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A tool

Çetin, S.; Raghu, D.; Honic, M.; Straub, A.; Gruis, V.

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5 Material passports for social housing stock

A tool

As highlighted in the preceding chapter, social housing organisations encounter significant challenges when incorporating digital technologies into their circular processes. In particular, issues surrounding the creation and implementation of Material Passports—a vital enabling tool—prompt the exploration of new research avenues. This chapter, therefore, addresses the identified challenges, such as *uncertainty regarding the data requirements* and *the lack of a data management mechanism.* Employing a mixed-methods research design, this chapter identifies the key users of Material Passports for existing social housing stock, delineates their data needs, and assesses the availability of required data. In response to identified data gaps, it proposes a digitally-enabled Material Passports framework designed to enhance the adoption of narrowing, slowing, closing, and regenerating strategies in the existing social housing stock.

Recap key research question 4: What are the data requirements of users from material passports for the existing housing stock? Are these data available? If not, how can digital technologies support fulfilling the data gaps?

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[1] Department of Management in the Built Environment, Faculty of Architecture and the Built Environment, Delft University of Technology, Julianalaan 134, 2628BL Delft, the Netherlands.

[2] Department of Civil, Environmental and Geomatic Engineering, Swiss Federal Institute of Technology Zurich (ETH Zürich), Stefano-Franscini-Platz, 5, Zürich 8049, Switzerland.

ABSTRACT Passports for circularity, e.g., digital product passports and material passports (MPs), have gained recognition as essential policy instruments for the Circular Economy goals of the European Union. Despite the growing number of approaches, there is a lack of knowledge about the data requirements and availabilities to create MPs for existing buildings. By deploying a mixed-method research design, this study identified the potential users and their data needs within the context of European social housing organisations. Three rounds of validation interviews with a total of 38 participants were conducted to create a data template for an MP covering maintenance, renovation, and demolition stages. This data template was then tested in a case study from the Netherlands to determine critical data gaps in creating MPs, including, but not limited to the composition of materials, presence of toxic or hazardous contents, condition assessment, and reuse and recycling potential of a product. Finally, an MP framework is proposed to address these data gaps by utilising the capabilities of enabling digital technologies (e.g., artificial intelligence and scanning systems) and supportive knowledge of human actors. This framework supports further research and innovation in data provision in creating MPs to narrow, slow, close, and regenerate the loops.

KEYWORDS Circular Economy, digitalisation, material passports, building industry, stakeholder identification, data requirements

5.1 Introduction

The building industry is one of the largest resource-intensive, carbon-emitting, and waste-creating industries in the European Union (EU) (European Commission, 2022a; European Construction Sector Observatory, 2018; Eurostat, 2020). Increasing demand for new housing, coupled with the requirements for energy-efficient building stock, puts tremendous pressure on countries to respond to the housing crisis while simultaneously respecting the natural environment. In recent years, as part of the EU's Green Deal (European Commission, 2019), the Circular Economy (CE) has gained attention as an alternative approach to address resource scarcity and climate change-related challenges by decoupling economic activity from the consumption of finite resources (Ellen MacArthur Foundation, 2013b). A CE can be defined as a system that minimises resource inputs, waste, and emissions by maximising the value of products and materials over time (Geissdoerfer et al., 2017) by applying four resource principles: *narrow* (use less), *slow* (use longer), *close* (use again), and *regenerate* (make clean) (Bocken et al., 2016; Konietzko et al., 2020).

Applying these CE principles to buildings, particularly closing the loops, is reflected in the buildings-as-material-banks concept (Matthias Heinrich & Werner Lang, 2019; Heisel & Rau-Oberhuber, 2020). Scholars argue that the current building stock can become a source of materials to construct new buildings or renovate existing ones in the future (Benachio et al., 2020; Matthias Heinrich & Werner Lang, 2019; Heisel & Rau-Oberhuber, 2020; Honic et al., 2021). This can be achieved by disassembling building products and materials that reach their end-of-life in one building and reusing or recycling them in another. Realising reuse or recycling in construction practices is a challenging process partly due to the lack of information regarding materials located in buildings (e.g., their quality, quantity, and properties) which is a result of insufficient documentation (Honic, Kovacic, & Rechberger, 2019; Iacovidou et al., 2018; Koutamanis et al., 2018). To address this information gap, the concept of material passports (MPs) was proposed by researchers and practitioners (e.g., Honic, Kovacic and Rechberger (2019); Platform CB'23 (2020)).

An MP is an instrument providing digitised qualitative and quantitative life cycle information on the characteristics of a product to enable circular principles of narrow, slow, close, and regenerate. MPs can be created at various scales (e.g., material, product, or building) (Platform CB'23, 2020) for supporting different circular building strategies such as design optimisation for increased recyclability (Honic, Kovacic, & Rechberger, 2019) as well as reusing building products at the end of life (Matthias Heinrich & Werner Lang, 2019). To date, several MP solutions have been proposed (Çetin, De Wolf, et al., 2021; Munaro & Tavares, 2021); however, their resulting frameworks remain mainly conceptual and tend to neglect the perspectives and needs of industry actors who are implementing circular strategies in designing, constructing and managing buildings. Identifying the users of MPs and their requirements is an overlooked research area. Also, the lack of understanding regarding MPs by the potential users can be a significant barrier to their adoption. For example, a multiple-case study from the Netherlands *(previous chapter)* showed that practitioners experienced considerable challenges in adopting MPs in their circular housing projects, including uncertainty around data requirements, lack of a data management mechanism, and high costs of creating and managing MPs (Çetin et al., 2022). Another issue with the current MP approaches is that they are primarily created for new buildings during the design stage to manage the whole life cycle data of buildings (Munaro & Tavares, 2021). Yet, very little attention has been paid to existing building stock which is poorly documented (Honic et al., 2021). Considering that the majority of the current building stock can be used in future as a resource for steadily growing new building construction in the EU (Göswein et al., 2022; Honic et al., 2021), it is critical to explore the ways in which MPs are created for existing buildings.

The aim of this research, therefore, is to develop an MP framework for existing buildings based on an empirical investigation of European social housing organisations. This study specifically focuses on the existing social housing stock due to several reasons. First, social housing organisations in Europe typically own a large portfolio of buildings. In some countries, such as the Netherlands, Austria, and Denmark, the social housing stock makes up around respectively 29%, 24%, and 21% of the total housing stock (Housing Europe, 2021). Second, these organisations manage their building portfolio professionally and are involved in all life cycle phases, from housing development until demolition, by closely collaborating with other building industry actors such as architects, construction companies, and material suppliers. They hold a powerful position in the market and can influence the circular practices of the industry. Third, social housing organisations are social entrepreneurs, and they are expected to use their resources in line with collective social interests (Nieboer & Gruis, 2014; Roders & Straub, 2015). Besides implementing carbon reduction measures, implementing circular building strategies, following the EU's CE targets, is becoming a part of their sustainability goals (see, e.g., Interreg North-West project CHARM (CHARM, 2023)). Particularly in some EU countries like the Netherlands, social housing organisations are leading the way towards achieving a circular building industry (Çetin, Gruis, et al., 2021) by not only implementing circular strategies but also experimenting with digital technologies, including the MPs, to enhance their circular operations (Çetin et al., 2022). Also, due to their large building stock and professional management, they typically operate in a data-rich environment.

Given the importance of social housing organisations in the circular transition of the existing housing stock, further research is needed to identify the data needs of key actors involved in circular housing projects. Although some research has been carried out on the data requirements and availabilities for passports in other industries (e.g., Berger et al. (2023); Jensen et al. (2023)), no studies have been found that investigate these matters in the building industry, particularly for existing buildings. This study is, therefore, an initial attempt to explore key MP users and their data needs and to what extent the required data are available in the digital systems of social housing organisations. Focusing on European social housing organisations, this study presents empirical insights and addresses the following research questions:

RQ1: Who are the potential users of MPs for the existing housing stock, and what kind of data do MPs need to provide to support them in implementing circular principles?

RQ2: Which data requirements of an MP can be fulfilled with available data and digital systems of a social housing organisation?

A mixed-methods research design is deployed to answer the research questions, consisting of a literature and practice review and three rounds of validation interviews with a total of 38 participants, including researchers, social housing professionals, and key stakeholders such as architects, consultants, and reuse companies. The developed data template is then applied in a case study from the Netherlands to demonstrate which data points can be fulfilled by available data and digital systems of social housing organisations. By providing empirical evidence from industry actors, this research contributes to the emerging literature on the intersection of digitalisation and the circular building industry from the standpoint of MPs.

The structure of the paper is as follows. Section 5.2 gives an overview of the research background, explaining current passport approaches in the building industry. Section 5.3 introduces the research design and methods for data collection and analysis. Section 5.4 presents and discusses the findings, and Section 5.5 concludes the study.

5.2 Current Material Passport approaches

5.2.1 European Union policy

To enable a transition from a linear economy to a CE, the EU initiated several strategies in the intersection of circularity and digitalisation in recent years. These strategies include the CE Action Plan (European Commission, 2020b), the European Green Deal (European Commission, 2019) and “A Europe fit for the digital age” (European Commission, 2023). Their common aim is to achieve climate neutrality by 2050 and establish a CE with the support of digitalisation. The EU has also introduced several passport instruments in response to the resource-intensive and waste-generating building construction that follow the targets of the above-mentioned EU strategies. Some examples are the MPs (BAMB, 2019), Digital Product Passports (European Commission, 2022b), and Digital Building Logbooks (European Commission, 2020c). They differ based on which industries they are applied in, their scope and the backbone on which they are based. However, they are developed with the common goal of enabling circularity.

