Material Passports and Circular Economy

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Abstract A set of trusted information in the form of material passports is necessary in order to understand the circular value of systems and materials in the built environment. Innovations such as digital technologies and material passports are useful circular economy transitional tools in managing the materials flows and decarbonizing the built environment. Material passports are datasets and reliable information consisting of the entire value chain—specifications of the materials used, and specific supply chains involved from the sources to producers, distributors and consumers or users; and technical facts to improve the re-use or recycling of materials and to enhance their residual value. This paper presents the material passports in the built environment for the transition towards a circular economy as well as the latest trends in research and practice.

Keywords Material passports · Circular economy · Digital marking · Fourth industrial revolution (4IR) · Digital technologies

Learning Objectives

- Understand the principles of material passports and circular economy.
- Understand material passports methodology.
- Identify and utilize software tools and digital technologies that are available to create a material passport.
• Identify and utilize current global applications and material passports databases.
• Understand and implement material circularity indicators, within material passports.
• Be able to create a material passport of your own in the built environment as a tool for transition towards a circular economy.

1 Introduction

Thomas Rau, a Dutch architect and pioneer had quoted: “Every building is a material depot.” Keeping this in mind, if material passports are utilized, therefore, a building about to be destroyed becomes a storage warehouse for useful materials or buildings as material banks (BAMB) [15].

Material passports can serve as a tool to bring residual value back to the market, using its value tracking capabilities. Imagine knowing the exact worth of every material used in a building and importantly what can be recycled or re-used. Parts of Europe, some of which are mentioned in Table 1 [17], have piloted the concept, which will have a global effect in the years to come. This follows upon the European Union (EU) commission unveiled vision in 2015 to make the economy more sustainable [23]. The full list of circular economy policies in EU countries can be found in Ref. [7].

There are other initiatives in place in other sectors:

The food processing or manufacturing industries—Hazard analysis and critical control points (HACCAP) is a preventative food safety approach to reduce risks and hazards. More recently, Blockchain and Artificial Intelligence (AI) is being utilized as a technique in the fourth industrial revolution (4IR), to track and solve issues such as food fraud, safety recalls, supply chain inefficiency and food traceability. Therefore, the record of a manufactured item’s journey, from the source to the consumer, is able to be traced in real-time [29].

The health and environmental sectors—Life cycle analysis (LCA) or Life Cycle Impact Assessment (LCIA) over cycles of cradle-to-grave or cradle-to-cradle is a system that tracks processes and transport routes used for raw materials extraction, production and waste management [27]. They also leverage other already available instruments such as technical data sheets (TDS) and material safety data sheets (MSDS), these contain information about product composition, applications, the potential hazards of these products and how to work safely with them.

Passports have the potential to incorporate the above standards and more, but in this case material passports would serve the built environment.
| Countries | Material passport implementations | Circular economy policies | Government websites |
|-----------|----------------------------------|---------------------------|---------------------|
| UK | Queen Elizabeth Olympic Park  
An Asset Disposal scheme was created to assist contractors to re-use materials after the games by selling them or gifting them to charities. Sustainability was a standout feature as the surrounding community have benefited from the complex | London’s circular economy route map | https://www.lwarb.gov.uk/what-we-do/circular-london/circular-economy-route-map/ |
| Germany | New office building in Essen  
Was previously a coal mine industrial complex. The project focused on sustainable design, especially on cradle-to-cradle design. Importantly this leads to a material passport (in this case the passport focuses on the entire building “Buildings’ Material passport” (BMP)), healthy materials and recyclability [4] | Resource efficiency | https://www.bmu.de/en/topics/economy-products-resources-tourism/resource-efficiency/overview-of-german-resource-efficiency-programme-progress/ |
| Netherlands | 1. Brummen Townhall  
Was the first building in the world equipped with a material passport. It served as a raw materials depot, the material passport made it possible to re-use the material after the building is dismantled  
2. Liander head office  
It is the first building in the Netherlands that is sustainable and energy positive. A material passport was developed. Less materials were used, re-use of materials, therefore, materials can continue their full life cycle and a reduction in carbon emissions | The government-wide circular economy program. No more waste as resources will be re-used across a number of sectors. They plan to achieve this by the year 2050 | https://www.government.nl/topics/circular-economy |
2 Background

In 2017, the world resource use was approximately 20 tons/person/year. The building sector produces the largest amount of waste and consumes the most resources. It is estimated that these amounts will double by the year 2050. Not forgetting the environmental impact such as CO₂ emissions. For this, the European Union (EU)’s commission in 2015, planned to make their economy more sustainable by implementing a circular economy approach.

**What is circular economy?** A circular economy basically entails materials being kept in use for longer periods of time.

Ken Webster who is the head of innovation at the Ellen MacArthur Foundation, had argued in the book publication, “The circular economy: A wealth of flows,” that our linear economy (take–make and dispose) is a nineteenth-century heritage unmoored in the twenty-first-century reality [33]. In previous years, building materials were re-used when constructing new buildings, but in the last 70 years this has decreased. This is due to the fact that newer material compositions make recycling or re-use complex [18]. For this reason, material passport is a tool that can be used for a transition from a linear model to a circular economy, both these models are depicted in Fig. 1 a and b [26].

