloqueo de pivote: desactivado
0
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0
588 MB

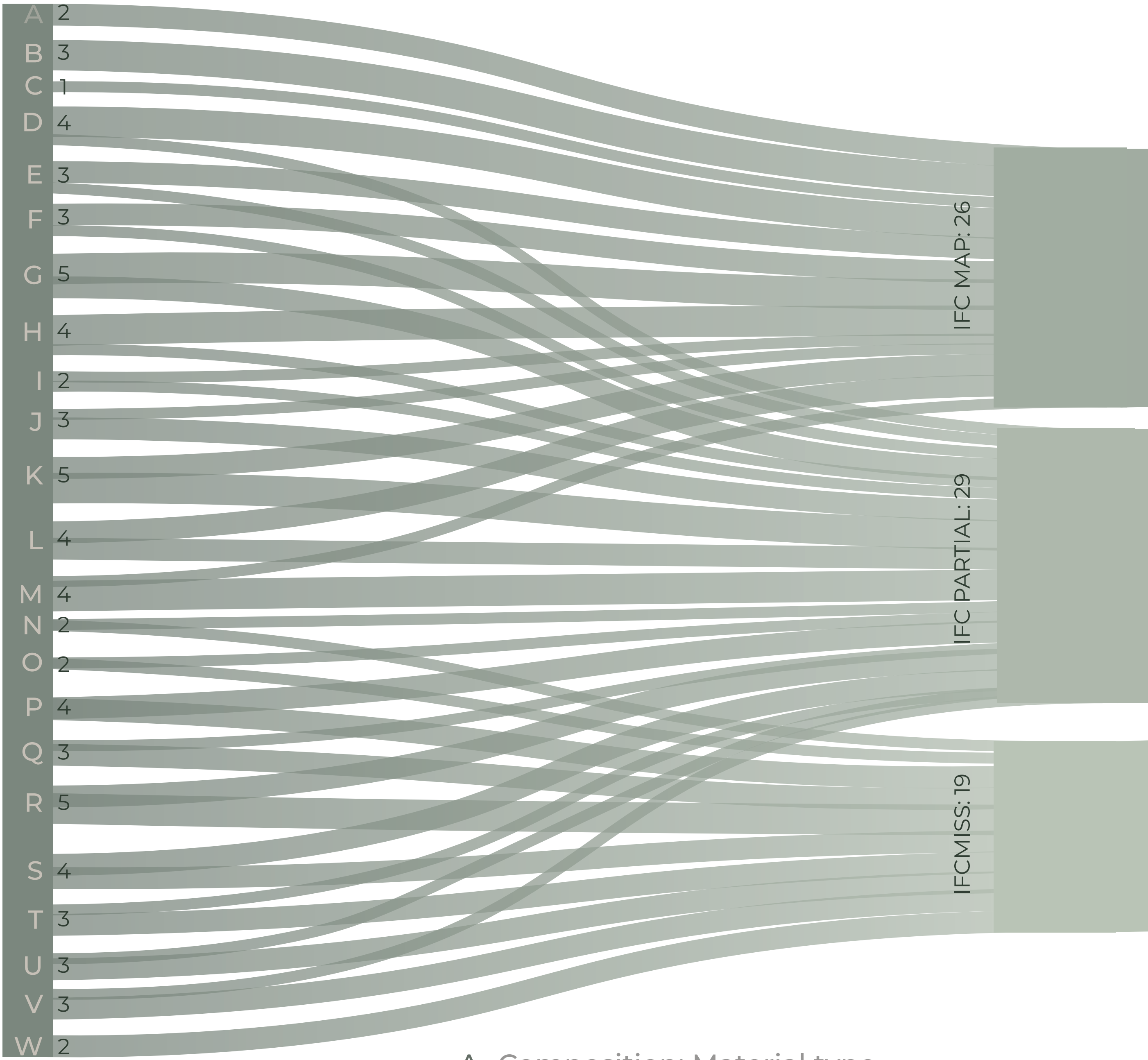
Standards Comparison

The verification of the dataset against ISO 16739 confirmed that the DPP was structurally compatible with the IFC EXPRESS schema. The custom property sets were correctly attached to IfcBuildingElementProxy and IfcBuildingElementProxyType, and all attributes used valid IFC datatypes. The naming structure of the Psets followed IFC conventions and ensured syntactic stability, which is essential because the EXPRESS schema enforces strict requirements on how data must be structured within an IFC file. This rigid structure guarantees consistency across BIM environments but limits how easily new or non-standardised attributes can be introduced or adapted.