In previous years, several MPs emerged in research and practice (van Capelleveen et al., 2023) (see also Section 5.2.2). Although MPs play a crucial role in transitioning from a linear to a circular building industry, a regulatory framework that enables standardisation and sets common bases does not exist for buildings. Alternatively, Digital Product Passports were proposed by the European Commission as a regulatory framework “for setting eco-design requirements for sustainable products” (European Commission, 2022b). Digital Product Passports ‘‘provide information on a product's origin, durability, composition, reuse, repair and dismantling possibilities, and end-of-life handling'' and shall apply to any physical good placed on the market or put into service. Digital Product Passports is a cross-sectoral concept that does not exclude the built environment (European Commission, 2022b). A concept proposed by the EU only for buildings is Digital Building Logbooks. It is defined as "a common repository for all relevant building data; it facilitates transparency, trust, informed decision making and information sharing within the construction sector, among building owners and occupants, financial institutions and public authorities" (European Commission, 2020c). This extensive concept covers several sustainability aspects, such as energy efficiency and is not limited to circularity.

Although several attempts exist to introduce new passport instruments at the EU level, a regulatory framework for buildings is missing. It is unclear if the Digital Product Passports framework will be adopted for MPs or if a new regulation for the built environment will be established. The alignment of MPs and Digital Building Logbooks is possible; however, their scope is significantly broader than those of MPs for a CE. Even if not adopted in existing MP concepts, the EU-driven regulations and frameworks concerning Digital Product Passports and Digital Building Logbooks might influence the future evolution of MPs. FIG 5.1 summarises the similarities and differences between these three passport initiatives.

	Digital Product Passports	Material Passports	Digital Building Logbooks
Scale	Product	Area, Complex, Building, Element, Product, Material, Raw material	Building
Industry	Cross-industry	(Mainly) Built environment	Built environment
Regulation	EU Ecodesign Directive	–	EU-wide Framework for a Digital Building Logbook

FIG. 5.1 Differences and similarities between digital product passports, material passports, and digital building logbooks.

5.2.2 Material Passport landscape in the building industry

Since CE became a popular concept in Europe, many sector-specific and cross-sector passport approaches have emerged (Jansen et al., 2022). There is no widely agreed terminology, definition, or standardisation of current approaches (van Capelleveen et al., 2023). Several terms are used for passports, including Data Templates (Mêda et al., 2021), Product Circularity Data Sheets (Mulhall et al., 2022), Material Passports (Matthias Heinrich & Werner Lang, 2019), Digital Product Passports (Jansen et al., 2022), Digital Battery Passports (Berger et al., 2022), and Circular Material Passports (Göswein et al., 2022). Some of these passport initiatives, e.g., Product Circularity Sheet (Mulhall et al., 2022), intend to cater towards several industries, while others have a specific focus, such as Digital Battery Passports (Berger et al., 2022) for the automotive industry.

The passport landscape for the building industry is also diverse. Current approaches lack a unifying scheme and vary in terminology, content, aggregation level, technology use, and maturity level. Although several terms exist, Material Passports (MPs) is the most frequently used term (van Capelleveen et al., 2023). One of the early conceptualisations of the MP is "Nutrition Certificates" by Hansen et al. (2013). Nutrition Certificates are proposed as a tool to enhance the value of building products by describing the characteristics of materials so they can be recovered or reused in continuous loops instead of becoming waste (Hansen et al., 2013). Building on this concept, the EU project BAMB developed an MP prototype tracking the residual value of building products along the supply chain (Luscuere, 2017). The BAMB project demonstrated the MP application on an interactive exhibition building whereby around 70 circular products were connected to data carriers (QR codes), and the visitors could access MPs via their phones (BAMB, 2019). Perhaps the first commercial MP for the building industry is developed by a not-for-profit entity Madaster Foundation in the Netherlands. Madaster is an online platform providing insights into the materials and products used in buildings, their prospective carbon emissions, and economic value (Madaster, 2023).

As outlined in TABLE 5.1, MPs can be used for different purposes. Recovering value from products through reuse and recycling is one of the functions frequently mentioned in the literature (see, e.g., Göswein et al. (2022); Matthias Heinrich and Werner Lang (2019); Heisel and Rau-Oberhuber (2020); Luscuere (2017); Munaro and Tavares (2021)). Some commercial MPs, such as Madaster, also determine the circularity level of a building for construction, use, and end-of-life phases based on material-specific parameters (Heisel & Rau-Oberhuber, 2020). The BIM (Building Information Modelling)-based MP tool developed by Honic, Kovacic and Rechberger (2019) combines LCA (life cycle analysis) method with design optimisation to support designers in making informed decisions on material selection during the early design stage, increasing the recyclability performance at the end-of-life. Similarly, Atta et al. (2021)'s BIM-based MP framework allows architects and engineers to select various building alternatives based on disassembly, recovery, and environmental scores. MPs are also seen as a life cycle data management tool, supporting use phase interventions such as maintenance, renovation, and repair, tracking the changes made in physical objects (Luscuere, 2017; Munaro & Tavares, 2021).

TABLE 5.1 Overview of material passport approaches in the building industry.

Category	Aspect	Illustrative references
Purpose	Recovering value through reuse or recycling Measuring the circularity level of a building Calculating the economic value of products Design optimisation Life cycle data management	(Matthias Heinrich & Werner Lang, 2019) (Heisel & Rau-Oberhuber, 2020) (Madaster, 2023) (Honic, Kovacic, & Rechberger, 2019) (Munaro & Tavares, 2021)
Technology use	Data template/datasheet Platform-based MP tools BIM-based MP tools Blockchain-based MP tools	(Platform CB'23, 2020) (Madaster, 2023) (Honic, Kovacic, & Rechberger, 2019) (Circularise, 2023b)
Maturity	Conceptual tools (TRL 1 to 3)* Prototypes (TRL 4 to 6)* Commercial tools (TRL 7 to 9)*	(Atta et al., 2021) (BAMB, 2019) (Cirdax, n.d.)
Aggregation level	Area Complex Building Element Product Material Raw material	(Orms, 2023; Platform CB'23, 2020)
Life cycle phase	Production Design/construction Use/operation End-of-life All life cycle phases	(Mulhall et al., 2022) (Honic, Kovacic, & Rechberger, 2019) - (Honic et al., 2021) (Platform CB'23, 2020)

**TRL: Technology Readiness Level. The given TRL scales are indicative of maturity level.*

Another different form of current MP approaches is the level of digitalisation and technological integration. MPs can be created simply as a data template using a spreadsheet tool or as complex as a supply chain infrastructure based on advanced digital technologies. For example, the Dutch public-private initiative Platform CB' 23 formed a large workgroup of stakeholders (e.g., architects, construction companies, and demolishers) and established an extensive list of data points to generate MPs (Platform CB'23, 2020). A similar attempt was made by the Ministry of the Economy of Luxembourg, which launched the Circularity Dataset Initiative in 2018 (PCDS, 2023). This initiative has also concluded a yes/no answer-based list of product circularity data sheets for various industries, including the building industry, to provide standardised information for circularity evaluations (Mulhall et al., 2022; PCDS, 2023). These simple data templates could be considered the first step in creating MP tools.

On the other hand, commercial MPs are typically operated on an online platform (e.g., Madaster, Cirdax, Concular, etc.), where data from BIM or product data spreadsheets are fed into the system to create material-related circularity indices (see, e.g., Heisel and Rau-Oberhuber (2020)). If available, BIM is the main source of data to create MPs for building products (Çetin, De Wolf, et al., 2021). Tools resulting from academic research are usually built with BIM and remain largely conceptual (e.g., Atta et al. (2021); Honic, Kovacic and Rechberger (2019); Honic, Kovacic, Sibenik, et al. (2019)). Regarding the digitalisation level, the passport tool of a Dutch start-up called Circularise is exceptional. This start-up uses traceability software based on blockchain technology and tracks products along the supply chain through physical data carriers, such as RFID tags or QR codes, while protecting the confidential information of supply chain actors (Circularise, 2023b). Circularise collaborates with the Municipality of Amsterdam to increase the traceability and transparency of procurement environmental impact insights from the upstream supply chain (Circularise, 2023a).

Depending on the users' needs and goals, MPs can be created at different aggregation levels and life cycle stages (Çetin, De Wolf, et al., 2021). As listed in TABLE 5.1, Platform CB'23 (2020) proposes a structure for MPs consisting of nested levels of raw material, material, product, element, building, complex (collection of buildings), and area. These scales can be composed of varying degrees of information, and smaller scales can be embedded under larger scales. For example, a British architecture firm developed a BIM-based MP solution generating passports for building products nested under a building passport (Orms, 2023). In addition, MPs can be created for one or multiple life cycle stages. Although the majority of current approaches are developed in the design stage to track products throughout the life cycle stages, very few MPs are created at other life cycle stages, partly due to a lack of information about the existing building stock.