3 Material passports

**Material passports?** Material passports can be defined as a value tracking tool and brings back residual value to the market. Material passports make information available and relevant from production to purchase to use to maintenance. A single material passport contains a set of information about a particular material, product or system.

The process of generating a material passport may involve a number of persons or companies. Therefore, they are able to contain information from a number of sources and provide a number of stakeholders with this information, this structure of material passports can be seen in Fig. 2, and for easy comprehension, we break down as each section below, i.e. Materials, Information and Stakeholders [24].
Fig. 1 (continued)

Fig. 2 The structure of material passports
3.1 Materials

The materials spectrum is based on different levels of hierarchy, Fig. 3. This is required in order to define the characteristics of a particular product/material and its level of recovery.

One example using the above approach would be the lighting in a building [11]:

- The finished lighting assembly in a “Building” would fall under “Product” and “System.”
- The parts of the lighting assembly would fall under “Component.”
- The chemicals needed to manufacture the components of the lighting assembly would fall under “Material.”

Material passports in the built environment require large amounts of data, some of which are already available in other sectors, a few examples were listed in the previous sections. The idea is to centralize all this data. Some of the most important product/material characteristics required for a material passport in the built environment are [18]:

- **Physical properties**—Dimensions and weight, density, energy and strength.
- **Chemical properties**—Chemical composition, health and safety, is it recyclable or not and lifespan.
- **Biological properties**—Renewable or not and is it recyclable or not.
- **Health of materials**—Emissions, what does the law say, certifications and MSDS.
- **Design and production**—MSDS, TDS, certifications, Bill of materials (BOM) and logistics.
• **Logistics**—Weight, dimensions, traceability and correct documentation.
• **Disassembly**
• **Recyclable.**

The choice of materials plays an important role in the design of a material passport for a circular economy, and to ensure that they can be re-used and there’s safety for humans and the environment. Let us look at the steps to follow in order to generate one [12]:

1. Create a Bill of materials (BOM) or a full product/material list for the particular project. Explore the properties of each product/material.
2. Assign a product/material type for each homogeneous product/material, e.g. metal, plastic, textile, glass, etc.
3. Classify each product/material with a group or cycle. This can be done by designating each product/material either as biological or technical. Biological means that the product can be returned to the environment whilst in use or after (wood, cotton, paper, etc.), whereas technical implies that products/materials that cannot be returned to the environment (metals and plastic, etc.).
4. Receiving information from suppliers about the chemical properties of the product/material. Request for MSDS and TDS and other certifications about the product/material as well as the supplier.
5. Understanding the hazards or health and safety of the product/material, as well as finding a suitable replacement if any.
6. Check if the product/material was part of a previous circular process.
7. Check the lifespan of the product/material, can we recover value in the future.
8. Finally, is our product/material recyclable?

### 3.2 Information

The construction industry is one of the largest sectors in the world’s economy. It employs approximately 7% of the world’s working population and spends around $10 trillion on construction goods and services per year. One of these services and goods are software-based design items. Computational thinking such as Building Information Modeling (BIM) software and material databases allow engineers and designers to create three-dimensional simulations and the ability to view the reality of the structure. Unlike the traditional computer-aided design (CAD), which represent flat shapes and two-dimensional representations.

Software models and databases allow us to create digital representations of real-life structures. From the geometry of the building, spatial and geographic information, and importantly, the exact quantities and the properties of the materials are required [13]. In order to allow high recycling rates and low environmental impacts of buildings, detailed information databases of the construction materials, as well as their building stock characteristics, are essential [20].
We are living in an era of digitization which is ideal for analytical purposes. Big data analytics enabled by machine learning using classification algorithms for anomaly detection and time series forecasting, among others, would allow maintenance predictions, how well the property may sell, modeling errors, recyclability, and, importantly, life cycle analysis of materials [6].

There have already been software and database developments and prototype models within the industry for the industry, some of which are mentioned in Table 2 [36].

3.3 Stakeholders

In order to complete a material passport and a transition toward a circular economy, all relevant stakeholders in Fig. 4, need to play their parts. Data needs to be shared via a material passport database, which allows for regular updates within a centralized location which is accessible to all stakeholders. Some of these databases already exist, namely BAMB and Madaster.

4 Goals and Benefits of Material passports

Below goals and benefits of material passports are summarized [18]:

- Resource for switching from a linear system to a circular economy
- Improving the importance, quality, and safety of material supplies
- Waste reduction
- Eco-footprint reduction
- Supply and demand management
- Managing resources rather than waste will lead to significant cost reduction
- An increase in residual value
-148- Sufficient data for all stakeholders.

5 Current Applications and Projects

In September 2015, 15 partners from seven European countries worked on a project called Buildings as Material Banks (BAMB), under the Horizon 2020 research programme, WASTE-1–2014 Moving toward a circular economy through industrial symbiosis. It is led by Brussels Environment, with an approximate budget of 10 million Euros.