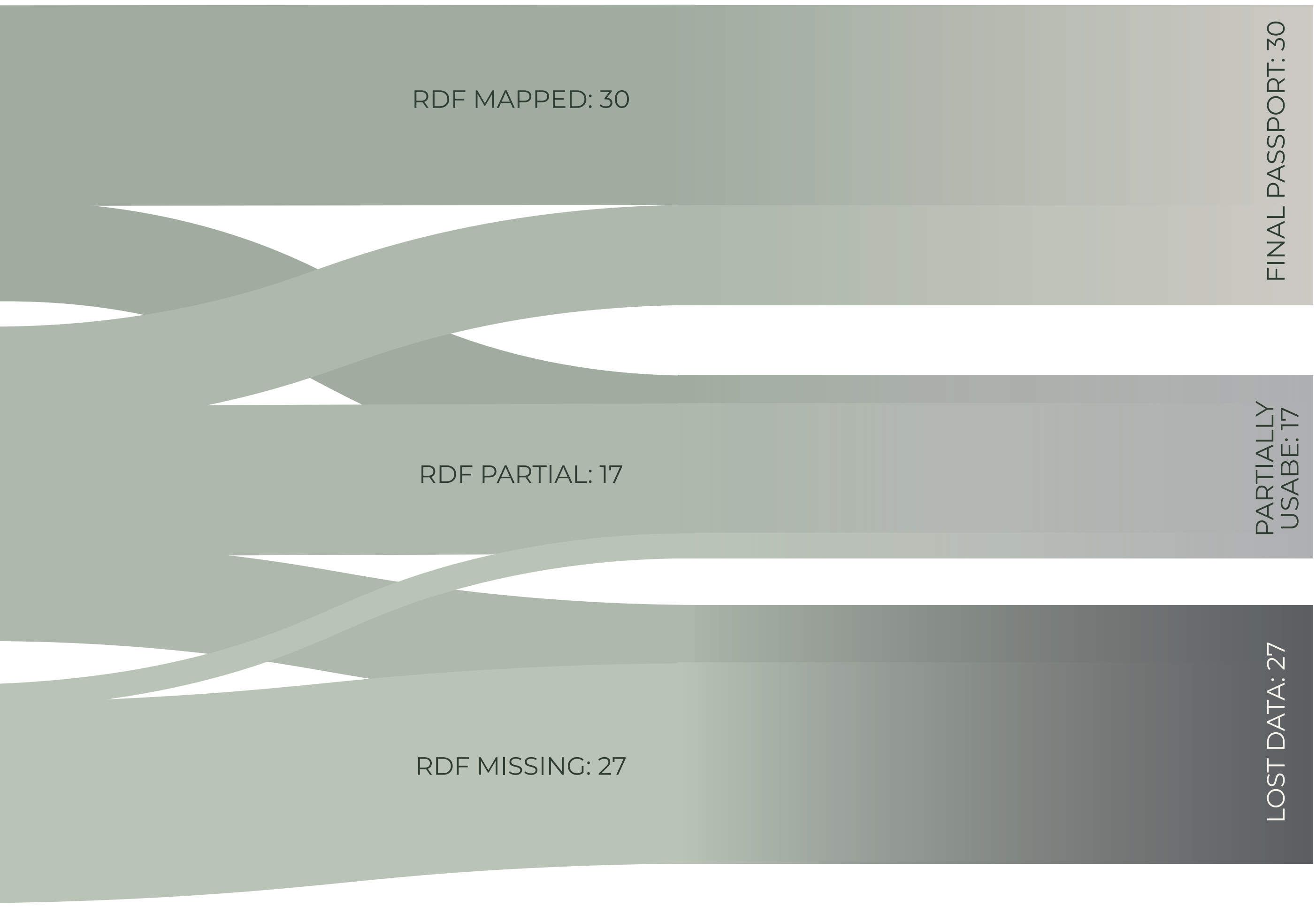
The conversion of the IFC file into RDF highlighted how the dataset behaved under the more flexible semantic OWL environment. The mapped TTL file showed that many environmental, safety, and mechanical attributes were successfully translated into semantic triples, with correct datatype assignments and meaningful ontology predicates. However, several performance parameters, cost fields, sourcing attributes, and circularity indicators did not appear in the RDF, which indicated incomplete IFC population, exporter limitations, or unsupported data mappings. The OWL representation also introduced an additional layer of abstraction by replacing IFC-specific Pset names with general ontology predicates, which improved semantic clarity but decreased one-to-one traceability. This contrast between IFC and OWL reflects a fundamental challenge: IFC requires precise, predefined structures, while OWL enables open-ended semantic models. For a Digital Product Passport, these two logics must be reconciled, since IFC offers stability and interoperability in BIM workflows, and OWL provides the adaptability needed for future circularity and linked-data applications.

The comparison with the Waterman material passport framework showed strong conceptual alignment in identity, composition, mechanical behaviour, carbon indicators, and circularity information. The DPP also included extended architectural and comfort-related attributes that go beyond Waterman's minimum requirements. However, several Waterman-defined fields related to certification structures, supply-chain traceability, and percentage-based circularity metrics were not visible in the exported RDF, confirming that the semantic output did not yet capture the full DPP scope. This reinforces the need for refinement in both IFC population and semantic export rules.

In summary, the dataset demonstrated correct implementation within the rigid IFC schema and functional semantic behaviour within the flexible OWL environment, but only partial coverage of the full DPP attributes in the final exported TTL. This gap illustrates a broader issue for future DPP frameworks: they must operate across two fundamentally different representational systems. IFC provides the required standardisation for industry adoption, while OWL provides the flexibility needed for interoperability, machine reasoning, and evolving sustainability metrics. A future framework must therefore develop clear rules and mappings that translate stable IFC structures into semantically rich OWL representations without data loss, ensuring that passports remain robust, complete, and adaptable as circularity regulations and data requirements continue to expand.



