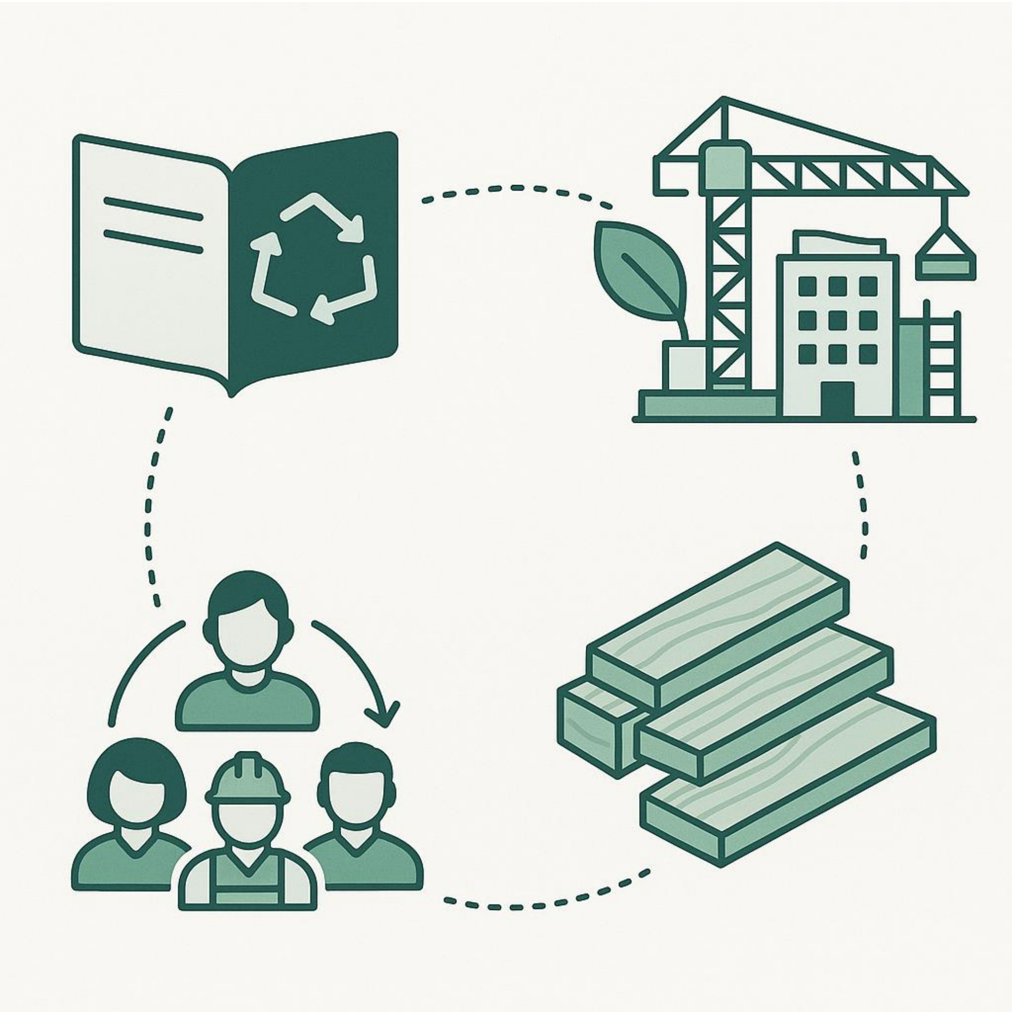
Simplified Multi-disciplinary Material Passport Workflow to Collect Key Reusable Materials Information

Shinta Litania Duhain



Simplified Multi-disciplinary Material Passport Workflow to Collect Key Reusable Materials Information

by

Shinta Litania Duhain

to obtain the degree of Master of Science in Construction Management and Engineering at Delft University of Technology, to be defended publicly on 25 August 2025

Student number : 5956994

Project duration : March, 2025 – August, 2025

Graduation thesis committee:

Chair : Prof. Dr. Ir. J.W.F. (Hans) Wamelink

First Supervisor : Dr. D.M. (Daniel) Hall

Second Supervisor : Dr. Ir. R. (Ranjith) Kuttantharappel Soman

Abstract

This thesis addresses the practical implementation of component-level Material Passports (MPs) in the construction sector to support circularity. While MPs offer potential for material reuse and lifecycle transparency, they face persistent barriers, including lack of standardization (Kedir, 2021) and the need for coordinated stakeholder involvement (Honic et al., 2019).

The objective of this research is to develop and evaluate a structured MP workflow applicable to new buildings from early design to manufacturing phases (RIBA Stages 1–5). A Design Science Research method was used across two iterations. In the first, literature reviews and expert interviews identified workflow objectives and stakeholder responsibilities, resulting in an initial workflow. The second iteration involved improving the workflow and testing it through a template-based data collection exercise within the Stanford AEC Global Teamwork course, where feedback was gathered from multidisciplinary participants.

Best practices observed include workflow clarity, ease of use, alignment with existing carbon accounting practices, and stakeholder agreement on responsibilities. Key challenges include difficulty in disassembly data interpretation, time-consuming manual data extraction, and hesitance from subcontractors accustomed to conventional practices. The workflow currently lacks automation and has limited real-world validation.

The scope focuses on component-level MPs, omits product-level inputs, and is limited to academic testing within a European policy framework. The full lifecycle impact of MPs remains theoretical, and applicability may be limited in regions without supportive reuse markets or regulatory incentives. Despite these limitations, the proposed workflow lays a foundation for future real-world MP adoption and suggests areas for expansion, including AI-assisted data extraction and integration across all lifecycle stages.

Table of Contents

List of Figures

List of Tables

Preface

Participating in the Global AEC Teamwork course was an unexpected but rewarding part of my thesis journey. I am thankful to Dr. Ranjith and Prof. Sander for trusting Emilio and me to represent CME TU Delft in this international collaboration. Initially, I was hesitant to join in my final semester as I had to complete my graduation thesis simultaneously. Dr. Daniel encouraged me and explained how the course and thesis could be integrated. Even before I officially asked him to be my first supervisor, he generously offered his guidance.

Selecting a suitable topic was challenging at first, but ultimately, Material Passports became the focus. This aligned well with the course's emphasis on sustainable structural material selection. I also identified a gap in the literature regarding stakeholder collaboration in MP implementation, which further motivated my choice.

I am sincerely grateful to Prof. Renate for her comprehensive guidance during the course. She was exceptionally accommodating, supporting me both during my time at Stanford and while I participated online. I also thank the professional network from the Stanford AEC Global Teamwork course, who agreed to be interviewed and shared their expert insights despite Europe–US time zone differences and busy schedules. Although their primary role was to support the course, they extended their support to my thesis, which I deeply appreciate. While it is unfortunate I cannot be there in person for the closing event, I value the connections we have built and look forward to continuing them.

My heartfelt gratitude goes to my thesis committee, Dr. Daniel, Prof. Hans, and Dr. Ranjith, for their thoughtful supervision and constructive feedback. I learned not only how to shape a research project but also how to apply the Design Science Research methodology effectively.

Finally, I thank LPDP (Lembaga Pengelola Dana Pendidikan) - Indonesia Endowment Fund for Education as my sponsor, for providing full financial support throughout my master's study. I am also grateful to my family and close friends for their unwavering emotional support, especially during times when balancing coursework and thesis work felt overwhelming. Completing this thesis on time, despite the challenges, is something I am proud of.

I hope you find this thesis insightful and relevant.

Shinta Litania Duhain,

18th August 2025

1. Introduction

1.1 Background

1.1.1 Construction Industry Waste Problem

The construction industry is a major environmental concern, known for its high energy use and considerable footprint. It accounts for 25–40% of worldwide carbon emissions, yet only 20–30% of construction and demolition waste (CDW) is recycled (World Economic Forum, 2016). In the European Union, this sector is responsible for about 40% of CO_2 emissions (European Parliament, 2022) and produces nearly a third of all waste (European Commission, 2018).

Likewise, in the United States, Construction and Demolition (C&D) waste hit 534 million short tons (484 million metric tons) in 2014, with over 90% coming from demolition (US EPA, 2016). Recycling and repurposing these materials helps save landfill space, reduces energy consumption, and lessens environmental harm by cutting the need for new resources (Thormark, 2001; Butera, 2015).

As the largest consumer of natural resources, the Architecture, Engineering, and Construction (AEC) industry must prioritize efficient resource use, waste reduction, and energy saving. Because of this, reusing materials has become a key strategy in fighting climate change. Embracing Circular Economy (CE) principles within the AEC sector has become essential for reducing its environmental impact.

1.1.2 Circular Economy and Material Passport

The Circular Economy (CE) framework represents an evolving economic model focused on sustaining product value at its highest level throughout extended lifecycles. Among key CE strategies, reuse holds particular significance as it eliminates environmental burdens linked to raw material extraction and manufacturing—processes that typically dominate a material's lifecycle impacts (Ellen MacArthur Foundation, 2019). While recycling offers carbon and energy savings by reducing primary resource demand, it still necessitates energy-intensive reprocessing.

Despite growing recognition of material reuse as a critical sustainability practice, widespread adoption remains constrained by implementation barriers. A primary challenge stems from uncertainties regarding material specifications in reused components, necessitating robust systems for documenting, maintaining, and disseminating product data.

To address this gap, the concept of Material Passports (MPs) is being introduced—structured digital records containing comprehensive product attributes, including circularity parameters.

By consistently collecting data on circularity from the initial design phase, Material Passports allow stakeholders to strategically manage a material's entire lifecycle. This leads to better decisions about the best end-of-life options, such as whether to reuse, recycle, or use other recovery methods. Figure 1 provides an example of a material passport and what it can do.

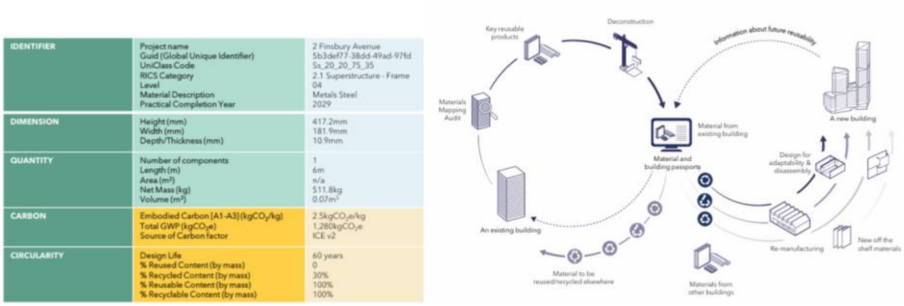


Figure 1 Circular building strategy (Webster et al., 2024)

This concept aligns with the Cradle-to-Cradle® philosophy, which advocates for reimagining buildings as "material banks"—a paradigm shift in managing material flows throughout a structure's lifecycle. The material bank concept frames building components as temporarily stored resources, emphasizing their retained value and the need for systematic maintenance and recovery.

Fundamentally, this approach requires high-quality, uncontaminated materials and predefined pathways for material recovery and regeneration. To make them easier to implement in practice, circular building principles can be combined with Design-for-Adaptability (DfA) methodologies—a set of evolving strategies refined in recent decades to enhance building flexibility and resource efficiency.

1.1.3 Material Passport Current State

The Material Passport (MP) has been suggested as a crucial tool for stakeholders to systematically document and track product information. Although definitions vary, MPs are broadly understood as (digital) datasets that record material characteristics, enhancing their value for current applications, recovery, and future reuse. Their primary objectives include reducing primary resource consumption, maximizing circular value, and minimizing construction waste (Damen, 2012; Heinrich & Lang, 2019; L. M. Luscuere, 2017; Mullhall et al., 2017). Hoosain (2021) further emphasizes that MPs can reactivate residual material value in markets through precise value tracking, enabling stakeholders to quantify the recyclability or reusability of every building material.

Currently, no universal standard exists for the data MPs should contain. However, Çetin et al. (2023) propose essential categories, such as: building and product general information, material properties, Environmental Product Declaration (EPD) information, operational aspects, and end-of-life aspects.

Several European nations—including the Netherlands, UK, and Germany—have pioneered MP implementations, setting precedents for global adoption. Industry innovations like Madaster, ECOPlatform, and BAMB have developed software, databases, and prototype models to operationalize MPs.

Literature identifies several challenges in MP adoption:

1. Unstructured data capture and sharing across value chains (Kedir, 2021)
2. Supply chain fragmentation and data standardization gaps (BAMB, 2016; Luscuere, 2017)
3. Limited stakeholder collaboration (e.g., between BIM managers, designers, MP consultants) (Honic, 2019)
4. Intellectual property concerns over material data (BAMB, 2016)
5. Data volume, storage, and maintenance demands (3XN Adepa, 2016)

Decisions made early in the design process significantly impact construction costs, influencing as much as 80% of the total budget (Bogenstätter, 2000). This highlights how crucial effective information management is for avoiding budget overruns. Schols (2022) highlights success factors for MP integration, including: Early alignment of circular economic goals among stakeholders, user-friendly MP systems enabled by automation, and knowledge-sharing between clients and contractors.

Looking from legal standpoint, regulations including Ecodesign for Sustainable Product Regulation (ESPR) in Europe and Calgreen in the United States are also being introduced to drive AEC stakeholders to record sustainability and circular information of materials. Especially in Europe, it is mandatory for manufacturer and importer to provide Digital Product Passport (DPP), which is equivalent of material passport, by 2028 for prioritized products including construction material like cement and steel.

Although it is not explicitly stated that AEC stakeholders will be mandated to provide passports, this regulation will help in wider MP adoption in AEC industry. As DPP manufacturers become more widely available, it will be easier for contractors or building owners to collect component level passports as opposed to the current process of collecting information from different sources.

1.1.4 US Context

Recent research by Eissa & El-Adaway (2024) systematically analyzed 41 U.S. construction case studies (22 journal articles and 19 USGBC projects) to evaluate Circular Economy (CE) strategy adoption. Their network analysis revealed fragmented implementation, with frequent adoption of sustainability certifications, passive design, and landfill diversion, but minimal integration of logistics/property-phase strategies. Notably, building material passports (Strategy D6) were absent across all projects, attributed to emerging adoption barriers like cost constraints, limited regulatory incentives, and technical challenges (Cruz Rios et al., 2021). However, parallel studies suggest untapped potential: Vegh et al. (2024) demonstrated feasibility through a battery passport model for North American critical minerals, while Munaro et al. (2019) proposed a wood-frame material passport system in Brazil, highlighting scalable prototypes for broader AEC industry adaptation.

1.2 Problem Definition

It's challenging to reuse materials in construction because key stakeholders like owners, architects, engineers, and contractors often lack access to essential material information. While MP is proposed as a solution, it still presents some barriers like the lack of structure / standardization (Kedir, 2021) and requiring close stakeholders' collaboration (Honic et al., 2019). It makes stakeholders lack understanding of the process on how to input which information and at what point in time in the lifecycle, which is design and construction planning in this case.

2. Research Objective

2.1 Research Objective and Question

Based on the background, there is a need for implementing MP, but the process is unknown. This research aims to design a simplified MP workflow to collect key reusable materials. It also aims to provide insights and challenges of implementing MP workflow.

A research question is put forward to achieve the research objective and answer the problem identified in Chapter 1. Therefore, the main research question is as follows:

"How can a simplified Material Passport workflow be designed and implemented to enable stakeholders to collect key reusable material's information? "

- SRQ1: What are the stakeholders' roles and responsibilities in providing relevant information to create Material Passport?

- SRQ2: How can a Material Passport workflow be designed, and when should each data be extracted and collected into MP?
- SRQ3: How effective is the workflow in supporting stakeholders to collect key reusable material information?
- SRQ4: What are the insights (best practices) and main challenges for implementing MPs?

2.2 Research Scope and Limitation

To complete this master's thesis within the given timeframe, it's essential to narrow the research's focus.

1. The levels of Material Passport considered are only for component level because it is the responsibility of contractors in construction stage (Stella et al., 2023). Products or material level passports should be provided by a supplier or manufacturer, so it is not discussed further in this study.
2. The workflow will be focused on creating Material Passport for new buildings from strategic definition to manufacturing phase (equivalent to RIBA stage 1-5). It might happen in parallel with the construction phase in some projects, as Stage 5 is for both Manufacturing and Construction.
3. The Stanford AEC Global Teamwork course was chosen as an implementation case for the demonstration phase. Only involving the students and interviewing the AEC industry network within the course from Europe and US. Involving sustainability-focused participants under non-commercial conditions does not replicate the pressures of real-world projects (e.g., cost, time, or risk). It also did not include critical actors such as project managers or cost consultants, who are typically responsible for incorporating MPs in contractual documents like Employer Requirements (ERs).
4. The workflow generally aims to store crucial material information to enable materials to be reused. Reuse is prioritized as it is the highest circular strategy in the 10R approach that extends the lifespan of materials (Potting et al., 2017). It also aligns with the implementation case goal, which is adaptable building. Other circular strategies such as recycling, refurbishment, or remanufacturing were not evaluated in detail, which may limit flexibility in different project types.
5. The workflow assumes manual data collection from sources like PDFs. Automation tools (e.g., AI-assisted data extraction) were discussed but not tested, which may hinder scalability for larger or time-sensitive projects.

6. The workflow draws heavily on European policy and tool references (e.g., ESPR, British Land, Rotor), which may not apply or translate well to regions with different regulations or circularity markets. It also assumes that increasing regulation (e.g., ESPR, CALGreen) will drive MP adoption. In areas without such regulations, building owners may not prioritize MP implementation.

2.3 Research Approach

This research primarily utilizes Design-Science Research (DSR). DSR aims to expand human knowledge by creating innovative artifacts and generating design knowledge through novel solutions to real-world problems (Hevner et al., 2004). It was chosen for its structured approach to process design, distinguishing it from methods like action research and ethnography. As illustrated in Figure 2, the DSR process involves six steps and offers four potential starting points.

Step 1. Problem identification and motivation: This initial step involves identifying the research gap and explaining why the proposed solution is important. It shows that the researcher understands the issue and motivates stakeholders. This requires a deep understanding of the problem's current state and the potential benefits of solving it.

Step 2. Define the objectives for a solution: The goals for a solution are developed from the problem definition and an understanding of what is achievable. These objectives can be quantitative, like how much better a new solution would be, or qualitative, such as describing how a new artifact is expected to help with previously unaddressed problems. These objectives should logically follow from the problem's specifications.

Step 3. Design and development: Here, an artifact is built. This artifact can be anything designed—like a model, tool, or framework—that contains a research contribution within its design. This step includes defining the artifact's intended functions and structure, then constructing it.

Step 4. Demonstration: This activity involves showing how the artifact can solve one or more instances of the problem. This might use empirical methods such as case studies, simulations, or proofs-of-concept.

Step 5. Evaluation: This step assesses how well the artifact meets its predefined objectives. The evaluation method can vary depending on the problem and the artifact itself. After this activity, researchers can decide whether to return to Step 3 to improve the artifact's effectiveness or proceed to communication, leaving further enhancements for future projects.

Step 6. Communication: In this final step, all aspects of the problem and the designed artifact are shared with relevant audiences using suitable communication formats.

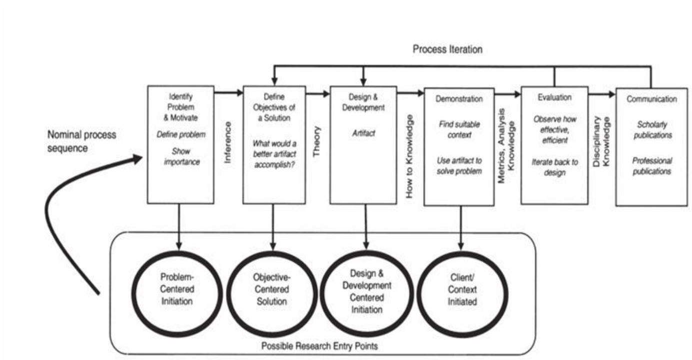


Figure 2 DSR Methodology Process Model (Peffers et al., 2008)

In this research there were two iterations done:

1. In the first iteration, literature reviews were carried out to find out material passport workflow barriers and identify what objectives should be achieved by the material passport workflow to ease initial adoption. Afterwards, stakeholders' roles and responsibilities were mapped into the information requirement. It was then translated into a sequence of project activities throughout the life cycle and sequenced to form a workflow. The initial workflow is then shown to five experts to gain their feedback on the sequence, and stakeholders' roles and responsibilities. Some feedback from the interviews is then used to improve the workflow and responsibilities list in the second iteration.
2. In the next iteration, the workflow is improved, and initial phases were followed to choose the materials to be recorded in the material passport. Afterwards, a template and the instructions to fill the information is created to simulate data collection. Four students working together with AEC Global Teamwork acting as structural engineers and construction managers are then asked to fill in the template. Efficiency of the workflow and the template is measured through a survey, along with the feedback for future improvement.
3. Finally, recommendations to improve the workflow and template are presented.

3. Research Method

Commented [SS1]: Improve more in the detail

To address the problem the DSR methodology is used to develop a Material Passport workflow to track high value material. First, a literature review is conducted to understand barriers for material passport implementation. Second, to develop solutions, objectives of the material passport workflow are defined. Third, a set of artifacts (workflow, responsibilities list, and template) is designed. Fourth, the workflow and responsibilities list are demonstrated through an implementation case. Finally, user and expert feedback is evaluated to improve the artifact. There was one iteration from evaluation phase to refine objectives and the artifact design. The specific DSR process is summarized in Figure 3.

