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Eight recommendations to adopt materials passports and accelerate material reuse in construction: insights from academia and practice

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The construction industry is not only one of the most resource-intensive industries, but is also responsible for nearly 40% of global energy-related CO_2 emissions. In this perspective paper we present eight recommendations to adopt materials passports and accelerate material reuse in construction. This approach will enable us to reduce embodied carbon expenditure and address Net Zero Targets. We should: 1) Prioritise the reuse of the whole building; 2) Complete a pre-redevelopment and pre-demolition audit; 3) Prioritise deconstruction over demolition; 4) Prepare a deconstruction plan; 5) Adopt a clear materials passports framework that allows interoperability between platforms and databases; 6) Produce a materials passports database according to the life stage of the building: existing, proposed and completed; 7) Incorporate reused materials in new buildings; 8) Promote regulation that supports a cultural shift to address the economic, social and environmental value of materials. In all of these cases, the involvement of all stakeholders across the industry is crucial to enable material reuse and extend the lifecycle of materials.

The construction industry is one of the most resource-intensive industries, therefore, the construction industry needs to stop compromising the environmental sustainability by optimising resource utilisation, improving construction efficiency, and minimising waste[1]. The construction industry is also responsible for nearly 40% of global energy-related CO_2 emissions[2]. As the energy grid is decarbonising[3] and new buildings have a better energy performance, operational carbon emissions are likely to be lower in the future, in particular for new builds. With a decrease of operational carbon emissions, the embodied carbon in new buildings can represent more than 50% of the total life cycle emissions for new energy-efficient buildings[4]. This is the carbon that is being released into the atmosphere now, by the manufacturers and we can reduce it significantly by reusing existing materials. If global economic development and the construction industry continue focusing on an ever-growing model, building new constructions and demolishing the existing ones, the Net Zero Targets defined by the Paris Agreement[5] will not be fulfilled. The World Green Building Council report defined that by 2030, all new buildings, infrastructure, and renovations should have (at least) 40% less embodied carbon and by 2050 the embodied carbon should be zero[6].

Reducing embodied carbon is a fundamental step towards meeting the Net Zero targets defined worldwide and the construction industry needs to develop a sector specific carbon budget[7]. Embodied carbon emissions in buildings encompass the total carbon footprint associated with the production, transportation, and assembly of building materials[8]. Promoting material reuse is crucial, as it can mitigate these emissions by utilising materials that generally have a lower environmental impact compared to newly manufactured ones. This approach not only addresses the sustainability challenges in the construction industry but also aligns with broader environmental goals[9].

According to Blanco et al. [10] 80% of buildings that will exist in 2050 have been already built, thus it is imperative to retrofit the existing buildings and make the most of the materials already in use. To promote a circular economy, the concept of 3R's (Reduce, Reuse and Recycle) suggested by the European Union (EU) and United Nations (UN) has been widely adopted in many waste regulations across the world[11]. After reducing the need for new buildings and materials, the reuse of existing (buildings and materials) appears to be the most energy-efficient solution for a circular economy by enabling the preservation of material value for a longer period[12]. By accel-

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erating material reuse in construction, we can significantly reduce the need for extraction and producing virgin materials, thereby decreasing the embodied carbon of construction projects, and minimising construction waste[13].

According to Thomas Rau, waste is a material with no identity[14]. Categorising materials is necessary to salvage them and recognise their potential for reuse. Therefore, we see materials passports (The term materials passports (MP) comprises all the different levels/types of materials, components, products, systems, elements used across the Architecture, Engineering and Construction Industry. When we use the term, 'material passport' we refer to a specific (raw) material with a passport.) (MP) as a digital data set that captures information about a material. The type and format of data collected depends on multiple factors that do not affect the MP main objective: gather enough data to avoid a material becoming waste.

Literature review - materials passports

The principle of providing a data sheet for a construction material is not something new. Back in in the 15th century AD, the deconstruction and reuse of the Christian Basilica of Santa Tecla, has a well-documented example of MP. The financial and material scarcity motivated the reuse and integration of building elements in the new Milan cathedral (Duomo) or sold to raise money for the same building[15].