A Composition: Material type
B Dimensions: Height/Width/Length
C Dimensions: Volume
D Identity: Basic info
E Performance: Mechanical
F Performance: Weight & density
G Safety: Fire classification
H Circularity: Reusability
I Composition: Components
J Identity: Traceability
K Safety: Hazard/ toxicity



L Circularity: Recyclability
M Circularity: Disassembly
N Composition: Details
O Thermal: Conductivity
P Thermal: Moisture performance
Q Identity: Supply chain
R Safety: Compliance
S Cost: Maintenance/ Replacement
T Circularity: EoL strategies
U Cost: Unit Cost
V Cost: LCC indicators
W Thermal: Heat capacity

Figure 68. *Sankey diagram of flow of DPP attributes through IFC and RDF/OWL mappings.*
Note. Created by author with SankeyMATIC.com

Final LOD Assessment

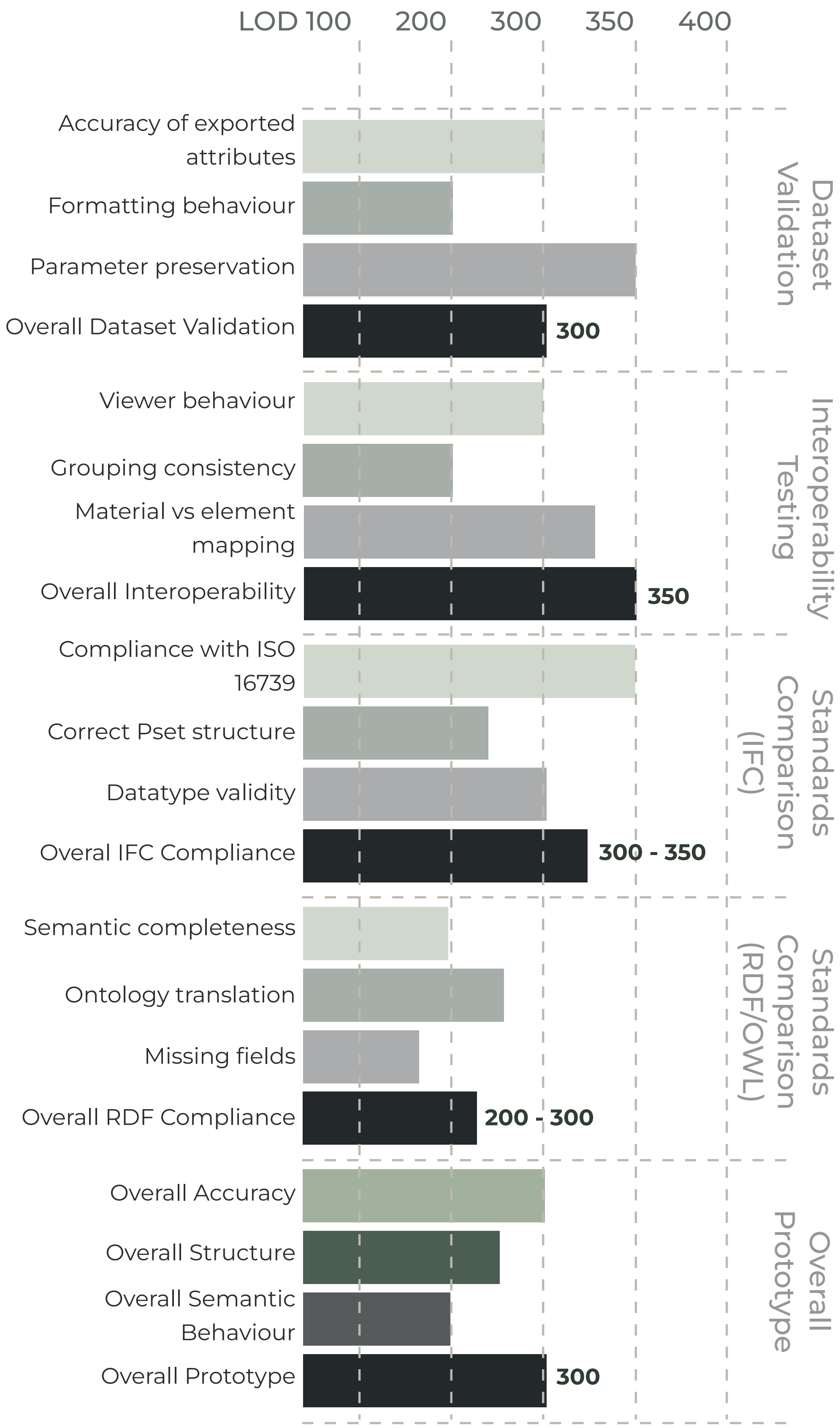


Figure 69. *LOD criteria assesment.*
Note. Created by author.

LOD Level	Meaning for This Thesis
LOD 100	Information is conceptual or missing
LOD 200	Information exists but is incomplete, inconsistently structured, or unstable across platforms
LOD 300	Information is coordinated, specific, and reliable for analysis and validatio
LOD 350	Information is consistently structured across systems with stable cross-platform behaviour
LOD 400 - 500	Fabrication or installation-level detail (outside the thesis scope)

Table 11. *LOD level defnitions.*

Note. Created by author.

Criteria	LOD	Reason
Accuracy of exported attributes	300	Data is correct and preserved; mismatches result only from formatting.
Formatting behaviour	200	Formatting varies across platforms; information present but unstable
Parameter preservation	350	Most parameters exported, though grouping changes between environments
Viewer behaviour	300	Attributes visible and readable across viewers
Grouping consistency	200	Parameter organisation remains between platforms
Material vs element mapping	300 - 350	Mapping is preserved but varies in layering depth
Compliance with ISO 16739	350	Schema-compliant Psets with correct attachment and datatype use
Correct Pset structure	200 -300	Psets exist and follow IFC rules, but internal structure is inconsistent
Datatype validity	300	Datatypes are valid and preserved but not consistently enforced semantically
Semantic completeness	200	Only part of the DPP dataset is captured in RDF
Ontology translation	200 - 300	Valid triples where present, but mapping logic incomplete
Missing fields	100 -200	Several attributes do not appear due to exporter or mapping limitations
Overall accuracy	300	Data is accurate and somewhat preserved across workflows
Overall structure	200 -300	IFC structure is usntableand, followed by semantic layers
Overall semantic behaviour	200	RDF export reduces completeness
Overall prototype	**300**	Suitable for analysis and validation; not fully stable in semantic form

Table 12. *LOD criteria and reasoning.*

Note. Created by author.