BAMB’s aim is to develop a circular model to the use of building, designs, and materials, thereby increasing the value of materials. Material passports and reversible building designs are tools that are used in this shift to a circular economy [3].
### Table 2 Various databases and software, implementations and prototypes

| Company and software         | Description                                                                 | Website                                                                 |
|-----------------------------|------------------------------------------------------------------------------|-------------------------------------------------------------------------|
| Substance flow analysis     | Software which is available online, analyses material flow by importing material data into the software, the software follows the Austrian standard | https://www.stan2web.net/                                               |
| OpenLCA                     | Another freeware available and still in development is openLCA which can be used for Sustainability and Life Cycle Assessment of materials data | https://www.openlca.org/ https://nexus.openlca.org/databases           |
| TOMRA expert line           | TOMRA Expert Line in Canada, have developed algorithms for material recycling and waste solutions | https://www.tomra.com/en                                                 |
| BigML                       | Apply Machine Learning to BIM                                                | https://bigml.com/                                                      |
| OPTORO                      | Have also developed algorithms for material recycling and waste solutions    | https://www.optoro.com/                                                 |
| CEP-AMERICAS                | This Circular Economy Platform (CEP) of the Americas is an initiative powered by the Americas Sustainable Development Foundation (ASDF). It fills the vacuum for an easy-access one-stop-shop portal where information about Circular Economy from and for the Americas is made available | https://www.cep-americas.com/                                           |
| Eco invent                  | Database for the Life Cycle Assessment on energy supply, resource extraction, material supply, chemicals, metals, agriculture, waste management services, and transport services | https://www.ecoinvent.org/home.html                                      |
| Eco2soft                    | Eco and recycling data                                                       | https://www.baubook.info/eco2soft/?lng=2                               |
| SimaPro                     | Database for Life Cycle Assessment                                          | https://simaprox.com/                                                   |
| USEtox                      | Characterizing human and Ecotoxicological impacts of metals, calculation of emission fractions, and characterization factors | https://usetox.org/                                                     |

(continued)
| Company and software | Description | Website |
|----------------------|-------------|---------|
| Thinkstep GaBi       | Life cycle assessments, product and organizational carbon footprints. This database spans over multiple sectors | [https://www.gabi-software.com/international/databases/gabi-databases/](https://www.gabi-software.com/international/databases/gabi-databases/) |
| Circularise          | An open, distributed and secure communications protocol for the circular economy. The platform allows information exchange between stakeholders throughout the value chain, creating transparency around product histories and material destinations | [https://www.circularise.com/](https://www.circularise.com/) |
| BuildingOne          | Efficient planning, management and analysis for building life cycle | [https://www.onetools.de/en/](https://www.onetools.de/en/) |
| Buildings as material banks (BAMB) | Material passport platform basically is digitally marking materials. It allows users to monitor the building cycle, from planning to construction, occupancy, repairs, renovations, repurposing and decommissioning, and the capacity to track materials quality and changes and track materials health | [https://www.bamb2020.eu/](https://www.bamb2020.eu/) |
| MADASTER             | Material passport platform for the public, which acts as an online library of materials in the built environment. Madaster utilizes 3D scans and building information modeling (BIM) to register or digitally mark the parts of buildings, all this information is put into a passport | [https://www.madaster.com/en/our-offer/Madaster-Platform](https://www.madaster.com/en/our-offer/Madaster-Platform) |
| Circular economy toolkit (CET) | An assessment tool, which identifies improvements in products circularity | [https://circulareconomytoolkit.org/](https://circulareconomytoolkit.org/) |
| Material circularity indicator (MCI) | Described by the Ellen MacArthur Foundation as a tool used to assess European products in regards to a circular economy | [https://www.ellenmacarthurfoundation.org/our-work/activities/ce100/co-projects/material-circularity-indicator](https://www.ellenmacarthurfoundation.org/our-work/activities/ce100/co-projects/material-circularity-indicator) |
| Company and software | Description | Website                                           |
|----------------------|-------------|---------------------------------------------------|
| Circularity calculator| Supports manufacturers in product designs for a circular economy | https://www.circularitycalculator.com/ |

**Fig. 4** Diverse stakeholders who would contribute to a material passport

BAMB’s Material passport platform basically is digitally marking materials. It allows users to monitor the building cycle, from planning to construction, occupancy, repairs, renovations, repurposing and decommissioning, and the capacity to track materials quality and changes and track materials health. BAMB has succeeded in the goal of generating 300 material passports, materials are developed together with a software solution, information is easily accessible by all stakeholders during each process [8].

The approach was applied to the wood frame system in Brazil, in order to test the application and feasibility of the system. The project had proved that stimulates circular thinking [25].

A similar project was investigated in the United Kingdom in the steel industry. Steel that is re-used is approximately 8–10% more expensive as compared to new steel. This is due to the reconditioning process that is required. The project had shown that, by utilizing material passports and the BAMB process, there was a reduction in financial barriers ranging from 150 to 1000 £/t [31]. The re-use of metal in ships have also come under the spotlight, with that in mind, Maersk Shipping Line had implemented its own material passport called ‘cradle-to-cradle passport.’ Every nut and bolt on a 60,000-ton ship can be identified using this passport, materials are numbered, thereby separating the quality of metals. This creates better recycling possibilities and safety [9].