A unique example is the study of Honic et al. (2021), which demonstrated a novel data collection method for creating MPs for buildings at their end-of-life. The authors built a BIM model using laser scanning technology and applied a combination of simplified demolition acquisition and invasive methods, such as drilling and cutting. The resulting MP tool provides an overview of the masses of materials, their environmental impact and the recycling potential (Honic et al., 2021).

From this brief overview, it is clear that there is a lack of standardisation and unity in creating, managing, and exchanging data in current MP approaches. Most academic studies attempt to propose conceptual models and overlook stakeholders' data needs. Although a few public and private initiatives, such as the Dutch Platform CB'23 (Platform CB'23, 2023), provide an extensive list of data requirements, there is no transparency regarding their methodology and whether these could be implemented in existing buildings. Considering the data collection and MP creation challenges identified in the practice (Çetin, Straub, et al., 2021; Göswein et al., 2022; Mulhall et al., 2022), this study will expand current knowledge by identifying key users of MPs and their data requirements.

5.3 Research design

The MP framework for existing buildings proposed in this paper was developed following a mixed-methods research design based on iterative data collection steps. A multiphase mixed-method design allows researchers to combine sequential qualitative and quantitative data collection and analysis methods over a period of time (Creswell & Clark, 2011). This approach leads to more complete, robust, and comprehensive research findings. As presented in FIG 5.2, the study consists of two parts. In the first part, a data and stakeholder identification method was deployed, and in the second part, building on the results from the subsequent steps, the developed data template for MPs was implemented in a case study to assess data gaps and inconsistencies. Finally, building on the findings, a vision for an MP framework is proposed.

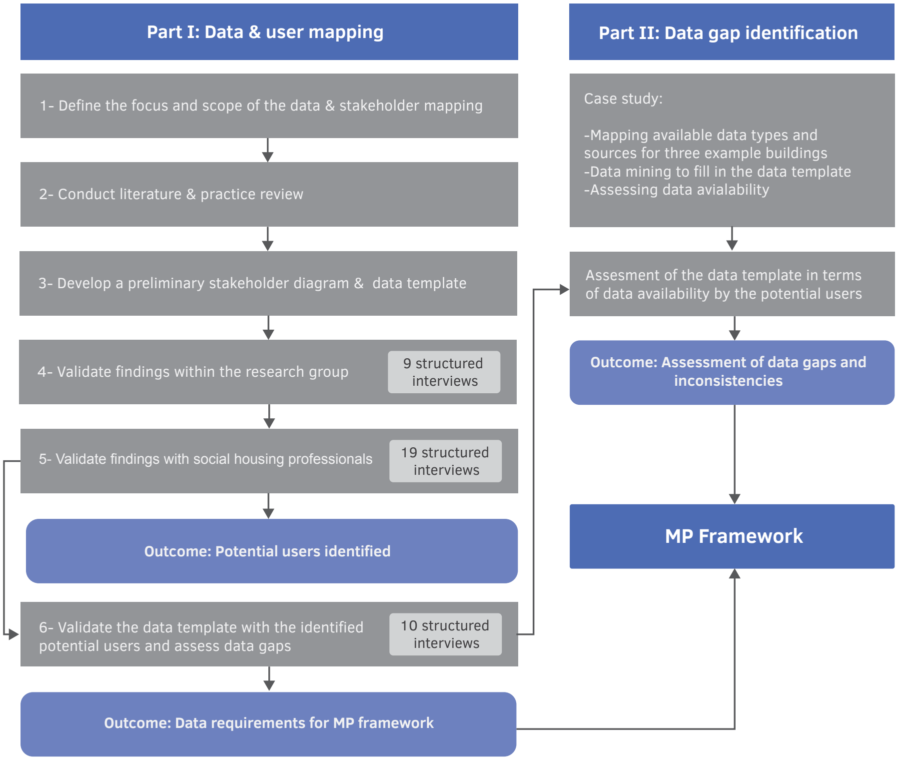

FIG. 5.2 Research design.

5.3.1 Part I – Data and user mapping

We applied the SCOPIS (supply chain-oriented process to identify stakeholders) method introduced by Fritz et al. (2018) to identify key stakeholders and their data needs. SCOPIS is an iterative multi-step method focusing on a service or a good during the identification process rather than concentrating on a single organisation as in the traditional methods (Fritz et al., 2018). Taking a supply-chain perspective is believed to minimise bias and acquire a mixed overview from various stakeholders on multiple issues (Fritz et al., 2018). This method was also used by Berger et al. (2022) to map users of digital battery passports for electric vehicle batteries in the context of CE. We followed six steps, as explained in detail in the following subsections and illustrated in FIG 5.2

Step 1- Defining scope and focus

As a first step, the focus and scope of the stakeholder data requirements identification analysis were determined based on background literature (Section 5.1). The scope of this research is limited to the housing stock and stakeholders involved in circular projects operating with and within social housing organisations across Europe. Since the main focus is the existing building stock, we considered the use and end-use phases of buildings. The primary activities of social housing organisations during these phases are maintenance (responsive, preventive, and predictive maintenance), renovation, and demolition projects (Çetin et al., 2022). These three project stages were included in the user mapping diagram.

Step 2- Literature and practice review

We conducted a literature and practice review between September and November 2022 to create the preliminary lists of stakeholders (i.e., potential users) and a baseline data template. This step helped us to set a master data template demonstrating all possible data points considered in the previous MP approaches. As presented in FIG 5.3, the review included publications in peer-reviewed and grey literature and was complemented with an additional search of commercial MP tools available in the market. For the literature review, a Scopus search was done by using "circular* AND passport*" as keywords in peer-reviewed articles, conference papers and book chapters. The Scopus database was selected for the review based on its broad coverage of journals relevant to both MPs and built environment research. The initial search yielded 58 results, where 29 papers were eliminated after reading titles, abstracts, and keywords based on the selection criteria. Following a snowballing procedure (Wohlin, 2014), eight additional papers were added. After reading the remaining articles in detail, 16 papers were selected for further in-depth analysis.

Acknowledging that practice is ahead of academic studies regarding MP applications, we also conducted a practice review using the same keywords. Web research in three languages (English, Dutch and German), coupled with the snowballing procedure, resulted in 17 practitioner reports and 20 commercial MP tools. Applying the same selection criteria, in total, 15 practice reports and MP tools were selected for in-depth analysis. We applied three selection criteria: (1) the MP approach should be proposed for CE strategies; (2) the MP approach should have applications in the building industry; and/or (3) stakeholders/users should be mentioned in relation to the use of MPs. The full list of selected sources with data categories and data points can be found in the Supplementary Material.

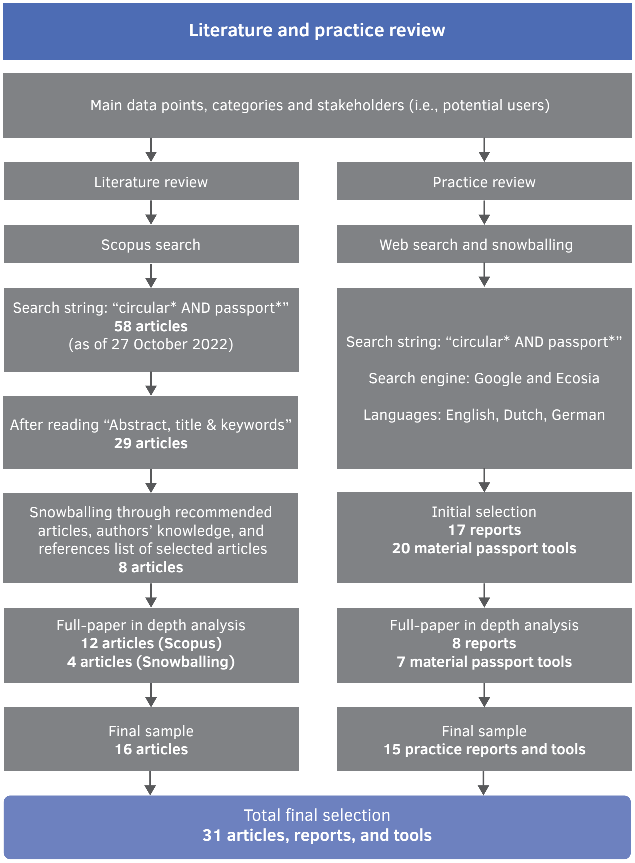

FIG. 5.3 . Practice and literature review process.

Step 3- Preliminary stakeholder mapping and data template

In the third step, we developed a diagram for stakeholder mapping by adapting the rainbow diagram developed by Chevalier and Buckles (2008) that allows allocating stakeholders in line with the degree to which they influence or get influenced by a matter (Reed et al., 2009). In the context of this study, stakeholders are the "potential users of the MPs for existing buildings". Instead of "affected" and "affecting", as proposed in the original method (Chevalier & Buckles, 2008), we classified stakeholders as "data requesters" and "data providers". Since the scope was limited to the use and end-of-use phases of buildings, the diagram included three project stages: maintenance, renovation, and demolition (Çetin et al., 2022). Based on the literature and practice findings, we listed potential users next to the diagram and created an online whiteboard template (see Supplementary Material). This online whiteboard template was used during interviews, allowing interviewees to drag and drop potential pre-identified stakeholders according to the degree of their need or provision of data across the project types. Interviewees were allowed to propose new users according to their experience with circular projects. Grouping users who request/provide data “slightly” and “significantly” helped us pinpoint the key users.