The DPP prototype reached LOD 300 across dataset accuracy, interoperability, and standards compliance. This level indicates that the model contains coordinated and reliable information suitable for analysis, verification, and early decision-making. The information is correct, comprehensive, and element-specific, although still shaped by modelling decisions and exporter behaviour. The dataset supports coordination within BIM workflows and provides consistent inputs for LCA procedures and DPP structuring, but it does not reach the completeness or stability required for construction-level coordination, fabrication, or automated processes that depend on full semantic interoperability. While the IFC export achieved a high level of structural reliability, the semantic RDF version captured only part of the intended DPP attributes. This confirms that translation rules between IFC and OWL environments remain incomplete and that additional mapping structures are needed to maintain attribute coverage.

For the purposes of the thesis, LOD 300 positions the prototype as a functional proof of concept rather than a finalised implementation. This level is appropriate because the objective was to test how a DPP can be embedded into a BIM environment, exported through IFC, validated, and converted into a semantic structure. The prototype allows an examination of how data behaves for a bio-based material such as Hempcrete and shows where information remains stable and where gaps appear in cross-format translations. It functions as an analytical tool that demonstrates the opportunities and limitations of current workflows for DPP development.

The results indicate several requirements for future DPP frameworks. First, consistent mapping rules between IFC and OWL are needed to avoid information loss during semantic export. This includes coherent vocabulary alignment, stable datatype translation, and predefined templates that preserve the full DPP scope. Second, data verification methods must shift away from string-precise comparisons toward flexible validation rules that incorporate numeric tolerances and adaptable ranges, reflecting the variability typical of BIM environments. Third, DPP assignment should be scale-dependent, with clear guidance on whether attributes belong to a material type, a building element, or an assembly. Fourth, export structures must remain lightweight and standardised, with predefined IFC property sets that avoid redundancy and include semantic equivalents. Finally, complete semantic interoperability requires structures capable of representing environmental, sourcing, certification, circularity, and versioning information without reducing completeness or traceability.

This overall assessment shows that the prototype meets the required level for research purposes while also revealing the technical adjustments that future industry frameworks must address to enable consistent, complete, and machine-readable DPPs across BIM and linked-data environments..

CIRCULAR DESIGN AND POLICY INTEGRATION

4.5.1 Material reuse scenarios

Circularity is often framed by manufacturers as deconstructability, meaning that components should be removable at the end of life. This view focuses on the object itself and overlooks the wider system required for circular flows. For bio-based materials such as Hempcrete, circularity depends not only on technical removability but also on traceability systems that indicate where elements are located, in what quantity, and in what condition. This information is necessary for buy-back schemes and reintegration loops, which are currently limited. Hempcrete is typically understood as a permanent infill material, not as a component intended for relocation. Increasing circularity therefore requires configuring Hempcrete as an element that can be reused in its assembled form. The DPP supports this shift by defining the data needed to characterise each element and document its installation context.

The comparison between the NBS module, which uses hemp infill within a reversible timber cassette, and the Schönthaler system, where Hempcrete forms a monolithic block, illustrates how construction logic determines reuse potential. Only the NBS case enables component-level disassembly, while the Sonthaler blocks cannot be removed without damage once installed.

Taking NBS as an example, a more viable circular strategy to reuse Hempcrete is on complete wall elements rather than individual blocks. Hempcrete blocks perform as continuous layer within timber, steel, or concrete frames, and its thermal, acoustic, and fire characteristics depend on maintaining that continuity. Removing discrete blocks would compromise performance and create thermal bridges or air leaks. Reversible connections placed at the wall–structure boundary allow full Hempcrete wall sections, including plaster layers to be also detached and reused as a whole. This approach preserves the integrity of the mortar-bonded blocks while introducing reversibility at the element scale.

Such connections can be achieved through continuous perimeter rails or angle brackets fixed to timber or steel frames, which can be unbolted during deconstruction so the entire wall can be lifted out intact. Alternatively, the wall can rest on a steel shoe or track anchored to a concrete slab, with concealed screws or plates securing the top edge to create a lift-off mechanism. These strategies provide structural stability while remaining fully reversible.

This element-level approach mantains the highest possible value and aligns with circularity principles. It offers a clear unit for DPP integration. As demonstrated in the proof of concept, DPP data could be captured at the material level (individual Hempcrete blocks) and, with better mapping structures, the element level (the assembled wall panel), supporting traceability, deconstruction planning, and future reintegration.