The Ellen MacArthur Foundation (EMF) collaborates with global partners such as Cisco, Google, H&M to name a few and The Circular Economy 100 (CE100) Network. Its ultimate goal is to accelerate the transition to a circular economy. The Built Environment Case Studies Co. Project is a collaboration between BAM, BRE, cd2e, London Waste & Recycling Board, Ouroboros, Tarkett, and Turntoo to
provide the CE100 Network with relevant circular information with regards to the built environment. The projects that were carried out are listed below [10]:

- Rehafutur Engineer’s House
- Olympic Park
- Resource Efficient House
- Brummen Town Hall
- Renovation offices, workshops and storage: Liander
- Bus Boarder
- Pôle de Police Judiciaire/Judicial Police Compound
- BioBuild
- Buildings as Material Banks (BAMB)
- Construction Re-use Platform: Bexleyheath
- ROC A12 School: Carpet Lease
- Reviva shelving.

Taiwan has increased its efforts toward a circular economy. In 2016, the government initiated several measures to implement a circular economy. In a recent publication, there were a total of 66 circular implementations in Taiwan, where over 360 partners are involved. Taiwan being the leading supplier and manufacturer of electronic equipment, the stand out initiative was they developed a circular economy for economic development with environmental protection [21, 32].

In 2017, at the real estate expo in Amsterdam, Madaster launched a material passport platform for the public, which acts as an online library of materials in the built environment. Thomas Rau described Madaster as being a ‘land registry for materials.’ This project inspired others in the industry to follow suit, ABN AMRO partnered with CAD & Company, Rendemint and the architects’ (specialists in circular economy) firm Architekten Cie to develop its own material passport [5]. Madaster utilizes 3D scans and BIM to register or digitally mark the parts of buildings, all this information is put into a passport.

There are other companies and organizations that have implemented or in the process of implementing the circular economy, namely:

- Timberland—From tires to shoes.
- Johnson controls—Recycled batteries.
- Aquazone—Water waste into fertilizer.
- Schneider Electric—Increase product lifespan through leasing and pay per use.
- AB Inbev—Returnable glass bottles.

### 5.1 A Material passport Case Study

We use a case study published in 2019, by three researchers from TU Wien, which is one of the major universities in Vienna, Austria. They had demonstrated how to generate a material passport, as well as assess the recycling potential and environmental impact of materials and an entire building [19].
The material passport concept was tested using a concrete office building. The building consisted of three stories. The following building components were considered for the assessment:

- Exterior and interior walls
- Roof
- Flooring
- Ceilings
- Basement
- Glass facade
- Concrete columns.

The first step was to model the building using BIM software. The above-listed components had to be inserted into the BIM software. Once the building has been modeled, the second step is to utilize some of the databases or software mentioned in Sect. 3.2. In this example, the modeled components were linked to BuildingOne for data management and assessment, and Eco2soft was used to determine the eco and recycling data of each component. Once all the suitable information had been acquired regarding each component, a material passport is developed. A graphical representation is depicted below in Fig. 5.

The case study had shown that Material passports can work together with current software and prototypes, the building was recyclable to around 50%, and the main environmental impact was caused by the concrete. This had proved that by utilizing material passports in the early stages of project developments, the correct choices of materials with regards to recyclability and eco-friendliness can be made. Which is an important step toward a circular economy.

![Fig. 5](image-url) A graphical representation of the development of a material passport, based on a case study
6 Barriers and Solutions of a Circular Economy and Material passports

In summary, most of our global economy is modeled around linearity rather than circularity. Humanity and their habit of wasting and polluting have brought the practice of a circular economy into the spotlight, in all sectors. As much as we develop tools such as material passports or digital marking of materials as well as many other so-called ‘ingredients lists,’ there are still some hurdles. In order to get over these hurdles, certain rules need to be put in place [35]:

- Stricter government policies and laws.
- Government support in form of incentives and funding to companies and public and private partnerships.
- Production of products or materials in a more circular fashion with innovation.
- Development of better recycling technologies and waste management with the introduction of 4IR.
- Finally, changing the mindset of humanity and consumption behavior.

7 Advances to Be Made in Terms of Digital Technologies and Software to Fully Realize ‘Material passport’ in a Circular Economy

Digitization seems to be lagging within the built environment, particularly in the construction sector. Implementation of this important aspect has been a challenge in the past years. As we stand at the cusp of a new industrial revolution (4IR), technologies such as Artificial intelligence (AI) and Cloud IoT platform. The tools for implementing material passports and a circular economy are now readily available, the idea of digitally marking materials is now a reality. This would also allow for an increase in profit for supply chains.

We are now able to integrate material passports within BIM, Geo-information (GIS), and Unified building modeling (UBM) systems. This will allow for capturing and accessibility of material data and their properties within a circular design.