To create the preliminary data template, we first compiled a master data template by categorising data points mentioned in the 31 sources selected in the previous review step. The master data template was extensive, consisting of 96 different data points (see Supplementary Materials). Since the selected sources varied in terms of intended life cycle stage and scale of focus, we decided to simplify the list by (1) selecting the most frequently mentioned data points, (2) eliminating data fields that are challenging to collect from existing buildings (e.g., social life cycle assessment), and (3) brainstorming with the research team. The resulting baseline data template, comprising 55 data points, was used for the first validation round with the researchers.

Steps 4,5 and 6 – Validation rounds through structured interviews

The first round of interviews was done with the research community in which the authors are involved. A total of nine researchers were consulted through video calls (n=7) and emails (n=2) in December 2022. TABLE 5.2 gives an overview of the interviewees, and Appendix A presents the interview questions for all interview rounds. We invited our colleagues who do research in the fields of circularity, digitalisation, or housing. Researchers were asked about the main users, functions, and scales of the MPs for existing buildings and to assess relevant data categories and data points that should be included in the data template. This step helped us to reorganise the baseline data template by scaling down data points to 49 points grouped under six main categories. The output generated by the researchers on the user diagram was then compiled and formed the initial set of stakeholder mapping for the following round.

TABLE 5.2 Overview of interviewees of three validation rounds.

Validation round	No	Role	Professional affiliation	Expertise	Years of experience	Country
First round with the research group	1	Assistant professor	University	Digitalisation for circular construction	10	Switzerland
	2	Associate professor	University	Asset management, circular procurement	32	Netherlands
	3	PhD Candidate	University	Circular building components	7	Netherlands
	4	Professor	University	Housing management, circular economy	26	Netherlands
	5	Senior researcher	Research institution	Design, construction and assessment in the built environment	18	Belgium
	6	Professor	University	BIM, digital design, circular construction	20	Austria
	7	PhD Candidate	University	Civil engineering	5	Switzerland
	8	Scientific assistant	University	Reality capture, scan-to-BIM	6	Switzerland
	9	Scientific assistant	University	Digitalisation for circular construction	4	Switzerland
Second round with social housing professionals	1	Project manager	Social housing	Project management new build, renovation, demolition	15	France
	2	Project manager	Social housing	Project management renovation	5	France
	3	EU Project manager	Social housing	Project management, civil engineering, city planning	10	France
	4	EU Project manager	Social housing	Project management	4	France
	5	Project manager sustainability	Social housing	New build, renovation projects	8	Belgium
	6	Program manager sustainability	Social housing	Circular renovation	20	Netherlands
	7	Director sustainability	Social housing	Internal advice on circularity	25	Netherlands

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TABLE 5.2 Overview of interviewees of three validation rounds.

Validation round	No	Role	Professional affiliation	Expertise	Years of experience	Country
Second round with social housing professionals	8	Real estate manager	Social housing	Maintenance, real estate management	20	Netherlands
	9	Design manager/ architect	Social housing	Sustainable housing projects	16	France
	10	Project manager	Social housing	New build, renovation projects	7	France
	11	Project manager	Social housing	Sustainability, circular housing projects	12	Belgium
	12	Project manager/ developer	Social housing	Circular demolition, new build, renovation projects	16	Netherlands
	13	Project manager	Social housing	Circular demolition, new build, biobased buildings	18	Netherlands
	14	Sustainability advisor	Social housing	Circular demolition, new build projects	22	Netherlands
	15	Project leader	Social housing	New build, renovation projects	10	Belgium
	16	Technical advisor	Social housing	Data management	12	Netherlands
	17	Technical policy advisor	Social housing	Data and sustainability	19	Netherlands
	18	Project manager real estate development	Social housing	Renovation, new build projects	8	Netherlands
	19	Senior project developer	Social housing	Renovation and maintenance projects	14	Netherlands

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TABLE 5.2 Overview of interviewees of three validation rounds.

Validation round	No	Role	Professional affiliation	Expertise	Years of experience	Country
Third round with the identified users	1	Project lead	Reuse company (harvester)	Data and innovation management	6	Netherlands
	2	Partner	MP Platform	Material reuse and data	33	Netherlands
	3	CEO	Reuse consultants	Circular renovation and dismantling	25	Austria
	4	Senior advisor	Circularity consultants	Circular new build and renovation projects	18	Netherlands
	5	Project manager	Reuse company (harvester)	Material and product reuse	13	Belgium
	6	Associate architect	Architecture firm	Circular design and data	30	Netherlands
	7	Senior advisor	Social housing	Real-estate portfolio data	15	Netherlands
	8	Architect	Architecture firm	Circular design projects	7	Netherlands
	9	Managing partner	Consultancy firm	Circular engineering	25	Austria
	10	Consultant	Consultancy firm	Circular buildings and MPs	29	Netherlands

A second iteration round was performed with the professionals who work in social housing organisations, such as project managers, architects, and internal advisors. In total, 19 online structured interviews were conducted in January 2023. Two selection criteria were defined: (1) the interviewee must work in a European social housing organisation, and (2) the interviewee must be engaged with circular housing projects, MPs, or real-estate data management. We used our networks to reach potential candidates and, once recruited, encouraged them to nominate further potential interviewees from their respective networks. For identifying the potential users, the diagram with the initial user mapping from the previous round was presented to the interviewees on an online interactive whiteboard application, and they were asked to place potential users according to data requesters/providers in line with their experiences with the circular projects. Housing professionals were further asked to evaluate each data point in terms of relevance to them on a three-point Likert scale: (1) not necessary, (2) nice-to-have, and (3) must-have. Structured interviews, in that sense, were useful for quantifying their answers while collecting their comments on certain data points.

Potential MP users were determined after the second validation round by analysing the outputs of the user diagrams (see Section 5.4.1). In the final round, ten interviews were conducted with the identified users, such as architects and consultants, in February 2023. The focus of the final round was finalising the data template and identifying the data gaps to compare with the case study results (Section 5.3.2). Therefore, next to data relevance, the interviewees were also asked to assess data points in terms of the availability of data from their perspectives on a three-point Likert scale: (1) no availability, (2) low availability, and (3) high availability. Similarly, we used our networks and an online professional networking platform to recruit professionals for the last round. The selection criteria were: (1) the interviewee must be one of the professionals identified as a user of the MPs, (2) the interviewee must have experience with housing projects, and (3) the interviewee must have experience with circular strategies. All interviews were held online and typically lasted between 40 to 60 minutes.

5.3.2 Part II – Data gap identification

The effectiveness of MPs is dependent on the quality and availability of the data used to create them. To gain insights into the complex issues surrounding data availability and accessibility for MPs in social housing organisations, a case study was conducted. A mid-size Dutch social housing organisation that owns around 15,000 homes was chosen as a case. Within the building portfolio, three random building examples were selected for analysis. The process involved the collection and analysis of data from internal company sources, public datasets, and additional data repositories. The repositories were sourced from a partner company which delivers digital services for data retrieval through artificial intelligence (AI)-based computer vision techniques. By leveraging computer vision, the data provider partner identifies and extracts detailed information on the materials and components used in buildings, including their dimensions, from street-level, satellite, and aerial imagery. The collected data was then fitted into the MP template to review the number of data points that were available. Through this process, coupled with the last round of interviews with the potential MP users, gaps and inconsistencies in the data template were identified, providing valuable insights into the challenges and opportunities for social housing organisations in the context of MPs.

5.4 Findings and discussion

5.4.1 Material Passport users

The analysis of the interviews showed that at least 15 different types of actors are involved in the use and end-of-use phases of social housing stock when executing circular maintenance, renovation, and demolition projects. The way in which these stakeholders engage with circular processes varies across organisations due to differences in organisational structure, collaboration with external companies, and the size of the building portfolio. For example, some organisations have in-house maintenance teams and sustainability consultants, while others work solely with external contractors and consultants. One interesting finding is that the majority of identified stakeholders take an interchangeable role in both providing and requiring data from the MPs in all project phases, depending on the decision-making along the project life cycle. Furthermore, some stakeholders play a crucial role in delivering data (e.g., architects), while others have little influence on the data flows (e.g., users). To pinpoint the difference in actor influence on data flows, FIG 5.4 divides identified users into two groups: data requesters/ data providers “slightly” and “significantly”. According to interviewees, in the present situation, tenants, municipalities, and the government have a minor role in data exchange as they are typically only informed about circular interventions. We summarise the identified users in the following sub-sections by grouping them as external and internal users in the context of social housing organisations.