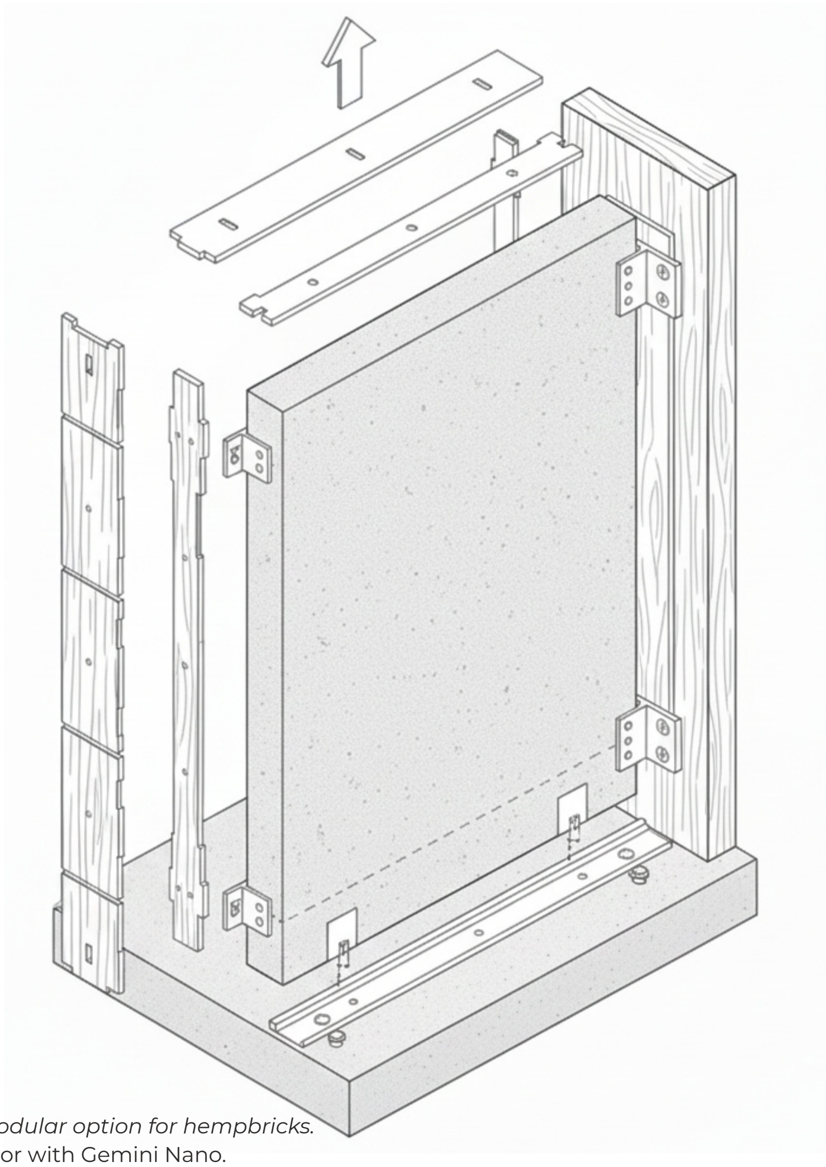


Figure 70. *Circular modular option for hempbricks.*
Note. Created by author with Gemini Nano.

4.5.2 Circularity score indicators

The DPP records both quantitative and qualitative circularity indicators. Quantitative values, such as Recycling Potential (100%), Deconstructability Score (0.5), Recovery Score (0.5), and Disassembly Potential (3), provide measurable information on the material's end-of-life pathways. Qualitative fields, including Reusability, Disassembly Instructions, Secondary Use, and End-of-Life Recommendations, describe conditions that cannot be expressed numerically but remain essential for interpreting circular performance. Together, these indicators reveal clear tendencies: while the material can be recycled efficiently, its current assembly logic limits reuse and restricts deconstructability to destructive processes such as crushing and sieving. The DPP therefore does not generate a single circularity score but instead presents a profile that users interpret according to project-specific priorities.

However, these indicators also expose limitations stemming from the absence of standardized methods for evaluating the circularity of bio-based materials. Reusability is treated as a binary field even though it is highly dependent on design decisions at the building-element level. Similarly, the meaning of a deconstructability or disassembly score is not harmonized across frameworks, making the values indicative rather than definitive. Despite these constraints, the DPP remains a valuable tool for highlighting where design changes can produce meaningful improvements in performance.

Introducing element-level circular design changes this profile. If Hempcrete wall panels are connected to the structural frame through reversible mechanical fixings, the entire panel can be removed and reused intact. This increases reusability and deconstructability and raises the overall circularity of the element, while recycling becomes a secondary rather than primary pathway. The resulting circularity profile shifts from a focus on material circularity to component circularity, where value is preserved at a higher level through the retention and redeployment of complete Hempcrete wall elements. This transition demonstrates how the DPP can support design decisions that extend material lifespan, reduce waste, and enable higher-value reuse pathways.