With the use of AI, material properties can be viewed using automated methods. Machine learning algorithms can analyze the above material data patterns. Or imagine material passports communicating with each other via wireless sensors, this can be achieved using IoT platform. This would allow for smoother and faster data exchange and input changes across different networks and stakeholders, lifespan monitoring of materials, and early maintenance warnings.

Digitization, marking, capturing, storing, and analyzing materials data for material passports allow for the introduction and implementation of a number of technology applications and technological advancements in this research area within a circular economy. We list some of the technologies below [18]:
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- Blockchain
- AI (Advanced Robotics and Machine Learning)
- Virtual Reality
- Augmented Reality
- IoT
- Big Data
- Radio-frequency Identification (RFID)
- 3D Printing and Scanning.

These technological advancements catalyze a circular economy implementation. The construction industry will change drastically in the coming years as a number of technologies will be adopted from the autonomous operation of construction equipment to digital marking of products. Digital marking is a link between the physical product and the performance of a product or material (Declaration of Performance (DoP)). It gives access to product or material information in a digital format in a harmonized way. This info can be remotely accessed via cloud-based platforms or applications. This contributes in reducing administrative burdens, traceability of products or materials, and serves as a link between manufacturers and consumers use of the product.

To date, there have already been applications and innovations from global leaders in other sectors. Apple’s iPhone disassembly robot is capable of dismantling an iPhone in 11s and sorts its components into re-usable materials. By doing this, Apple has captured materials that are re-usable for future products to the value of approximately $40 million [34].

8 Conclusion

Material passport will increase the value of materials and incentivize suppliers and manufacturers to produce circular materials. It enables the easy acquisition of sustainable materials and reversed logistics. Given the number of ongoing initiatives globally, it is reasonable to say that there is room for possibilities in this research area. The concept of circular economy in the built environment, as well as material passports and digital marking tools, provide opportunities for innovation and value creation.

9 ANNEX: A Case Study

In this second case study, we used a student-oriented construction project report in order to come up with a material passport, and demonstrate the quantitative benefits before and after material passport analysis.

Step 1
Identify a project: in this case, the project chosen was the Delft University of Technology, Faculty of Architecture, Urbanism and Building sciences, Track Building Technology, where a student had worked on a project located in Rotterdam, Netherlands. A typical old office building is refurbished into livable housing [1].

Step 2
Make up a list of the materials used in the construction process or create a BOM, their quantities and specific use in the construction process. In this case, we had selected some of the most important components.

- Concrete
- Aluminium
- Glass
- Wood.

Step 3
Once all the components and their respective quantities are determined, develop a BIM model using design software or acquire the building design. The site plans and graphical BIM models of this project can be viewed in Fig. 6a before design and Fig. 6b after design [1].

Step 4
Acquire each materials eco and recyclable properties, as well as the material-specific fixed data such as MSDS, TDS, LCAs, etc., or whether it has been used in previous cycles, all these data can be acquired from one of the databases in Table 2; in this case, we had used Thinkstep Gabi Database.

Step 5
We create our own material passport in Table 3; this can be done by utilizing the information in the previous steps. For the purpose of this paper, we had created a tabular design. Since the material data is of large amounts, links have been provided in the table. Newer trends are based on online material passport databases where passport information can be accessed and adjusted accordingly by the building’s stakeholders.

In order to see the benefits of this material passport, we will look at the circularity index of the above-listed materials. Circular indicators are decision-making tools for developers, it assesses how well a company or product performs in the transition from a linear to a circular economy. Material circularity indicator (MCI) of a product gives a value between 0 and 1 (or 0%-100% recirculated parts), a value that is higher than 1 means a higher circularity. In order to calculate the indicator value, complex mathematical calculations and input values are required, these involve Mass, Recycled feedstock, and Recycling efficiency.

\[
Product\ Level\ Circularity = \frac{\text{Economic Value of Recirculated Parts}}{\text{Economic Value of All Parts}}
\]
MCI data requirements are as follows:

- Source of the material (virgin, recycled, re-used)
- Manufacturing process losses
- How the manufacturing losses treated?
- How is the waste of the product or end of life treated?
- Recycling process efficiency
- The mass of the product
- The lifetime of the product

**Fig. 6**  
*a* A graphical representation of the construction project before design.  
*b* A graphical representation of the construction project after design
Fig. 6  (continued)

- Intensity of use of the product
- The average lifetime of the average product
- The average use intensity of the average product.

The same datasets are required for life cycle analysis (LCA), except for the last two points, i.e., the average lifetime and average use intensity of the average product.

