Ranking domain data sources which influence building circularity passports

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Abstract

At the EU level, the Digital Product Passport has been defined across several industries, which seems to overlap with material passports. The industry is divided, and confusion persists on what a material passport is, what it contains, and how it should be issued. In this article, we try to address some of these concerns and identify the data sources, tools, and methodologies that could influence the building circularity passport. To this end, we adopt two key perspectives: (1) product/component level and (2) building level. For each perspective, we analyse existing frameworks, literature, and case studies and rank the importance of the identified tools and methodologies which have become prevalent. The ranking of data sources is done considered several data domains (e.g. composition, circularity, etc.). A discussion of the two levels is provided based on the several approaches, with limitations highlighted.

Keywords: material passport, data requirements, environmental, lca, circularity.

1 Introduction

Material passports are emerging as key tools to facilitate our transition towards a digital circular economy. The idea of a “material passport” dates back to the 80’s but under different terms, as summarised by (Mulhall et al., 2017). While the concept was initially used in the construction sector with varying interpretations, it is now gaining broader relevance. The scope of a material passport can encompass materials, components or systems (assemblies of components), and the concept is now also expanding to a building level, usually termed a “building circularity passport”, as defined by the DGNB certification scheme for example (see Table 1). As recent relevant research has been rapidly evolving, the concept of a material passport has yet to achieve clear definition in terms of scope, fields and data and it should cover. As the drive towards a circular economy expands across industries, a convergence of various initiatives, standards and ideas become increasingly significant. Most notably, there are overlaps and synergies between the Environmental Product Declaration (EPD) based on the ISO 14025 (ISO, 2006), the European Commission's Product Environmental Footprint (PEF), and Digital Product Passports (DPP) when it comes to product level data. A disambiguation on the subject is given by (Honic et al., 2024), contrasting similarities and differences between concepts and initiatives. Within our study we distinguish between a product as something which comes from a manufacturer and a component as something which is part of a building (which may have been a product beforehand), following the definitions and boundaries set by (Terndrup et al., 2023), both of which are made up of materials (or ingredients in some studies). A building level circularity passport is a wider scope concept whereby the aggregation of building components facilitates a comprehensive view of the entire building. Sustainability rating schemes such as BREEAM, LEED, DGNB and Level(s) (see Table 1) would effectively provide a building-level material circularity passport.

To streamline the adoption of material passports, the use of BIM is paramount, along with the more recent Product Data Template standards under ISO 23387:2020 (ISO, 2020), as highlighted by (Honic et al., 2024; Pedro Mêda et al., 2021). Data sources from Building Information Models (BIM), LCA databases, Building Energy Model (BEM) tools, their availability, trust and uncertainty propagation remain problematic along the supply chain and fragmented over the building life cycle. The use of Open BIM standards has recently improved across the spectrum, and standards such as the Industry Foundation Classes (IFC) are useful as shown by (Tomczak et al., 2024), but remain limited when a material passport should include several domain data outside of the BIM scope. To tackle these challenges, in this paper we aim to answer the following research questions (RQ):

- *RQ1. What makes a material passport at the product/component vs building level?*
- *RQ2. What are the data required to facilitate the effective implementation of material passports?*

In terms of structure, the paper goes over related work on material passports over products versus buildings, supporting tools and methods, and relevant data structures and standards. Based on this, a methodology is presented that groups the material passport based on several key domains, where the data requirements of the underlying tools and methods are highlighted and discussed in the next sections. The data sources are then ranked on the basis of the interrelationships between these domains. Finally, the discussion and conclusions are presented, by highlighting limitations and future steps.

2 Related work

2.1 Product vs building passports

Within the construction industry and the research domain a multitude of efforts are underway to develop material passports at several levels. Table 1 provides an extended list of relevant approaches for both element level (material/product/component) and building level, while section 4 provides an analysis of the various categories of data these approaches consider. While the creation of material passports for product and component levels has been a longstanding research focus (Mulhall et al., 2017) , the aggregation of data at the building level and its different contexts remains a data integration challenge (Göswein et al., 2022). Building level certification schemes (Table 1) include several other assessment areas ranging from energy and water use, thermal comfort, indoor air quality, and even social benefits. The study by (Ferreira et al., 2023) provides a valuable comparative analysis of some of these schemes for retail building types, and highlights which domains are covered by each of them and where their priorities lie. Finally, different Digital Building Logbook (DBL) initiatives are also considered as a way to provide comprehensive information about an entire building (Gómez-Gil et al., 2022), at EU level, covering most data domains. This is also true for other aspects, but the tools and methodologies differ. The bottom line is that to facilitate the calculation of indicators, data availability, trust and quality are key aspects that in most cases are hard to come by, as concluded by (Çetin et al., 2023).