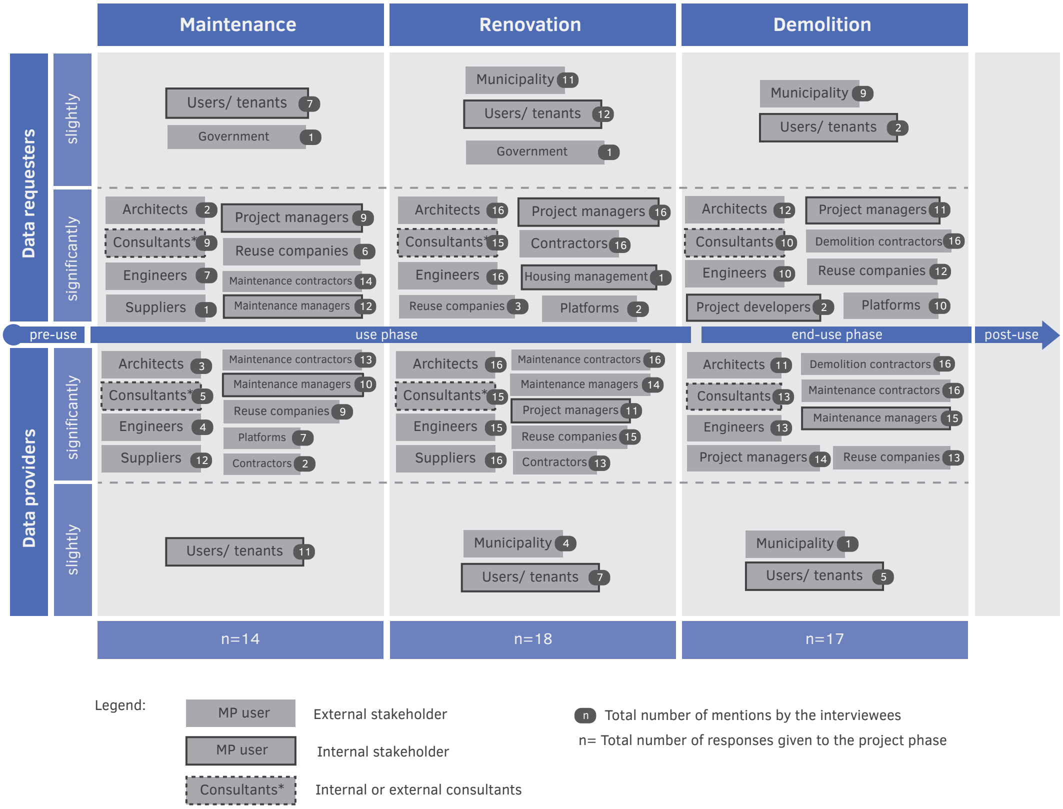

FIG. 5.4 Identified users of the MPs for existing housing stock mapped onto the user identification diagram.

External users

As presented in FIG 5.4, architects, engineers, and consultants are frequently mentioned as external stakeholders who influence the decision-making process in circular projects. In renovation projects, architects make decisions on circular interventions, reusable elements, and new material selection based on the present conditions of a building, thus requiring data from the MPs. They can also feed data to the MPs on renovation design (e.g., architectural drawings or 3D models) and new material selection. Material data from the newly added products are typically provided by the suppliers through architects or project managers. In demolition projects, according to our interviewees, architects have a dual role acting as consultants inspecting the buildings to be demolished (also called donor buildings), making an inventory of reusable elements, thus can provide data as well as require

TOC

data on the elements to be reused in another new build or a renovation project. Consultants advise on the circularity level of a building and thus require data from the MPs to perform calculations. They mainly hold a high-level position in projects, providing recommendations based on the present situation of the existing stock or building. Compared to architects and engineers, their influence in data generation and provision is low because they are not decision-makers. Similar to architects, engineers are also active across project types. Engineers need life cycle data on an element to assess its physical properties properly (e.g., the age of a timber beam and whether it has been treated before). As some interviewees noted, engineers play an important role in providing data on the functional state of building equipment (e.g., boilers) and assessing the structural condition of donor buildings before demolition.

Social housing organisations work with a diverse set of contractors across circular projects. Maintenance is one of their core tasks and involves responsive (i.e., repair), preventive and predictive (i.e., planned regular maintenance) maintenance processes. Some organisations deliver these services through in-house maintenance teams, whilst others work with external maintenance contractors. Maintenance management software or data platforms support operations where maintenance contractors or managers keep a log of repair works, contracts, and invoices and plan and schedule routines. This system is believed to be fundamental in creating life cycle data for elements and products in buildings. However, in their current workflows, interviewees noted that their organisations lack the ability to integrate MPs into their maintenance systems; thus, this important link is missing.

During the renovation process, contractors deliver the construction works and require data on design and execution. They cooperate with project managers of housing organisations and provide data on the finished works and further coordinate data received from subcontractors and suppliers. In some cases, subcontractors who scan the existing building with laser-point scanners engage with the data collection process. Such scanning data is a valuable source for creating MPs at the building and element levels. Reuse companies that collect, clean, and sell secondary construction materials have an important role, especially if they also supply reclaimed products by using take-back contracts. They provide data on the incoming reclaimed products to the renovation interventions.

Demolition and reuse companies are key actors in the end-of-life phases of buildings. Demolition contractors inspect donor buildings and make inventories of reusable and recyclable parts. This valuable information can then be fed into the MPs and support architects in designing with reusable elements in other new build and renovation projects. Especially in the Netherlands, as interviewees noted, there is a shift in the business models of some demolition companies from being simply demolishers to harvesters. Therefore, it was challenging to distinguish demolition contractors from reuse companies during the data collection process. In addition, next to demolition and reuse companies, consultancy firms specialised in reuse also play a crucial role in identifying and listing reusable elements from the donor buildings. Finally, our interviews confirmed that only a few social housing organisations used MP platforms in pilot projects.

Internal users

Project managers and developers, maintenance managers, and consultants are the key internal actors in circular projects. Project managers are at the centre of data flow, coordinating projects and bridging their organisations with external actors. Thus, their role is dual regarding data delivery and request from the MPs. Similar to external consultants and maintenance contractors, in-house company consultants inform project stakeholders about circular intervention options, thereby also providing data, while maintenance managers are thought to be important in updating the life cycle data of products across the life cycle phases.

Overall, the potential users identified and their engagement with the MPs slightly differ from the previous research due to the focus of this study being the existing building stock. Other research, e.g., particularly the ones on the BIM-based MPs (e,g., Atta et al. (2021); Atta et al., (2021); Honic, Kovacic and Rechberger (2019)), use material data in decision-making for designers (i.e., architects, consultants, and engineers), while our findings indicate that these actors need data on the reclaimed material identification and selection in the use and end-use phase of buildings. Some researchers identify data managers or BIM managers as crucial actors in maintaining life cycle data in the MPs (Aguiar et al., 2019; Honic, Kovacic, Sibenik, et al., 2019). However, such actors were not mentioned by the interviewees. A possible explanation for this could be that the real estate and maintenance data in social housing organisations are not integrated into MP tools yet, although these actors exist in some organisations (e.g., we interviewed one data manager). Instead, maintenance managers or contractors seem to link this gap in creating and updating product information across the life cycle phases.

5.4.2 Data template

Data points that form an MP are directly related to its function and the scale at which it is created. As explained in Section 5.2.2, MPs can be used for various purposes at different aggregation scales. Of 38 interviewees across three interview rounds, 29 indicated that "enabling reuse and recycling" must be a crucial function of the MPs for the existing building stock (FIG 5.5 (a)). This finding aligns with the emergence of the MP concept, which was built on recovering materials from the existing stock to close the loops (BAMB, 2019; Hansen et al., 2013; Heisel & Rau-Oberhuber, 2020). Furthermore, other supportive objectives for narrowing and slowing the loops, such as maintenance (n=22) and renovation (n=20), were also thought to be an essential function of MPs. An interesting finding is that "design optimisation" was not considered a relevant feature by the respondents for the existing housing stock, as it was mainly considered at the design stage in the previous research (Atta et al., 2021; Honic, Kovacic, & Rechberger, 2019). MPs as a measurement tool of the economic value of products and the circularity level of buildings are thought to be less relevant.

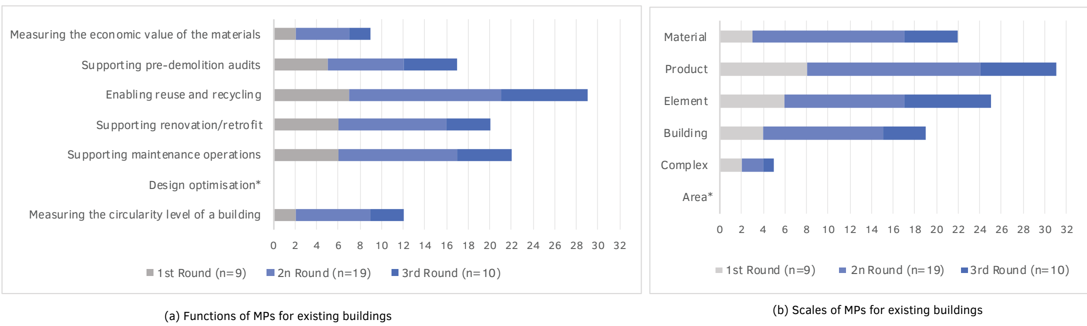

FIG. 5.5 Functions (a) and scales (b) of MPs for existing housing stock according to respondents. Each bar color presents an interview round. n= number of interviewees. The total number of interviewees in all rounds is 38. *None of the interviewees chose "Design optimisation" as a main function and "Area" as a scale of MPs for existing buildings in the first and second rounds. Therefore, it was left out on the last round.