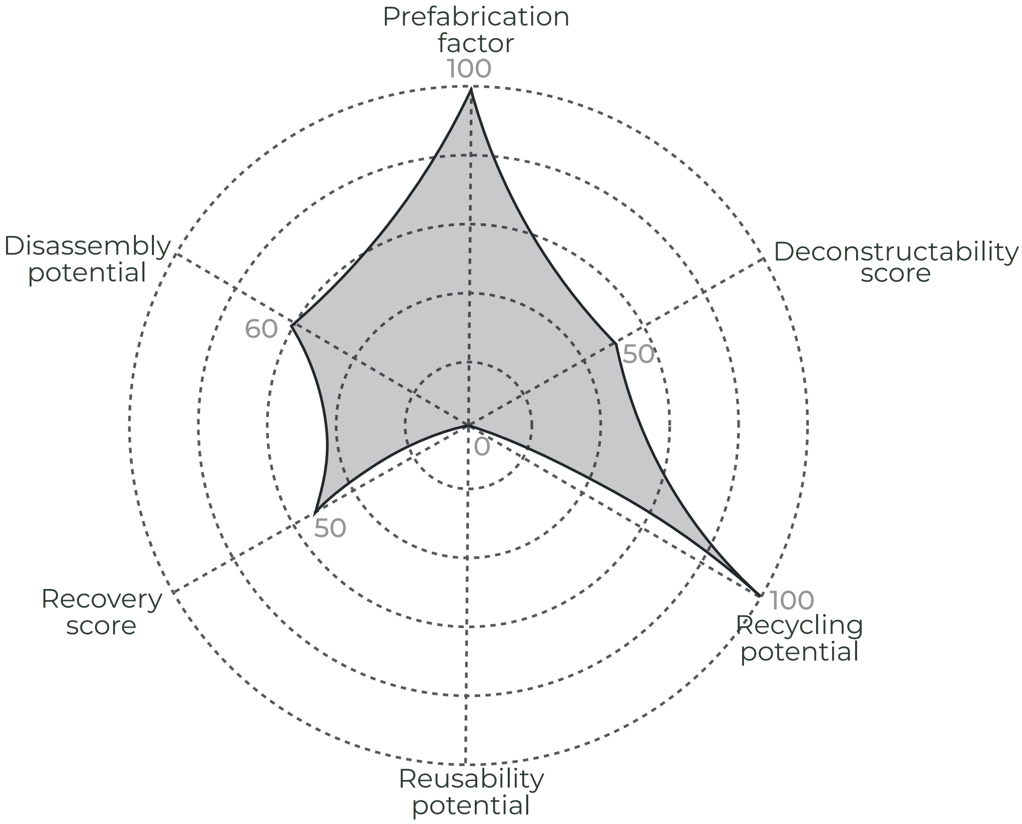


Figure 71. *Circularity profile of actual hanfstein.*
Note. Created by author.

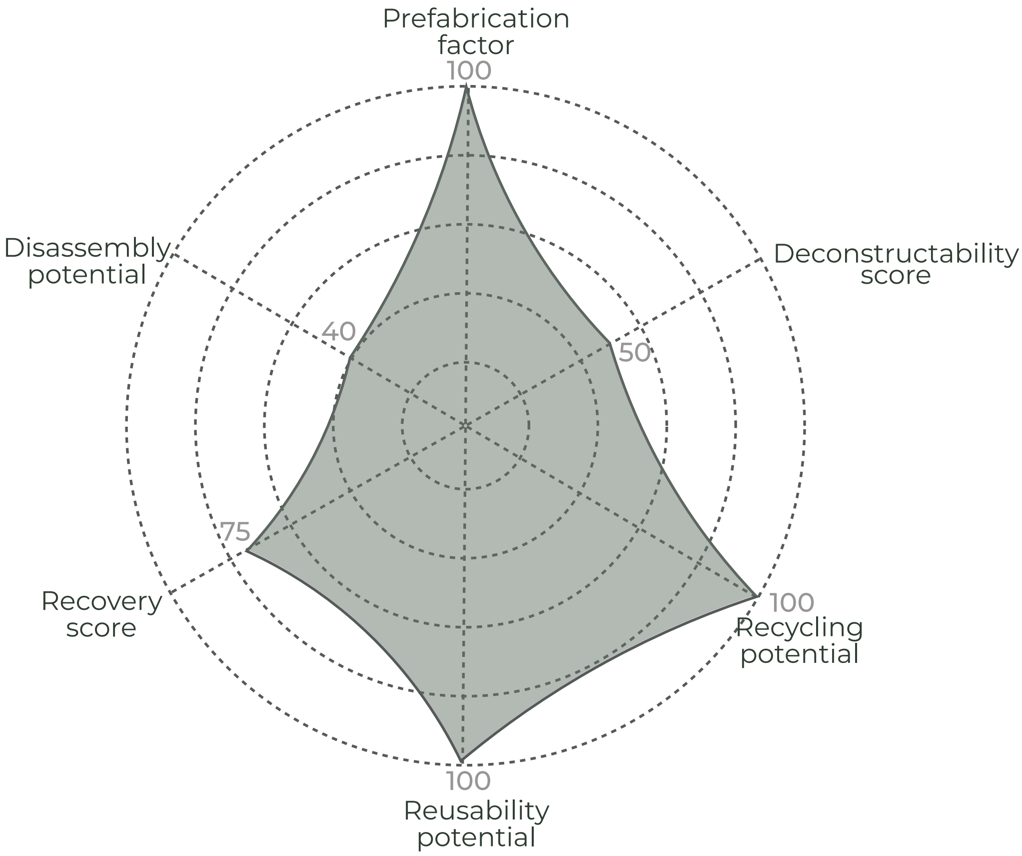


Figure 72. *Circularity profile of modular hanfstein.*
Note. Created by author.

4.5.3 Mapping to EU frameworks

Within the ESPR, circularity is framed around products that remain within the technical cycle, where durability, reusability, reparability, and long performance lifespans are central. The introduction of the Digital Product Passport (DPP) reinforces this model by establishing a digital identity for products, components, and materials. The DPP will store information on technical performance, material origins, repair activities, recycling capabilities, and lifecycle environmental impacts, and will support automated compliance checks and more informed decisions across supply chains. The ESPR also introduces new rules addressing the destruction of unsold products and strengthens Green Public Procurement by requiring public authorities to prioritise products that achieve the highest levels of sustainability and circularity.

However, this policy architecture reveals a structural gap when applied to bio-based construction materials. Materials such as Hempcrete belong to the biological cycle, where circularity typically involves degradation rather than multiple technical reuse loops. Although Hempcrete can offer long-term performance in buildings, its conventional end-of-life pathways involve crushing or composting, meaning that value is preserved only at the material level rather than at the component level. As a result, despite their low environmental impacts, bio-based materials are disadvantaged by a circularity framework that inherently values stability, technical lifespan, and multi-cycle reuse. The ESPR's focus on reusability and reparability, which aligns poorly with assemblies that require destructive processes for reintegration.