Table 1. Different approaches to material passports with different scopes and focuses

	Approach	Reference	Scope	Type
1	Environmental Product Declaration (EPD)	ISO 14025	Material or Product or Component	Label
2	Product Environmental Footprint (PEF)	(European Comission, 2024)		Label
3	Digital Product Passport (DPP)	(Jensen et al., 2023)		Passport
4	BAMB Material Passport (MP)	(Heinrich & Lang, 2019; Mulhall et al., 2017)		Passport
5	Product Circularity Data Sheet (PCDS)	(Mulhall et al., 2022)		Data
6	Product Data Templates (PDT)	(Mêda et al., 2021)		Data
7	Circular Material Passport (CMP)	(Göswein et al., 2022)		Passport
8	Material Passport Framework (MPF)	(Terndrup et al., 2023)		Passport
9	BREEAM	https://bregroup.com	Building	Certification
10	LEED	https://www.usgbc.org		Certification
11	DGNB	https://www.dgnb.de		Certification
12	Level(s)	(Commission et al., 2017)		Framework
13	Passive House (PH)	https://passivehouse.com/		Certification
14	Energy Performance Certificate (EPC)	(European Parliament, 2018)		Certification
15	Smart Readiness Indicator (SRI)	(European Parliament, 2018)		Certification
16	WELL Building Standard	https://www.usgbc.org		Certification
17	Digital Building Logbook (DBL)	(Commission et al., 2020)		Digitalisation

2.2 Supporting tools and methodologies

The approaches listed in Table 1 are used for various purposes, and with time they added more aspects to consider. The product level approaches rely mostly on raw data about a product, its compositions, properties and various meta-data about its manufacturing and usage. With circular economy initiatives, assembly, disassembly, waste management and environmental indicators become more important. LCA is the prime method at both the product and building levels because it provides ways to model any product system. In fact, most of the building certification schemes in Table 1 include or demand at least some form of LCA. In terms of circularity, we can consider several existing methodologies which look at the material makeup, their reusability and disassembly potential for products and buildings. The most widely used one is the Material Circularity Indicator (MCI) (MacArthur, 2015), which was then adapted and used in the Madaster platform[1]. Following the open specification of this methodology, (Zhang et al., 2021) adapted it to include several new aspects such as costing and social aspects when compared to other similar indicator schemes. MCI can be aggregated from a product level to an entire building, scaling linearly. The MCI needs comprehensive data about the material compositions, ratios of their recycling and generated waste at several stages, for effective calculation. Where the MCI is focused on the material flows, the reuse potential (Durmisevic et al., 2021) is complementary indicatory looking at deconstruction decision-making, that takes into account materials, component connection types and other empirical factors, based on the BIM model. Another methodology, the design for disassembly (DfD) indicators for entire buildings were tested by (Cottafava & Ritzen, 2021) with embedded carbon in the mix, concluding that more research is needed to better understand the relationship between product and building level when employing circularity indicators, especially when looking at the data requirements for the calculation methodologies.

In terms of the other aspects related to energy efficiency, the product passport levels need to include basic information on product performance (if needed) which is then used for the building-level performance simulations. Additional aspects such as wellbeing (indoor air quality, thermal comfort, water usage, etc.) do not concern the product level directly, but are indicators which are useful for the building level and these usually require additional dedicated simulations and monitored data, bordering on digital twin (DT) applications (Boje et al., 2023). We will consider these out of scope for our current study.