The EU Horizon 2020 project, Building Materials as Materials Banks (BAMB), was an important initiative to raise awareness and provide guidance on MP[16]. The Materials Passport Framework produced by BAMB[17] has inspired and guided the development of different product data initiatives[18]. Often referred to as material inventories or a datasheet, MP terminology embodies the concept of materials that can be tracked and traced throughout their lifecycle, ensuring they do not get lost[19]. This aligns with the fundamental principles of circular economy, promoting multiple life cycles for materials. MP are a tool designed to enhance the reclamation of materials and facilitate material reuse, in both existing buildings and new constructions[20].

Research evidence shows multiple advantages of MP approach: 1) provide deconstructability score, recovery score and environmental score[21]; 2) quantify building material and component stock and flows[22]; 3) enable measurement of the circularity of materials by quantifying their in-use occupation[23]; 4) improve recyclability of new buildings as well as making assumptions for upcoming materials through displaying embedded materials[18]; 5) outstanding advantage regarding recycling and reuse[24]; 6) digital interface composing a certified identity of a single identifiable product[25]. One of the key advantages of MP is their ability to ensure that crucial information related to circularity is effectively communicated to the primary actors responsible for facilitating the circularity of products[26].

MP should be seen as key tools to promote a circular economy and resource efficiency in the construction industry because they can provide digital sets of data that describe defined characteristics of materials and components in products and systems that give them value for present use, recovery, and reuse[27]. MP enable stakeholders to overcome the information gaps, one of the major barriers to circular economy[28]. They provide structured and relevant data to all actors across the construction cycle, on existing and future building materials. They also offer the opportunity of storing, linking and preserving the data. This statement has recently been illustrated in the digital framework aimed to improve practical utility and applicability in real-world construction practices[29]. In this context, MP emerge as a critical tool. These passports serve to identify and document essential information about materials, including their composition, origin, and lifecycles.

The MP value and its advantages for the circular economy are well documented in literature. Markou et al. [30] provide a comprehensive systematic literature review on the current approaches for creating MP. These approaches can focus on different tools to deliver MP. The most common tools are: a) BIM-based: e.g. a research approach to augment materials passports by integrating the information related to the components recovery capacity using a BIM-based Semantic Enrichment Engine for Disassembly Planning (SEEDP)[31,32]; b) Blockchain-based: e.g. adoption of Blockchain non-fungible token (NFT) to ensure uniqueness, authenticity and enhance transparency and traceability, as all information is stored on a distributed ledger accessible to all parties[33]; c) platform-based: e.g. calculation and evaluation of circularity for the built environment using case studies of Urban Mining and Recycling[19] d) QR code/RFID-based: e.g. RFID-based material passport system in a recycled concrete circular chain[34].

Currently, in practice, there are a series of materials passports platforms offering different commercial solutions worldwide, with their own data templates and MP approach (e.g. Circuland, Concular, Madaster, Upcyclea). However, these commercial MP platforms focus essentially on developing business opportunities[35] and do not ensure interoperability of data.

Despite several studies on data requirements for creating MP[25,36–38], the main challenges to adopt MP is due to the lack of standardisation of data templates and MP and difficulties in collecting data throughout material's lifecycle[39]. Regarding the ideal MP, there are several studies exploring the incorporation of advanced technologies e.g. Artificial Intelligence for automated data collection, real-time updates, automated MP[40,41], geographic information systems, laser scanning[39] and dynamic MP application[42], although, the implementation of these solutions may delay the creation of MP for materials currently being sent to waste.

According to the European Union Circular Economy Action Plan[43] the construction sector is responsible for over 35% of the EU's total waste generation. This plan highlights the importance of revising the Construction Product Regulation[44], develop digital logbooks for buildings[45], use Levels[46] to integrate life cycle assessment in public procurement and revised material recovery targets set in EU legislation for construction and demolition waste. Alongside with Digital Product Passports (DPP)[35,47], these initiatives advance transparency of data and encourage sustainability for new materials, however, none of these initiatives focuses on the materials already in existence. Moreover, despite individual attempts, the multiple approaches currently published in academic literature on MP do not foresee a standardised approach and data interoperability.