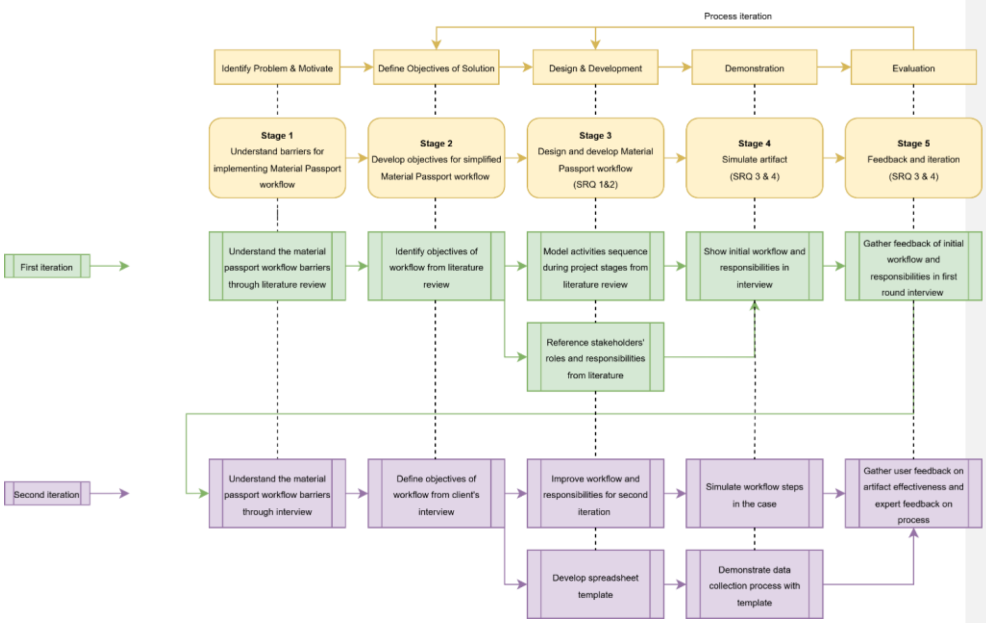


Figure 3 Research Method

Commented [SS2]: Update

3.1 Problem Identification

Initially, literature review is done to investigate the bigger context of construction industry waste problem urgency (World Economic Forum, 2016; European Parliament, 2022; US EPA, 2016). Afterwards, it was investigated how reuse (Potting et al., 2017; C. Zhang et al., 2022;

Ellen MacArthur Foundation, 2019; Tirado et al., 2022) and its application through material passport (Damen, 2012; Heinrich & Lang, 2019; L. M. Luscuere, 2017; Mullhall et al., 2017) can solve the problem. Existing regulation and green building certification in Europe and the US regarding sustainability and circularity was also explored. A material passport workflow is then proposed to be the solution.

Current state and innovation of material passport in several countries and innovations were studied. Despite all that, it still has its limitations. While the main material passport implementation barriers were identified from Kedir (2021) and Honic (2019), more challenges and opportunities regarding material passport implementation were found from the systematic literature review done by Munaro & Tavares (2021). The literatures cited include BAMB (2016), Luscuere (2017), WEF (2014), 3XN Adepa (2016), and Honic et al., (2019). Afterwards, through the first-round interview, in which the interviewees details are available in Table 1, aims to investigate what kind of material passport workflow enables stakeholders in adopting material passports.

3.2 Define Objectives of Solution

Subsequently, a literature review is performed to determine the necessary characteristics or objectives required to ease initial adoption of the workflow. A report by Webster et al. (2024) and an article by Ozinsky (2024) on how British land as one of the first developers to use material passport on large-scale project in the UK was found and therefore chosen as a reference. The main report (Webster et al., 2024) includes their general process on creating a material passport. This report is referenced to set the initial objectives, because of its realistic approach. It aims to only collect specific information that is required from the supply chain rather than all the building materials.

Next, first-round semi-structured interviews with three construction managers and two structural engineers are conducted to confirm the initial objectives or identify new objectives when possible. Their credentials are presented in Table 1.

Table 1 First Round Interviewees

Code	C1	C2	C3	S1	S2
Title	Project Engineer / life cycle analyst	Prefabrication Lead	Sustainability Manager	Project Engineer	Senior Structural Engineer
Company	Contractor	Contractor	Contractor	Engineering Consultant	Engineering Consultant
Years of experience	2	17	16	7	8
Country	US	US	US	US	Germany
Role	CM	CM	CM	Structural Engineer	Structural Engineer

However, the objective of the workflow was eventually decided through discussion with the project's owners to accommodate the project specific circularity goal. The project owner's role in this research is simulated by the project owner at the Global AEC Teamwork course. In the course, it was simulated by a group of industry experts from the US and Europe in construction management, architecture, structural engineering, and MEP. The course activities were chosen as an implementation case of this research, and more details about the course setup can be found in Section 3.4.

3.3 Design and Development

Initial artifacts consist of workflow and responsibilities list. The workflow was modelled based on the material passport creation steps and objectives from Webster et al. (2024). The workflow is modelled with Business Process Modelling Notation (BPMN) in which the swimming lanes represent different stakeholders (Appendix B). The steps were sequenced according to project stages referencing the information flow through project lifecycle modelled by Kedir (2024).

Commented [SS3]: Pertama desain initial sel karena kirain butuh itu. Source blabla. Kedua setelah feedback ditambah template untuk demonstrate data collection.
The initial artifact in first iteration consists of workflow (which is coded as initial workflow in Appendix B) and stakeholder's roles and responsibilities in data collection (presented in Appendix D).
In the second phase the artifact will consist of improved workflow and responsibilities, and a template for data collection demonstration.

Not only sequence, roles and responsibilities should be assigned to different stakeholders across the project lifecycle. Ensuring that every stakeholder understands it will ensure that the workflow is implemented. Initially, the responsibilities presented are more defined in regards of data collection. MP-relevant information by component level from Waterman MP Framework (Stella et al., 2023) is mapped to the stakeholders' responsibilities as shown in Appendix D. Afterwards, first-round interviews were conducted to gain feedback on the workflow and responsibilities. The summarized responsibilities are added which is referenced from the responsibility matrix in (Webster et al., 2024). Additional interview with one of the authors of the British Land material passport approach was also conducted to elaborate the process of identifying key reusable materials. The author's opinion will be later cited as B1.

The feedback is applied to improve the workflow and responsibilities list, including the project owner's feedback on the objectives. Afterwards, the second iteration started with the artifact including the improved workflow, responsibilities list, and a newly added template and instruction in spreadsheet. The template is designed to demonstrate data collection process by users. The information scope of the template was referenced from Waterman Material Passport framework (Stella et al., 2023). It was chosen because it is the first comprehensive framework that gives an outline about what information should be collected regarding manufacturing, design, and construction, along with the suggested input option. Although the workflow initially is designed to collect construction-related data as well, the demonstration case could only collect the design and manufacturer-related data.

A crucial design-related information on this research is to enable component disassembly, therefore Disassembly Measurement Potential Methodology from DGBC (Dutch Green

Building Council) is referenced (Van Vliet et al., 2021), specifically the four steps, including assessing connection types, connection accessibility, independence, and product edge.

3.4 Demonstration

Firstly, the initial artifact consisting of the workflow and data collection responsibilities list is shown to the experts to get an evaluation. Before the workflow is shown, an initial brief about material passports is given to give relevant context especially to the ones who are not familiar with material passport or even circularity concept. And then the workflow and responsibilities are shown, while asking questions on how it can be improved regarding the sequence and focusing on their roles as structural engineers or construction managers.

In the next iteration the artifact consisted of improved workflow and responsibilities list, which is supplemented by a spreadsheet template. Workflow steps are carried out throughout a project and templates are then filled to demonstrate data collection. The project is part of a global multidisciplinary course at Stanford called Global AEC Teamwork. It is chosen as an implementation case for this research.

Commented [SD4]: why global AEC?

The course aims to bring together students from around the world to collaboratively design an advanced building project using cutting-edge technologies. I participated in a team of global multidisciplinary students which consists of 1 architect, 1 apprentice, 3 structural engineers, 1 MEP engineer, and 2 construction managers, in which I am one of the construction managers. As a team we need to collaborate to deliver a conceptual design and project simulation of a university building in San Juan, Puerto Rico within five months. During the process, a team of multidisciplinary experts act as project owners to give feedback on the design. Project owners are industry professionals in Europe and the US. The details are in Appendix A. In addition to the role of construction manager, I also took a role as a sustainability consultant for this research demonstration purposes. More details are presented in Figure 4.

This case was chosen because of several reasons. First, the multidisciplinary nature of the team and high collaboration level from conceptual design phase enable workflow implementation. Secondly, the team has never heard about Material Passport before, and thus creating a Material passport would not have been their priority. Therefore, this research can investigate how a simplified material passport workflow can be introduced . Thirdly, the industry mentors acting as “owners” enable the simulation of the role needed in the workflow.

Figure 4 Project team members and owners (top), renders and location (bottom)

The initial step of the workflow is done by discussion with the whole team and owner. Subsequently, four students, of which two students are construction managers and the other two students are structural engineers, participated in data collection demonstrations. Initially the improved workflow is shown, and then the spreadsheet template is introduced. Guidance in filling in all required fields and what are the input options for all stakeholders are available in instruction sheet.

Table 2 Students Credential in Data Collection Demonstration

Code	CA	CB	SA	SB
Years of experience	2.5	5	0.5	-
Country	UK	Indonesia	US	China
Role	CM	CM	Structural Engineer	Structural Engineer

They had to fill in the material passport template in a spreadsheet for a beam made of structurally engineered bamboo (SEB). For the construction manager, the required information includes multiple PDFs of the materials' technical sheets, environmental declaration, and email conversation which is provided to simulate the disparate sources that a subcontractor or supplier need to go through to fill in the material passport. For the structural engineers, they had to provide different connection designs for a beam based on their design.

3.5 Evaluation

The initial version of the artifact, which is the workflow and responsibilities list, was evaluated by conducting first-round interviews. They are interviewed instead of the students as they are more professionally experienced and assumed will provide more practical and realistic feedback. Interview questions are mostly about the data collection responsibilities of the stakeholders, the activities sequence, and the potential challenges in implementing the workflow. Additionally, their opinions on data storage, templates and integration with existing platforms were also asked. Anonymized information about interviewees and interview questions is available in Appendix C. The feedback is then used to improve the workflow and responsibilities.

Evaluation for the second version of the artifact (workflow, responsibilities list, and template with its instructions) is done after it is demonstrated for data collection to the AEC Global Teamwork teammates. A quick survey is conducted to measure the workflow efficiency and gain feedback from the four students, in which the questions are available in Appendix F.

4. Literature review

4.1 Circular Economy in the Construction Sector

Construction industry waste in Europe

The construction sector is well-known for its substantial energy use and environmental impact. It contributes between 25% and 40% of global carbon emissions, yet only 20% to 30% of construction and demolition waste (CDW) gets recycled (World Economic Forum, 2016). In the European Union, this industry accounts for roughly 40% of CO_2 emissions (European Parliament, 2022) and produces almost a third of all waste (European Commission, 2018). Table 3 indicates that concrete and masonry make up 40% to 84% of CDW in Europe, with exceptions in countries where wood is the main building material, and this trend is expected to continue (Intelligence Service, 2011).

Table 3 Ranges of composition of C&D waste in Europe member states except for Estonia and Finland (Intelligence Service, 2011)

Ranges	% - Min	% - Max	Million tonnes - Min	Million tonnes - max
Concrete and Masonry - total	**40,0%**	**84,0%**	**184**	**387**
Concrete	12,0%	40,0%	55	184
Masonry	8,0%	54,0%	37	249
Asphalt	**4,0%**	**26,0%**	**18**	**120**
Other mineral waste	**2,0%**	**9,0%**	**9**	**41**
Wood	**2,0%**	**4,0%**	**9**	**18**
Metal	**0,2%**	**4,0%**	**1**	**18**
Gypsum	**0,2%**	**0,4%**	**1**	**2**
Plastics	**0,1%**	**2,0%**	**0**	**9**
Miscellaneous	**2,0%**	**36,0%**	**9**	**166**

In the United States, in 2014, Construction and Demolition (C&D) waste totaled 534 million short tons (484 million metric tons), with over 90% generated from demolition activities (US EPA, 2016). Repurposing and recycling these C&D materials helps conserve landfill capacity while also reducing energy consumption and environmental harm by decreasing the demand for new resources (Thormark, 2001; Butera, 2015).

Given its status as the largest consumer of natural resources, the Architecture, Engineering, and Construction (AEC) industry must prioritize resource efficiency, waste reduction, and energy conservation. Consequently, material reuse has emerged as a crucial strategy in addressing climate change. Embracing Circular Economy (CE) principles within the AEC sector has become a foundational approach to mitigating its ecological footprint.

Concept

Norouzi et al. (2021) stress the critical need to shift from a linear to a circular economic model. This change is vital due to increasing environmental damage, dwindling resources, and unsustainable consumption habits. This need is especially pressing in the construction industry, where embracing circular economic principles offers a practical solution by harmonizing material and waste flows (Tirado et al., 2022).

The sector is shifting from a linear model to a circular economy (CE), which aims to keep materials in use and regenerate natural systems. The 10R framework ranks CE strategies from most to least preferred, including reuse, repair, remanufacture, and recycling (Potting et al., 2017). Prioritizing upstream strategies like reuse and reduce is crucial to cut emissions and waste.

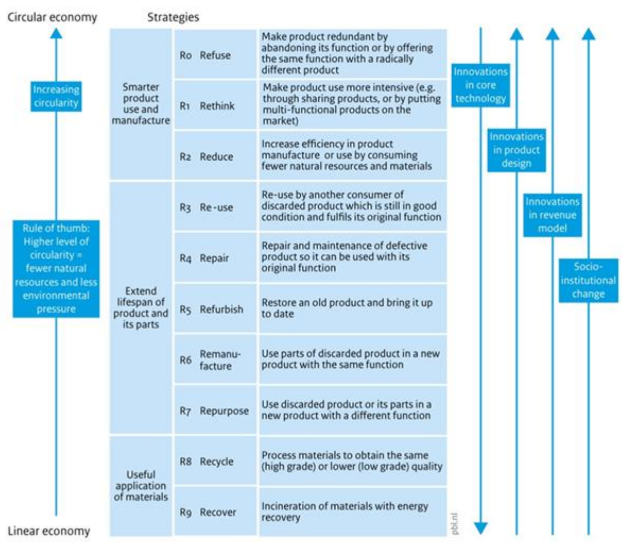


Figure 5 10R Framework (Potting et al., 2017)

4.2 Material Passport

Material Passports (MPs) are digital datasets documenting product characteristics to support reuse, recycling, and recovery. They track data across the lifecycle to support circularity strategies.

Definition

According to the BAMB (Buildings as Material Banks) project, Material Passports (MPs) are essentially digital, interconnected datasets that document the characteristics of materials and building assemblies. Their purpose is to empower suppliers, designers, and users to maximize the value of these materials, guiding them towards circular material flows. By making data on a component's characteristics, usage history, and reuse potential readily available and relevant, MPs make it easier to reuse, recycle, and biodegrade components. It's also crucial to select components that are inherently reusable in the future. Therefore, developing MPs is seen as a way to encourage innovative product design and the adoption of circular business models (BAMB, 2019).

BAMB also defines Material Banks as "repositories or stockpiles of valuable Materials that might be recovered." The idea here is that if these recovered materials can replace new, primary resources in construction, operation, or refurbishment, we can eliminate the need for extracting new resources, like rare earth elements. This concept, often called urban mining, relies on effective material reuse to create true material loops. However, to successfully harvest materials or building parts, they must be designed for easy disassembly and recovery.

While definitions can vary, MPs can be broadly understood as a digital collection of data describing specific material characteristics that enhance their value for current use, recovery, and reuse. Their ultimate goal is to reduce reliance on new primary resources, maximize circular value, and minimize construction waste (Damen, 2012; Heinrich & Lang, 2019; L. M. Luscuere, 2017; Mullhall et al., 2017). Hoosain (2021) further emphasizes that MPs can revitalize the value of residual materials in the market by precisely tracking their worth, allowing stakeholders to quantify the recyclability or reusability of every building material.

Lifecycle Perspective of Material Passports

MPs meticulously record information throughout the entire lifecycle of materials and building elements, covering stages such as manufacturing, on-site construction, use, any subsequent reuses, and ultimately, end-of-life. This lifecycle of a built asset is structured according to BS EN 15978:2011, which divides it into distinct lifecycle stages, further broken down into modules: Product and Construction Stage (Life Cycle Modules A1-A5)

- In-Use Stage (Life Cycle Modules B1-B3)
- End-of-Life (Life Cycle Modules C1-C4)
- Beyond Life Cycle (Life Cycle Module D)

This standardized structure, commonly used for Whole Lifecycle Assessments, has been adopted for organizing information within MPs.

Levels of Material Passports

It's important to note that MPs exist at different levels. Information gathered at lower levels is then aggregated to form the data at higher levels. This hierarchical structure allows for detailed tracking from individual materials up to entire buildings or even broader areas.

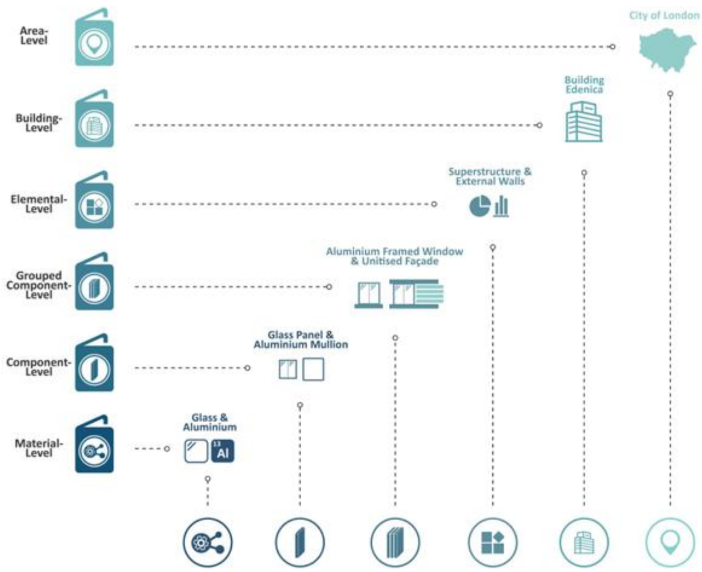


Figure 6 Example of different Material Passports levels (Stella et al., 2023)

Figure 7 illustrates the hierarchical structure of Material Passports (MPs) implemented in the Edenica project by Waterman Group, demonstrating six interconnected documentation levels:

- Material level: Passports can be created for individual materials, such as glass and aluminum.
- Component level: These passports apply to specific components, like glass panes or aluminum mullions.
- Grouped component level: For assemblies, passports can cover items like an aluminum-framed window or an entire unitized facade.
- Elemental level: Broader elements of a structure, such as external walls and the superstructure, can also have passports.
- Building level: A comprehensive passport can be generated for an entire structure, like the Edenica building.
- Area Level: In a broader scope, passports can even be applied to a defined geographic area, such as the City of London.

This study focuses on component level passports to optimize practical implementation.

Benefits or Use Case

Stella et al. (2023) summarizes benefits of MPs for the construction industry on different levels. On material level, MPs offer :

- Standardizes digital documentation of material specifications, properties, and performance
- Enables reliable reuse of materials through verified data transparency
- Reduces virgin resource consumption by facilitating circular material flows
- Preserves material value across multiple lifecycles

On building level application, it can

- Automate generation of comprehensive building inventories
- Quantify material quantities, properties, and circularity metrics
- Support Design for Disassembly (DfD) through:
    - Digital-physical linkages (QR codes/NFC tags)
    - Embedded disassembly manuals
    - Reversible construction documentation

After MPs is generated, it can be used as a one-stop database that can facilitate or automate the completion of different assessments when integrated with LCA platforms or storing platform like Madaster or Cirdax. Some of the assessments are embodied carbon assessment, circularity performance report, disassembly manual, and reuse and/or recycling catalogue.

4.2.1 Typical Data Requirements

Several literatures put out what data should be included in material passport (Munaro & Tavares, 2021; Çetin et al., 2023). Munaro & Tavares (2021) illustrates the different information on the proposed MP in each building's life cycle stage as shown in Figure 8.

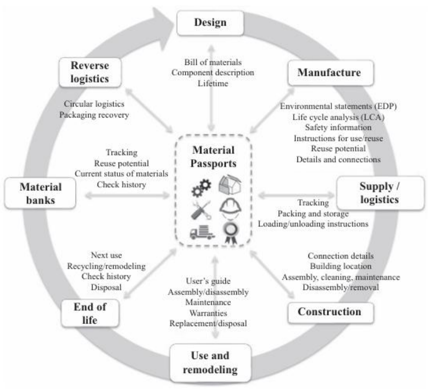


Figure 7 Information shared across a building's lifecycle to improve material recovery and reuse (Munaro & Tavares, 2021)

Moreover, Stella et al. (2023) offers a clear differentiation of material passport data requirement at different levels.

A component-level passport captures design, manufacturing, and construction details for a building component.

- Design-related section records the component's type, classification, geometry, and circularity details.
  - Component type information: Includes a unique ID, image or visualization, and type (new, reused, or existing).
  - Classification: Specifies the building level and element category the component belongs to.
  - Geometry: Documents the component's mass, volume, and dimensions (length, width, height).
  - Design-related circularity: Notes whether the component can be disassembled without damage, its relationship with adjacent elements, and connection accessibility. This section aims to link to digital Disassembly Guides in the future.
    - Connection types:
      - Welded: Formed by melting and fusing two metal surfaces.
      - Mechanical: Joined using bolts, screws, or other fasteners.
      - Adhesive: Bonded with strong adhesives like epoxy.

        - Connection accessibility: Options include directly accessible, hidden, removable layers (with or without damage), or inaccessible connections.
- Manufacturing-related section details the component's manufacturer, certifications, value, and maintenance expectations, sourced from product-level passports or suppliers.
    - Manufacturer details: Includes logo, name, address, website, contact email, and production location.
    - Certifications/Datasheets: Lists certifications and datasheets with details on properties, specifications, and performance, including name, type, description, and expiration date (if applicable).
    - Value: Records the component's value, priced unit, and warranty duration.
    - Expected Maintenance: Estimates the annual percentage of the component's mass to be replaced and provides maintenance guidance.
    - Circularity summary: Covers expected lifespan, recycled content, takeback programs, reuse potential, separability, and endoflife options.
    - Carbon summary: Details carbon datasheet type, declared unit, manufacturing carbon (A1A3), sequestered carbon, usestage carbon (B1B3), and endoflife carbon (C1C4).
    - Composition summary: Outlines the materials in the component and their percentage by mass.
    - Performance summary: Functional performance varies by building element category and materials, requiring further development to define reporting needs for each component type.
- Construction-related section documents contractor details and data carriers.
    - Contractor details: Includes the contractor's name, address, website, and contact email for onsite or prefabricated component construction.
    - Data carriers: The passport serves as a digital twin linked to the physical component via data carriers like RFID tags, NFC tags, QR codes, or smart labels, enabling stakeholders to access and update information throughout the building's lifecycle.

4.2.2 Enabled Potential Automations

Material passports serve as a detailed database that streamlines the creation of various evaluations and reports for buildings or structures. These include:

1. Embodied carbon analysis

Material passports store critical data like material types, quantities, production locations, carbon factors, maintenance schedules, and lifespans, enabling automatic calculation of a building's embodied carbon footprint. This supports ongoing carbon performance evaluations at component, element, building, or complex levels and verifies Net Zero Construction claims.