2.3 Data structures

The study by (Pedro Mêda et al., 2021) emphasises the importance of information stored at the product level, be it as DPP or PDT which would facilitate the context of BIM and DT at building-

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[1] https://madaster.com/inspiration/madaster-circularity-indicator/

level. The studies by (Çetin et al., 2023; Göswein et al., 2022; Mulhall et al., 2022; Munaro & Tavares, 2021; Terndrup et al., 2023) already offer descriptions of data and information which should be included in a material passport. More recently, a comprehensive framework on material passports on different levels (from product to building) and the necessary data fields is given by (Terndrup et al., 2023). Most of the aforementioned studies take the BAMB project material passport framework (Heinrich & Lang, 2019; Mulhall et al., 2017) as a key reference and build on it. Considering the initiatives listed in Table 1, several categories of data can be discerned from these studies:

- Identity data – names, identifiers, classification codes, locations, manufacturer details, etc.
- Composition – material type names, densities, quantities, dimensions, proportions, ingredients, classification codes, physical, chemical and biological properties;
- Assembly – connection types, assembly and disassembly information;
- Environmental – embedded carbon ratings, environmental impact indicators;
- Circularity - calculated indicators, reuse cycles, waste classification codes, life spans, safety information on hazardous ingredients;
- Energy – embedded energy, performance values (e.g. U-value);
- Water – use of water, domestic hot water, water recovery during operation stages;
- Wellbeing – indoor air quality, thermal comfort of occupants, etc;
- Transport – logistics in product transportation to site, packaging sizes, restrictions, etc;
- Usage – other relevant information on how the product was used, maintenance requirements and guidance, etc;
- Economic – data on the real, predicted or market adjusted value;
- other – support documentation, drawings, models, metadata, etc.

The above-mentioned categories clearly intersect with LCA and BIM. In particular, (Tomczak et al., 2024) address the compatibility of IFC schema with circularity principles, concluding that while IFC can effectively support identity data, material compositions, and environmental properties, it may face challenges with more complex operations requiring reasoning and calculations. An alignment with IFC properties and classes is also made by (Terndrup et al., 2023) in their proposed framework. The new addition of properties for the decommissioning and reuse[2] by BuildingSmart[3] now enables BIM to represent and store relevant circularity data at product level, which can then be used at the building level calculations (e.g. LCA or circularity indicators), but further testing and implementation is needed.

In terms of databases for identity data and material compositions, there are several commercial solutions, such as CoBuilder, with high information quality of the construction supply chain. There are also several known initiatives, such as the buildingSmart Data Dictionary[4] (bSDD) which offers open access information on certain properties, or EPD repositories, such as OkobauDat[5], Inies[6] or The EPD Portal[7] that publish EPDs of products. In terms of LCA background processes, several dedicated databases which can be used for the building sector exist (e.g. ecoinvent, gabi, etc.) which are adapted depending on the scope and location of the study (Obrecht et al., 2020). For circularity of buildings, Madaster employs and adapted version of the MCI (*Madaster Circularity Indicator Explained*, 2021) , but not open access. The main concern over data availability is quality and accessibility. However, as transparency is also a key issue for material passports, tracing back or re-calculating certain indicators may not be possible without access to these databases at later stages (i.e. ecoinvent, madaster recycling datasets, etc.).

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[2] https://search.bsdd.buildingsmart.org/uri/TUe/DOR/0.0.2
[3] https://www.buildingsmart.org/

[4] https://www.buildingsmart.org/users/services/buildingsmart-data-dictionary/
[5] https://www.oekobaudat.de
[6] https://www.inies.fr/en/
[7] https://portal.environdec.com/

3 Methodology

Our approach is to rank the different data sources which are needed for material passports in the contexts aforementioned. To this end, we identified several studies which propose material passport data structures, and which are openly available. Most notably we will look at the studies by (Çetin et al., 2021; Göswein et al., 2022; Jensen et al., 2023; Mulhall et al., 2022; Munaro & Tavares, 2021; Terndrup et al., 2023). By analysing, comparing and contrasting these initial examples, we bundle our data requirements according to several domains, as already evidenced in the previous section. The interdependencies between these domains will facilitate an objective ranking in terms of importance for the data.