Regarding the scales considered, the majority of the interviewees (n=31) emphasised that the "product level" is the most appropriate scale to consider. However, as some interviewees mentioned, there is ambiguity between scales, and sometimes the "element" and "material" scales could be relevant depending on the situation. The "building" is usually considered an overarching scale consisting of nested MPs for elements, products, and materials. This tendency is also present in the MP approaches developed in the practice (Orms, 2023; Platform CB'23, 2020) and research (e.g., Kedir et al. (2021b)).

The data template developed in this study comprises 50 data points derived from existing MP approaches following three validation rounds through structured interviews. FIG 5.6 presents the data points grouped under six categories— the first one gives generic information at the building scale, and the other five, embedded under the building, give information at the product or element level. Based on the output from FIG 5.5 (b), an MP could be created at the material (e.g., glass), product level (e.g., window) or element (e.g., façade component) levels depending on the potential for re-use at those scales.

Data requirements

FIG 5.6 (a) and (b) illustrate the perspectives of housing professionals (n=19) and potential users (n=10), respectively, where the dark grey, light blue, and blue coloured bars present the total number of responses given on the data requirement degrees of “not necessary”, “nice-to-have”, and “must have”, respectively. Some data points on the building level, such as “Building location” (A.0), “Building year” (A.1), and on the product level, such as “Product name” (B.11), “Location in building” (B.14), “Dimensions” (C.21), “Quantity” (C.24), “Composition of materials” (C.25), “Toxicity/hazardous substances” (D.28), and “Condition and quality assessment” (E.44) were classified as must-have data by the majority of interviewees (both second and third round interviewees). These data points are directly related and imperative to the assessment of a product’s condition and suitability for reuse (Addis, 2006) and also were included in the many reviewed MP approaches (see Supplementary Materials). Therefore, our findings confirm the previous approaches that included these data points (e.g., BAMB (2019); Göswein et al. (2022); Munaro and Tavares (2021)).

Among the five product data categories (B to F), “C- Product Properties” and “F-Product End-of-Life Aspects” seem to be critical to meet users’ data requirements, while many of the data points included under “E-Product Operational Aspects” are assigned to be “nice-to-have”. There could be several reasons for this trend. First, categories C and F support reuse and recycle strategies, thus, closing the material loops, while category E is, to a large extent, related to expanding the life cycle of products, so slowing the material loops. MPs, therefore, are seen as tools for circularity at the end-of-life by the practitioners rather than a whole life cycle data solution as proposed by researchers (Aguiar et al., 2019; Göswein et al., 2022; Munaro & Tavares, 2021). Another reason could be that maintenance activities, although maintenance itself is a circular strategy, are not yet fully operationalised through circular material flows by social housing organisations. Therefore, the link between the use and end-of-use phases of products is not explicitly made in terms of data management. The empirical findings of Çetin et al. (2022) support this, as their multiple-case study with three social housing organisations also showed that practitioners tend to see MPs as an end-of-life tool due to the difficulties in managing life cycle data for a long time. However, though, as some interviewees mentioned, the maintenance log of a product could be a fruitful source of data when deciding on end-of-life treatment options.

There are modest differences between the data requirements of housing professionals (FIG 5.6 (a)) and identified potential users (FIG 5.6 (b)). Three data points, namely, “Building energy label” (A.06), “Drawings and BIM model” (B.18), and “Cleaning instructions” (F.35), seem to be insignificant for the potential external users while many interviewed housing professionals perceive them as nice-to-have. A possible explanation for this could be that the majority of the third-round interviewees (nine out of ten) have expertise in reuse practices (e.g., harvesting, design, and consultancy), and these three data points do not directly impact their decisions in reusing products. For example, one interviewee from a reuse company noted that they need to inspect the donor building for the identification of reclaimable products, whether they have drawings and maintenance or cleaning instructions or not. Building products are subject to changes throughout their lifetime, and condition assessment needs to be performed on the location even though the building is fully documented.

Compared to extant studies that are listed in Supplementary Materials, which delineate a dispersed range of data requirements, this study concentrated on the existing housing stock and developed a data template in a systematic way by building on previous MP approaches and validation interviews with practitioners. Thus, in a way, the data points presented in FIG 5.6 are the first empirical attempt to illustrate the data requirements and their necessity from the practitioners’ perspective. Our findings reveal that the MPs for existing buildings should prioritise data points that explicitly support the reuse and recycling interventions (i.e., Data categories C and F) during maintenance, renovation, and demolition operations. Data categories that are not critical for closing the loops but beneficial for slowing the loops (i.e., Data category E) are also related to the end-of-recovery of building products and must be kept in MPs where possible. Another important aspect of creating MPs is the availability of data, whether these data points are readily available or need an afford to obtain, is explained in the following section.

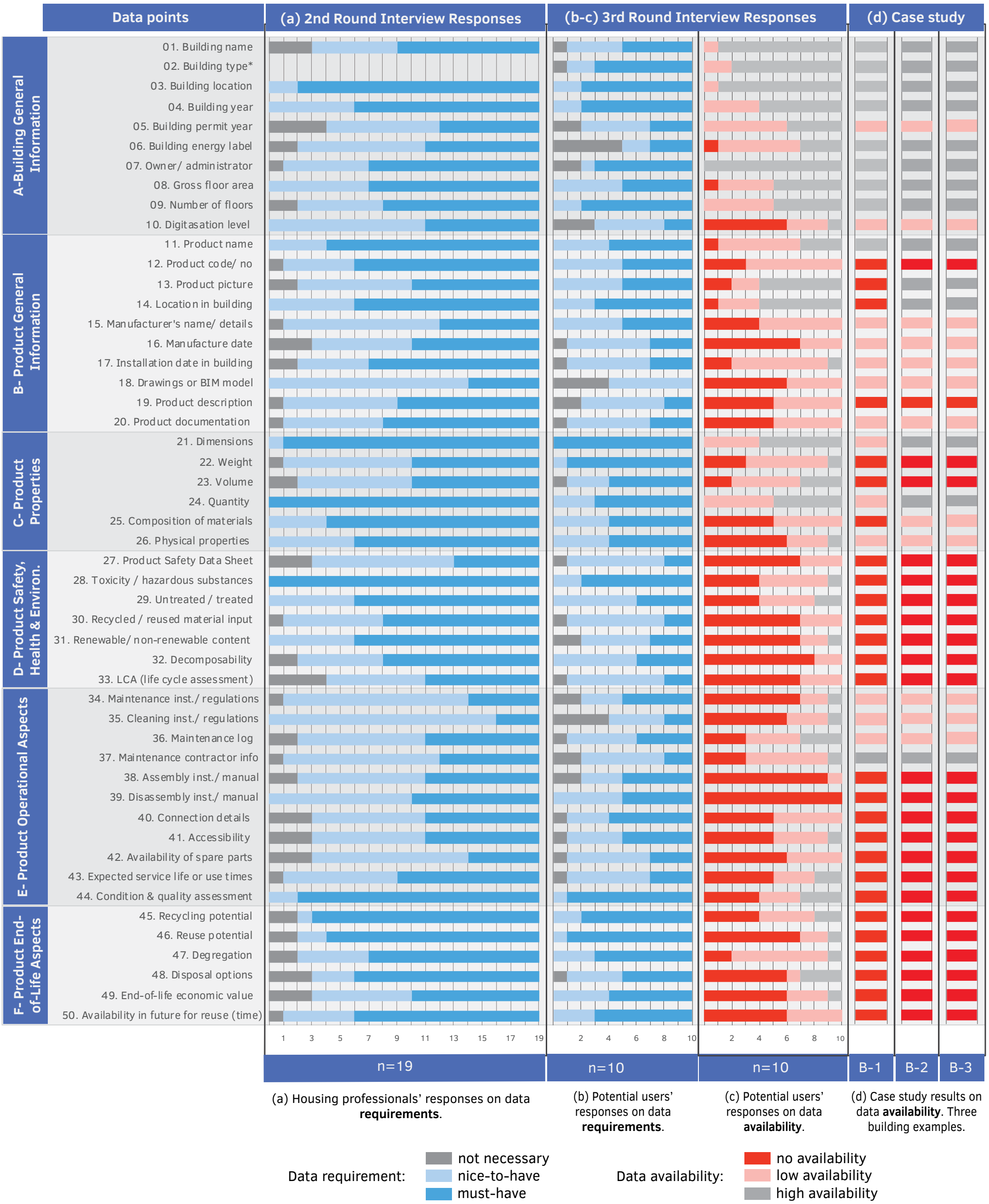

FIG. 5.6 Interviewee responses in the second and third interview rounds and case analysis were mapped as bar charts onto the data template. *Building type is added to the template as a data point on the third round upon interviewee suggestions.

Data availability

Our findings provide crucial insights into the availability and accessibility of data required to create MPs in social housing organisations. FIG 5.6 (c) presents the responses of ten interviewees (i.e., potential users) on the data availability based on their experience with circular projects, and FIG 5.6 (d) illustrates the analysis of three sample buildings from the case study. In Building 1 (B-1), data were obtained for the roof at the element scale, and in Building 2 (B-2) and Building 3 (B-3), data were retrieved for the gutters at the product level (see Supplementary Materials for details).