For the purpose of MCI calculations, online tools are available such as Circular economy toolkit (CET), Circularity calculator, Ellen MacArthur’s Material circular indicator (MCI) tool, OpenLCA, and Gabl software, the links to these platforms and many others are available in Table 2. In this case study, we used Ellen MacArthur’s Material circular indicator (MCI) tool. Tables 4 and 5 shows the material circularity
| Materials       | Mass (kg) | Life expectancy (years) | CO₂ per year | Fixed material data, manufacturers, LCA                                                                 | Eco and recycling properties                                                                                                                                                                                                                                                                                                                                 |
|-----------------|-----------|-------------------------|--------------|-------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Concrete        | 33,600    | 100                     | 2657         | [link](https://gabi-documentation-2020.gabi-software.com/xml-data/processes/606a5ad9-3317-4311-91b7-6c2147955729.xml) | The concrete structure and brick work is considered to have a lifespan of 100 years and is re-usable at end of use phase of the building. 1 ton concrete = 1 ton of CO₂                                                                                                                                                                                                                           |
| Aluminium       | 810       | 50                      | 145          | [link](https://gabi-documentation-2020.gabi-software.com/xml-data/processes/695f3519-ea45-414b-9f18-a1dd9200b765.xml) [link](https://gabi-documentation-2020.gabi-software.com/xml-data/processes/76a28c07-f7d7-40f9-8fed-1f23237daf2e.xml) | Aluminium and steel are high embodied, due to the energy required to produce, mining, heating, manufacturing, and transportation. The more they are recycled their embodiment reduces making it more recyclable and eco-friendly. Long-lasting, durable, and able to withstand ambient conditions                                                                                                                                                                                                 |
| Wood for balconies | 89       | 100                     | 70           | [link](https://gabi-documentation-2020.gabi-software.com/xml-data/processes/3e4bd27e-caa6-42b4-8e4e-95da9a96eed3.xml) | Wood, just like steel and aluminium, is a good recyclable material but with less strength. Perfect for structural framing, flooring, furniture. Cork and bamboo are good alternatives                                                                                                                                                                                                                                                  |
Table 3 (continued)

| Materials          | Mass (kg) | Life expectancy (years) | CO₂ per year | Fixed material data, manufacturers, LCA | Eco and recycling properties |
|--------------------|-----------|-------------------------|--------------|----------------------------------------|------------------------------|
| Glass for balconies | 211       | 50                      | 210          | https://gabi-documentation-2020.gabi-software.com/xml-data/processes/6d58cca8-213a-447e-942c-89701a609005.xml | Recycling glass reduces air and water pollution. Environmentally and economically friendly |

Table 4 Material circularity indicator (MCI) before the implementation of the Material passports

| Materials | Virgin % | Re-used % | Recycled % | Re-usable % | Recyclable % | Waste % |
|-----------|----------|-----------|------------|-------------|--------------|---------|
| Concrete  |          |           |            |             |              |         |
| Aluminium | 0        | 8         | 0          | 3           | 0            | 0       |
| Glass     | 7        | 0         | 35         | 0           | 28           | 28      |
| Wood      | 56       | 41        | 0          | 60          | 13           | 9       |

MCI value of building before material passport is 69%

Table 5 Material circularity indicator (MCI) after the implementation of the Material passports

| Materials | Virgin % | Re-used % | Recycled % | Re-usable % | Recyclable % | Waste % |
|-----------|----------|-----------|------------|-------------|--------------|---------|
| Concrete  | 0        | 69        | 0          | 95          | 0            | 0       |
| Aluminium | 0        | 0         | 0          | 0           | 0            | 0       |
| Glass     | 7        | 1         | 35         | 0           | 6            | 7       |
| Wood      | 56       | 1         | 0          | 3           | 1            | 1       |

MCI value of building before material passport is 73%

indicator of the building in this case study, before and after developing the material passport [1].

For further reading on materials circularity indicators, measuring and mapping circularity, as well as the International Organization for Standardization (ISO) TC 323 on Circular Economy, refer to these references [2, 16, 22, 30].

The original glass can be broken down for recycling, the aluminium can be reused in the building renovation process or recycled, and glass and stone are recycled.
Finally, the concrete which is 70% of the structure is expected to last for 100 years, therefore re-usable. Based on this information, we were able to select the correct materials and we had developed our material passport in Table 3 above. The new MCI value is shown in Table 5.

We find that there is an increase in the MCI value from 69 to 73% based on the selection of materials in this case study. This change in MCI is due to the fact that we had kept the specific materials in a circular flow (re-used or recycled or recyclable) for as long as possible, with a reduction in waste.

Material selection plays a huge role in circular design processes. In this case, standardization of components, cleaner material flows, material cost factors, and simpler disassembly or modular designs were taken into account when selecting materials. By comparing the material indicators based on the selected components for the renovation of this building, we can conclude that Material passports generation from the beginning of the building’s lifespan proves to be an important feature in the construction process, and would assist in creating a perfect balance in selecting the correct materials and their quantities in order to create a more circular economy.

10 Questions and Answers

1. Define a Material passport
   Material passports can be defined as a value tracking tool and brings back residual value to the market. Material passports make information available and relevant from production to purchase to use to maintenance. A single material passport contains a set of information about a particular material, product, or system.

2. Define a Circular economy
   Materials being kept in use for longer periods of time.

3. What is the difference between a linear economy and a circular economy?
   In a linear economy, raw materials are transformed into a required product and, at the end of its life cycle, it is thrown to waste. Whereas in a circular economy, the product is not thrown to waste, rather it is recycled or re-used.

4. What is the basic structure of material passport?
   Input material data.
   A material database.
   Output material data accessible by stakeholders.