4 Domain data requirements for material passports

4.1 Product and component level

Table 2. Product and component level approaches for material passports and their data scopes across domains

Approaches from Table 1*	EPD	PEF	DPP	MP	PC DS	(Munaro & Tavares, 2021)	(Çetin et al., 2023)	(Tomczak et al., 2024)	CMP	MPF
Identity	x	x	x	x	x	x	x	x	x	x
Composition	x	x	x	x	x	x	x	x	x	x
Assembly			x	x		x	x	x	x	x
Environmental	x	x	x	x		x	x	x		x
Circularity			x	x	x	x	x	x	x	x
Energy	x	x								
Water	x	x								
Wellbeing	x									
Transport	x	x		x		x				
Usage	x	x	x	x	x	x	x	x	x	x
Economic										x
other				x		x			x	x

* some of the studies are excluded if data was not the primary focus, and others initiatives were added which look at data requirements but do not explicitly define a passport

The studies by (Çetin et al., 2023) and (Tomczak et al., 2024) do not define a material passport per se, but they carry out a study on the data points that industry stakeholders consider important, which we will consider as data requirements, and compare with other more explicit proposals. The proposals by (Mulhall et al., 2022) and (Munaro & Tavares, 2021) take the BAMB project framework (Mulhall et al., 2017) for material passports at product levels and cover more fields than the other studies, with a focus on digitalisation not data structures specifically. The proposal for a Circularity Material Passport by (Göswein et al., 2022) is defined under alignment with the Level(s) framework. The works of both (Göswein et al., 2022) and (Mulhall et al., 2022) put an emphasis on the design for disassembly (DfD) processes.

If we compare the EPD labels and the newer PEF with material passport initiatives, there are several overlaps, although the focus of the first two are on environmental indicators. The PEF is very similar to the EPD, with the addition of obtaining a single aggregated result for the several environmental indicators which are present in an EPD. Depending on the LCA study scope, an EPD can contain data related to the use of energy and water, during the manufacturing and usage process, and also transportation across several stages, in line with the EN15804 norm on the sustainability of construction products. However, this depends if the type of product consumes energy and water during the its use stage. Thus, the composition of materials is fully described in an EPD, to enable LCA. It does not include technical information on the assembly, installation or disassembly of the product (but it sometimes includes the impacts of product assembly - module A5), which seems to be a key focus of several product passport initiatives in literature, such as the DPP (Honic et al., 2024). In terms of circularity indicators, an EPD/PEF does not explicitly provide any, but the quantities of certain recycled materials in new products or the potential for its recyclability (as part of module D) is present. These types of recycled materials are required for the MCI, the DGNB certification, and also mentioned in several other frameworks, which we consider as part of the composition of the product/component and the properties of the embedded materials. Thus, we notice similar needs for information, but expressed in different ways, and use for different purposes. **This poses a question as to what makes a material passport different from an EPD?** We can consider that an EPD is sufficient for a product as a material passport, but this may no longer be valid for a building component, due to a change of context and an EPD's time-limited validity. However, an EPD is a label on a type of product, whereas a material passport wants to provide a way to track specific products more transparently and associate a unique identity for each component/product instance. The issue remains the digital format of the information, as EPD take the form of reports and are difficult to share and include in automatic processes which required aggregation from product to building levels, a limitation that material passport initiatives want to tackle (i.e. DPP).

We highlight the domain data interdependencies in Figure 1. We suggest that the minimum requirements for any material passport at product and building component level should have identity and composition-based information, as these are reliant on first-hand information from stakeholders. The priorities of the other domains can vary according to life cycle stage.

Based on our analysis of data criteria across the several initiatives above, there is consensus on several points. As expected, identity data is required for transparency and tracing across all initiatives. At the product level these are complemented by manufacturer information, whereas once the component is part of the building, additional contextual data is needed (e.g. location). The second vital category of information is related to the composition of a product/component or building describing its materials, dimensions, quantities along with their respective properties (e.g. density, strength, conductivity). These fields are required across the board and are pre-requisites for several other categories, most notably the circularity and environmental indicators. The composition of materials for components, sub-components and eventually at building layers require some form of aggregation for a correct quantity take of at each level. A modular and linked hierarchy of material composition is provided by (Terndrup et al., 2023). It is expected that BIM models can provide such data. Although identity and composition data are vital to all initiatives, they are also the ones dependent on first-hand input, that comes either from manufacturer, designers, or other contractors on site, depending on the life cycle stage.