In general, most general building information, such as “Building name (A.01)”, “Building type (A.02)”, “Building location (A.03)”, “Building year (A.04)”, “Gross floor area (A.08)”, and “Number of floors (A.09)” can be easily accessed through internal databases and shared with the project stakeholders, so these data are typically highly available. However, “Building permit year (A.05)” and “Digitalisation level (A.11)” are generally not available in the main system but may be present in ancillary system databases.

Regarding products and elements within the building, the analysis of exemplar buildings showed that there is limited information available on their composition, installation dates, and manufacturing details. There is often only high-level information on the existence of roofs and facades, but element pictures or codes are usually non-existent. While the dimensions and quantity of certain elements, such as that of windows, could be retrieved if the BIM model of the building is accessible, other physical properties of the element or product, including their weight, volume, and composition, are generally unavailable. These data can also be generated through site inspections by external stakeholders (e.g., reuse companies and architects) or maintenance contractors.

In exemplar buildings B-2 and B-3 (FIG 5.6 (d)), additional data points were available through the case organisation’s maintenance data provider partner. The additional data retrieved include street view, aerial, and satellite imagery of the building assets. Through the use of computer vision algorithms, various elements and features on building roofs and facades were identified, such as windows, doors, shutters, rain pipes, and masonry finishes. The algorithms also allowed for the dimensions and area of these elements to be determined. While the data provider typically utilises their algorithms for condition assessments of buildings, no information on this aspect was available for the selected buildings. Although promising, these data points still do not include element codes for identification and long-term documentation.

TOC

Furthermore, data points under Category D, related to product safety, toxicity, decomposability, and life cycle assessment, are not readily available in the social housing organisation's databases, as these were not considered necessary data points in previous projects and are challenging to obtain for existing buildings. Nevertheless, a sustainability metric is typically provided by the maintenance inspectors, which gives a sustainability label to the building. In addition, the risk of asbestos presence in existing buildings is a critical issue in renovation and demolition projects, and an inventory needs to be made by inspectors. As some interviewees noted, sometimes it is possible to estimate the asbestos risk based on the building type and year. Operational aspects (Category E), such as maintenance instructions, logs, and contractor information, may be retrieved from internal maintenance software or secondary external repositories but are not saved in the main central database.

Additionally, assembly and disassembly instructions, as well as the availability of spare parts or condition assessment, are not typically documented. Data points considered in the category "F- Product End-of-Life Aspects", including the reuse and recycling potential, economic value, and availability for reclamation, have also not been a priority for documentation, and hence, no data exists on these aspects. These data points are time-dependent, meaning that they could be produced at the demolition stage if a reuse company, consultant, or architect inspects the building and assesses the condition of recyclable and reusable products. Data point F.50 on the future availability of products could ideally be estimated by using the social housing organisation's demolition planning documentation. However, in the case study's digital systems, this is not considered.

5.4.3 A Material Passport framework to address the data gaps

Overall, the study identified several data gaps and inconsistencies that hinder the collection and access of the required data for creating MPs. The lack of available data points highlights the need for an integrated data management system that can maintain life cycle data in a standardised manner. As shown in FIG 5.7, we propose a framework to address data gaps by combining the capabilities of digital technologies alongside the support of stakeholders. The capabilities of digital technologies, namely, *data collection* (generation and collection of data), *data integration* (organising, storing, sharing and maintaining data) and *data analysis* (interpreting data and obtaining actionable decisions), were drawn from the previous studies (Çetin et al., 2022; Kristoffersen et al., 2020; Siow et al., 2018). For each data category, the framework suggests improvements in technology integration with enabling digital technologies (Çetin, De Wolf, et al., 2021; Yu et al., 2022). The critical data gaps are based on the results presented in FIG 5.6 and are highlighted in red for each data category in FIG 5.7. These data gaps are thought to be "must-haves" in an MP by more than half of the interviewees, and correspondingly their availability is found to be at the scales of either "low" or "no" (FIG 5.6).

Data category	Digital technologies and human actors			Life cycle phase
	Data collection	Data integration	Data analysis	
A-Building General Information	Automated data retrieval from public records Employees of SHOs	Data harmonisation in the central data system, BIM, data lake or alternatively in an MP Platform Employees of SHOs and external stakeholderss	Big data analytics; machine learning	All life cycle phases *(ideally data should be collected in the design stage)*
B- Product General Information [Critical data gaps: B.12, B.14, B.17]	Automated data retrieval from third-party websites Project managers or maintenance managers of SHOs	Data harmonisation in the central data system, BIM, data lake or alternatively in an MP Platform Employees of SHOs and external stakeholderss	Web scraping; machine learning	All life cycle phases *(ideally data should be collected in the design stage)*
C- Product Properties [Critical data gaps: C.22, C.23, C.25, C.26]	Sensing and scanning technologies (e.g., Lidar systems) Site inspectors (e.g., pre-demolition auditors)	Data harmonisation in the central data system, BIM, data lake or alternatively in an MP Platform	Computer vision; machine learning Site inspectors and reuse experts (e.g., consultants)	Use and end-of-use phases *(ideally data should be collected in the design stage)*
D- Product Safety, Health & Env. Aspects [Critical data gaps: D.28, D.29, D.31, D.32]	Drones to capture building images; data retrieval from waste repositories, building registers, satellite images, etc. Safety inspectors and experts	Data harmonisation in the central data system, BIM, data lake or alternatively in an MP Platform	Computer vision; machine learning Safety inspectors and experts	Use and end-of-use phases *(ideally data should be collected in the design stage)*
E- Product Operational Aspects [Critical data gaps: E.44]	Drones to capture building images; data retrieval from satellite images, etc. Maintenance managers or contractors, inspectors or experts	Data harmonisation in the central data system, maintenance system, BIM, data lake or alternatively in an MP Platform Maintenance managers or contractors (to update data)	Computer vision; machine learning; augmented reality, virtual reality Inspectors or experts	Use phase *(ideally data should be collected in the design stage)*
F- Product End-of-Life Aspects [Critical data gaps: F.45, F.46, F.47, F.48, F.49, F.50]	Scanning technologies, drones to capture building images; data retrieval from satellite images, etc. Reuse companies, consultants or architects	Data harmonisation in the central data system, maintenance system, BIM, data lake or alternatively in an MP Platform	MP; computer vision; machine learning; simulations Reuse companies, consultants or architects	End-of-use phase *(data can be obtained during design and use stages)*

Digital technologies
Stakeholders (potential users of MPs)

FIG. 5.7 Proposed MP framework to address identified data gaps.

Overall, data in "A-Building General Information" are highly available and are not critical. A possible improvement for data collection can be made with automated data retrieval from public records, if available online. For example, in the Netherlands, several government agencies and public institutions make their data openly accessible online through open data portals, APIs, and other sources. The Basisregistratie Adressen en Gebouwen is the Dutch national database for addresses and buildings, containing information on all buildings in the Netherlands (BAG, 2023). Big data analytics can then be used to analyse and make sense of the vast amount of data contained in public databases by identifying patterns and trends in the data that may be difficult to discern manually. General data at the building and product level can be harmonised in the central data system (in some cases in the BIM model of the portfolio or data lake (Çetin et al., 2022)) of housing organisations according to the data template presented in FIG 5.6 from an early design stage. If general product data are not available in the main data systems, then the manufacturer's website or third-party websites can be used to retrieve data via web scraping and machine learning (ML) techniques. Web scraping is an efficient technique to gather large amounts of data on buildings that are available online in various informal forms. For example, Yang et al. (2020) created a web crawling algorithm to access building material properties information for energy analysis. ML algorithms can then be trained on the retrieved data to predict future performance (Egwim et al., 2022). These predictions can be added to an MP as new data points, enabling building managers to make more informed decisions about building maintenance and renovation.

The critical data gaps identified in "C-Product Properties", especially "Weight (C.22)" and "Volume (C.24)" of a product, can be calculated or estimated based on dimensions and other physical properties. "Dimensions (C.21)" and "Quantity (C.24)" are typically determined by the inspectors (e.g., reuse companies) before the selective demolition process and can be registered on an external MP platform (see, e.g., the case analyses of Çetin et al. (2022)). In addition, various digital technologies and methods can help with further data acquisition from existing buildings. For example, Gordon et al. (2023) demonstrated a data-capturing technique in a real-world case where authors applied photogrammetry, Scan-to-BIM, and computer vision methods to identify reusable structural steel elements from a demolition site. By using accessible technologies, such as mobile devices as well as Lidar systems, it was possible to collect data to construct a BIM model, which was then used to detect structural elements through computer vision techniques (Gordon et al., 2023). Another interesting image-based material recognition technique tested by researchers is based on laser scanning and ground-penetrating radar technology to identify the geometry and material composition of the building elements (Kovacic & Honic, 2021). Such innovations are promising for completing missing data points during the use or end-of-use phases of buildings.