2. Circularity assessment

By collecting data on material and element circularity—such as recycled content, end-of-life options, take-back programs, separability, and design for disassembly—material passports facilitate automated reports that measure a building's circularity performance against key metrics.

3. Material efficiency benchmarking

Aggregating material passport data at a regional level allows for the creation of benchmarks for material intensity across various building types and components. These benchmarks enable automated evaluations of a building's overall and component-level material efficiency.

4. Disassembly guide

Material passports are essential for generating disassembly guides, outlining which components can be disassembled, their connection types, and accessibility. Paired with detailed instructions (text, diagrams, or 3D models) accessible via QR codes or NFC tags, this simplifies disassembly and reveals concealed elements.

5. Reuse and recycling inventory

Material passports automatically produce inventories of reusable and recyclable components, documenting anticipated end-of-life scenarios. This provides data on reuse and recycling rates for the building and its elements, highlighting reusable categories and estimating diversion from landfills.

6. Maintenance planning

By tracking component lifespans and maintenance needs, material passports enable the automatic generation of maintenance plans, detailing tasks, timelines, and remaining material life to guide future refurbishment decisions.

7. Facility management optimization

Material passports log real-time maintenance data throughout a building's lifecycle, allowing comparison with initial manufacturer estimates. This helps identify inefficiencies, enhance facility management performance (crucial for Net Zero goals during operation), and supports Digital Building Logbooks by recording key events and changes.

8. End-of-life summary

At a building's end-of-life or during refurbishment, material passports can automatically generate reports comparing actual material end-of-life outcomes with their projected lifespans.

4.2.3 Implementation Challenges and Opportunities

While MP offers a lot of benefits, implementing it comes with its challenges and opportunities. Munaro & Tavares (2021) summarized the challenges and opportunities through comprehensive literature review. The challenges can be classified as political, commercial, and social, while the opportunities are mostly in economic aspect as shown in Table 4 and 5.

Table 4 Challenges of Material Passport Implementation (Munaro & Tavares, 2021)

Challenges			Related aspects	Authors
Political	1	Complex and fragmented supply chain	The lack of integration of the different segments of the construction chain can increase the waste, deadlines and costs of buildings	BAMB (2016), Luscuere (2017)
	2	Conflicting environmental and energy policy measures	Prioritization of energy efficiency and high energy performance of buildings can result in construction projects and materials that do not lend themselves to deconstruction and reuse	BAMB (2016)
	3	Lack of data standardization/design information	As data on product properties and specifications are missing, it is difficult to identify the potential for reuse of products and materials	BAMB (2016), Luscuere (2017)
	4	Lack of certification and quality assurance for recycled or by-products	Few suppliers offer competitively priced quality assurance by-products and/or recycled materials	BAMB (2016)
Commercial	5	Complexity of materials/ systems/ components	Product and material separation is a key challenge to identify and separate materials, maintain quality and ensure purity	WEF (2014)
	6	Lack of data standardization/qualitative information about the product	Similar to item 3	BAMB (2016), Luscuere (2017)
	7	Longevity of buildings and infrastructures	Divergences regarding the different life cycles of buildings and their components with maintenance and occupancy profiles over time	Luscuere (2017)
	8	Intellectual property of materials and product-related data	Manufacturers and suppliers are reluctant to provide information that could compromise their business status	BAMB (2016)
	9	Reliable data collection and availability	Stakeholder engagement is required for reliable data to ensure reuse potential and material circularity	3 XN Adepa (2016), BAMB (2016)
	10	Volume and data storage	Managing and storing information about the building elements of a building entails big data	3 XN Adepa (2016), BAMB, 2016
	11	Lack of knowledge in BIM	BIM bears large potentials to serve as a knowledge basis for an MP, as all elements and materials exist in the BIM-model; however, there is a need for specific knowledge in BIM execution	Honic *et al.*, (2019b)
	12	Constant update of data and information	The passport information should represent the current state of the materials. This leads to the need to test and examine the status of materials and provide security for their reuse	3 XN Adepa (2016)
	13	Incorporation of sensors in materials	Embedded sensors may be able to detect and communicate current passport status while being accessible in real-time	3 XN Adepa (2016)
	14	Lack of circular and flexible business models	The way the product is connected to a building is crucial to its potential for reuse without contamination	BAMB (2016)
Social	15	Perception that reversible design leads to high financial costs	While reversible design can reduce long-term construction and maintenance costs, it often entails higher investments. Moreover, it is difficult to estimate financial savings as they occur in the future and depend on the context	BAMB (2016)
	16	Reversible buildings are still widespread	Decision-making protocols for building owners and users are lacking	BAMB (2016)
	17	Other priorities in the construction sector	Including accessibility, health and safety, and energy efficiency	Luscuere (2017)

Table 5 Opportunities of Material Passport Implementation (Munaro & Tavares, 2021)

Business opportunities	Aspects of materials passport
Circular index	Know product performance in the circular economy (EPEA, 2015)
Design guidance	By providing the opportunity for a producer to provide essential information about their products, it makes it easy for the user to verify which data are compatible with their purpose and which is missing
A market differential	Opportunity for manufacturers or suppliers to stand out for the transparency or circular potential of their products (Luscuere, 2017)
Information clarity and authentication	A better understanding of products is crucial for innovating and optimizing processes and products (Luscuere, 2017). In addition to protecting companies against industrial counterfeiting, tampering and misuse (EPEA, 2015)
Increase traceability	Buildings involve a large flow of materials and passports would facilitate tracking in terms of volume, location and other specifications (3 XN Adepa, 2016)
Understand the gain/loss ratio	Instead of waste, materials become part of the building's value chain, which can increase lease and resale value. Besides, if the material is destroyed, for example by incineration, the passport is invalidated or modified to verify the residual value of the ash by measuring the cost of incineration (Hansen *et al.*, 2013)
Enable operations	Circular design can enable assembly, disassembly and material production. This would facilitate removal, repair, maintenance and replacement services (3 XN Adepa, 2016)
Guide users	Inform users about installation, maintenance, cleaning, disassembly and reuse possibilities to keep products in recoverable condition (EPEA, 2015)
New business models and partnerships	Reversibly designed products and systems may be of interest to property and business models for leasing and material banks (Luscuere, 2017). Business partnerships could be established between waste management companies and product manufacturers (Hansen *et al.*, 2013)
Secondary materials market	Take control of material value streams; increase residual value and reduce material flow uncertainty; use secondary materials with known and defined content (EPEA, 2015)
Supply security	Passports provide conditions for the reliable recovery of materials, ensuring the supply and improvement of material residual value (Luscuere, 2017)
Decrease environmental footprint	Waste production and demand for new raw materials will be reduced (Heinrich and Lang, 2019)

Several key challenges in MP adoption includes:

1. Unstructured data capture and sharing across value chains (Kedir, 2021)
2. Supply chain fragmentation and data standardization gaps (BAMB, 2016; Luscuere, 2017)
3. Limited stakeholder collaboration (e.g., between BIM managers, designers, MP consultants) (Honic, 2019)
4. Intellectual property concerns over material data (BAMB, 2016)
5. Data volume, storage, and maintenance demands (3XN Adepa, 2016)

4.2.4 Sustainability and Circularity Information Source

When it comes to Life Cycle Analysis (LCA), an Environmental Product Declaration (EPD) provides a standardized method for measuring the environmental footprint of a product or system. EPDs quantify impacts such as raw material extraction, energy consumption and efficiency, emissions to air, soil, and water, and waste generation. These assessed impacts cover crucial environmental concerns like global warming potential and ozone depletion potential, among others. In case product specific information is not available, there are available generic databases for benchmark such as Okobaudat / IBO and Ecoinvent. Platforms or websites like Eco Platform, EPD Portal, and Building Transparency offers Product Category Rule (PCR) which provides industry-wide EPD and also some product specific EPD. LCA calculations are usually conducted with platform or tool such as eco2soft, One Click LCA, openLCA, Tally, Idemat, Simapro, and Sphera GaBi. Some of these tools offer integration with BIM which can ease the process of retrieving such information.

Regarding materials reusability, European Interreg NWE - FCRBE project provides a collection of 32 material sheets. Each of them highlights a specific building material or element that is commonly available on the reclamation market or via other secondhand channels, such as glulam timber, steel beam, interior doors, concrete shear wall, etc. These information sheets are designed to support designers, specifiers, and other construction project team members who want to incorporate reclaimed materials into their work. Their primary goal is to centralize existing knowledge to make the extraction and reintegration of these materials easier.

Specifically, the sheets address key questions such as:

- Which building materials are suitable for reclamation?
- What are the performance characteristics of these products, and how can their "fitness for reuse" be assessed?
- What are the correct procedures for dismantling or installing these materials?
- Where and in what quantities can these materials be sourced?
- How can these materials be properly integrated into prescriptive documents, especially specifications?

By providing answers to these questions, the sheets aim to overcome common barriers to material reclamation, ultimately promoting the reuse of construction materials through enhanced understanding of available options and practical methodologies. These material sheets are currently accessible in French, Dutch, and and English.

The links or sources of different platform and tool is summarized in the Table 6 below.

Table 6 Sustainability and Circularity Database and Tools

Platform / tool name	Function	Link
IBO	Generic LCA database	https://www.ibo.at/materialoekologie/produktauswahl/datenbanken-fuer-baustoffe
Ecoinvent	Generic LCA database	http://www.ecoinvent.com/
Eco2soft	LCA assessment	https://www.baubook.at/eco2soft/?SW=27&lng=2
Eco Platform	EPD / PCR	https://www.eco-platform.org/epd-data.html
EPD Portal	EPD / PCR	https://portal.environdec.com/login

Building Transparency	EPD / PCR	https://www.buildingtransparency.org/
Interreg NWE - FCRBE	Material reuse toolkit	https://opalis.eu/en/documentation

4.2.5 Pilot Project and Approach

A variety of platforms and templates have emerged to support MP practices:

- Platforms: Madaster and Circuland focus on lifecycle tracking and digital passports; One Click LCA and Tally support embodied carbon analysis with BIM integration.
- Frameworks and Templates: British Land and Waterman developed simplified templates; Rotor's FCRBE project provides 32 material sheets for reclaimed components.

However, these tools often operate in silos, are region-specific, or lack circularity-specific indicators. Data entry formats, indicator definitions, and user roles are rarely harmonized.

British Land's 1 Broadgate development exemplifies early MP adoption in large-scale projects. Their standardized framework includes identifying key reusable materials, defining data scope with sustainability consultants and architects, embedding MP requirements in contractor tenders, and compiling individual Material Passports into a Building Passport. This structured approach ensures consistent data capture for future reuse (Webster et al., 2024).

4.3 Regulation and Certiffication

Certification and regulation are powerful forces encouraging sustainability and circularity in construction. LEED remains the most widely recognized building certification system, rewarding actions such as embodied carbon tracking and material reuse. However, most AEC stakeholders still prioritize carbon-related target. There are others certification for different sustainability and circularity metrics which are summarized in the Table 7 below.

Table 7 Sustainability and Circularity Targets for Building Certification

Metric	**Target Reference in Standard**	**Framework/Standard**
Construction Waste Diversion	≥ 75% diversion from landfills	LEED, Zero Waste Certification
Design for Disassembly (DfD)	≥ 80% of components demountable	ISO 20887
Recycled Content	≥ 10–20%	LEED (MRc4 credit)
Reused / recycled content	≥30% reused or recycled in new projects	WorldGBC
Recycled / bio-based content	≥10% (Basic) / ≥50% (platinum)	C2C Certification
Regional Materials	≥ 20–30% sourced within 500 km	LEED
Embodied Carbon Reduction	20–50% reduction (project-specific)	EC3 Tool, Buy Clean California Act
	40% reduction by 2030 (vs 2020 baseline)	WorldGBC
	5-15% reduction vs baseline	LEED

In Europe, the Ecodesign for Sustainable Products Regulation (ESPR) mandates Digital Product Passports (DPPs) for nearly all products by 2028, with phased rollouts beginning in 2024 (EU - 2024/1781 - EN - EUR-LEX, 2024). Priority categories include iron and steel, aluminum, furniture, textiles, paints, and ICT equipment. These DPPs will capture key material characteristics, environmental impacts, and end-of-life guidance. Construction products will fall under the revised Construction Products Regulation (CPR), requiring environmental reporting from January 2026, with full DPP integration by 2028 (EUR-LEX - 02011R0305-20241117 - EN - EUR-LEX, 2024).

Meanwhile, the U.S. has adopted a different regulatory path. California's 2022 CALGreen Intervening Code update introduces embodied carbon requirements for nonresidential buildings over 100,000 sq ft and schools over 50,000 sq ft. ICC (2022) states that from July 2024, projects must comply via one of three pathways: reuse 45% of the existing structure (Section 5.105.2), achieve a 10% reduction in embodied carbon through Whole Building Life Cycle Assessment (Section 5.409.2), or meet prescriptive Environmental Product Declaration (EPD) thresholds for core materials like steel, glass, mineral wool, and concrete (Section 5.409.3)

4.4 Prioritised Material for Material Passport

In some literature it is generally stated to start creating material passports for material with high embodied carbon and/or highly reusable (Webster et al., 2024). In terms of economic consideration, Olumo and Haas (2024) created a framework to optimally select and combine reused construction material and new construction material based on their cost and carbon footprint. Their finding concluded that using reused material with new material in new projects can be a practical and economical choice. Therefore, adding cost consideration as a deciding criterion in addition to embodied carbon and reusability can attract more actors that are not sustainable driven to start creating material passport for material of that.

Commented [SS5]: update

Commented [SD6]: not in literature? but in finding / discussion

Collecting information for all materials will take too much time and cost and run the risk of data not being used at the end of life. Therefore, tracking valuable materials with high reusability and embodied carbon which will be more impactful in reducing emission or waste should be prioritized. While this can motivate some bigger companies or actors driven by sustainability, mostly other companies still prioritise profitability. Therefore, material with high economic value can also be prioritized in some cases. Adding the material price in new and used condition in material passport can help actors to decide in which case it is profitable to reuse material in case of renovation or demolition. In case the goal of a material is to be recycled or sold, resale or scrap value will be a deciding factor as well.

4.5 Information Flow in Project Lifecycle

Along with the project lifecycle, different information gets produced and updated. It is important to understand when MP-relevant information gets produced to determine when it could be extracted and then input to MP template. The filled MP template then needs to be stored properly to prevent the risk of missing information.

4.5.1 Project Stages

Project stages according to Royal Institute of British Architects (RIBA) Plan of Work 2020 is as presented in Figure 9. However, in this research, the project stages will be divided into 4 phases as presented in Table 8 which will be marked in the workflow.

Table 8 RIBA Project Stages to Workflow Phases (RIBA, 2020)

RIBA Stage no	RIBA Stage name	Workflow phases
0	Strategic Definition	1. Strategic Definition
1	Preparation and Briefing	
2	Concept Design	2. Conceptual Design
3	Spatial Coordination	3. Design Development
4	Technical Design	
5	Manufacturing and Construction	4. Manufacturing/Procurement
6	Handover	Not demonstrated
7	Use	Not demonstrated

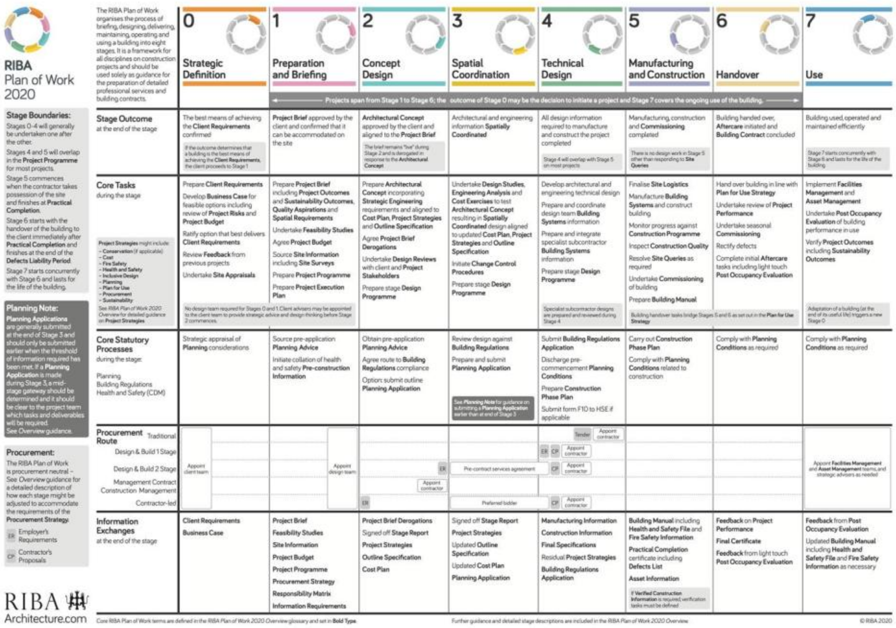


Figure 8 Project Stages according to RIBA Plan of Work 2020 (RIBA, 2020)

4.5.2 MP-Relevant Information Provider along Lifecycle

Kedir (2024) summarized MP-relevant information, its availability and main stakeholders generating information during the building lifecycle in an industrialized housing construction case, as shown in Table 9.

Table 9 MP-Relevant Information Provider along Lifecycle (Kedir, 2024)

Building lifecycle phase	MP-relevant information	Availability per functional level P	B	A	S	C	M	Type/format of information	Main actor generating the information
Find land	Building location and site plan	✓	✓					Drawing/PDF	Public authority and IC firm
	Unique building identifier		✓					Numerical code/PDF	IC firm – business developer
Design	Detailed design and specifications of building		✓	✓	✓	✓		Drawing/3D model	IC firm – business and product development
	Module name				✓			Text/3D model	IC firm – product development
	Dimensions		✓	✓	✓	✓		No./3D model	IC firm – product development
Prepare	Global trade item No. (GTIN)							–	Supplier
	Manufacturer details				✓	✓	✓	Text/PDF	Supplier
	Manufactured on				✓	✓	✓	Text/PDF	Supplier
	Dimensions				✓	✓		No./PDF	Supplier
	Weight					✓		No./PDF	Supplier
	Density							No./PDF	Supplier
	Thermal resistance and conductivity					✓		No./PDF	Supplier
	% of recycled material amount							–	Supplier
	% of renewable material amount							–	Supplier
	Reuse/recycle potential				✓	✓		–	Supplier
	Service life				✓	✓	✓	Text/PDF	Supplier
	Maintenance instruction				✓	✓		Text/PDF	Supplier
	Assembly instruction				✓	✓		Text/PDF	Supplier
	Disassembly instruction							–	Supplier
	Product certifications and labels				✓	✓		Text/PDF	Supplier
	Warranties and guarantees				✓	✓		Text/PDF	Supplier
	Take back options							–	Supplier
Execute	Manufacturer details				✓			Text/Drawing	IC firm – manufacturing team
	Manufactured on				✓			Text/Drawing	IC firm – manufacturing team
	Product function				✓			Text/Drawing	IC firm – product development
	Weight	✓			✓			No./Excel	IC firm – construction and manufacturing
	% of renewable materials amount							–	IC firm – sustainability team
	% of recycled materials amount							–	IC firm
	Reuse/recycle potential							–	IC firm
	Embodied carbon		✓	✓	✓	✓	✓	No./Excel	IC firm – sustainability team
	Operational carbon		✓	✓	✓	✓		No./Excel	IC firm – sustainability team
	Waste				✓			No./Excel	IC firm – manufacturing team
	Assembly instruction				✓			Text/Drawing/PDF	IC firm – construction team
	Disassembly instruction							–	IC firm
	Quality test		✓		✓	✓		Text/PDF	IC firm – manufacturing team
	Tracing mechanism				✓			No./sensor data	IC firm – manufacturing team
	Health and safety certifications		✓		✓	✓	✓	Text/PDF	IC firm – procurement
	Fire resistance class		✓		✓	✓		Text/PDF	IC firm – project leaders
	Building certifications and labels							–	IC firm
	Take back options							–	IC firm
Hand over	Tenancy agreement			✓				Text/PDF	Housing association
	Building ownership	✓	✓					Text/PDF	IC firm – housing association representative
Follow- up	Maintenance log							–	IC firm – follow-up team
	Annual maintenance cost		✓		✓	✓		No.	IC firm/external consultant

Source: Author's own creation

Bajare et al. (2024) emphasize the critical need for cross-sector collaboration within the built environment to maximize the effectiveness of material passports. Their research advocates for three key collaborative actions:

1. Standardization and data integration
   The establishment of unified protocols for data collection and the systematic incorporation of material passports into BIM workflows are essential to enable seamless information exchange across project lifecycles.
2. Manufacturer engagement
   Material producers must prioritize developing Environmental Product Declarations (EPDs) to validate environmental performance and ensure materials meet reuse eligibility criteria for passport inclusion.
3. Design and construction integration
   - Design Phase: Architects and engineers should integrate material passport requirements into specifications, with explicit consideration of end-of-life material value during initial design decisions
   - Construction Phase: Contractors and developers need to utilize material databases to select products based on circularity performance metrics aligned with project sustainability objectives

This multi-stakeholder approach addresses fundamental implementation barriers while creating synergies between material documentation practices and circular economy goals in construction.

5. Findings

5.1 Problem Identification

From the literature review, transition to circular economy in the construction industry context is urgent due to its high energy consumption, waste generation and carbon emission while at the same time depleting resources. Therefore, reusing material, instead of other R-strategies, has become so important to reduce waste and consumption which in turn will reduce the environmental impact (Potting et al., 2017; C. Zhang et al., 2022). However, it is hard to reuse materials whose specification is unknown. Material passports are then proposed to capture product's information regarding sustainability and circularity. Green building certification like LEED and regulation like ESPR and Calgreen will also create urgency of creating material passport soon.

However, there are some challenges associated in implementing MP. Firstly, lack of standardized approach and complexity of component data which can make MP creation process unclear (Kedir, 2021). Second, gathering data for Material Passports demands close cooperation across the value chain. However, the fragmented nature of the construction industry often leaves stakeholders unsure of who to coordinate with or when. (Honic et al., 2019). Therefore, a material passport workflow is proposed to solve both problems.

However, based on the first-round interview, everyone agrees that a more general problem is the low understanding of how to implement circularity in AEC industry within the stakeholders themselves. Consequently, material passport is a concept they never heard before and let alone consider using it. Therefore, a simplified material passport workflow could work as a starting point (S2) to adopt material passport in existing project workflow, which will eventually increase stakeholders understanding of building material circularity.