Considering the current literature review and data collected, in this perspective paper we aim to respond to the following hypothesis:

- MP can adopt a standardised approach, follow material's lifecycle and ensure data interoperability with future platforms and policy requirements.
- MP can be adopted according to material's context and allow a cumulative data collection.
- MP can be created once the material is in use to reduce construction waste.

Goal and scope

The current literature on MP does not provide guidance on how to adopt MP and accelerate material reuse in construction in a standard and scalable way. Drawing on the work completed for the materials passports policy paper[20], this perspective paper explores knowledge exchange between academia and industry to close the knowledge gap. It proposes a standardised approach to materials passports and provides a timely adoption of MP to accelerate material reuse in construction.

The objectives of this paper are: (1) Support the Architecture, Engineering and Construction (AEC) industry to integrate MP at different stages of the life cycle of the building; (2) Highlight the advantages of MP and describe the creation of an existing and proposed MP database; and (3) Provide clear recommendations to support the transition to a net zero built environment.

Based on 22 dialogic interviews augmented by a graphic elicitation process and two consultation events involving more than 50 professionals and academics across the AEC industry, this paper gains insights from the industry and practice and summarises eight recommendations to adopt MP and accelerate material reuse in construction.

The eight recommendations describe a process that is clear enough to understand, simple enough to use and cost effective enough to implement.

Furthermore, the standardised classification system allows iterative data collection according to its context and ensures future interoperability of data colected.

The eight recommendations are presented across the following four sections:

- Existing buildings: adoption of materials passports and accelerate material reuse in construction (recommendation 1–4).
- Provide a clear standardisation system that allows compatibility and interoperability between MP databases (recommendation 5).
- Produce a materials passports database according to the lifecycle of the building – existing, proposed and completed (recommendation 6).
- A collective effort from the industry, research and policy (Recommendation 7 and 8).

Existing buildings: adoption of materials passports and accelerate material reuse in construction

The reuse of existing materials can reduce waste and minimise the extraction of raw materials. It is imperative that we retrofit existing buildings and preserve as many materials as possible.

Recommendation 1: prioritise the reuse of the whole building

Research shows great opportunity to achieve Net Zero Targets[5] through retrofit approaches[48] and embodied carbon reduction. However, there is a wide range of criteria that influence the decisions to demolish or retain, reuse and adapt existing buildings[49,50] Social, cultural, and economic environmental values need to be assessed, context-specific factors need to be considered, and detailed building analysis needs to be carried out.

Research evidence[49,51] shows two main reasons for retaining and reusing buildings, the first one is the retention of heritage assets and the second to reduce embodied carbon when compared with demolition and rebuild.

The reuse and refurbishment of existing buildings is the most efficient way of reducing carbon emissions and waste from the building sector[52]. Therefore, the most efficient measure to accelerate material reuse in construction and achieve Net Zero Targets is to extend the life cycle of the existing buildings and materials and improve their technical performance to reduce operational carbon expenditure. The decision tree proposed by Cheshire[53] should be followed to inform the design process. According to the author, retaining the existing assets should be the first level of consideration. When the retention and retrofit of the building is not possible, a partial retention and refurbishment should be considered. In a strip-out approach, when only non-structural components are removed, keeping the structure and substructure retains most of the embodied carbon. To inform the deconstruction of complex buildings, the pre-redevelopment and pre-demolition audits play a key role in the design decision process[54,55].

Recommendation 2: complete a pre-redevelopment and pre-demolition audit

In the UK, the Great London Authority Circular Economy Statement (2022) encourages the delivery of a Pre-Redevelopment and Pre-Demolition Audit at the pre-application stage. These are 'important tools to establish whether building components can be reclaimed and how any demolition materials will be managed'[54]. The pre-redevelopment audit can help to understand if the existing buildings can be fully or partially retained, refurbished, or incorporated into a new development or extension. This information can also inform the feasibility study development, be used as supportive evidence to the circular economy statements and characterise the passports of existing materials.