Next, we rank the domains of assembly, circularity and environmental data sets, which are important and required across the board in nearly all approaches. The assembly needs to include installation instructions, as well as disassembly/deconstruction aspects, usually in the form of some documentation from the manufacturer, in the case of products. Otherwise, this data is not explicit for in-situ building components. This is of no real concern for the building level. The circularity and environmental aspects rely on composition data and background databases on materials and their impacts and usually employ dedicated methodologies which calculate different indicators. In the case of environmental indicators, nearly all studies rely on LCA, some more strict than others when it comes to transparency of the method used, background data and assumptions used. Circularity and environmental data are expected to be pre-calculated by manufacturers and an aggregation is expected for complex components or at the building level, which would employ automatic software tools. The availability of both circularity and LCA data is high for new products, but very ambitious for old components, which thus have to be subjected to time-consuming studies, or be compared to new equivalent products of the same type. In the case of end-of-life studies, the inclusion of transport data (to the next site) is also required. This raises concerns with regards to uncertainty propagation from product to building level, or from moving from one life cycle stage to the next, as shown in the case study by (Guerriero et al., 2024).

We notice that data related to energy, water or wellness are out of scope for the material/product/component levels (apart from the EPD/PEF as discussed above), but become widely adopted for building level certification schemes, and need to rely on monitored and modelled data (via simulations, predictions, etc.), more in line with DT than the BIM (Boje et al., 2023). Finally. categories related to usage of products are also in quite prevalent in certain advanced product type (e.g. heat pumps, boilers, household appliances, etc.), and these are expected to come from manufacturers directly in the form of supplementary documentation. Economic and transport data domains are situational, dependent on the context.

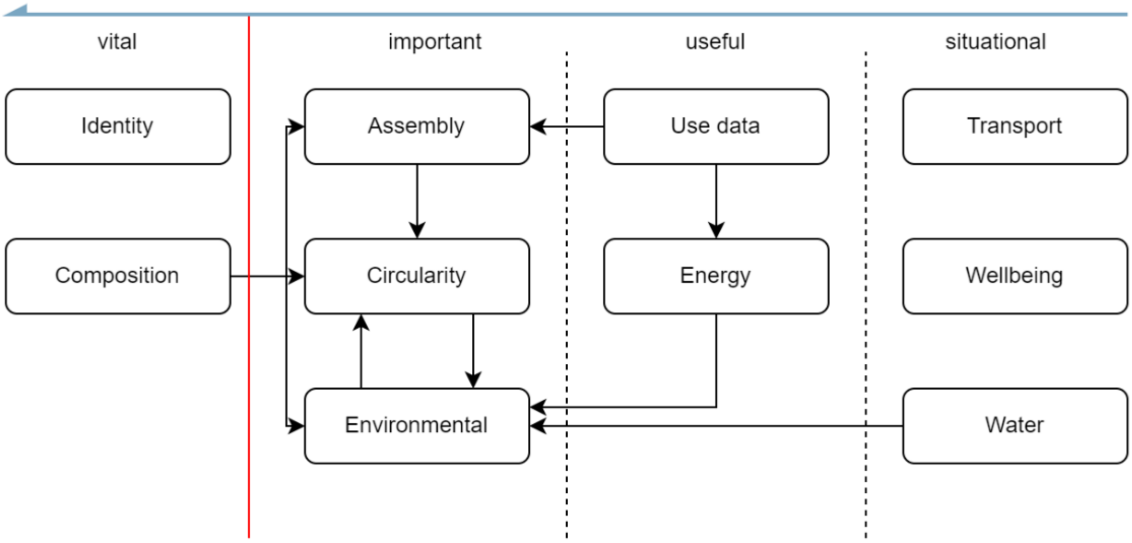

Figure 1. Domain data interdependencies for material passports at all levels. Black arrows indicate data input

4.2 Building level

With a change in scope from product/component to the building level, as well as the change of context with each life cycle stage, building related data can change significantly. Most building accreditation schemes look at achieving sustainability by design, but do not really consider the building as a bank of materials, and so in function they are not aligned with material passport concepts. The DBL initiative seems to want to complement this limitation by adding use stage relevant information, and at the same time it appears to be concerned with everything (Table 3), acting however more as a container of domain specific data. Several initiatives are contrasted and compared by (Gómez-Gil et al., 2022), along with a list of 86 data fields which the different initiatives consider or not. Only some of the initiatives studied by (Gómez-Gil et al., 2022) explicitly define a material inventory, along with certificates for materials (if available). Most DBL initiatives seem to be very focused on energy efficiency, monitoring and control of building systems. BREEAM and LEED are more focused on the design stage, with some credits being offered under the building operation phase after additional short-term monitoring, while DGNB is more suited for the entire life cycle, according to (Ferreira et al., 2023). This is a key limitation of these schemes, complemented by the DBL, which focuses on gathering and maintaining all data about the building in a digital context, which is a very challenging initiative. For example, whilst the economic indicators in certifications is to design a cost-effective system, the DBL concerns itself with keeping track of actual yearly running costs of the building.