5.2 Define Objectives of Solution

As the workflow should be simple and have a manageable scope to ensure success adaptation of first-time users, these objectives of the workflow were adapted from British Land material passport approach (Webster et al., 2024):

1. Break it down to a clear goal: First, pinpoint the exact purpose of the material passport, as this can vary by company and project. For instance, it might aim to improve reuse or recycling. This helps narrow down which materials to consider and streamline data collection, focusing only on what's essential to achieve the passport's defined objective.
2. Be specific about which material and parameters: Gathering data for every single material is time-consuming and costly, and there's a risk that unused data won't be helpful later. So, it's vital to filter which materials to record in the passport. Being clear about what information to collect, when, and from whom is key. Research by 3XN shows that contractors often ask for precise expectations when providing material passports. This allows for tailoring specific information protocols for materials and developing tools to collect, record, and store data at both material and parameter levels. Instead of trying to collect all possible data, it's more effective to clearly define what information is needed from the supply chain.
3. Start now with real projects to test and learn: While a fully standardized system is ideal, testing ideas on actual projects is crucial to drive widespread action. By working with supply chains and setting up collaborative ways to share information, you can identify real-world obstacles and find practical solutions. Therefore, it's essential to begin with live projects immediately and use the feedback to continually refine the process.

The first round of interviews was then carried out to gain general feedback on the workflow and the objectives above. While interviewees agree with all three objectives, there were some suggestions regarding additional objectives.

1. Integration with existing used platforms like building management or facility management software, and some degree of automation (C2, C3, S1).
2. This workflow might be more attractive if it enables them to reduce costs or embodied carbon due to reusing materials, rather than only reusing the material itself (S1, S2).
3. Streamline the material passport relevant data extraction and collection process to project activities sequence to prevent the risk of missing the relevant information and minimize the effort needed during the project (S1).

Commented [SS7]: Move to discussion?

1. In terms of reusing material, most owners would not think in that direction yet (C1, S1). Currently building owners are only interested in reducing embodied carbon or cost (C1, S2). Therefore, the workflow is expected to prioritize tracking higher value materials.
    1. Prioritise tracking high value materials.

Collecting information for all materials will take too much time and cost and run the risk of data not being used at the end of life. Therefore, tracking high value materials with high reusability and embodied carbon which will be more impactful in reducing emission or waste should be prioritized. While this can motivate some bigger companies or actors driven by sustainability, mostly other companies still prioritises profitability. Therefore, material with high economic value can also be prioritized in some cases. Adding the material price in new and used condition in material passport can help actors to decide in which case it is profitable to reuse material in case of renovation or demolition. In case the goal of a material is to be recycled or sold, resale or scrap value will be a deciding factor as well.

However, these objectives were collected from general interviewees and considered as additional objectives that could be considered. For the specific implementation case in this research, after some discussion with the owners it was agreed that the workflow objective is to collect relevant data to enable future disassembly of the building. As this finding is related to the demonstration phase, other findings leading to this decision are available in Section 5.4.

All objectives were summarized in the Table 10 below.

Table 10 Identified objectives

No	Objective	Source
1	Break it down to a clear goal	Literature (Webster et al., 2024)
2	Be specific about which material and parameters	
3	Start now with real project to test and learn	
4	Integration with existing used platforms	Interview (C2, C3, S1)
5	Enables stakeholders to reduce costs or embodied carbon	Interview (S1, S2)
6	Streamline MP creation to project activities	Interview (S1)
7	Collect relevant data to enable future disassembly of the building	Project's client

5.3 Artifact Design and Development

The initial artifact in the first iteration consists of stakeholder roles/responsibilities in data collection (presented in Appendix D) and workflow (which is coded as initial workflow in Appendix B).

Initially, the data points in responsibilities list were benchmarked from the Waterman Material Passport Framework (Stella et al., 2023) and assigned to relevant stakeholders which produce the data during the lifecycle. During the first-round interview, it received some feedback. While structural engineers (S1, S2) agree with their responsibilities as designers, construction managers (C2, C3) think there are a lot of responsibilities, and they will need to assign a dedicated person just to do the workflow. All construction managers (C1, C2, C3) also mentioned the importance of starting the workflow early to enable appropriate planning and setting up for implementation in the project.

The responsibilities of the stakeholders are closely related to the workflow or activities sequence as one stakeholder cannot fulfill their responsibility if another stakeholder of previous activity has not completed the activity. Initially, the workflow is adapted from British Land approach to circular economy (Webster et al., 2024) approach in creating new Material Passports which consist of these practical steps:

1. Identify key materials that is reusable
2. Define specific data needed for these materials
3. Establish the material passport requirements for the Employer.
4. Gather required data for Material Passports
5. Submit this collected information to the British Land Portfolio Overview.

Steps 1, 2, and 4 are then mapped into the logical sequence of project activities. The initial version of the workflow is available in Appendix B. This initial version does not have a template yet because it focuses on determining the right sequence and responsibilities.

Commented [SD8]: MP-relevant data will be extracted from BIM models, manufacturer product specification, EPD, supply chain and logistic data, and when not available, generic databases will be used as benchmark. The data will then be organised into pre-defined component-level and building-level MP templates. The templates will be created with spreadsheets and then resulting MPs will be stored into BIM360 / Autodesk Construction Cloud.

Relevant feedback of the workflow from the first-round interview which is incorporated to improve in the second iteration is as follows:

1. The process looks correct at a high level (C2, C3, S1).
2. The process lacks the loop between engineers and owners in discussing material passport scope in initial phases (S2).
3. The process lacks differentiation between principal contractors and sub-contractors' roles (C2, S1).
4. Activities should be marked or mapped into different project lifecycles: conceptual design, design development, procurement, construction, handover/operation (C1).
5. The process needs to start as early as possible, and to enable early planning (C1, C2, C3) and align the relevant data extraction timing to project activities (S1).
6. It is not clear how to identify key reusable materials (S2).

Because it was not clear how to identify key reusable materials, material filters were also designed. The filters sequence is based on an interview with one of the authors (will be cited as B1) of the British Land material passport approach (Webster et al., 2024).

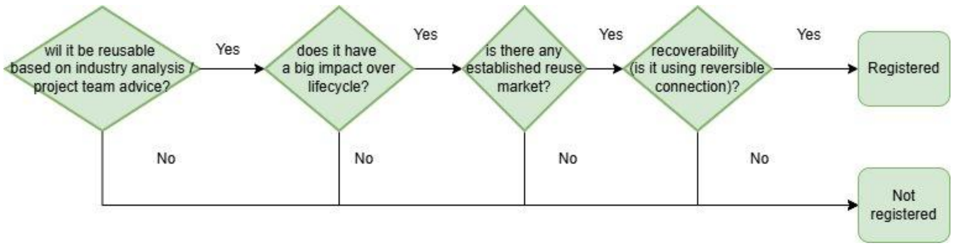


Figure 9 Highly Reusable Material Filter

More explanations about the filters are as follows:

1. Will it be reusable based on industry analysis or project team advice?
   Industry analysis should be done first to understand which materials are usually reused or recycled globally. The project team may advise other materials that are not on the list, given the potential reusability in the future due to the building service life or potential growing reuse market of certain materials.
2. Does it have a big impact on lifecycles?
   If a material is high in quantity and/or often gets replaced during the building's lifespan, then it is considered to have a big impact on the building, because the total embodied carbon over the lifecycle or waste volume in the end of life would be high.
3. Is there any established reuse market?
   Afterwards, whether a material has an established reuse market (e.g. reclaimed material store) in the nearby region is investigated.
4. Recoverability: is it using reversible connection?
   Finally, if the material will be installed using a reversible connection (e.g. dry connection or bolt and screw) that will enable easy disassembly, then the material should be registered into the material passport.

After the first-round interview, the second iteration starts. In this phase the artifact will consist of improved workflow and responsibilities, and a template for data collection demonstration. For clearer visuals, the improved workflow is presented on Appendix B.

Before the data collection is started, stakeholders are also required to collaborate in planning how material passports can be implemented and how key circular design principles are implemented. The steps were referencing the key actions of circular strategy from the responsibility matrix in the British Land report (Webster et al., 2024). The summarized responsibility of each step / action is shown in Table 11, while the detailed data collection responsibilities are shown in Table 12. Responsibilities are expressed with RACI terms, which is R=Responsible, A=Accountable, C=Consulted, I=Informed. Only one party can be the accountable one.

Table 11 Summarized Responsibilities List

Phase / RIBA stage	No	Activities	O	SC	A	SE	GC	S
Strategic Definition (0-1)	1	Define project circularity goal	R,A	R	C	C	I	-
Concept Design (2)	2	Define material passport concept	A,C	R	C	C	-	-
Developed Design & Technical Design (3-4)	3	Identify or select key reusable materials	A,C	R	R	R	-	-
	4	Determine material passport scope and create template	A	R	C	C	I	-
	5	Incorporating key circular design principle	I	R	R	R	A,C	-
	6	Extract design-related information and fill in the template	I	C	R	R	A,C	-
Manufacturing (5)	7	Extract manufacturer-related information from various sources	I	C	I	I	R,A	R
	8	Fill in manufacturer-related information to the template	I	C	I	I	R,A	C

O	Owner
SC	Sustainability Consultant
A	Architect
SE	Structural Engineer
GC	General Contractor
S	Supplier / Sub-contractor

Table 12 Stakeholders Roles and Responsibilities in Material Passport Data Collection

Commented [SS9]: update

Category		Input field	Description	Document Source	Provided by	Input by	Check by	By the end of RIBA Stage?
Design - related	Classification	Discipline	From which discipline is the product mainly	BIM Model	designer	designer	general contractor	4
		Layer	Layer of the component	BIM Model	designer	designer	general contractor	4
		Family	Family type from Revit Model	BIM Model	designer	designer	general contractor	4
		MID	Unique code of the component type	BIM Model	designer	designer	general contractor	4
		Component	Subclassification of component	BIM Model	designer	designer	general contractor	4
		Type	Size and/or shape variation of component	BIM Model	designer	designer	general contractor	4
	Component geometry	Length	Length of the component	BIM Model	designer	designer	general contractor	4
		Width	Width of the component	BIM Model	designer	designer	general contractor	4
		Height	Height of the component	BIM Model	designer	designer	general contractor	4
		Volume	Volume of the component	BIM Model	designer	designer	general contractor	4
		Density	Density of the component	Technical sheet	designer	designer	general contractor	4
		Mass	Mass of the component	Calculated	designer	designer	general contractor	4
	Design for disassembly	Connection Variation	Which connection variation is this?	Shop Drawing	designer	designer	general contractor	5
		Designed for disassembly	Is the component designed to enable disassembly from adjacent components?	Shop Drawing	designer	designer	general contractor	5
		Connection Type (CT)	What is the connection type that has a load-bearing function for the product in question?	Shop Drawing	designer	designer	general contractor	5
		Connection Accessibility (CA)	Can the connecting elements be accessed physically and to what extent does damage occur to surrounding objects?	Shop Drawing	designer	designer	general contractor	5
		Independency (IC)	How products are intermingled with other system or layer with differing lifetimes	Shop Drawing	designer	designer	general contractor	5
		Product Edge (PE)	How products are placed in a composition and whether this is open or closed.	Shop Drawing	designer	designer	general contractor	5
	Intended Performance - structural	Compression strength (psi)	Required structural properties for design	Design specification schedule	designer	designer	general contractor	4
		Tensile strength (psi)		Design specification schedule	designer	designer	general contractor	4
		Flexural strength (psi)		Design specification schedule	designer	designer	general contractor	4
		Shear strength (psi)		Design specification schedule	designer	designer	general contractor	4
		Modulus of elasticity (ksi)		Design specification schedule	designer	designer	general contractor	4
Manufacturing - related	Manufacturer information	Product Name	Name of the product	Technical sheet	supplier/subcontractor	general contractor	Sustainability consultant	5
		Manufacturer Name	Name of the manufacturer company	Technical sheet	supplier/subcontractor	general contractor	Sustainability consultant	5
		Manufacturer location	Location of the manufacturer company	Technical sheet	supplier/subcontractor	general contractor	Sustainability consultant	5
		Certification of product	List of important certification of the product 3-	Technical sheet	supplier/subcontractor	general contractor	Sustainability consultant	5
	Material composition	Material composition	List of the material composition	Technical sheet / EPD	supplier/subcontractor	general contractor	Sustainability consultant	5
		Material percentage	Corresponding percentage of the	Technical sheet / EPD	supplier/subcontractor	general contractor	Sustainability consultant	5
	Use stage	Assembly instruction	Is the assembly instruction available?	Assembly manual	supplier/subcontractor	general contractor	Sustainability consultant	5
		Maintenance instruction	Is the maintenance instruction available?	Maintenance manual	supplier/subcontractor	general contractor	Sustainability consultant	5
		Annual replacement percentage	What percentage of the mass of the	Technical sheet / EPD	supplier/subcontractor	general contractor	Sustainability consultant	5
	Carbon	Carbon- declared unit	What is the functional unit that has been	EPD / Sustainability sheet	supplier/subcontractor	general contractor	Sustainability consultant	5
		Carbon- Manufacturing A1-A3	What is the manufacturing carbon (A1-A3) of the material for the selected functional unit in kgCO2eq?	EPD / Sustainability sheet	supplier/subcontractor	general contractor	Sustainability consultant	5
		Carbon- Sequestered A1-A3	If applicable, what is the sequestered carbon	EPD / Sustainability sheet	supplier/subcontractor	general contractor	Sustainability consultant	5
		Carbon-EOL C1-C4	If applicable, what is the end-of-life carbon	EPD / Sustainability sheet	supplier/subcontractor	general contractor	Sustainability consultant	5
		Carbon-Recovery D	If applicable, what is the resource recovery	EPD / Sustainability sheet	supplier/subcontractor	general contractor	Sustainability consultant	5
	Circularity	Lifespan (years)	How many years the component can be used	EPD / Sustainability sheet	supplier/subcontractor	general contractor	Sustainability consultant	5
		Take-back service	Does the manufacturer support a take-back scheme ?	EPD / Sustainability sheet	supplier/subcontractor	general contractor	Sustainability consultant	5
		Reuse potential	How can the component be reused ?	EPD / Sustainability sheet	supplier/subcontractor	general contractor	Sustainability consultant	5
		Detachability	Can the elements be disassembled based on connection details of the built construction	-	supplier/subcontractor	general contractor	Sustainability consultant	5
		Recyclability	How can the component be recycled?	EPD / Sustainability sheet	supplier/subcontractor	general contractor	Sustainability consultant	5
		Biodegradability	Is the material organic / can fully decompose and return to the environment?	EPD / Sustainability sheet	supplier/subcontractor	general contractor	Sustainability consultant	5
	Performance overview - Structural	Compression strength (psi)	Required structural properties for design	Technical sheet	supplier/subcontractor	general contractor	designer	5
		Tensile strength (psi)		Technical sheet	supplier/subcontractor	general contractor	designer	5
		Flexural strength (psi)		Technical sheet	supplier/subcontractor	general contractor	designer	5
		Shear strength (psi)		Technical sheet	supplier/subcontractor	general contractor	designer	5
		Modulus of elasticity (ksi)		Technical sheet	supplier/subcontractor	general contractor	designer	5
	Material specific	Properties	What are the key properties considered to reclaim the material?	Technical sheet	supplier/subcontractor	general contractor	Sustainability consultant	5
		Values	What is the value of that property?	Technical sheet	supplier/subcontractor	general contractor	Sustainability consultant	5

The following explanation is an example of using Table 11 to fill in the data Product Name under the manufacturing related and the manufacturer information. First, the information needs to be provided by the supplier / manufacturer of the product through the document source of technical sheet which is indicated in the columns "Provided by" and "Document Source" respectively. Then, as it is assumed that it will be hard to grant access to all suppliers, the data will be input by general contractor as indicated by the column "input by". When all data (other fields and products) is gathered, the data might be checked by the sustainability consultant by the end of RIBA stage 5 as shown in the columns "check by" and "By the end of RIBA stage?" consecutively.

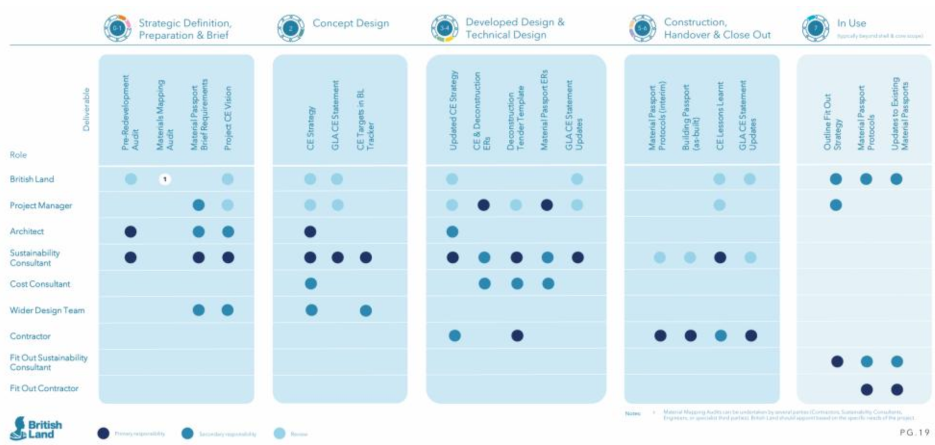


Figure 10 Circularity Action Responsibility Matrix (Webster et al., 2024)

Based on the matrix in Figure 11, the sustainability consultant is given a lot of primary responsibilities, from strategic definition to handover phase, in preparing the strategic circular economy requirements to the detailed template for use. Therefore, in this research, I acted as a sustainability consultant with those responsibilities. It was newly added to the workflow and responsibility list in the second iteration.

A template (Table 14) paired with its instructions (Table 13) was then created for data collection demonstration. The full template and instructions are available in Appendix E. One suggestion for the template from the first-round interviewee (S2) is to use a widely used format like spreadsheet so that suppliers or contractors will easily access that. The level of the data that should be collected was also investigated through a data collection demonstration.

Commented [SS10]: Add appendix template

Table 13 Instruction

Category		Input field	Description	Document Sourc	Input type	Input option	Description
	Design for disassembly	Designed for disassembly	Is the component designed to enable disassembly from adjacent components?	-	list	yes / no	-
		Connection Type (CT)	What is the connection type that has a load-bearing function for the product in question?	-	list	CT.DC - Dry connection	include : loose (no fastening material), click, velcro, magnetic
						CT.AE - Connection with added elements	include : bolt and nut, spring, corner, screw, connections with add
						CT.DI - Direct integral connection	include : pin, nail
						CT. SC - Soft chemical connection	include : caulking, foam (PUR)
						CT.HC - Hard chemical connection	include : adhesive, dump, weld, cementitious, chemical anchor
		Connection Accessibility (CA)	Can the connecting elements be accessed physically and to what extent does damage occur to surrounding objects?	-	list	CA.FA - Freely accessible without additional actions	freely accessible without additional equipment with no damage to
						CA.AN - Accessible with additional actions (no damage)	accessible with additional equipment with no damage to surroun
						CA.AR - Accessible with additional actions (repairable damage)	accessible with additional equipment with repairable damage to s
						CA.NI - Not accessible (irreparable damage)	not accessible with irreparable damage to surrounding objects
		Independency (IC)	How products are intermingled with other system or layer with differing lifetimes	-	list	IC.NI-No independency, modular zoning	products are not traversing other products and can be disassembl
						IC.OI-Occasional independency	products are occasionally traversing other products and can be d
						IC.FI-Full integration	products are fully integrated with other products and cannot be d
		Product Edge (PE)	How products are placed in a composition and whether this is open or closed.	-	list	PE.OP - Open, no obstacle	Products are not enclosed by surrounding products
						PE.OV - Overlapping, partial obstruction	Products are partially enclosed by surrounding products
						PE.CL - Closed, complete obstruction	Products are fully enclosed by surrounding products
	Intended	Compression strength (psi)	Required structural properties	Design	numbers	-	-

Table 14 Template

<table>
<tr><th colspan="3">Classification</th><th colspan="5">Design for disassembly</th><th colspan="4">Manufacturer</th><th colspan="2">Material composition</th></tr>
<tr><td>Discipline</td><td>Compone nt</td><td>Type</td><td>Designed for disassembly</td><td>Connection Type (CT)</td><td>Connection Accessibility (CA)</td><td>Independency (IC)</td><td>Product Edge (PE)</td><td>Product Name</td><td>Manufacturer Name</td><td>Manufacturer location</td><td>Certification</td><td>Material composition</td><td>Material percentage</td></tr>
<tr><td>Structure</td><td>Beam</td><td>SEB 4"x6"</td><td>Yes</td><td>CT.DC - Dry connection</td><td>CA.AN - Accessible with additional actions (no damage)</td><td>IC.NI-No independe ncy, modular zoning</td><td>PE.OV - Overlappin g, partial obstruction</td><td>Renuteq frame SEB</td><td>Renuteq</td><td>USA</td><td>EA Credit 1 | Optimize Energy Performance; MR Credit 6 | Rapidly Renewable Resources; MR Credit 7 | Certified Woods; EQ Credit 4.1 | Low-Emitting Adhesives and Sealants; EQ Credit 4.1 | Low-Emitting Materials</td><td>(Sturctually Engineered) Bamboo; VOC Finish</td><td>100%; Not Found</td></tr>
</table>

The artifact is then demonstrated focusing on the data collection process.

5.4 Demonstration

The initial artifact of the workflow and responsibilities list was presented in the first-round interview, to show the sequence and responsibilities in data collection. While it received some valuable feedback, a template is still needed to investigate users' perspective.

The second iteration aims to demonstrate the workflow and observe data collection process through an implementation case. The Global AEC Teamwork course was then chosen as an implementation case.

Following the workflow, I gained some insights as follows:

1. Define project circularity goal
   During strategic definition (RIBA stage 1), the client has three main goals for the building, which are net zero energy, adaptable building, and highly prefabricated. From those three goals, adaptable building is identified as a key circular goal of the project. The building will be designed to be easily disassembled, which enables redevelopment in the future due to the changing need of future learning.
2. Define material passport concept
   As a sustainability consultant I suggest implementing material passports to record the required information to achieve the circularity goal. In this project's case, to implement a material passport with a goal to collect data enabling Design for Disassembly (DfD). This step can be implemented between strategic definition and the start of conceptual design (RIBA stage 1-2).
3. Identify or select key reusable materials
   During conceptual design (RIBA stage 2), two structural system alternatives, concrete and bamboo, were compared. Based on various considerations, mainly regarding the three project goals, bamboo alternatives were chosen. It marked the end of RIBA stage 2. Below is the building model in Revit.