5. What are the properties or characteristics one should look out for when selecting materials?
   Physical properties.
   Chemical properties.
   Biological properties.
   Health of materials.
   Production and design.
   Logistics.
Disassembly.
Recyclable.

6. **List and explain the types of data we can get from the above Material properties and characteristics**

   Life cycle analysis (LCA) or Life Cycle Impact Assessment (LCIA) is a system that tracks processes and transport routes used for raw materials extraction, production, and waste management.

   Technical data sheets (TDS) and material safety data sheets (MSDS), these contain information about product composition, applications, the potential hazards of these products and how to work safely with them.

   Bill of materials (BOM), list all the required materials, their quantities, and their use.

7. **List the steps to follow to generate a Material passport.**

   1. Create a Bill of materials (BOM) or a full product/material list for the particular project. Explore the properties of each product/material.
   2. Assign a product/material type for each homogeneous product/material, e.g., metal, plastic, textile, glass, etc.
   3. Classify each product/material with a group or cycle. This can be done by designating each product/material either as biological or technical. Biological means that the product can be returned to the environment while in use or after (wood, cotton, paper, etc.), whereas technical implies that products/materials that cannot be returned to the environment (metals and plastic, etc.).
   4. Receiving information from suppliers about the chemical properties of the product/material. Request for MSDS and TDS and other certifications about the product/material as well as the supplier.
   5. Understanding the hazards or health and safety of the product/material, as well as finding a suitable replacement if any.
   6. Check if the product/material was part of a previous circular process.
   7. Check the lifespan of the product/material, can we recover value in the future.
   8. Finally, is our product/material recyclable?

8. **Name two current Material passport databases**
   BAMB and MADASTER.

9. **Who are the typical stakeholders involved in the development of Material passport? (Name five or more)**
   Engineers, architects, owners, builders, material suppliers.

10. **Name three benefits of Material passports**
    Eco-footprint reduction.
    An increase in residual value.
    Sufficient data for all stakeholders.

11. **What is digital marking of materials?**
    Digital marking is a link between the physical product and the performance of a product or material (Declaration of Performance (DoP)). It gives access to product or material information in a digital format in a harmonized way. This info can be remotely accessed via cloud-based platforms or applications.
12. Which of the approach creates the highest value—Recycling, Re-use, or remanufacturing?
Re-use.

13. What are Material circular indicators?
Circular indicators are decision-making tools for developers, it assesses how well a company or product performs in the transition from a linear to a circular economy. Material circularity indicator (MCI) of a product gives a value between 0 and 1 (or 0%–100% recirculated parts), a value that is higher than 1 means a higher circularity.

14. True or false—Design for endless RECYCLING is a key principle in a circular design?
False.

15. Develop a Material passport of your own, based on a construction project you are currently busy with.
(Example: ANNEX: A Case Study)