Identifying toxic and hazardous contents in the building products is of utmost importance in the maintenance, renovation and demolition of the existing building stock. Our findings indicate that there is a critical data gap in this field (FIG 5.7). AI applications can offer solutions. For example, as Wu et al. (2022) showed, ML can be used to anticipate the presence of hazardous materials (i.e., asbestos and polychlorinated biphenyls) in the building stock based on hazardous waste repositories and building register records. The authors used several building-related parameters such as building year, floor area and the number of apartments to train the ML algorithms. Considering the availability and accessibility of general building data, the building stock of social housing organisations can be analysed with such methods to identify hazardous contents. Another AI application, computer vision, can also be used to detect deficiencies and hazardous contents on the building façade by using images created with drones, satellite images or publicly available street views (Çetin et al., 2022). This technology, as discussed in the case analysis, can be used to identify various elements and features on building roofs and facades. Such methods for automated retrieval of material information are becoming increasingly popular due to advancements in both software and hardware sensors. For instance, Raghu et al. (2022b) built a model to detect external façade materials such as brick, stone, wood and stucco, while Kim et al. (2021) explored the generation of algorithms to identify concrete and metal roofs. The algorithms can also be leveraged for condition assessment of buildings, providing insights into the current state of the building and identifying potential maintenance issues, thus, supporting maintenance operations. This is observed in the use of infrared thermal imaging in combination with computer vision to detect facade anomalies (Resende et al., 2022) and in the use of automated inspection systems to detect visually discernible defects in buildings (Munawar et al., 2021).

Furthermore, augmented reality and virtual reality technologies can be used to visualise and simulate buildings' design and maintenance processes. Augmented reality can be used to overlay digital information on the physical building, allowing for more efficient and accurate maintenance and repair. For instance, Wibranek and Tessmann (2023) developed a mobile app with information about reusable building components from nine different MPs. Virtual reality can be used to simulate buildings' performance and energy consumption and predict a building's future maintenance needs (Niu et al., 2016). Additionally, virtual reality can help create a visual representation of materials and parts that can be reutilised in construction projects (O'Grady et al., 2021). A similar application can be carried out to depict MP information across the building life cycle.

Finally, the most critical data gaps were identified in the "F-Product End-of-Life Scenarios" category. Determining the reuse and recycling potential and degradation of a product is typically done by experts (e.g., reuse contractors or consultants) based on condition assessment. Therefore, as mentioned above, computer vision technology can help experts is assessing the quality and quantity of products. In addition, as demonstrated by Honic et al. (2021), an MP approach can alternatively be deployed based on laser scanning and traditional data acquisition methods (i.e., demolition acquisition and urban mining assessment) to evaluate the recycling potential of materials embedded in existing buildings. Some commercial MP platforms, such as Madaster (Madaster, n.d.), provide the economic residual value of materials in buildings. In terms of finding out the availability of a product for reuse in the future various simulation techniques can be deployed based on the demolition planning of social housing organisations.

5.4.4 The emerging role of AI for Material Passports

The use of AI in the building industry can bring about significant advancements, one of which is the implementation of MPs. By leveraging ML and computer vision algorithms, AI can identify and categorise materials, track their origin, assess their environmental impact, and predict their future performance. Following the MP framework introduced in Section 5.4.3, the emerging role of AI can be summarised as follows:

- Data Collection: AI can automate the collection of material-related data from various sources, such as product databases, material suppliers, manufacturers, and construction documents (Bodenbender et al., 2019), as well as crawl and extract relevant data from websites, documents, and other digital sources, minimising the manual effort required (Kovačević & Davidson, 2008).
- Data Integration: AI can help organise material data into structured databases or digital MPs. Automated tagging and categorisation of materials can create a searchable and easily navigable repository of information (Kovačević & Davidson, 2008; Radinger et al., 2013).
- Data Analysis: AI algorithms excel in analysing large and complex datasets. They can process the collected data to identify and categorise materials, including their properties, certifications, and compliance with sustainability standards. ML techniques can be employed to recognise patterns and correlations within the data, enabling insights into material performance, life cycle assessments, and potential environmental impacts (Barros & Ruschel, 2021). Computer vision can be used to analyse images of materials and help identify their types and existing conditions (Munawar et al., 2021).

Thus, the use of AI for MPs can enable architects, designers, and construction professionals to make informed decisions regarding material reuse, recycling, and disposal, leading to reduced waste, and improved resource efficiency.

5.5 Conclusion

This study set out to explore data requirements and availabilities to create MPs for existing buildings in the European social housing context. There are many MP approaches to support circular strategies in the building industry. However, they vary in terminology, content, scale, technology use, and maturity level and largely overlook users' data needs. This paper thus addressed this research gap by deploying an empirical study based on a multi-step data collection method, including a literature and practice review, three rounds of interviews with a total of 38 respondents, and a case study. A data template consisting of 50 data points is developed and tested in a case study.

By confronting data requirements with data availability, this study identified several critical data gaps, including, but not restricted to, the composition of materials, existence of toxic or hazardous contents, condition assessment, and reuse and recycling potential of a product. Considering the identified critical data gaps, an MP framework is proposed that draws on data collection, integration, and analysis capabilities of digital technologies alongside the knowledge support of key stakeholders. This framework sketches an overview of enabling digital technologies such as AI and scanning technologies to address the data gaps in creating MPs to apply narrow, slow, close, and regenerate principles. As such, the framework can be used to give direction to further research and innovation in data provision for enabling the adoption of circular strategies in (social housing) construction, renovation, and maintenance practice.

5.5.1 Limitations and recommendations

The scope of the present work was limited to existing buildings within the context of European social housing organisations and stakeholders involved in circular housing projects. Further research could examine other countries, building typologies (e.g., commercial or public real estate), and life cycle stages (e.g., design stage) to determine the data needs of stakeholders involved in the respective value chains. Since the number of interviewees in the last validation round was limited (n=10), we could not collect data from all identified MP users. A further detailed survey is recommended with a large sample of stakeholders involved in MPs and circular construction projects. Although the developed data template is based on a robust research methodology (i.e., multi-step data collection consisting of literature and practice review and validation interviews), identified data requirements will likely differ among stakeholders based on the purpose of use. Further research could investigate the link between the functionalities of MPs and the data points required to create MPs. This will help to develop tailored MPs for certain functions and/or stakeholder groups.

Although this research took a supply chain perspective to identify the data requirements of actors, data exchange and data confidentiality issues between actors were out of scope. Thus, further research could examine how data can securely be stored, tracked, and shared with relevant stakeholders such that the data is available across project stages (design, construction, operation, maintenance, and end-of-life) and beyond (the second life of a product). Furthermore, blockchain technology's potential in handling MP data across life cycles could be studied by considering confidential data and trust issues.

The effectiveness of AI algorithms in extracting relevant information depends on the quality and consistency of the data inputs. Therefore, efforts should be made to ensure the availability of comprehensive and up-to-date data to maximise the potential of AI in material data collection and analysis. Another challenge lies in the standardisation of data formats, terminologies, and classifications across different sources and stakeholders. Further research and collaboration are needed to develop common standards and protocols for data integration, enabling seamless exchange and interoperability of material data among various systems and platforms. Furthermore, while AI algorithms can make predictions and provide insights into material performance, their accuracy can also rely on the robustness of the algorithms themselves. Thus, it is crucial to validate and refine AI models continuously. Future research should focus on developing methodologies for validating AI-generated insights and integrating user feedback to improve the accuracy and usefulness of the generated MPs.

For professionals working at social housing organisations as well as other professional real estate owners and their supply chain partners, it is recommended that they attune their periodical data collection for maintenance purposes (in particular condition assessments) to data requirements for enabling circular practices. Thus, they can use 'natural' moments for data collection to create MPs and thereby facilitate the adoption of circular strategies in their maintenance, renovation, and end-of-life practices.

Author contributions

Sultan Çetin: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Visualization, Project administration Deepika Raghu: Methodology, Validation, Investigation, Data Curation, Writing - Review & Editing Meliha Honic: Methodology, Investigation, Data Curation, Writing - Review & Editing Ad Straub: Conceptualization, Writing - Review & Editing, Supervision Vincent Gruis: Conceptualization, Writing - Review & Editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

TABLE 5.A.1. Interview guideline for validation rounds.

No	Interview questions	Validation round
1	What should be the main function of a material passport for existing buildings? a) Measuring the circularity level of a building b) Design optimisation c) Supporting maintenance d) Supporting retrofit/renovation e) Enabling reuse and recycling (i.e., dismantling) f) Supporting the creation of pre-demolition audits (material inventories) g) Measuring the economic value of the materials Other:	1, 2, 3
2	Material passports can be created at varying degrees of detail. Which scale should be the material passports for existing buildings developed for? a) Area b) Complex or building portfolio (collection of buildings) c) Building d) Element (e.g., façade glazing) e) Product (e.g., window) f) Material (e.g., glass) g) Raw material (e.g., sand)	1, 2, 3
3	Please indicate on the (online) stakeholder diagram who needs and feeds data onto material passports.	1, 2
4	Please indicate which of the data points on the data template are “must-have”, “good-to-have”, and “no-needed” for creating material passports for existing buildings in your opinion. *(Interviewees are provided with 50 points data template to answer this question).*	2, 3
5	Please indicate which of the data points on the data template are “highly available”, “low availability”, and “no availability” for creating material passports for existing buildings from your professional experience. (Interviewees are provided with 50 points data template to answer this question).	3
6	Is there any crucial data point missing in the data template? If so, could you please add it.	1, 2, 3