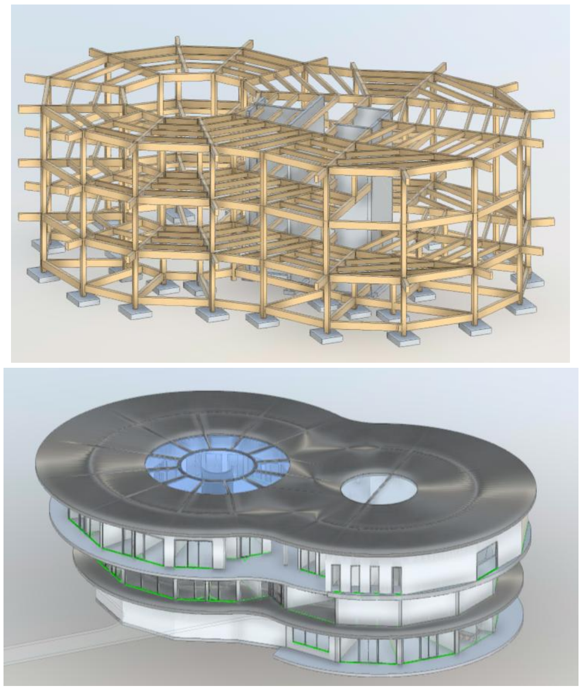


Figure 11 BIM Model: Structural system (top) and linked model (bottom) in conceptual phase (RIBA Stage 2)

In design development (RIBA stage 3) using the four filters in Figure 10, building materials in Figure 12 is filtered to select the reusable materials to be recorded in the material passport. The full result is presented in Table 15.

Table 15 Reusable Materials

Family	Type	Area (SF)	Length (LF)	Volume (CF)	Volume in the building (%)	Filter 1	Filter 2	Filter 3	Filter 4	Registered?
Doors	Alumunium door 6x10	120		120	0%	-	-	-	-	-
	Alumunium door 3x7	1071		223.125	0%	-	-	-	-	-
Floors	CLB 6	27216.5		13608.25	21%	Yes	Yes	Yes	Yes	Yes
Furniture	-				0%	-	-	-	-	-
Generic Models	-				0%	-	-	-	-	-
Pipes	-				0%	-	-	-	-	-
Railings	-				0%	-	-	-	-	-
Roofs	CLB 9	13721.84		10291.38	16%	Yes	Yes	Yes	Yes	Yes
Specialty Equipment	-				0%	-	-	-	-	-
Structural Columns	SEB 14 X 14		1953	2658.25	4%	Yes	Yes	Yes	Yes	Yes
Structural Foundations	CIP concrete			9456.03	15%	No	-	-	-	-
Structural Framing	Beam 8x16		2818	2504.888889	4%	Yes	Yes	Yes	Yes	Yes
	Girder 12x24		4248	8496	13%	Yes	Yes	Yes	Yes	Yes
Walls	concrete 8' high, 12" thick	2745		2745	4%	No	-	-	-	-
	Metal stud 2 coat Gypsum	66358		13824.58333	21%	No	-	-	-	-
Windows	Alumunium window 2'8" x 5'	680		680	1%	No	-	-	-	-

At this stage, it is estimated that 58% of the building's material is structurally engineered bamboo (SEB). It was assumed to have similar characteristics as timber, therefore it passed through the first filter, as recommended/suggested by the project team. It also has a big impact on the lifecycle for its big quantities in the building. Afterwards, timber is widely used in the US, so it passed through the third filter. Typical structural bamboo is designed using a bolt and screw connection (Figure 13), which is considered reversible and therefore will enable easier disassembly.

Other materials like cast-in-place (CIP) concrete and its reinforcing steel used in foundation, are assumed to be not easily recoverable. The exact specifications of interior walls, windows, and door types are not known at this moment, so it is assumed not reusable. However, the final specification of the interior walls (which is known after the end of RIBA stage 4 / step 5) were using click connection, in which it is even more reusable than the SEB components.

Figure 12 SEB Beam to Column Connection (RENÜTEQ, n.d.)

4. Determine material passport information scope and create template
   The general information scope for all materials is adapted from Waterman Material Passport Framework (Stella et al., 2023). Additionally, based on the selected material, which is structurally engineered bamboo (SEB), specific information scope is added which is adapted from the glulam timber's information requirement (Rotor vzw/asbl, 2021) as SEB in this case is assumed to have similar characteristics compared to mass timber. The additional information is species, natural durability to fungal attacks, humidity level, and fire resistance. The full scope is illustrated in Table 16. A template is then created to collect the required information based on the scope. It is important to implement this step before the tender to select the main contractor (end of RIBA stage 2), so it can be included in the Employer Requirements (ER) and contractors can also include their approach of collecting the material passport information (B1). However, in this demonstration case it was implemented during design development (RIBA stage 3-4) phase due to time limitation in conceptual design.

Table 16 Material Passport information scope

Category		Input field	Description	Document Source
Design - related	Classification	Discipline	From which discipline is the product	BIM Model
		Layer	Layer of the component	BIM Model
		Family	Family type from Revit Model	BIM Model
		MID	Unique code of the component type	BIM Model
		Component	Subclassification of component	BIM Model
		Type	Size and/or shape variation of component	BIM Model
	Component geometry	Length	Length of the component	BIM Model
		Width	Width of the component	BIM Model
		Height	Height of the component	BIM Model
		Volume	Volume of the component	BIM Model
		Density	Density of the component	Technical sheet
		Mass	Mass of the component	Calculated
	Design for disassembly	Connection Variation	Which connection variation is this?	Shop Drawing
		Designed for disassembly	Is the component designed to enable disassembly from adjacent components?	Shop Drawing
		Connection Type (CT)	What is the connection type that has a load-bearing function for the product in question?	Shop Drawing
		Connection Accessibility (CA)	Can the connecting elements be accessed physically and to what extent does damage occur to surrounding objects?	Shop Drawing
		Independency (IC)	How products are intermingled with other system or layer with differing lifetimes	Shop Drawing
		Product Edge (PE)	How products are placed in a composition and whether this is open or closed.	Shop Drawing
	Intended Performance - structural	Compression	Required structural properties for design	Design specification
		Tensile strength		Design specification
		Flexural strength		Design specification
		Shear strength		Design specification
		Modulus of		Design specification
Manufacturing - related	Manufacturer information	Product Name	Name of the product	Technical sheet
		Manufacturer	Name of the manufacturer company	Technical sheet
		Manufacturer	Location of the manufacturer company	Technical sheet
		Certification of	List of important certification of the	Technical sheet
	Material composition	Material	List of the material composition	Technical sheet / EPD
		Material	Corresponding percentage of the	Technical sheet / EPD
	Use stage	Assembly	Is the assembly instruction available?	Assembly manual
		Maintenance	Is the maintenance instruction	Maintenance manual
		Annual	What percentage of the mass of the	Technical sheet / EPD
	Carbon	Carbon-	What is the functional unit that has been	EPD / Sustainability sheet
		Carbon-Manufacturing A1-A3	What is the manufacturing carbon (A1-A3) of the material for the selected functional unit in kgCO2eq?	EPD / Sustainability sheet
		Carbon-	If applicable, what is the sequestered	EPD / Sustainability sheet
		Carbon-EOL C1-	If applicable, what is the end-of-life	EPD / Sustainability sheet
		Carbon-	If applicable, what is the resource	EPD / Sustainability sheet
	Circularity	Lifespan (years)	How many years the component can be	EPD / Sustainability sheet
		Take-back service	Does the manufacturer support a take-back scheme ?	EPD / Sustainability sheet
		Reuse potential	How can the component be reused ?	EPD / Sustainability sheet
		Detachability	Can the elements be disassembled based on connection details of the built construction	-
		Recyclability	How can the component be recycled?	EPD / Sustainability sheet
		Biodegradability	Is the material organic / can fully decompose and return to the environment?	EPD / Sustainability sheet
	Performance overview - Structural	Compression	Required structural properties for design	Technical sheet
		Tensile strength		Technical sheet
		Flexural strength		Technical sheet
		Shear strength		Technical sheet
		Modulus of		Technical sheet
	Material specific	Properties	What are the key properties considered to reclaim the material?	Technical sheet
		Values	What is the value of that property?	Technical sheet

5. Incorporating key circular design principle
   During design development (RIBA stage 3-4), architecture and structural engineers were encouraged to apply Design for Disassembly (DfD) principles if it is still within the primary constraints (environmental, site, budget). Acting as the sustainability consultant, I also suggested some alternative reversible connections usually used in mass timber in addition to the typical steel connection options for the SEB members. The proposed traditional mortise and tenon joint in glulam beam-to-column connection eliminate the use of steel connection and enable easier deconstruction. It was implemented by Swinerton in collaboration with Timberlab in the Heartwood project (Swinerton, 2023), which is the tallest mass timber building in Washington. However, due to the performance requirement, the steel connection option was chosen. After the design is ready for construction (RIBA stage 5) data collection can be simulated.
6. Extract design-related information and fill in the template
   Design-related information is demonstrated to be extracted and filled in to the template by structural engineers in RIBA stage 3-4. As the geometry and classification data can be automatically generated from BIM, the demonstration with the team skipped that step and focused on the process of collecting information regarding Design for Disassembly (DfD).
   The questions and input option for assessing DfD is referenced from the Disassembly Potential Measurement Methodology from DGBC (Dutch Green Building Council) which is presented by Van Vliet et al., (2021). It assesses four indicators, including assessing connection types, connection accessibility, independence, and product edge. Below are the options of each indicator and its score in which a higher score indicates easier disassembly.

Table 17 Disassembly Potential Indicators Scoring (Durmisevic, 2006)

Connection type (CT)		Score
Dry connection	Loose (no fastening material)	1,00
	Click connection	
	Velcro connection	
	Magnetic connection	1.00
Connection with added elements*	Bolt and nut connection	0,80
	Spring connection	
	Corner connections	
	Screw connection	
	Connections with added connection elements**	
Direct integral connection	Pin connections***	0,60***
	Nail connection	
Soft chemical connection	Caulking connection	0,20
	Foam connection (PUR)	
Hard chemical connection	Adhesive connection	0,10
	Dump connection	
	Weld connection	
	Cementitious connection	
	Chemical anchors	
	Hard chemical connection	

Connection accessibility (CA)	Score
Freely accessible without additional actions	1.00
Accessible with additional actions that do not cause damage	0.80
Accessible with additional actions with fully repairable damage	0.60
Accessible with additional actions with partially repairable damage	0.40
Not accessible - irreparable damage to the product or surrounding products	0.10

Independency (ID)	Score
No independency - modular zoning of products or elements from different layers.	1.00
Occasional independency of products or elements from different layers.	0.40
Full integration of products or elements from different layers.	0.10

Geometry of product edge (GPE)	Score
Open, no obstacle to the (interim) removal of products or elements.	1.00
Overlapping, partial obstruction to the (interim) removal of products or elements.	0.40
Closed, complete obstruction to the (interim) removal of products or elements.	0.10

The design that was assessed for the disassembly potential was the detailed design phase shown in Figure 14.

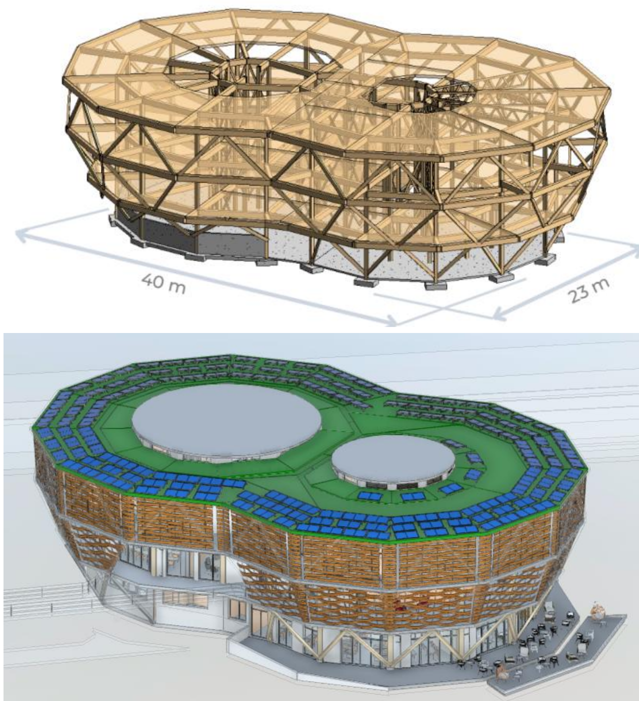


Figure 13 BIM Model: Structural system (top) and linked model (bottom) in detailed design phase (RIBA Stage 4)

Instead of the whole structural bamboo system, only the beams were assessed. The structural engineers assessed disassembly potential of each beam connection design variant using four indicators, as shown in Table 17, including connection types, connection accessibility, independence, and product edge. Overall, structural engineers need 8 minutes to assess the disassembly potential of beams based on the four-connection design variant: beam-to-beam, beam-to-column, beam-to-truss, and beam-to-diagrid using shop drawings like in Figure 15. The filled data is presented in Table 18.

Table 18 Design-related information from BIM and technical specifications

Classification	Discipline	Structural
	Layer	Shell
	Family	Bracing
	MID	111
	Component	Beam
	Type	SEB 8"x16"

Component geometry	Length	<varies>
	Width (inch)	8
	Height (inch)	16
	Total Volume (CF)	2505
	Density (lbs/ft3)	42
	Mass (lbs)	105210
Intended Performance - structural	Compression strength (psi)	13488
	Tensile strength (psi)	21465
	Flexural strength (psi)	13100
	Shear strength (psi)	2901
	Modulus of elasticity (ksi)	4086

Table 19 Design for disassembly data from structural engineers

Design for disassembly					
Connection variation	Designed for disassembly	Connection Type (CT)	Connection Accessibility (CA)	Independency (IC)	Product Edge (PE)
Beam - beam	Yes	CT.AE - Connection with added elements	CA.AN - Accessible with additional actions (no damage)	IC.NI-No independency, modular zoning	PE.OP - Open, no obstacle
Beam - column	Yes	CT.DI - Direct integral connection	CA.AR - Accessible with additional actions (repairable damage)	IC.NI-No independency, modular zoning	PE.OP - Open, no obstacle
Beam - truss	Yes	CT.AE - Connection with added elements	CA.AN - Accessible with additional actions (no damage)	IC.NI-No independency, modular zoning	PE.OP - Open, no obstacle
Beam - diagrid	Yes	CT.DI - Direct integral connection	CA.AN - Accessible with additional actions (no damage)	IC.NI-No independency, modular zoning	PE.OP - Open, no obstacle

Although it only took 8 minutes to fill in the data assessing the disassembly potential, initially it took around 20-30 minutes to introduce the four indicators of disassembly potential to structural engineers.

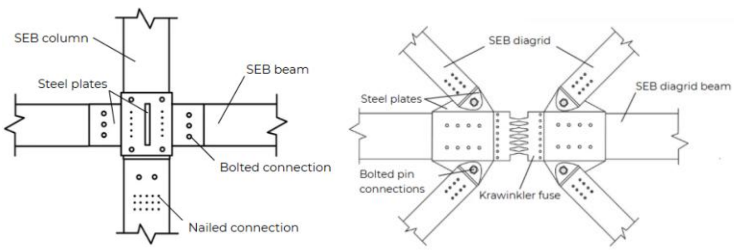


Figure 14 Shop drawing of typical SEB connection: beam-to-column (left) and beam-to-diagrid (right)

7. Extract manufacturer-related information from various sources
   Manufacturer-related information in PDF format was collected by me from the manufacturer website and email communication, in which some are shown in Figure 16. The PDFs are then shown to the participant acting as construction manager so that they can extract the information and input it into the template.

Specifics of ReNüTeq SEB product End of Life:

Recyclability:
ReNüTeq products are considered as <u>non-recyclable</u>, as the definition requires that products may be blended and/or dissolved down, and reconstituted into the exact same product, such as what is possible with most aluminum/steel, and many plastics. SEB may be ground down or cut down into smaller elements and manufactured into other non-structural products such as: fiber board, particle board, flooring, furniture, or other commodity applications.

Reusability:
ReNüTeq products are considered as reusable: SEB may be implemented into similar applications with minimal modification. In most cases, ReNüTeq products may be lightly sanded, fabricated, and re-used for many other applications, both structural and non-structural.

Adhesive Content:
ReNüTeq implements only <u>Low VOC Adhesives</u> and finishes. SEB, at the cellular level is very dense and has a very closed cellular structure: Because of this, adhesives and finishes are unable to penetrate below the surface of the SEB material. The result of this low penetration is very low adhesive content absorption into the finished product.

ReNüTeq®

<u>ReNüTeq® Frame Series (SEB)</u>
<u>Component Mechanical Properties</u>

*Allowable/Design Values for ReNüTeq **(SEB) Structural Engineered Bamboo (Species: Guadua Angustifolia)**

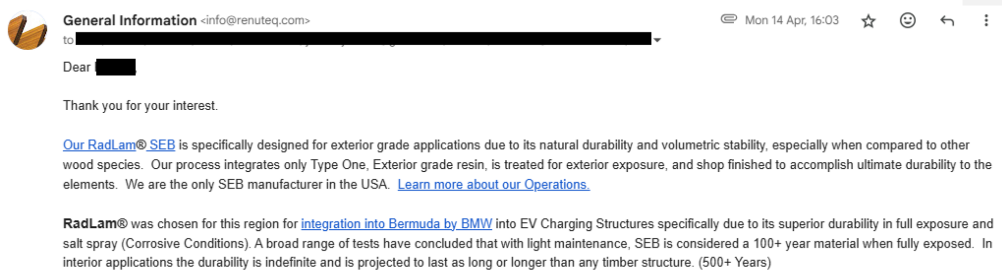
<u>Compression:</u>
- **Parallel to grain: 13,488 psi (93 MPa) - Perpendicular to grain: 3043 psi (20 MPa) (ASTM D198)**

<u>Tensile Strength:</u>
- **Parallel to grain: 21,465 psi (147 MPa) - Perpendicular to grain: 543 psi (3.7 MPa) (ASTM D198)**

<u>Flexural Strength:</u>
- **13,100 psi (90.3 MPa) (ASTM D 198)**

<u>Shear Strength:</u>
- **2,901 psi (20 MPa) (ASTM D 198 (Section 45)**

<u>Modulus of Elasticity & Modulus of Rigidity</u>
- **MOE: 4,086 Ksi (28,172 Mpa) - MOR: 28,000 psi (193 Mpa) (ASTM D 198)**



General Information <info@renuteq.com> Mon 14 Apr, 16:03
to [redacted]
Dear [redacted]

Thank you for your interest.

Our RadLam® SEB is specifically designed for exterior grade applications due to its natural durability and volumetric stability, especially when compared to other wood species. Our process integrates only Type One, Exterior grade resin, is treated for exterior exposure, and shop finished to accomplish ultimate durability to the elements. We are the only SEB manufacturer in the USA. Learn more about our Operations.

RadLam® was chosen for this region for integration into Bermuda by BMW into EV Charging Structures specifically due to its superior durability in full exposure and salt spray (Corrosive Conditions). A broad range of tests have concluded that with light maintenance, SEB is considered a 100+ year material when fully exposed. In interior applications the durability is indefinite and is projected to last as long or longer than any timber structure. (500+ Years)

Figure 15 Manufacturing related information of structural bamboo

8. Fill in manufacturer-related information to the template
   For the construction managers, CA and CB needed 28 and 35 minutes respectively to scan the information and register the information of the structural bamboo beam material. Embodied carbon information collection demonstration is skipped, assuming it can be automatically generated from an LCA software. Therefore, the data filled with the structural bamboo is as follows (Table 20 and 21).

Table 20 Manufacturer-related information from construction managers

Manufacturer information	Product Name	Renuteq frame series (SEB)
	Manufacturer Name	Renuteq
	Manufacturer location	USA
	Certification of product	EA Credit 1 | Optimize Energy Performance; MR Credit 6 | Rapidly Renewable Resources; MR Credit 7 | Certified Woods; EQ Credit 4.1 | Low-Emitting Adhesives and Sealants; EQ Credit 4.1 | Low-Emitting Materials
Material composition	Material composition	(Structurally Engineered) Bamboo
	Material percentage	100%
Use stage	Assembly instruction	Yes
	Maintenance instruction	No
	Annual replacement percentage	No
Carbon	Carbon- declared unit	m3
	Carbon- Manufacturing A1-A3	6057
	Carbon- Sequestered A1-A3	-1316
	Carbon-EOL C1-C4	-
	Carbon-Recovery D	-
Circularity	Lifespan (years)	100+ Years for fully exposed exterior / 500+ Years for interior
	Take-back service	Not known

	Reuse potential	Yes
	Detachability	Yes
	Recyclability	Yes, downcycle
	Biodegradability	Yes
Performance overview - Structural	Compression strength (psi)	13488
	Tensile strength (psi)	21465
	Flexural strength (psi)	13100
	Shear strength (psi)	2901
	Modulus of elasticity (ksi)	4086

Table 21 Material specific information: SEB

Material specific	Properties	Species	Glue	Moisture level	Natural Durability	Fire resistance	Treatment
	Values	Guadua	VOC	6-9%	Durable and resistance to mold and organic attack by organisms through treatment	Class B (ASTM E-84 Surface Burning)	Boric Acid

5.5 Evaluation

Some feedback was gained through first round interview on the initial version of the artifact which is the initial workflow and the responsibilities, including:

1. Understanding how the process will give them tangible value is crucial (all).
2. This workflow might be more attractive if it enables them to reduce costs or embodied carbon due to reusing materials, rather than only reusing the material itself (S1, S2).
3. The process looks correct at a high level (C2, C3, S1).
4. Some of the steps, e.g. general contractors gathering EPD from subcontractors or suppliers, have already being done in some project for carbon accounting (C3).
5. The process lacks the loop between engineers and owner in discussing material passport scope in initial phases (S2).
6. The process lacks differentiation between principal contractors and sub-contractors' roles (C2, S1).
7. Activities should be marked or mapped into different project lifecycles: conceptual design, design development, procurement, construction, handover/operation (C1).
8. The workflow would only be feasible if the owner mandated material passport creation from an early phase through contract (C2, C3, S1).
9. The process needs to start as early as possible to enable early planning (C1, C2, C3, S1)

10. Streamline the material passport relevant data extraction and collection process to project activities sequence to prevent the risk of missing the relevant information and minimize the effort needed during the project (S1).
11. It is not clear how to identify key reusable materials (S2).
12. Designers (S1, S2) agree with their responsibilities, but construction managers (C2, C3) think their responsibilities are a lot and they will need to assign a dedicated person just to do the workflow.
13. Integration with existing used platforms like building management or facility management software, and some degree of automation (C2, C3, S1).
14. Use usable format like spreadsheet for the template to enable contractor or supplier to fill in the template (S2, C2).