16. Come up with a circular designed product of your own, not necessarily in the built environment.

References

1. Ankur, G. (2019). Accelerating circularity in built-environment through “Active-Procurement”: An aggregated assessment framework to make sustainable choices while using secondary material at early design phase. TU Delft Architecture and the Built Environment.
2. Assets.website-files.com. (2020). Retrieved March 19, 2020, from https://assets.website-files.com/5e185aa4d27bcf348400ed82/5e318d51e9eac45e7a658aaceasuring%20Circularity%20-%20%20technical%20methodology%20document.docx.pdf.
3. BAM. (2020). About bamb—BAMB. Retrieved February 1, 2020, from https://www.bam2020.eu/about-bamb/.
4. BAM. (2020). New office building—BAMB. Retrieved March 16, 2020, from https://www.bam2020.eu/topics/pilot-cases-in-bamb/new-office-building/.
5. Bikker, A. (2020). MADASTER-materials passport opens the way for waste-free building culture. Abnamro.com. Retrieved February 3, 2020, from https://www.abnamro.com/en/newsroom/press-releases/2017/madaster-materials-passport-opens-the-way-for-waste-free-building-culture.html.
6. The Official Blog of BigML.com. (2020). Building information modeling (BIM): Machine learning for the construction industry. Retrieved March 12, 2020, from https://blog.bigml.com/2018/08/07/building-information-modeling-bim-machine-learning-for-the-construction-industry/.
7. Böhme, K., Holstein, F., & Salvatori, G. (2019). Circular economy strategies and roadmaps in Europe. Visits and Publications.
8. C2c-centre.com. (2020). Materials passports platform prototype for materials banking now live | C2C-centre. Retrieved February 2, 2020, from https://www.c2c-centre.com/news/materials-passports-platform-prototype-materials-banking-now-live.
9. C2c-centre.com. (2020). Maersk cradle to cradle® passport | C2C-centre. Retrieved February 4, 2020, https://www.c2c-centre.com/library-item/maersk-cradle-cradle%C2%AE-passport.
10. CE100. (2016). Circularity in the built environment: Case studies. Compilation of case studies from the CE100. Ellen Macarthur Foundation.
11. Charter, M. (2019). Designing for the circular economy. London: Routledge.
12. Circulardesignguide.com. (n.d.). Material selection. Retrieved February 18, 2020, from https://www.circulardesignguide.com/post/material-selection.
13. Community, B. (2020). Could machine learning be the new scope for BIM? | Bimcommunity. Retrieved March 12, 2020, from https://www.bimcommunity.com/news/load/948/could-machine-learning-be-the-new-scope-for-bim.
14. Construction-products.eu. (2020). Smart CE marking: Construction products Europe AISBL. Retrieved March 19, 2020, from https://www.construction-products.eu/services-jobs/smart-ce-marking.
15. Material District. (2020). The material passport as next step in circular economy—Material District. Retrieved January 23, 2020, from https://materialdistrict.com/article/material-passport-next-step-circular-economy.
16. Ellenmacarthurfoundation.org. (2020). Retrieved March 18, 2020, from https://www.ellenmacarthurfoundation.org/assets/downloads/insight/Circularity-Indicators_Project-Overview_May2015.pdf.
17. Finamore, M. (n.d.). Circular Economy in the Built Environment. Oneplanetnetwork.org. Retrieved February 11, 2020, from https://www.oneplanetnetwork.org/sites/default/files/circular-economy-versio-7.11.2017-pdf.pdf.
18. Heinrich, M., & Lang, W. (2019). Materials passports—Best practice. München: Technische Universität München.
19. Honic, M., Kovacic, I., & Rechberger, H. (2019). Assessment of the recycling potential and environmental impact of building materials using material passports - a case study. In Energy efficient building design and legislation. Croatia: SMSS2019 (pp. 172–179). Retrieved February 29, 2020, from https://www.researchgate.net/publication/334611379.
20. Honic, M., Kovacic, I., & Rechberger, H. (2019). Concept for a BIM-based material passport for buildings. IOP Conference Series: Earth and Environmental Science, 225, 012073. https://doi.org/10.1088/1755-1315/225/1/012073
21. Ibitz, A. (2020). Assessing Taiwan’s endeavors towards a circular economy: The electronics sector. Asia Europe Journal. https://doi.org/10.1007/s10308-019-00568-w
22. International Organization for Standardization. (2019). ISO/TC 323—Ad-Hoc Group 3 ‘Measuring Circularity’ Explanatory note as part of the New Work item proposal (NWIP). Retrieved March 19, 2020, from https://www.iso.org/committee/7203984.html.
23. Architects Journal. (2020). Material passports: Finding value in rubble. Retrieved January 26, 2020, from https://www.architectsjournal.co.uk/news/material-passports-finding-value-in-rubble/10043989.article.
24. Luscuere, L. (2017). Materials passports: Optimising value recovery from materials. Proceedings of the Institution of Civil Engineers—Waste and Resource Management, 170(1), 25–28.
25. Munaro, M., Fischer, A., Azevedo, N., & Tavares, S. (2019). Proposal of a building material passport and its application feasibility to the wood frame constructive system in Brazil. IOP Conference Series: Earth and Environmental Science, 225, 012018.
26. Peters, M., Oseyan, J., & Ribeiro, A. (2016). BAMB value network by phase. BAMB—Buildings as material banks consortium.
27. DEAT. (2004) Life cycle assessment, integrated environmental management, information series 9, department of environmental affairs and tourism (DEAT), Pretoria.
28. Pyzyk, K. (2020). 5 of the world’s most eco-friendly building materials. Smart Cities Dive. Retrieved March 14, 2020, from https://www.smartcitiesdive.com/news/most-eco-friendly-building-materials-world-bamboo-cork-sheep-wool-reclaimed-metal-wood/526982/.
29. Qiu, E. (n.d.). How blockchain will transform the food supply chain. Retrieved February 11, 2020, from https://www.plugandplaytechcenter.com/resources/how-blockchain-will-transform-food-supply-chain/.
30. Saidani, M., Yannou, B., Leroy, Y., & Cluzel, F. (2017). How to assess product performance in the circular economy? Proposed requirements for the design of a circularity measurement framework. Recycling, 2(1), 6.
31. Smeets, A., Wang, K., & Drewniok, M. (2019). Can material passports lower financial barriers for structural steel re-use? *IOP Conference Series: Earth and Environmental Science*, 225, 012006.

32. Towards a circular Taiwan. (2019). 1st ed. Taiwan: Taiwan circular economy network.

33. Webster, K. (2017). *The circular economy*. Isle of Wight: Ellen MacArthur Foundation Publishing.

34. World Economic Forum. (2020). These 5 disruptive technologies are driving the circular economy. Retrieved March 6, 2020, from https://www.weforum.org/agenda/2017/09/new-tech-sustainable-circular-economy/.

35. World Resources Institute. (2020). Barriers to a circular economy: 5 reasons the world wastes so much stuff (and why it’s not just the consumer’s fault). Retrieved February 5, 2020, from https://www.wri.org/blog/2018/05/barriers-circular-economy-5-reasons-world-wastes-so-much-stuff-and-why-its-not-just.

36. Wright, S. (2020). AI and a circular economy | Stephen J. Wright. Retrieved February 23, 2020, from https://www.stephenjwright.com/ai-and-a-circular-economy.

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