The pre-demolition audit provides the detail of the materials in the building that will need to be managed upon demolition and is used to support the circular economy statement. This document should provide 'an explanation as to why it is proposed that the building(s) be demolished', with a 'summary of the key components and materials present in the existing buildings, with an estimate of the quantities and associated embodied carbon and whether they are suitable for reclamation'[54]. Furthermore, the information gathered on the pre-demolition audit should be used to characterise MP and identify the reuse and recycling potential of buildings/elements. MP can be used to quantify the value of existing building elements, the amount of demolition waste and used to target reuse and reclamation rates.

However, based on a circular economy approach, the pre-demolition audit should be renamed as a pre-deconstruction audit. By deconstructing a building, rather than demolishing it, we should be able to reclaim more materials, minimise waste and raw material extraction[56].

Recommendation 3: prioritise deconstruction over demolition

The AEC industry is one of the biggest resource-consumers and waste-producers of our planet. This sector uses up to 40% of the total raw materials extracted globally and generates about 35% of the world's waste[57]. We should consider buildings as material banks, filled with reusable components for future construction projects. Deconstructing buildings instead of demolishing them (carefully disassembling and salvaging their materials for reuse) can repurpose much of the typical waste.

This strategy has been adopted by different countries across the world. For example, since 2015, the French government launched several laws and incentives favouring deconstruction[58]. The Netherlands has a national programme[59] aiming to halve the use of primary raw materials in the construction industry by 2030. Vancouver's Zero Waste 2040 plan[60] aims to reduce waste from construction and demolition and encourage reuse of deconstruction materials. The city of Oakland, in California, established a deconstruction requirement in its 2030 Equitable Climate Action Plan[61] which supports the reuse of building materials to reduce their lifecycle emissions. This regulation ensures that salvageable materials are identified and removed for reuse instead of being recycled or sent to landfill.

In 2020, the UK produced a staggering 59.1 million tons[62] of non-hazardous construction waste. Despite the recovery rate of 92.6%, much of this recovery consists of downcycling recovered materials, often crushed for use in roads and building foundations[63]. By recognising its social, economic, and environmental (including carbon) value[64] much of this waste can find new life through deconstructing rather than demolishing buildings. Therefore, we need to avoid demolition and prioritise deconstruction. As illustrated in the Fig. 1; to promote a circular construction economy, we should be able to deconstruct existing buildings, salvage materials to be reused off-site or preferably on-site. New buildings should be made from reused materials, new materials with a recycled content, new renewable materials and an increasingly reduced amount of new non-renewable materials.

Depending on the scale of the project and construction methods, a building can take 6–24 months on average to be built. However, during the demolition period, clients under financial pressure aim to demolish the building as soon as possible, sometimes within less than a week[65]. The creation of a MP database at the pre-demolition phase can support the brokerage of materials and reduce the storage demand. Furthermore, there is a need for a paradigm shift in construction supported by policy and financial incentives to privilege a deconstruction approach where the main priority is to preserve as many materials as possible, extend their life cycle and reduce waste.

Recommendation 4: prepare a deconstruction plan

When a building is not suitable for full reuse, a deconstruction plan should be prepared. In a partial or full demolition, the deconstruction plan enables the diversion of end-life waste from landfills[66] and reclamation of as many materials as possible. Waste is a growing concern in the construction industry particularly in demolition works[67]. The European Union has set up a minimal 70% recovery rate for building public works[68]. In the UK, around 90% of construction waste is recycled or recovered, nevertheless, most of it is processed through a downcycling process and a non-reversible manufacturing method. The waste prevention programme for England aims 'to reduce construction waste and increase the reuse of construction materials at their highest value. This means designing buildings for adaptability and deconstruction, increasing reuse of components, using materials that can be reused and recycled, and improving demolition systems'[69].