Commented [SS11]: More on finding, should connect to literature.
What do I think and how does it connect to lit

In the second iteration, the artifact consists of the improved workflow, responsibilities, and a template. The template and workflow efficiency were measured through an online survey filled by the four students to give subjective rating with 4 indicators, in which the result is as follows.

1. Efficiency in collecting the required information: 4.75 / 5
2. Ease of using the template: 4.25 / 5
3. Workflow clarity: 4.5 / 5
4. Ease of adaptation to real project: 4 / 5

Therefore, the total score is 4.4 / 5.

It was also evaluated whether all objectives were achieved. The result is in Table 22.

Table 22 Objectives achievement

No	Objective	Achieved	Source
1	Break it down to a clear goal	Yes	Literature (Webster et al., 2024)
2	Be specific about which material and parameters	Yes	
3	Start now with real project to test and learn	Yes	
4	Integration with existing used platforms	No	Interview (C2, C3, S1)
5	Enables stakeholders to reduce costs or embodied carbon	No	Interview (S1, S2)
6	Streamline MP creation to project activities	Yes	Interview (S1)
7	Collect relevant data to enable future disassembly of the building	Yes	Project’s client

Some best practices identified throughout the research are:

Commented [SS12]: If updated, update to 7.1.4

1. The workflow is quite clear and helpful in knowing which stages of the project are in following the activities (CB).
2. The workflow will enable designers to gather required information to design for circularity (C3).
3. The workflow is realistic because it doesn't collect all the material information about the whole building but only the valuable information (S1).
4. Some of the steps, e.g. general contractors gathering EPD from subcontractors or suppliers, have already being done in some projects for carbon accounting (C3).
5. The template is straightforward and easy to follow (CA).
6. The template is done in a spreadsheet which is usable for all stakeholders (S2).
7. The data is helpful to reference connection types (SA) and material usage for future projects (SB).
8. Designers (S1, S2) agree with their responsibilities.

On the other hand, some identified challenges that remains are:

1. Disassembly potential instruction needs to be made more detailed for first-time users, possibly with guiding picture and ease of disassembly score.
2. Regarding manufacturer-related information, different materials have different document structures because they are usually purposed for marketing, in which different materials have different qualities that the manufacturer wants to highlight (CB). Therefore, extracting manufacturer-related information manually from disparate unstructured data takes too much time (CA). CA suggested using an AI agent-based tool like ChatGPT that can automate extracting material passport relevant information from the uploaded PDFs.
3. In data collection process, while the structural engineers need 8 minutes to fill in the disassembly potential, it takes quite some time initially to explain the meaning of the different indicators of disassembly potential.
4. There are also doubts from CMs about how to convince suppliers and subcontractors that has been operating with the "old way" for decades with low understanding or awareness to do this process.
5. Regarding material filter, specifically recoverability filter, can be done at a high level in early phase like RIBA stage 2, but it should be updated in stage 4 when connection details design is already determined, which usually happens just before the construction.
6. Construction managers (C2, C3) think there are a lot of responsibilities and they will need to assign a dedicated person just to do the workflow.

6. Discussion

6.1 Stakeholders Need for a Simplified Material Passport Workflow

This research responds to a key industry gap: the lack of a standard, user-friendly process for creating Material Passports (MPs). As noted by Honic et al. (2019), fragmented stakeholder collaboration and unclear implementation pathways have hindered MP adoption. Similarly, Kedir (2021) highlights the challenge of unstructured data capture and unclear data responsibilities across the value chain. While some practices like embodied carbon tracking are growing due to green building certifications (e.g., LEED), circularity remains underexplored.

The artifacts developed here address these issues by offering structured templates, a phased project-lifecycle workflow, and clearly mapped responsibilities. Figure 17 illustrates how this proposed framework supports improved data and stakeholder coordination, aligned with the multi-stakeholder engagement models recommended by Bajare et al. (2024). Owners play a central role, as their early buy-in and contractual mandates are essential to ensure that MPs are implemented from the start of a project (Webster et al., 2024).

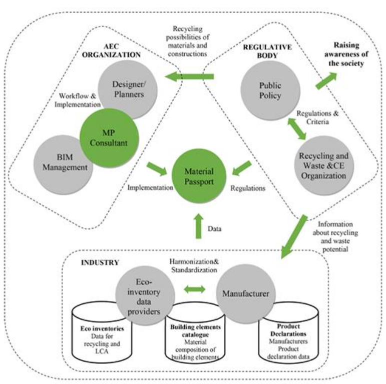


Figure 16 Data and stakeholder management framework (Honic, 2019)

However, one of the deeper challenges is that many AEC stakeholders lack familiarity with circularity and sustainability concepts. While carbon accounting practices are increasing, their meaning is often unclear to practitioners, and circularity metrics remain unfamiliar. Most interviewees had never heard of material passports, although they agreed that implementation should be mandated via Employer Requirements (ER). As awareness and regulatory pressure (e.g., ESPR) increase, this workflow can serve as a practical entry point to help stakeholders begin collecting circularity-related material data, even if broader understanding takes time to develop.

6.2 Objectives Achievement and Definition

This research primarily aims to develop a simplified workflow that enables collaboration among different stakeholders to collect material passport information across the project lifecycle. Of the seven defined objectives mentioned in section 5.2 (Table 10), five were achieved. The first three objectives set by Webster et al. (2024) including clear goal definition, prioritizing key materials and parameters, and early testing in real projects. It is proven particularly effective because they reduce the complexity of MP adoption while aligning with existing stakeholder practices. A clear goal helps stakeholders focus on relevant outcomes (e.g., reuse or disassembly), reducing scope uncertainty. Prioritizing high-value materials streamlines data collection and minimizes effort, which is crucial for first-time users. Lastly, testing in real-world settings facilitates rapid feedback and iteration, which supports practical learning and adoption. in shaping a simplified MP workflow suitable for first-time users. By narrowing the MP's data scope to reusable structural bamboo (SEB) components, this project reduced the documentation burden while retaining actionable value.

However, integration with existing platforms and the use of MPs to reduce embodied carbon or cost was not achieved. These limitations are consistent with those noted by Çetin et al. (2023), who found that data availability and system interoperability remain common barriers. Despite this, structuring the MP workflow according to RIBA stages, and testing it in the AEC Global Teamwork course, confirmed its clarity and practicality. Challenges in achieving cost-related objectives stemmed from difficulties in obtaining accurate and timely cost data, as material prices fluctuate and responsibilities for providing or updating this information remain unclear. Tools like Madaster and Circuland can help estimate the future residual value of materials at demolition, which may offset demolition costs as demonstrated in the Triodos Bank case (Madaster Global, 2022b). For large developers, this also opens reuse opportunities across their project portfolios, lowering future procurement costs.

6.3 Stakeholders' Responsibilities

The workflow expands upon the Circular Action Responsibility Matrix (Webster et al., 2024) by detailing responsibilities during RIBA stages 0–6. In early phases, sustainability consultants play a key role in goal setting and planning. For first-time MP users, they also need to support later phases to ensure smooth implementation, although this role should eventually shift to designers and contractors as stakeholders gain experience.

However, assigning more responsibility to sustainability consultants may not always be feasible given their existing workload in green certification tasks. Honic (2019) proposed a new role, MP consultants, with expertise in material, construction, circularity, and environmental impact. This differs from the current skillsets of most sustainability professionals, but as the field grows, upskilling is expected.

Design-related data should be finalized by RIBA stage 4, with additional details like disassembly specifics addressed in stage 5. Designers input this data, and general contractors validate it. Manufacturing-related data is gathered by subcontractors or suppliers and input by the contractor by the end of stage 5. In future practice, suppliers could take on more of this responsibility contractually. Interior components add complexity, as architects and MEP engineers often lack construction method knowledge. Collaboration with subcontractors is needed to assess disassembly feasibility.

The timing and sequence of responsibilities are influenced by procurement methods. Early contractor involvement allows for proactive MP planning; otherwise, late-stage contractor entry risks missing data or scope changes. Although roles like the project manager and cost consultant were not simulated here due to the academic setting, they play a critical role in practice. The project manager or client is responsible for including MP scope and templates in the Employer Requirements (ER), or Employer Information Requirements (EIR), typically by the end of RIBA stage 2 (Webster et al., 2024). This enables contractors to propose implementation approaches during tendering. The sustainability consultant can support this by advising on the appropriate level of detail, while the cost consultant helps assess its feasibility. The step is included in the previously demonstrated responsibilities list is highlighted in step 5 in Table 23.

Table 23 Recommended updated responsibilities for Employer Requirements

Phase / RIBA stage	No	Activities	O	SC	A	SE	PM	CC	GC	S
Strategic Definition (0-1)	1	Define project circularity goal	R,A	R	C	C	I	C	I	-
Concept Design (2)	2	Define material passport concept	A,C	R	C	C	I	I	-	-
	3	Identify or select key reusable materials	A,C	R	R	R	I	I	-	-
	4	Determine material passport scope and create template	A	R	C	C	R	C	I	-

	5	Include material passport scope and template in the ER	A,C	C	I	I	R	C	I	-
Developed Design & Technical Design (3-4)	6	Incorporating key circular design principle	I	R	R	R	I	-	A,C	-
	7	Extract design-related information and fill in the template	I	C	R	R	I	-	A,C	-
Manufacturing (5)	8	Extract manufacturer-related information from various sources	I	C	I	I	I	-	R,A	R
	9	Fill in manufacturer-related information to the template	I	C	I	I	I	-	R,A	C

O	Owner
SC	Sustainability Consultant
A	Architect
SE	Structural Engineer
PM	Project Manager
CC	Cost Consultant
O	General Contractor
O	Supplier / Sub-contractor

6.4 Clauses for Material Passport Contract

Material Passports can be embedded into contracts by adapting clause structures from BIM protocols, such as the CIC BIM Protocol (2018). The clauses can be included as a particular condition of the contract or Employer Information Requirement (EIR). This includes clearly defining stakeholder responsibilities, data formats, and variation mechanisms. Recommended contract sections include: (1) Definitions, (2) Coordination and Resolution of Conflicts, (3) Obligations of Employer, (4) Obligations of Project Team Members, (5) Electronic Data Exchange, (6) Use of Information, (7) Liability in Respect of Proprietary Material, (8) Remedies – Security, and (9) Termination, (10) Defined Terms, Appendix 1 - Responsibility Matrix, Appendix 2 - Information Particulars, and Appendix 3 - Security Requirements. Contents outlines are moved to Appendix H.

Including MPs in the tender process ensures contractor commitment and aligns with early lifecycle data planning, which is essential for circular construction. This research artifact

Commented [SS13]: Explain deeply about recommendations here,
In rec for practice just mention shortly but specific (at certain time) and why this help them to make better decisions about which materials to use. Don't add new thing.
Discussion is a bit broader not just specific for findings. Split into contract and filter section.

can also serve as a reference for developing contract appendices. The responsibility list can be reformatted into a matrix for Appendix 1, while the workflow and template can be included in Appendix 2 to outline the data collection process. To support variation management, scope changes such as new materials, data fields, or platforms, can be addressed under Project Team Member Obligations. These updates should be recorded in Appendix 2 (Information Particulars) to ensure clarity and traceability throughout the project.

6.5 Workflow for Existing Building

Although focused on new builds, the proposed workflow can be applied to pre-demolition audits of existing buildings. While data collection would occur late in the lifecycle (RIBA stage 7), applying the workflow can still reduce time spent on pre-demolition audits, especially where deconstruction must proceed quickly. For developers with upcoming projects, this enables reuse of recovered materials, reducing procurement needs and supporting circular practices. Demonstrating reusability in demolition projects may also help raise awareness and encourage wider adoption of MPs.

6.6 Material Filter Adjustment

The stepwise material filter (Figure 10) was effective in identifying reusable materials like bamboo. However, the third filter, which focused on reuse markets, must be contextualized to local conditions. In Europe, strong markets for reclaimed bricks and stone support MP adoption (Intelligence Service, 2011), while the U.S. shows less maturity. Regulatory efforts like ESPR further support regional implementation by prioritizing product groups such as steel, aluminum, and furniture for digital passport development. This makes it easier for contractors to create MPs for these components downstream.

Since some widely used materials like concrete are not directly reusable, an additional filter of “Is it valuable if recovered in lower quality?” can capture recyclable resources like crushed aggregates and recycled rebar (Figure 18).

While the demonstration focused on reusable structural bamboo, interviews (B1, C3) highlighted the potential of targeting interior components with shorter lifespans for disassembly, as these are more likely to retain consistent removal methods. Conversely, long-lifespan structural elements may require future innovations to become viable for reuse, such as non-destructive disassembly.

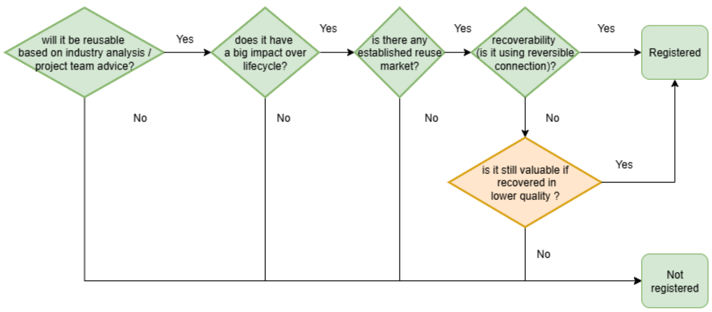


Figure 17 Material filter recommendation for valuable scrap materials

6.7 Template and Demonstration

The development and application of the data collection template followed a structured progression. Initially based on the Waterman framework (Stella et al., 2023) and timber-specific inputs from Rotor (2021), the template aimed to standardize reusable material data. While comprehensive, the Waterman dataset may require simplification of some information like certifications or contact details could be appended separately. British Land's more streamlined format offers a useful comparison.

The template was demonstrated in the implementation case, where stakeholders used a spreadsheet to record data. While spreadsheets are accessible and integration-friendly, some users found them less intuitive compared to platforms like Madaster or Circuland. Despite this, the format remains valuable for early-stage use and platform flexibility.

Initial implementation required educating stakeholders unfamiliar with MPs. Some sections, especially Design for Disassembly (DfD), proved difficult due to unfamiliar indicators and lack of visual aids. Therefore, clearer instructional material and visual examples are essential.

Manufacturer-related data posed further challenges due to unstructured formats like PDFs and handwritten documents (B1). Manual extraction is time-consuming and inconsistent, making this a prime area for AI-enabled automation. Simplifying input through predefined options also improved consistency and reduced human error.

To future-proof the tool, more iteration is needed to accommodate different material types, regional reuse markets, and stakeholder capabilities. Automated LCA tools like One Click

LCA, and platforms like Madaster and Circuland, may streamline integration, but coordination across multiple suppliers remains a barrier in large-scale projects.

6.8 Implementation Case

This implementation case, conducted in an academic setting, benefited from an innovation-driven environment and a client highly supportive of sustainability and circularity. However, in real-world practice, owners often have limited knowledge of circular principles and must first be convinced of the financial value of Material Passports (MPs). Early education and alignment of circularity goals, such as Design for Adaptability (DfA), can improve buy-in.

Project goals don't always translate into MP needs. For example, adaptability might be achieved with movable partitions, reducing perceived value of MPs in early project phases. Yet, the need becomes clear at demolition, when decisions about material recovery are critical, an insight echoed by C1.

Incorporating circular design principles early helps identify more components for reuse, but technical constraints can reduce feasibility. In this case, some structural connections were redesigned using nails instead of bolts to meet performance requirements, limiting disassembly potential, supporting Luscuere's (2017) observation that structural priorities often override circular goals.

While circular design is not always mandated, all buildings eventually face end-of-life decisions. As such, MPs remain valuable long-term tools, and building owner awareness is key to advancing adoption.

6.9 Best Practices and Challenges

Commented [SS14]: Connect with munaro tavares

The workflow was evaluated twice: through first-round interviews and a demonstration survey. While Section 6.7 already detailed challenges in data collection particularly for manufacturer-related information, this section reflects on broader implementation insights. In real-world projects, more frequent evaluations could enable iterative improvement and surface project-specific best practices.

Interviewees noted that the workflow clarified stakeholder responsibilities across project phases, and the template was straightforward to use. Designers found the collected data valuable for future material selection and disassembly planning, echoing EPEA (2015) on the practical utility of MPs. Sustainability-oriented manager (C3) found workflow alignment with existing LEED-related practices, although even these firms had no protocols for reversible design,an issue consistent with BAMB (2016).

The continued difficulty of collecting unstructured product data underscores the need for standardized inputs and automation. While Section 6.7 addressed AI-enabled extraction and template improvements, this section reinforces the urgency of establishing circularity data protocols for suppliers. Standards like the ISO 59040 Product Circularity Data Sheet could guide this transition. Additionally, the template developed in this research can serve as a practical starting point for suppliers to structure circular data collection and align with emerging standards.

Ultimately, industry-wide adoption hinges on building owner engagement. Stakeholder education and early exposure to MP benefits, especially in financial or regulatory terms, remain vital.

7. Conclusion

7.1 Sub-Research Questions

7.1.1 SRQ1: Roles and Responsibilities

SRQ1: What are the stakeholders' roles and responsibilities in providing relevant information to create Material Passport?

This research summarized the material passport setting up and data collection responsibilities across RIBA stages 1-5 for construction industry stakeholders including client, sustainability consultant, designers (architect, structural engineer), general contractors, and sub-contractor/suppliers. While Table 11 summarized key action responsibilities across the lifecycle, Table 12 outlined the detailed responsibilities of providing, inputting, and checking each data point before a certain RIBA stage. These tables help to make it very clear for all stakeholders on the project who are responsible for doing each information at each project stage.

7.1.2 SRQ2: Material Passport Workflow Design

SRQ2: How can a Material Passport workflow be designed, and when should each data be extracted and collected into MP?

I developed a new workflow which considered five different project stages (color coded as four different ones) and six different stakeholders. I designed the simplified material passport workflow through two iterations of Design Science Research, and then I asked expert feedback for improvement. Afterwards, I demonstrated the workflow through the implementation case's stakeholders, in which some industry professional acted as project owners and students acted as designers (architect and structural engineer), suppliers and builders (general contractors, sub-contractors). In these swim lane diagrams/Business Process Modelling Notation (BPMN), the different activities/responsibilities of each stakeholder in relation to the predecessor and successor activities are modelled. It visualizes how one activity constrains each other. The final workflow is available in Appendix B.

In addition to the workflow, I also developed a template and instructions which gives very clear instructions for the relevant stakeholders to fill in each data they are responsible for based on the detailed responsibilities in data collection in Table 12. The sample of the template and instruction is presented in Table 13 and Table 14 respectively. Moreover, the full template and instruction is available in Appendix E.

7.1.3 SRQ3: Material Passport Workflow Efficiency

SRQ3: How effective is the workflow in supporting stakeholders to collect key reusable material information?

The evaluation results were presented in section 5.5. A survey was given out to assess four aspects to four people (two construction managers and two structural engineer students) through an online survey, in which their credentials are available in Table 2. The result showed that the workflow scores were rather high in all aspects (4.4/5), but it scored the highest in efficiency in collecting the required information (4.75/5) but scored the lowest in the ease of adaptation to real project (4/5).

It was also assessed whether the workflow achieved the initially defined objective which is presented in Table 22. Overall, it achieved five out of the seven objectives.

7.1.4 SRQ4: Best Practice and Challenges

SRQ4: What are the insights (best practices) and main challenges for implementing MPs?

Some best practices and main challenges of the artifact (responsibilities, workflow, and template) were identified through the first-round interview (credentials in Table 1), online survey, and observation in data collection demonstration phase. In total there are eight best practices and six challenges which were presented in Section 5.5. While the best practices are mostly implementation, some challenges are regarding the bigger context of circularity.

7.2 Main-Research Question

How can a simplified Material Passport workflow be designed and implemented to enable stakeholders to collect key reusable material's crucial information?

This research aims to design a simplified multidisciplinary workflow to collect key reusable material information which in this specific case enables Design for Disassembly (DfD). It also aims to provide best practices and challenges of the workflow implementation. A set of artifacts was designed to guide stakeholders in creating material passports across different project lifecycles for the first time. The artifact consists of responsibilities list, workflow, and template. It was demonstrated through Stanford's AEC Global Teamwork Course as an implementation case. Then, the artifact was evaluated through first-round interview and online survey to measure its efficiency and identify best practices and challenges. Objectives achievements were also evaluated.

This research will give the reader insights into the design process of simplified material passport workflow and its practical implications. The next section will give some recommendations for practice in deploying the workflow considering industry practice and future research directions for academics.

7.3 Future Recommendations

Some recommendations for industry stakeholders implementing the workflow and academics research in the topic are as follows.

7.3.1 Recommendations for Practice

Recommendations for industry practitioners implementing the workflow include the following:

1. Owners need to be introduced early to possible automations enabled by MPs as mentioned in section 4.2.2, including embodied carbon assessments, circularity performance report, disassembly manual, reuse and recycling catalogue, end-of-life report, maintenance schedule, and facility management. Especially the last two will be valuable for current practice, so it can motivate them to start creating Material Passport.
2. While the workflow is not primarily intended for maintenance, collecting manufacturer-related information for shorter lifespan materials can also provide relevant information needed for building maintenance or management. Therefore, this workflow can be attractive for companies developing a streamlined maintenance system, in which the collected data is integrated with the existing building management platform, as requested by stakeholders in section 5.2.
3. For stakeholders creating material passports for the first time, it is recommended to set the three objectives from Webster and at least one specific objective translated from project goal as mentioned in section 6.2 to make the goal realistic.
4. In terms of potential cost reduction estimation, platforms like Madaster and Circuland can be utilized, as they can automate the hypothetical future value estimation of the building, as described in section 6.2. This is valuable for bigger

developers with known future projects so they can reuse their building materials from an existing building soon to be demolished which reduces the cost of buying new materials for new construction.