The DPP can partially mitigate this gap by documenting the conditions under which bio-based materials may achieve higher-value circular pathways. In this thesis, the DPP is applied at both the material and element levels, which makes it possible to record not only the properties of Hempcrete blocks but also the characteristics of complete wall panels, including connection types, installation context, and disassembly strategies. This aligns with the ESPR's emphasis on transparency and enables users to avoid premature disposal by identifying reuse opportunities before biological or downcycled routes are chosen. Nevertheless, bio-based materials remain in a grey zone: they can deliver substantial environmental benefits and long service life but cannot fully satisfy the technical-cycle expectations embedded in current EU circularity policy without design modifications.

A further limitation is that bio-based composites are not circular without external energy inputs. Their production often requires energy, and several end-of-life pathways also depend on energy-intensive handling, processing, or biodegradation processes that ultimately release the stored CO_2 back into the atmosphere. This contradicts the assumption, implicit in many circular economy models, that biological loops function naturally and without significant resource use. In practice, biological-cycle circularity in construction relies on logistical and energetic infrastructures similar to those required for technical materials. This reduces the intrinsic sustainability of the biological loop and reinforces the need to preserve the material at the highest possible level before biological pathways are engaged.

4.5.4 Discussion of scalability

The methodology developed in this thesis has not yet been tested at higher levels of complexity, but its structure suggests that it is logically scalable across the hierarchy of construction levels. Because the workflow operates successfully at the material and wall-element scales, and these correspond to the lowest tiers, it is reasonable to assume that similar procedures could be extended to components, rooms, whole buildings, and project-level systems through aggregation. Industrial deployment also remains to be demonstrated, yet the method is simple, well-structured, and organised around parametrised steps that could support future

Figure 73. Schönthaler Hanfstein sizes.
Note. Provided directly by Schönthaler.

automation if data availability and industry workflows continue to develop. The DPP structure reinforces this scalability: it follows requirements for material-level and element-level information rather than Hempcrete-specific fields, meaning that the same data categories can be populated for other bio-based materials with similar hybrid biological–technical cycles. Only material-specific parameters change. This makes the DPP adaptable to a wide range of bio-based composites and suitable for future frameworks that integrate multiple materials within one interoperable circularity system.

CHAPTER 5

CONCLUSION

This thesis investigated the role of a Digital Product Passport (DPP) in strengthening the circularity and wider adoption of bio-based construction materials by developing and testing its integration into Building Information Modeling (BIM) frameworks. The conclusions presented here synthesize the findings, reflect on their implications for practice, and identify remaining gaps for future research.

The results showed that with a DPP, structured, accessible, and verifiable material information can be integrated into a BIM environment. This integration has ensured that circularity-related data can remain connected to the material's digital representation. The study demonstrated that there is clear potential to support future frameworks that improve traceability, increase information reliability, and facilitate circular decision-making in construction.

The objective of developing a BIM-based DPP proof of concept for hempcrete was achieved. The thesis defined data requirements, mapped material properties, created a structured workflow for DPP integration, and demonstrated successful export and semantic representation through IFC and RDF. Validation identified the points where information transfer breaks down and where current standards are insufficient. The outcome contributes a practical and methodological foundation that can inform future DPP frameworks that actively support the adoption of bio-based materials in the construction industry.

The DPP ensured transparency by uniting material information that is normally scattered across certificates, reports, and external databases. The ability to access clear data during early design stages can improve choices related to adaptability, disassembly, and long-term maintenance. Designers can identify material properties, trace sourcing information, and evaluate environmental impacts, which supports more informed decision-making and allows materials to be compared in order to select the most suitable option. This increased visibility aligns with existing research on the role of information in circular design and the adoption of bio-based materials (Dams et al., 2023). The case study demonstrated that traceable material information in the form of structured digital formats represents one of the key enabling conditions for design approaches that require accuracy and traceability.

This transparency is, however, reliant on the digital environment that hosts the DPP, which in this case is provided by BIM. BIM enables the DPP to operate as more than a static document because its structured environment centralizes information and links it to specific building components. This connection supports traceability across the life cycle, since each object in BIM is associated with a unique identifier that keeps its properties consistently linked to the element it represents. Strengthening transparency in this way helps address several barriers identified by Dams et al. (2023), who emphasize that clearer information is essential to overcome limited familiarity, uncertainty about performance, and challenges in the specification and certification of bio-based materials. The findings of this thesis show that consistent identification, verifiable data, and traceability contribute to this required level of transparency, enabling more informed assessment and demonstrating material suitability without relying on assumptions.

On one hand, several external drivers can incentivize industry adoption. Carbon accounting obligations require firms to quantify and report their emissions, which increases the need for structured and verifiable material data. Although these obligations differ from carbon-credit schemes, the two are connected: companies that cannot meet reduction targets often purchase carbon credits, and these transactions frequently finance circular-economy initiatives. Emerging material banks and reuse platforms can be supported through such mechanisms, since accurate information on material composition and traceability is essential for verifying the environmental benefits expected by carbon-credit buyers.

ESPR requirements also push manufacturers and designers toward transparency, product traceability, and structured data reporting, all of which align directly with the functions of a DPP. Public and private procurement increasingly prioritize materials with clear environmental documentation and traceable supply chains, creating competitive advantages for products supported by standardized digital data. These trends collectively reward practices based on verified and interoperable information and create favorable conditions for integrating DPPs into design and construction workflows, while also underscoring the need for bio-based materials to meet these emerging data standards.