BREEAM, LEED and DGNB explicitly adopt a triple bottom line approach for sustainability, looking at environmental, social and economic factors. BREEAM and LEED follow the ISO 21929-1:2011 (ISO, 2011) norm for sustainable buildings. According to (Ferreira et al., 2023) the DGNB is the most balanced when considering the three pillars of sustainability together. Additionally, the economic indicators of these schemes actively consider operational costs. The newer Level(s) framework is a standardisation initiative, covering several objectives and macro-level indicators where most data domains represent required data, with an emphasis on LCA, material composition, but also indoor air quality, and resilience to climate changes. It can be positioned between the other certification schemes and the DBL in terms of scope. Approaches such as PH and EPC have an environmental component, but it is a very simplified calculation based on the operational energy of the use stage. However, material data and key indicators are required. Looking at the WELL certification, we notice an emphasis on indoor air quality, where emanations from materials is important, their toxicity hazards and effects. WELL indicators define certain thresholds for indoor pollutants, based on past studies, but actual calculations methodologies are employed for these aspects, where material data is an actual input. The inputs are rather on sensed data.

A pattern is formed where material compositions, their embedded ingredients and quantities are required all along the process chain, where product/component material passports are vital to run passive house calculations, calculate the EPC for both passive (walls, windows, insulation layers, etc.) and active components (heat pump, boiler, ventilation equipment, etc.). The key challenge remains the transformation of component level information to the building level in an accurate and automatic manner. Overall, however, there is a large gap between a product/component passport and a building level one across domains, as they are inherently different in function.

Table 3. Building level approaches for and their data scopes across domains

Approaches from Table 1	***BREEAM***	***LEED***	***DGNB***	***Level(s)***	***PH***	***EPC***	***SRI***	***WELL***	***DBL***
Identity	x	x	x	x	x	x	x	x	x
Composition	x	x	x	x				x	x
Assembly									x
Environmental	x	x	x	x	x	x			x
Circularity	x	x	x	x					x
Energy	x	x	x	x	x	x			x
Water	x	x	x	x	x	x	x		x
Wellbeing	x	x	x	x				x	x
Transport	x	x	x						x
Usage							x		x
Economic	x	x	x	x					x
Other								x	x

5 Discussion and conclusions

In an attempt to answer RQ1, the key difference lies in the scale and purpose of the information: product/component passports are detailed and specific for technical assessments, while building-level passports are holistic and strategic for long-term sustainability planning. EPDs provide nearly all data requirements at product level to feed into the other domains and certifications systems at building level. The material passport initiatives analysed are a form of extended EPD, with additional, more detailed data on assembly and circularity aspects, and with a focus on building context, to facilitate the reuse of older products, at the end-of-life of the building in question.

In an attempt to tackle RQ2, there exists an emphasis on digitalisation to facilitate component identity, transparency, and interoperability across the life cycle of a building. The material component identity and composition properties stand out as the most critical data elements, necessary for circularity and environmental calculations. The relationship between circularity and environmental is inherently synergistic, yet distinct in their computational approaches. Assembly and disassembly information is also very important in the literature for the component level passport, which is usually presents as annexed documents, not suitable for automation. Identity data for each component is not as important for the building level, due to higher level scopes. The accessibility of product data, while expected to be streamlined by BIM, presents the ongoing challenge of aligning with domain-specific datasets. The other domains (energy, water, transport, wellbeing and usage data) are of very little direct concern at product/component level, but quite prevalent at the building certification level. This represents the key divide between the two scales, where the building context wants to provide added value related to better building management and increased quality of life, while the product/component level facilitates circular economy practices.

The implementation of material passports is a nuanced process that should be tailored to the product or system level to ensure accuracy and adaptability throughout a building's life cycle. The data requirements for a building component passport is varied and subject to change, from LCA to circularity aspects, and thus a dynamic, digital process is required. It is acknowledged that the simplification and subjectivity inherent in these data categories need refinement, as part of our future work.

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