5. Initially, sustainability consultants are expected to lead the earlier process before the material passport creation as discussed in 6.3. As stakeholders' knowledge of material passports grows, the responsibility can be shifted gradually to the client and designer in earlier phases, and contractor in construction phase. It could be also explored how suppliers/subcontractors can be subcontracted to create material passports of the product they supply.
6. Project managers or clients setting up a contract for material passport can reference section 6.4 or Appendix H. It provides sample clauses to be included in the employer's requirement in RIBA stage 2 before setting out a tender to select the general contractor which is committed to creating material passport. The clauses were adapted from the BIM protocol outlined by UK CIC/BIM Pro team. It can be explored how different BIM protocol like Singapore BCA might suit the project condition better or develop a new contract structure adjusted to the local regulation.
7. Material filters to register valuable scrap materials is available in Section 6.6 to enable wider stakeholders of more traditional building/ project to recover building materials although it cannot be directly reused.
8. For stakeholders creating material passports of different materials, it is recommended to develop the specific material information scope and template as discussed in section 6.7. European stakeholders can reference the reuse toolkit developed by European Interreg NWE - FCRBE project which provides a collection of 32 material sheets outlining how different materials can be reclaimed, and what information will be needed to assess its performance in end-of-life stage.
9. Some degrees of automation (C2, C3, S1) are important to reduce the barriers of implementing the workflow. As mentioned in Section 6.7, it is recommended to automate manufacturing-related data collection to accelerate the data collection process, which will reduce the cost due to reduced manhours needed to do the activity. Collecting embodied carbon information can also be automated from LCA analysis software. This effort will in turn reduce the barriers mentioned in section 5.5.
10. While implementing the workflow, it is recommended to apply the suitable circular design principles to the project goal as discussed in section 6.8.
11. Companies having extensive experience in carbon accounting or sustainability efforts for LEED certification are highly recommended to implement this workflow, as they will be more familiar with some of the procedures discussed in 6.9. It will drive companies to set circularity goals including reusing or recycling materials (some

circularity goals Table 7) on top of the sustainability goals, e.g. embodied carbon reduction, for certification purposes as well.

7.3.2 Recommendations for Research

Recommendations for future researchers includes the following:

1. QR code is already used to store and access building services such as ducting for maintenance purposes during operation stage (C2). Therefore, it can be investigated how the workflow can be extended to embed the materials with QR code during construction to store information about circularity and maintenance which can be accessed in the existing building management platform. Byers and De Wolf (2023) explored the impact of QR Code-Based material passports in small-scale construction which can be relevant for further development. It is important as it is mentioned as additional objectives by some interviewees as presented in section 5.2. Reflection on why it could not be achieved in this research is available in section 6.2.
2. How integrating deconstruction model in BIM (Sanchez et al., 2021) to the workflow can also give more clarity rather than manually assessing different connection types with the four indicators as demonstrated in 5.4.
3. The process of architect or MEP engineer collecting data for interior material (partition wall) or building services can be investigated as the component is often replaced before the building lifespan ends, as mentioned in section 6.3.
4. Contract forms for digital deliverables of construction projects such as BIM which is referenced in section 6.4 are still being developed. While contracts for material passports currently can adopt the condition set out by BIM, it can be investigated how contracts can be adjusted to accommodate variation of material passports in case information scope changes during detailed/technical design and construction phase.

Commented [SS15]: Literaturs of qr code in building material?

Commented [SS16]: source

8. Personal Reflection

In this section, author personal reflection about research process, Stanford Global AEC teamwork, and research limitation and applicability is described.

8.1 Research Process

This was my first experience conducting a research thesis, and it came with several challenges. One of the most difficult aspects early on was choosing and narrowing down a research topic. It took three kickoff meetings before my topic was finalized. Even after passing the kickoff, I struggled to fully understand my topic and how to approach it.

What helped significantly was my biweekly meetings with Prof. Daniel. His guidance and probing questions helped me focus and identify which aspects of the topic needed further development. The iterative nature of the Design Science Research Method was also difficult to navigate at first. I found it hard to define a structured methodology early in the process, which made it challenging to maintain direction. Prof. Daniel's support was instrumental in helping me apply this method effectively to my thesis. During the two progress meetings, my committee members, Prof. Hans Wamelink and Prof. Ranjith, provided helpful feedback through guiding questions that pushed my thinking forward.

Throughout this process, I learned valuable lessons about how to select a topic, narrow it down, and appreciate the importance of a clearly defined methodology. Looking back, I would have benefited from selecting a topic earlier and narrowing the scope before the kickoff to avoid being distracted by too many options. I also would have established a clearer methodology from the beginning. Initially, I believed the method would naturally unfold during the process, but this led to confusion and a lack of structure. The iterative nature of Design Science Research contributed to this challenge, and in hindsight, I would have spent more time studying the method and examining other thesis examples to build a clearer foundation.

Despite these challenges, I was able to complete the thesis on time, which I'm grateful for. The experience taught me a great deal about how to manage a research process and the importance of structure and mentorship in navigating it.

8.2 Stanford Global AEC Teamwork

The demonstration of this thesis was conducted during the Stanford AEC Global Teamwork course. Due to the intensive nature of the course and its deliverables, I had limited time to fully implement and test the proposed Material Passport workflow. Coordinating with teammates for participation proved difficult, especially in the data collection phase, which impacted the completeness of the demonstration.

Despite these limitations, I do not regret participating in the course. It provided valuable exposure to interdisciplinary collaboration, real-world client feedback, and technical tools such as cost estimation, schedule optimization, VR-BIM coordination, and site logistics simulation. I am especially grateful for the opportunity to engage with industry professionals, such as architects, structural engineers, MEP engineers, and construction managers from both the US and Europe, who supported the coursework and gave feedback on my thesis.

8.3 Research Limitation, Impact and Applicability

This thesis adopted a clear scope that introduced several limitations to its broader applicability. First, the focus was on component-level Material Passports (MPs), which are typically handled by contractors during construction (Stella et al., 2023). Product- or material-level passports, which fall under supplier or manufacturer responsibility, were not addressed. This restricts upstream integration and limits the framework's alignment with initiatives like the Product Circularity Data Sheet (PCDS).

The workflow was developed for new buildings during RIBA Stages 1 to 5, ending before operation or end-of-life phases. These later stages, where reuse or disassembly decisions materialize, remain untested in this study, leaving lifecycle benefits largely theoretical. Reuse was prioritized as the primary circularity strategy (Potting et al., 2017), but other strategies such as recycling or refurbishment were not explored.

The implementation case occurred within the Stanford AEC Global Teamwork course, featuring academic participants and industry professionals primarily from the US and Europe. While interdisciplinary, the demonstration setting did not replicate real-world pressures such as cost constraints, timelines, and risk. Key roles such as project managers were not involved, even though they are central to embedding MPs contractually via Employer Requirements (ERs).

Moreover, the lack of automation for collecting manufacturer-related data, such as AI-assisted PDF extraction, may hinder scalability. Manual input can become a barrier in large or fast-track projects where efficiency is critical. Regional generalizability is also limited. The workflow draws heavily on European policies and tools, and its usefulness in regions with less-developed reuse markets or different regulatory contexts may be constrained. Finally, where policies like ESPR or CALGreen are not yet enforced, MPs may not be prioritized by building owners, weakening the workflow's adoption potential without clear incentives.

Reference

Architects, A. I. O. (2013). The Architect's Handbook of Professional Practice. John Wiley & Sons.

Bajare, D., Zsembinszki, G., Yiatros, S., Kaewunruen, S., Cidik, M. S., Schiller, G., Zhang, N., Rizzo, A., Tambovceva, T., Hendawy, M., Cavdar, A. D., & Borg, P. R. (2024). Stakeholders' role, Inter-Relationships, and obstacles in the implementation of circular economy. In Springer tracts in civil engineering (pp. 629–646). https://doi.org/10.1007/978-3-031-73490-8_20

BAMB, 2019. Materials Passports - BAMB. https://www.bamb2020.eu/topics/materials-passports/ (accessed 12.4.25).

Bogenstätter, U. (2000). Prediction and optimization of life-cycle costs in early design. Building Research & Information, 28(5–6), 376–386. https://doi.org/10.1080/096132100418528

Byers, B. S., & De Wolf, C. (2023). QR Code-Based material passports for component reuse across life cycle stages in Small-Scale construction. *Circular Economy*, *1*(2), 1–16. https://doi.org/10.55845/iweb6031

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

Construction Industry Council et al., 2018. BUILDING INFORMATION MODELLING (BIM) PROTOCOL SECOND EDITION. https://www.cic.org.uk/uploads/files/old/bim-protocol-2nd-edition-2.pdf

Cruz Rios, F., D. Grau, and M. Bilec. 2021. "Barriers and enablers to circular building design in the US: an empirical study". Journal of Construction Engineering and Management. 147(10), 04021117.

Damen, M. A. (2012). A resources passport for a circular economy [Universiteit Utrecht]. http://igitur-archive.library.uu.nl/student-theses/2012-1121-200521/UUindex.html

Eissa, R., & El-Adaway, I. H. (2024). Circular Economy Strategies for Decarbonization of the Built Environment Value Chain Scope 3 Emissions: A Network analysis. *Construction Research Congress 2022*, 10–20. https://doi.org/10.1061/9780784485279.002

Ellen MacArthur Foundation. (2016). Circular design: turning ambition into action. https://ellenmacarthurfoundation.org/topics/circular-design/overview?gclid=Cj0KCQiAtvSdBhD0ARIsAPf8oNlNYHkXZXGTCCDEgySu-uTipxdoKx6CtshCR5Uz9qZWovS_ocJMYLUaAv5uEALw_wcB

Ellen MacArthur Foundation. (2019). The Butterfly Diagram: Visualising the Circular Economy. Ellen MacArthur Foundation. https://ellenmacarthurfoundation.org/circular-economy-diagram

EU - 2024/1781 - EN - EUR-LEX. (2024). http://data.europa.eu/eli/reg/2024/1781/oj

EUR-LEX - 02011R0305-20241117 - EN - EUR-LEX. (2024, November 17). http://data.europa.eu/eli/reg/2011/305/2024-11-17

European Commission (2018). Construction and demolition waste. Retrieved from: Construction and demolition waste (europa.eu)

European Parliament (2022). Reducing carbon emissions: EU targets and measures. Retrieved from: Reducing carbon emissions: EU targets and measures | News | European Parliament (europa.eu)

Heinrich, M., & Lang, W. (2019). Materials Passports - Best Practice Innovative Solutions for a Transition to a Circular Economy in the Built Environment. Technical University of Munich, in association with BAMB. https://www.bamb2020.eu/wp content/uploads/2019/02/BAMB_MaterialsPassports_BestPractice.pdf

Hevner, A.R., March, S.T., Park, J., & Ram, S. (2004). Design Science in Information Systems. MIS Quarterly, 28(1), 75-105.

Hoosain, M.S., Paul, B.S., Raza, S.M., Ramakrishna, S. (2021). Material Passports and Circular Economy. In: Liu, L., Ramakrishna, S. (eds) An Introduction to Circular Economy. Springer, Singapore. https://doi.org/10.1007/978-981-15-8510-4_8

Intelligence Service, B. (2011). Final Report Task 2 – Management of C&D waste. In *European Commission DG ENV*.

International Code Council (ICC). (2022). 2022 California Green Building Standards Code, Title 24, Part 11 (CALGrEEN). https://codes.iccsafe.org/content/CAGBC2022P1

Kedir, F., Bucher, D. F., & Hall, D. M. (2021). A proposed material passport ontology to enable circularity for industrialized construction. Computing in Construction. https://doi.org/10.35490/ec3.2021.159

Kneese, A. v. (1988). The Economics of Natural Resources. Population and Development Review, 14, 281. https://doi.org/10.2307/2808100

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

Madaster Global. (2022b, August 18). Madaster Global. https://madaster.com/inspiration/triodos-bank-a-material-bank. Accessed in 23rd June 2025.

Mullhall, D., Hansen, K., Luscuere, L., Zanatta, R., & Willems, R. (2017). Framework for Materials Passports. Extract from an Internal BAMB Report. BAMB Consortium, EPEA, SundaHus.

Munaro, M. R., & Tavares, S. F. (2021). Materials passport's review: challenges and opportunities toward a circular economy building sector. Built Environment Project and Asset Management, 11(4), 767–782. https://doi.org/10.1108/BEPAM-02-2020-0027

Norouzi, M., Chàfer, M., Cabeza, L. F., Jiménez, L., & Boer, D. (2021). Circular economy in the building and construction sector: A scientific evolution analysis. Journal of Building Engineering, 44(April). https://doi.org/10.1016/j.jobe.2021.102704

Olumo, A., & Haas, C. (2024). Building material reuse: An optimization framework for sourcing new and reclaimed building materials. *Journal of Cleaner Production*, *479*, 143892. https://doi.org/10.1016/j.jclepro.2024.143892

Ozinsky, A. (2024, September 24). Passport to circularity. RIBA Journal. https://www.ribaj.com/intelligence/material-passport-to-circularity-3xn

Platform CB'23, Van Twillert, W., Heijster, D., Braat, D., Peters, F., Van Haagen, F.,

Gaasbeek, H., Drissen, J., Sukel, M., Emanuel, M., Bonduel, M., Blaauw, O., De

Klerk, R., Voermans, S., & Huijsmans, T. (2022). Guide to passports for the construction sector. In *Guide to Passports for the Construction Sector*.

Potting, J., Hekkert, M., Worrell, E., & Hanemaaijer, A. (2017). Circular economy: Measuring innovation in the product chain. In PBL Netherlands Environmental Assessment Agency (Issue 2544). https://www.pbl.nl/sites/default/files/downloads/pbl-2016-circular-economy-measuring-innovation-in-product-chains-2544.pdf

RENÜTEQ | United States. (n.d.). ReNüTeq. https://www.renuteq.com/. Accessed in 1st May, 2025.

RIBA. (2020). *RIBA Plan of Work 2020 Overview*. https://riba-prd-assets.azureedge.net/-/media/GatherContent/Business-Benchmarking/Additional-Documents/2020RIBAPlanofWorkoverviewpdf.pdf?rev=4fb72169b1fd4e52a164bdd5f9aa202a

Rotor vzw/asbl. (2021). REUSE TOOLKIT Structure and shell → Structural timber Glued laminated timber structural elements. In Interreg FCRBE.

S. Butera, T.H. Christensen, T.F. Astrup, Life cycle assessment of construction and demolition waste management, Waste Manag. 44 (2015) 196–205.

Sanchez, B., Rausch, C., Haas, C., & Hartmann, T. (2021). A framework for BIM-based disassembly models to support reuse of building components. Resources Conservation and Recycling, 175, 105825. https://doi.org/10.1016/j.resconrec.2021.105825

Sauter, Elke M., and Martijn Witjes. 2018. "Linked Spatial Data for a Circular Economy Exploring Its Potential through a Textile Use Case." CEUR Workshop Proceedings 2044: 1–6.

Stella, A., Terndrup, M., Pilcher, N., Nilsson, S., Buhagiar, J., 2023. Waterman Materials Passports Framework Introducing a Standardised Approach to Materials Passports in the Construction Industry. Waterman Group.

Swinerton. (2023). 2022 Sustainability Report. https://swinerton.com/wp-content/uploads/2023/07/2022-Swinerton-Sustainability-Report-v7_070623.pdf

Tirado, R., Aublet, A., Laurenceau, S., & Habert, G. (2022). Challenges and Opportunities for Circular Economy Promotion in the Building Sector. Sustainability 2022, Vol. 14, Page 1569, 14(3), 1569. https://doi.org/10.3390/SU14031569

U.S. Environmental Protection Agency, Advancing Sustainable Materials Management: 2014 Fact Sheet, Washington, DC, (2016).

van Buren, N., Demmers, M., van der Heijden, R., & Witlox, F. (2016). Towards a circular economy: The role of Dutch logistics industries and governments. Sustainability (Switzerland), 8(7), 1–17. https://doi.org/10.3390/su8070647

Van Vliet, M., Van Grinsven, J., Teunizen, J., Alba Concepts, Dutch Green Building Council, Netherlands Enterprise Agency, W/E Adviseurs, & Ministry of the Interior and the Circular Building Economy Transition Agenda. (2021). Circular Buildings - Disassembly Potential Measurement Methodology. DGBC.

Webster, M., Sezgin, S., Samoluk, E., & GXN. (2024). Full circle, full potential: British Land's approach to the circular economy [Book]. https://www.britishland.com/media/la5h5wbe/full-circle-full-potential-british-lands-approach-to-the-circular-economy-1.pdf

Zhang, C., Hu, M., di Maio, F., Sprecher, B., Yang, X., & Tukker, A. (2022). An overview of the waste hierarchy framework for analyzing the circularity in construction and demolition waste management in Europe. Science of the Total Environment, 803, 149892. https://doi.org/10.1016/j.scitotenv.2021.149892

Appendix A: AEC Global Teamwork Course Detail

About AEC Global Teamwork:

This prestigious program brings together students from around the world to collaborate on advanced building projects using cutting-edge technologies. Students work remotely across disciplines, time zones, and cultures, with final presentations taking place at Stanford University in May 2025. Three teams of multidisciplinary students (architecture, structural engineering, MEP, CM, LCFM) from universities across US and Europe will work together in concept development and project development phases of an university building, to come up with a design that is sustainable (mostly using prefabricated and/or modular materials), resilient and repurposable. More about the course (https://pbl.stanford.edu/).

About the Project:

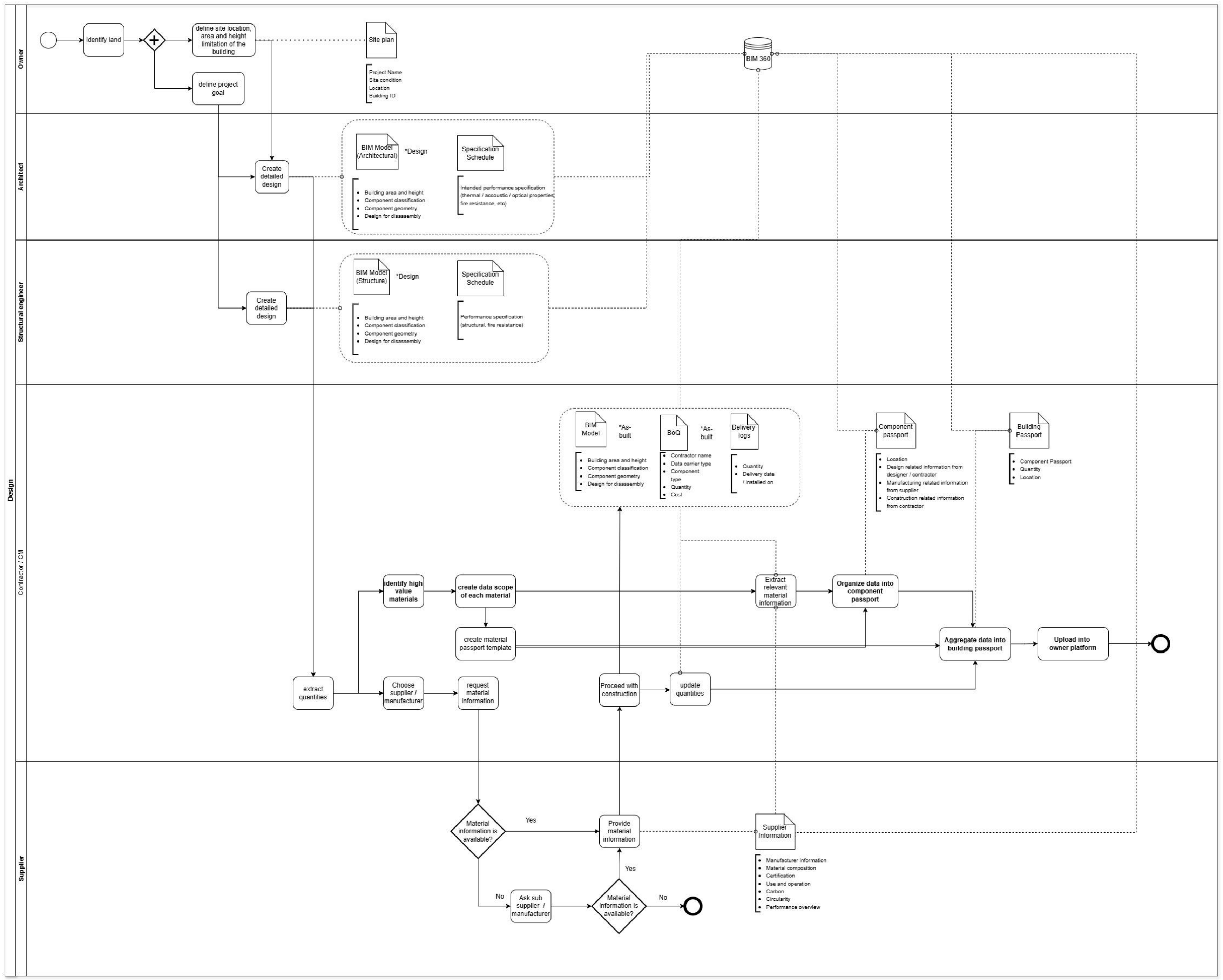
My team (Island 2025) consist of Architect, Structural Engineer, MEP and CM. We will deliver a concept/design (11 April 2025) and project/construction development (30 May 2025) of a new facility located on the Engineering School of Island University in San Juan Puerto Rico. During the process, a team of multidisciplinary owners will give feedback on our design. Principles like TVD, STV, IPD are also incorporated.