On the other hand, the adoption of DPPs in real projects depends not only on technical feasibility but also on organizational readiness and broader industry conditions. While the integration of DPPs into practice is achievable, it requires changes in how firms manage data and structure their BIM workflows. This includes training, improved modelling routines, clearer internal standards, and more consistent data management.

The need for stronger standards was also evident in the technical layers of this study, particularly when comparing IFC and OWL. IFC offers stability and widespread industry adoption, yet its structure is rigid. Representing new concepts related to bio-based materials or circularity requires custom property sets, which are constrained by naming rules and inconsistent export behavior. OWL provides far greater semantic flexibility and can capture complex life cycle relationships and circularity indicators. This flexibility, however, depends on continuous maintenance and shared agreement among stakeholders, which complicates large-scale adoption.

Blockchain has been proposed as a complementary tool for data verification, timestamping, and maintaining transparent modification histories. Although these functions can support material traceability, blockchain does not ensure data accuracy, introduces environmental burdens, and requires governance models that manage transparency and responsibility. A combined approach, using IFC for geometry, OWL for semantic depth, and selective blockchain components for verification, may be viable but remains an area for future research.

These developments bring forward the need to consider enforcement mechanisms and governance structures that ensure DPP reliability. Regulation alone will not guarantee effective implementation. Policy frameworks, including the EU's forthcoming DPP legislation, provide direction but do not yet define the practical systems required for consistent data delivery (Psarommatis & May, 2023). Technical development is still emerging, and progress requires academic involvement and iterative testing, particularly because the scope of material passports remains undefined and scattered.

Scalability presents another challenge. Materials differ in structure, supply chains vary, and data completeness, reliability, and ownership remain unresolved. A comprehensive framework should address these differences, yet creating such a system introduces new challenges related to hosting, updating, and protecting digital information. This thesis showed that even a single material requires a complex integration of geometry, properties, semantics, and export processes. Extending this approach to full product systems increases the complexity significantly. These findings suggest that interoperable standards and shared ontologies must be strengthened before large-scale DPP deployment becomes feasible.

Despite these challenges, the thesis was able to address several gaps in the current landscape. It established a BIM-based structure for material-level and element-level DPPs and identified the parameters, data types, and ontologies required for hempcrete. It demonstrated a full workflow from dataset creation to BIM integration, IFC export, RDF conversion, and interface mock-up. Validation processes identified where data transfer breaks down, including issues related to parameter mapping, unit handling, naming conventions, and GUID tracking. The thesis also developed a supplementary ontology to reduce part of the semantic gap associated with circularity and bio-based materials. Together, these contributions provide a foundation for future DPP development.

Several gaps, however, remain unresolved. Full automation of the DPP workflow is not yet possible because semantic inconsistencies persist and circularity indicators are not standardized.

Identifier tracking continues to be difficult, and industry-ready tools capable of supporting the entire workflow do not yet exist. Data governance also remains undefined, including questions of ownership, correctness, and the long-term maintenance of shared ontologies. Finally, the approach has only been tested with hempcrete, and its scalability must be evaluated across a wider range of bio-based and non-bio-based materials. These gaps indicate that interdisciplinary research is required to support the development of robust and scalable DPP frameworks.

The findings also carry broader implications for sustainable architectural practice. The integration of BIM-based DPPs has the potential to influence how designers select and specify materials. Increased access to verified information encourages decisions that consider durability, adaptability, and long-term environmental impact. This shift can support a broader transition within the construction sector toward practices that prioritize maintenance, reuse, and circularity, properties that are often characteristic of bio-based materials. The growing need for data-driven sustainability strategies suggests that architects will increasingly work with structured digital information and will require new skills in data interpretation and material analysis. The findings of this thesis indicate that tools such as DPPs can support this transition by embedding circularity considerations within workflows and by improving the reliability of material knowledge.

In conclusion, this thesis demonstrated that a BIM-based Digital Product Passport can support the development of future frameworks for circular construction by improving transparency, strengthening traceability, and enabling the structured representation of bio-based material information. Although significant challenges remain, the work provides a foundation for further research and highlights the importance of integrating semantic tools, interoperable standards, and responsible governance. The findings show that digital material information has the potential to contribute to a long-term transformation of the construction sector toward more sustainable and circular practices.

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LIST OF FIGURES & TABLES

ANNEXES

All methodological and computational files developed or used in this thesis are provided in the accompanying GitHub repository. These include:

1. Excel base template used for data structuring.
2. Shared Parameters file for the BIM model.
3. Material Library used in the Revit model.
4. Dynamo scripts for parameter input and parameter setting.
5. pyRevit script for automated data input.
6. IFC export setup, including Pset and mapping file.
7. IFC-to-LBD converter (Python).
8. Python tool for ontology mapping.
9. Four-way ontology mapping files, including the full ontology.
10. Semantic data validation tool (Python) and the associated SHACL shapes file.
11. Validation tool for the Excel dataset.
12. Qualitative persona evaluation tool (Python).

The complete repository is accessible at: https://github.com/catalinacadena-boop/DPP_Hempcrete_Repostory

The mock-up visualisation of the Digital Product Passport is also available in the GitHub repository, together with an online version accessible at: https://github.com/catalinacadena-boop/DPP-MockUp-Visualiation + https://material-passport-viewer-830392354730.us-west1.run.app/

The final Digital Product Passport (DPP) produced for the company is not included in this thesis or in the public repository, as it forms part of the company's proprietary deliverables. This includes the filled Revit model families with their IFC exports (for both element and material levels), the converted IFC files in TTL and Excel formats, the ontology-mapped TTL files, and the validation reports for both TTL and Excel datasets, together with their associated PDF outputs

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