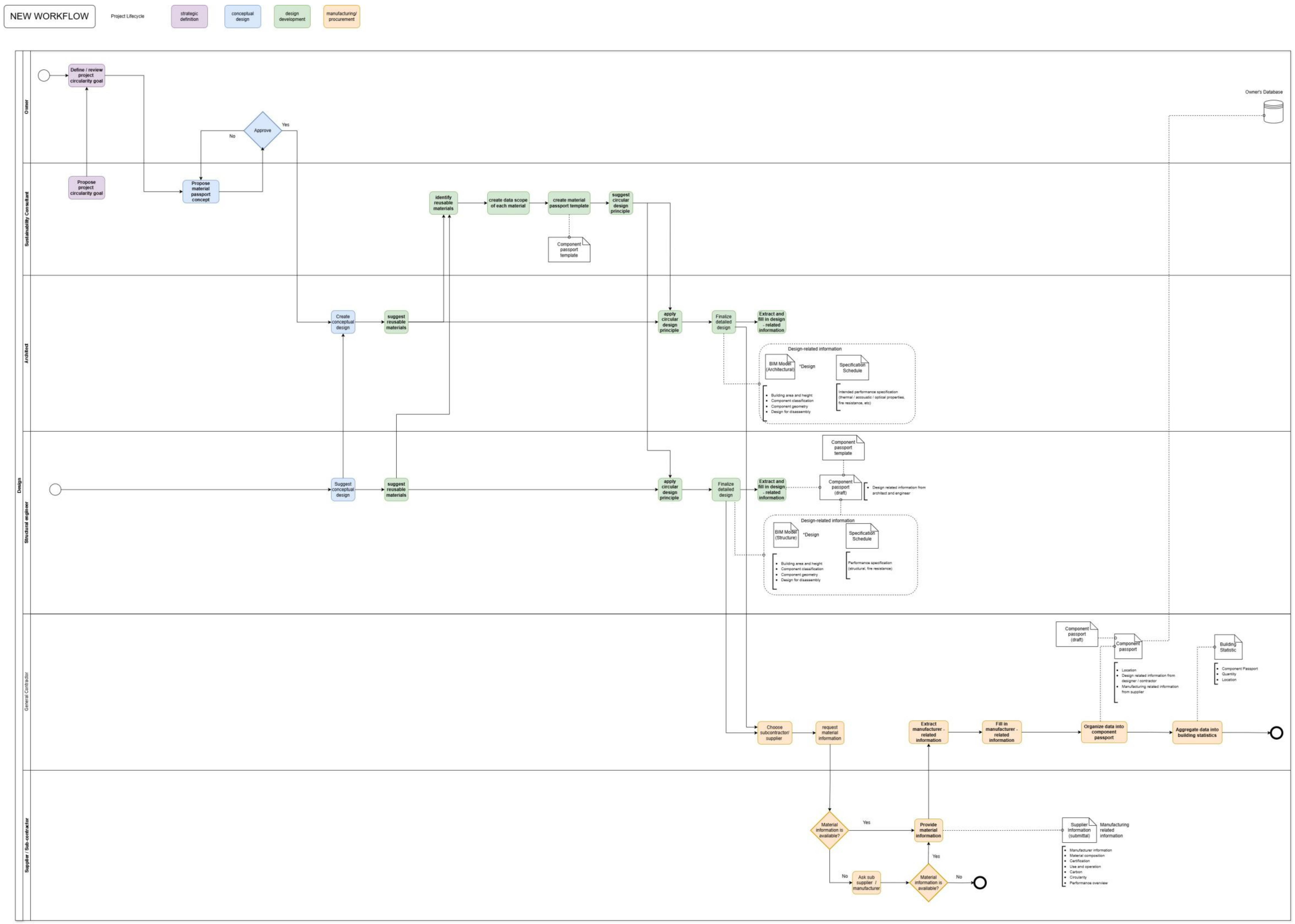
The objectives from the owners are :

1) to make an adaptable university building for future purpose,
2) targets net-zero energy to address the current climate emergency
3) deploy buildings as products approach to virtual design and construction, and intelligent supply chain to create adaptable construction, and reconfigurable building through digitalization, industrialization, prefabrication of kit of parts – by using advanced technologies.

Appendix B: Initial and Improved Workflow

INITIAL WORKFLOW




NEW WORKFLOW
Project Lifecycle
strategic definition
conceptual design
design development
manufacturing/ procurement
Owner
Sustainability Consultant
Architect
Design
Structural engineer
General Contractor
Supplier / Sub-contractor
Define / review project circularity goal
Propose project circularity goal
Propose material passport concept
Approve
Yes
No
identify reusable materials
create data scope of each material
create material passport template
suggest circular design principle
Component passport template
Create conceptual design
suggest reusable materials
apply circular design principle
Finalize detailed design
Extract and fill in design - related information
Design-related information
BIM Model (Architectural)
*Design
Specification Schedule
Building area and height
Component classification
Component geometry
Design for disassembly
Intended performance specification (thermal / accoustic / optical properties, fire resistance, etc)
Suggest conceptual design
Component passport template
Component passport (draft)
Design related information from architect and engineer
BIM Model (Structure)
Performance specification (structural, fire resistance)
Owner's Database
Component passport (draft)
Component passport
Location
Design related information from designer / contractor
Manufacturing related information from supplier
Building Statistic
Component Passport
Quantity
Location
Choose subcontractor/ supplier
request material information
Extract manufacturer - related information
Fill in manufacturer - related information
Organize data into component passport
Aggregate data into building statistics
Material information is available?
Provide material information
Ask sub supplier / manufacturer
Supplier Information (submittal)
Manufacturing related information
Manufacturer information
Material composition
Certification
Use and operation
Carbon
Circularity
Performance overview

Appendix C: First-Round Interview Details

There are five different interviewees with following information :

Code	C1	C2	C3	S1	S2
Title	Project Engineer / life cycle analyst	Prefabrication Lead	Sustainability Manage	Project Engineer	Senior Structural Engineer
Company	Contractor	Contractor	Contractor	Engineering Consultant	Engineering Consultant
Years of experience	2	17	16	7	8
Country	US	US	US	US	Germany
Role	CM	CM	CM	Structural Engineer	Structural Engineer

There are several questions that were asked:

- Have you used MP?
- How have you tracked or applied sustainability and circularity in your projects and what for?
- Do you agree with the table of data provider?
- Can you provide disassembly potential data?
- What do you think about high value material? Reusable / high scrap value?
- Each material have its own key properties data scope, should the table be separated or combined for all types of material?
- What will be a good data collection and data storage approach?
- How to improve in the workflow?
- What will be the barrier of implementing the workflow?
- What will be the opportunities of implementing the workflow?

Appendix D: Initial Stakeholders Role and Responsibilities

Initial version

Category		Information	Provider	Input option
Component level				
Design - related	Classification	element type	designer	new/used material
		element category	designer	foundation/ steel frames/ floors, ...
	Component geometry	mass	designer, updated by contractor	number
		volume	designer, updated by contractor	number
		length	designer, updated by contractor	number
		width	designer, updated by contractor	number
		height	designer, updated by contractor	number
	Design for disassembly	disassembly potential	designer, updated by contractor	yes / no
		connection types	designer, updated by contractor	welded / glue / mechanical
		accessibility	designer, updated by contractor	Directly accessible connection/ Hidden connection/ Layer(s) to be removed - no damages/ Layer(s) to be removed - damages/ Not accessible connection
	Intended performance specification	structural properties, thermal properties, acoustic properties, material health, fire resistance, corrosion resistance/mold resistance, finish / treatment	designer	numbers
Manufacturing - related	Manufacturer information	name	supplier, input by contractor	text
		location	supplier, input by contractor	text
	Material composition	material	supplier, input by contractor	text
		percentage	supplier, input by contractor	text
	Certification / datasheet	name	supplier, input by contractor	text
		type	supplier, input by contractor	text
	Use and operation	assembly instruction	supplier, input by contractor	text
		annual replacement rate	supplier, input by contractor	number
		maintenance	supplier, input by contractor	text
	Carbon	declared unit	supplier, input by contractor	unit
		manufacturing (A1-3)	supplier, input by contractor	number
		sequestered (B1-3)	supplier, input by contractor	number
		End of Life (C1-C4)	supplier, input by contractor	number
	Circularity	lifespan	supplier, input by contractor	number
		take back	supplier, input by contractor	yes/no
		Reusability	supplier, input by contractor	text
		Recyclability	supplier, input by contractor	text
		detachability	supplier, input by contractor	yes/no
	Performance overview	structural properties, thermal properties, acoustic properties, etc	supplier, input by contractor	numbers

Appendix E: Template and Instruction

Instruction

Category		Input field	Description	Document Source	Provided by	Input by	Check by	By the end of RIBA Stage?	Input type	Input option	Description
Design - related	Classification	Discipline	From which discipline is the product mainly	BIM Model	designer	designer	general contractor	4	list	Architecture / Structural / Service	-
		Layer	Layer of the component	BIM Model	designer	designer	general contractor	4	text	-	-
		Family	Family type from Revit Model	BIM Model	designer	designer	general contractor	4	text	-	-
		MID	Unique code of the component type	BIM Model	designer	designer	general contractor	4	number	-	-
		Component	Subclassification of component	BIM Model	designer	designer	general contractor	4	text	-	-
		Type	Size and/or shape variation of component	BIM Model	designer	designer	general contractor	4	text	-	
	Component geometry	Length	Length of the component	BIM Model	designer	designer	general contractor	4	number	-	-
		Width	Width of the component	BIM Model	designer	designer	general contractor	4	number	-	-
		Height	Height of the component	BIM Model	designer	designer	general contractor	4	number	-	-
		Volume	Volume of the component	BIM Model	designer	designer	general contractor	4	number	-	-
		Density	Density of the component	Technical sheet	designer	designer	general contractor	4	number	-	-
		Mass	Mass of the component	Calculated	designer	designer	general contractor	4	number	-	-
	Design for disassembly	Connection Variation	Which connection variation is this?	Shop Drawing	designer	designer	general contractor	5	list	-	-
		Designed for disassembly	Is the component designed to enable disassembly from adjacent components?	Shop Drawing	designer	designer	general contractor	5	list	yes / no	-
		Connection Type (CT)	What is the connection type that has a load-bearing function for the product in question?	Shop Drawing	designer	designer	general contractor	5	list	CT.DC - Dry connection	include : loose (no fastening material), click, velcro, magnetic
										CT.AE - Connection with added elements	include : bolt and nut, spring, corner, screw, connections with added connection elements
										CT.DI - Direct integral connection	include : pin, nail
										CT. SC - Soft chemical connection	include : caulking, foam (PUR)
										CT.HC - Hard chemical connection	include : adhesive, dump, weld, cementitious, chemical anchor
		Connection Accessibility (CA)	Can the connecting elements be accessed physically and to what extent does damage occur to surrounding objects?	Shop Drawing	designer	designer	general contractor	5	list	CA.FA - Freely accessible without additional actions	freely accessible without additional equipment with no damage to surrounding objects
										CA.AN - Accessible with additional actions (no damage)	accessible with additional equipment with no damage to surrounding objects
										CA.AR - Accessible with additional actions (repairable dama	accessible with additional equipment with repairable damage to surrounding objects
										CA.NI - Not accessible (irreparable damage)	not accessible with irreparable damage to surrounding objects
		Independency (IC)	How products are intermingled with other system or layer with differing lifetimes	Shop Drawing	designer	designer	general contractor	5	list	IC.NI-No independency, modular zoning	products are not traversing other products and can be disassembled without more actions
										IC.OI-Occasional independency	products are occasionally traversing other products and can be disassembled with more act
										IC.FI-Full integration	products are fully integrated with other products and cannot be disassembled separately
		Product Edge (PE)	How products are placed in a composition and whether this is open or closed.	Shop Drawing	designer	designer	general contractor	5	list	PE.OP - Open, no obstacle	Products are not enclosed by surrounding products
										PE.OV - Overlapping, partial obstruction	Products are partially enclosed by surrounding products
										PE.CL - Closed, complete obstruction	Products are fully enclosed by surrounding products
	Intended Performance - structural	Compression strength (psi)	Required structural properties for design	Design specification schedule	designer	designer	general contractor	4	numbers	-	-
		Tensile strength (psi)		Design specification schedule	designer	designer	general contractor	4	numbers	-	-
		Flexural strength (psi)		Design specification schedule	designer	designer	general contractor	4	numbers	-	-
		Shear strength (psi)		Design specification schedule	designer	designer	general contractor	4	numbers	-	-
		Modulus of elasticity (ksi)		Design specification schedule	designer	designer	general contractor	4	numbers	-	-
Manufacturing - related	Manufacturer information	Product Name	Name of the product	Technical sheet	supplier/subcontractor	general contractor	Sustainability consultant	5	text	-	-
		Manufacturer Name	Name of the manufacturer company	Technical sheet	supplier/subcontractor	general contractor	Sustainability consultant	5	text	-	-
		Manufacturer location	Location of the manufacturer company	Technical sheet	supplier/subcontractor	general contractor	Sustainability consultant	5	text	-	-
		Certification of product	List of important certification of the product 3-	Technical sheet	supplier/subcontractor	general contractor	Sustainability consultant	5	text	-	-
	Material composition	Material composition	List of the material composition	Technical sheet / EPD	supplier/subcontractor	general contractor	Sustainability consultant	5	text	-	-
		Material percentage	Corresponding percentage of the	Technical sheet / EPD	supplier/subcontractor	general contractor	Sustainability consultant	5	text	-	-
	Use stage	Assembly instruction	Is the assembly instruction available?	Assembly manual	supplier/subcontractor	general contractor	Sustainability consultant	5	list	Available / Not Available	-
		Maintenance instruction	Is the maintenance instruction available?	Maintenance manual	supplier/subcontractor	general contractor	Sustainability consultant	5	list	Available / Not Available	-
		Annual replacement percentage	What percentage of the mass of the	Technical sheet / EPD	supplier/subcontractor	general contractor	Sustainability consultant	5	percentage	-	-
	Carbon	Carbon- declared unit	What is the functional unit that has been	EPD / Sustainability sheet	supplier/subcontractor	general contractor	Sustainability consultant	5	text	-	-
		Carbon- Manufacturing A1-A3	What is the manufacturing carbon (A1-A3) of the material for the selected functional unit in kgCO2eq?	EPD / Sustainability sheet	supplier/subcontractor	general contractor	Sustainability consultant	5	number	-	-
		Carbon- Sequestered A1-A3	If applicable, what is the sequestered carbon	EPD / Sustainability sheet	supplier/subcontractor	general contractor	Sustainability consultant	5	number	-	-
		Carbon-EOL C1-C4	If applicable, what is the end-of-life carbon	EPD / Sustainability sheet	supplier/subcontractor	general contractor	Sustainability consultant	5	number	-	-
		Carbon-Recovery D	If applicable, what is the resource recovery	EPD / Sustainability sheet	supplier/subcontractor	general contractor	Sustainability consultant	5	number	-	-
	Circularity	Lifespan (years)	How many years the component can be used	EPD / Sustainability sheet	supplier/subcontractor	general contractor	Sustainability consultant	5	number	-	-
		Take-back service	Does the manufacturer support a take-back scheme ?	EPD / Sustainability sheet	supplier/subcontractor	general contractor	Sustainability consultant	5	list	yes / no / not known	-
		Reuse potential	How can the component be reused ?	EPD / Sustainability sheet	supplier/subcontractor	general contractor	Sustainability consultant	5	list	yes / no	-
		Detachability	Can the elements be disassembled based on connection details of the built construction	-	supplier/subcontractor	general contractor	Sustainability consultant	5	list	yes / no	-
		Recyclability	How can the component be recycled?	EPD / Sustainability sheet	supplier/subcontractor	general contractor	Sustainability consultant	5	text	-	-
		Biodegradability	Is the material organic / can fully decompose and return to the environment?	EPD / Sustainability sheet	supplier/subcontractor	general contractor	Sustainability consultant	5	list	yes / no	-
	Performance overview - Structural	Compression strength (psi)	Required structural properties for design	Technical sheet	supplier/subcontractor	general contractor	designer	5	numbers	-	-
		Tensile strength (psi)		Technical sheet	supplier/subcontractor	general contractor	designer	5	numbers	-	-
		Flexural strength (psi)		Technical sheet	supplier/subcontractor	general contractor	designer	5	numbers	-	-
		Shear strength (psi)		Technical sheet	supplier/subcontractor	general contractor	designer	5	numbers	-	-
		Modulus of elasticity (ksi)		Technical sheet	supplier/subcontractor	general contractor	designer	5	numbers	-	-
	Material specific	Properties	What are the key properties considered to reclaim the material?	Technical sheet	supplier/subcontractor	general contractor	Sustainability consultant	5	text	-	-
		Values	What is the value of that property?	Technical sheet	supplier/subcontractor	general contractor	Sustainability consultant	5	text	-	-

Template

Design-related																						
Classification						Geometry - from BIM						Design for disassembly						Intended performance - Structural				
Discipline	Layer	Family	MID	Component	Type	Length	Width (inch)	Height (inch)	Total volume (CF)	Density (lbs/ft3)	Mass (lbs)	Connection variation	Designed for disassembly	Connection Type (CT)	Connection Accessibility (CA)	Independency (IC)	Product Edge (PE)	Compression strength (psi)	Tensile strength	Flexural strength	Shear strength	Modulus of
Structure	Shell	Bracing	111	Beam	SEB 8"x16"	<varies>	8	16	2505	42	105210	Beam -	Yes	CT.AE - Connection	CA.AN - Accessible	IC.NI-No	PE.OP - Open, no	13488	21465	13100	2901	4086
												Beam - column	Yes	CT.DI - Direct integral connection	CA.AR - Accessible with additional actions (repairable damage)	IC.NI-No independency, modular zoning	PE.OP - Open, no obstacle					
												Beam - truss	Yes	CT.AE - Connection with added elements	CA.AN - Accessible with additional actions (no damage)	IC.NI-No independency, modular zoning	PE.OP - Open, no obstacle					
												Beam - diagrid	Yes	CT.DI - Direct integral connection	CA.AN - Accessible with additional actions (no damage)	IC.NI-No independency, modular zoning	PE.OP - Open, no obstacle					

Manufacturing-related																						
Manufacturer				Material composition		Use stage			Carbon						Circularity						Material Specific - Bamboo	
Product Name	Manufacturer Name	Manufacturer location	Certification	Material composition	Material percentage	Assembly instruction	Maintenance instruction	Annual replacement	Carbon-declared	Carbon-Manufacturing	Carbon-Sequestered	Carbon- Use B1-B7	Carbon-EOL C1-	Carbon-Recovery	Lifespan	Take-back	Reusability	Detachability	Recyclability	Biodegradability	Properties	Values
Renuteq	Renuteq	USA	EA Credit 1 |	(Sturctually	100%	Yes	No	No	m3	6057	-1316	-	-	-	100+ Years	Not	Yes	Yes	Yes,	Yes	Species	Guadua
																					Glue	VOC
																					Moisture level	6-9%
																					Natural Durability	Durable and resistance to mold and organic
																					Fire	Class B
																					Treatment	Boric Acid

Appendix F: Online Survey

The questions asked in the online survey after data collection demonstration is as follows:

1. What is your role (Structure / CM)?
2. How many input fields did you fill?
3. How can manual input be reduced?
4. In your opinion, how efficient is the template in collecting the required information for reuse? (Rate 1-5)
5. How easy is it to follow the instructions to fill in the template? (Rate 1-5)
6. How clear is the workflow to follow along, regarding its sequence and people's responsibilities? (Rate 1-5)
7. How easy will this workflow be adapted to a real project? (Rate 1-5)
8. How did this workflow increase your awareness or understanding of circularity in design and/or construction?
9. What is the best practice of the workflow and template?
10. What are the challenges or things to be improved in the workflow and template?
11. Are there any other suggestions?

Appendix G: Contract Outline for Material Passport

Sections	Outline
1. Definitions	Define key terms such as Material Passport, Building Passport, Base Data, Product-Specific Data, Permitted Purpose, Material Passport Execution Plan (MPEP), and Common Data Environment (CDE).
2. Coordination and Resolution of Conflicts	Procedures for resolving any inconsistencies in material passport data or responsibilities are detailed, emphasizing documentation in the MPEP and coordination with the BIM/Information Manager.
3. Obligations of Employer	The Employer's duties include setting information requirements for material passports (EIRs), potentially appointing a data manager, and ensuring standards and platforms are kept up-to-date.
4. Obligations of the Project Team Member	Contractors and subcontractors are responsible for creating, sharing, updating, and submitting the required material information as per the MPEP and Responsibility Matrix.
5. Electronic Data Exchange	This section describes how material passport data should be generated, formatted, and exchanged via the CDE or other agreed-upon formats. It notes that interoperability isn't guaranteed unless explicitly stated in the MPEP.
6. Use of Information	Define data licensing rights for reuse, sharing, or certification purposes (e.g., LEED, circular reporting).
7. Liability in Respect of Proprietary Material	Limit contractor liability for passport data misuse beyond agreed scope or detail, consistent with permitted uses.
8. Remedies – Security	(Optional) Define how to handle proprietary or sensitive data included in the material passports if applicable.
9. Termination	Clarify that obligations to submit or access passport data survive contract termination.
10. Defined Terms	List and standardize all key protocol terms used throughout the document.
Appendix 1 – Responsibility Matrix	Identify who submits which passport data, when, and for which materials or building components.
Appendix 2 – Information Particulars	Include or reference the Material Passport Execution Plan (MPEP), circular goals, and level of data detail per stage / template.
Appendix 3 – Security Requirements	(Optional) Detail restrictions or special handling rules for sensitive material passport data.

Commented [SS17]: Note only
Previous version in gemini
paraphrase
1. Definitions
Define key terms such as Material Passport, Building Passport, Base Data, Product-Specific Data, Permitted Purpose, Material Passport Execution Plan (MPEP), Common Data Environment (CDE), and Specified Material Information.
2. Coordination and Resolution of Conflicts
Outline procedures for resolving inconsistencies or ambiguities in material passport data or responsibilities, to be documented in the MPEP and coordinated with the BIM/Information Manager.
3. Obligations of the Employer
Specify the Employer's responsibilities, including defining the Employer's Information Requirements (EIRs) for material passports, appointing a data manager if applicable, and maintaining updates to standards, formats, and platform decisions.
4. Obligations of the Project Team Member
Define the responsibilities of the Contractor and any subcontractors for producing, sharing, updating, and submitting Specified Material Information in accordance with the MPEP and the Responsibility Matrix.
5. Electronic Data Exchange
Describe how material passport data should be created, formatted, and shared using the CDE or interim formats, and note that interoperability is not guaranteed unless specifically required in the MPEP.
6. Use of Information
Clarify licensing terms, including non-exclusive rights for the Employer to use, share, and archive submitted material passport data for operational, maintenance, and sustainability reporting purposes.
7. Liability in Respect of Submitted Information
Limit liability for misuse of material passport data beyond its intended Permitted Purpose and provide disclaimers if data is amended without consent.
8. Remedies – Security and Data Breach
Specify actions in case of security breaches or failure to submit data as required, and allow the Employer to issue instructions or terminate scope in serious cases.
9. Termination and Survival of Rights
State that obligations related to archival access, data licensing, and liability for prior use of passport data survive termination of the agreement.
10. Defined Terms
List and define all capitalised terms used in the protocol, mirroring the CIC BIM Protocol structure and terminology (e.g. Specified Material Information, MPEP, Permitted Purpose, Responsibility Matrix, CDE).