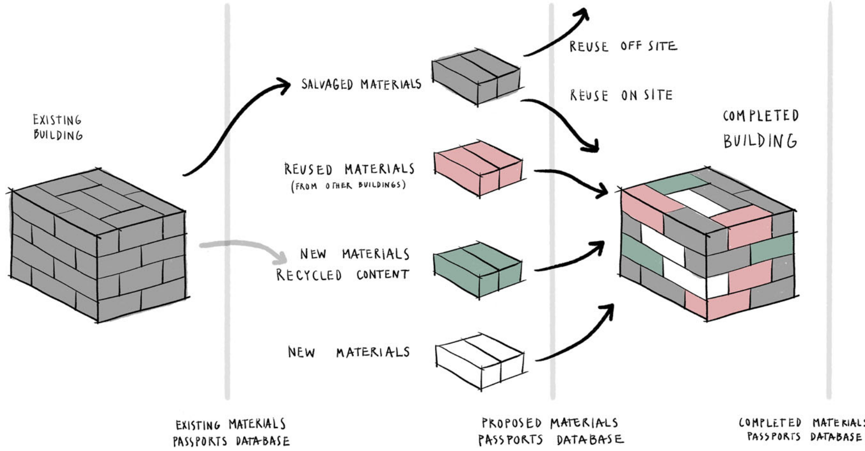

Fig. 1 | Design for deconstruction approach, illustration by Ana Rute Costa (Costa and Hoolahan, 2024).

For existing buildings, the deconstruction plan can be informed by the pre-redevelopment and pre-deconstruction audits. However, in some cases, the visual inspection and characterisation of existing materials are not enough, only during the deconstruction process is possible to evaluate if materials can be salvaged in reuse conditions or need to be recycled[70]. In France, the Grenoble-Alpes Metropole's grand green experiment[71] is an example of a participatory project that brought residents, architects and contractors to enable the reuse and recycling of 320 tons of building materials. The FCRBE Interreg North-West Europe research project has a series of useful research outputs on how to deconstruct and reuse materials, including 32 detailed project sheets with reused rates and reused elements[72]. The Reuse Toolkit: the reclamation audit, provides guidance on how to conduct a reclamation audit and create an inventory before demolition of materials with reuse potential[73]. This is a useful tool for building professionals and any stakeholder involved in the (de)construction process, e.g. clients, contractors, architects, and engineers.

Adopting simple systems alongside the 'layers approach,' as outlined in the Shearing Layers or Building Layers Theory[74], is fundamental to implementing most sustainable building strategies. This approach could be used to structure circular economy data[75]. The Building Layers have been aligned with the Building System Carbon Framework which has been proposed by the World Business Council for Sustainable Development[76]. It can be used to provide standardised data. To maximise future reuse potential, it is advisable that every completed project should have a deconstruction plan prepared alongside the already required Health and Safety file, and Operation and Maintenance manual. It is recommended to create a deconstruction plan that considers the life expectancy of each building layer. This should also identify where the detailed information on how to deconstruct the element can be accessed through MP.

Figure 2 summarises the ideal cycle to accelerate material reuse in construction and use MP. When assessing existing buildings (green circle – top left), the full spectrum of reuse should be considered (Section "Recommendation 1: Prioritise the reuse of the whole building") and therefore the pre-redevelopment and pre-demolition audits (Section "Recommendation 2: Complete a pre-redevelopment and pre-demolition audit") can identify the possible retrofit solutions, prioritise deconstruction over demolition (Section "Recommendation 3: Prioritise deconstruction over demolition") and inform a deconstruction plan (Section "Recommendation 4: Prepare a deconstruction plan"). At this stage, we recommend the creation of an existing materials passports database to classify the materials to be reused onsite or offsite. Once the building has been deconstructed, the salvaged materials can be incorporated into take back schemes, traded by material reuse stakeholders, recycled and ideally avoid becoming waste. The recycled materials can also be incorporated into new products. When designing new buildings or reusing existing buildings, the design team should consider design for disassembly, adaptability, loose fit and deconstruction approaches. At the design stage, we recommend the creation of a proposed materials passports database. This will facilitate the procurement process, and it can be updated into a completed materials passports database once the building has been constructed. The completed materials passports database can then be used to inform the operation and maintenance of the building and its deconstruction plan (Section "Recommendation 5: Provide a clear standardisation system that allows compatibility and interoperability between MP databases"). After a period in use, if a building is reaching the end of life we can go straight for the deconstruction stage. If the building as potential to be reused again, we can develop a new cycle and produce a new pre-redevelopment and pre-demolition audit.

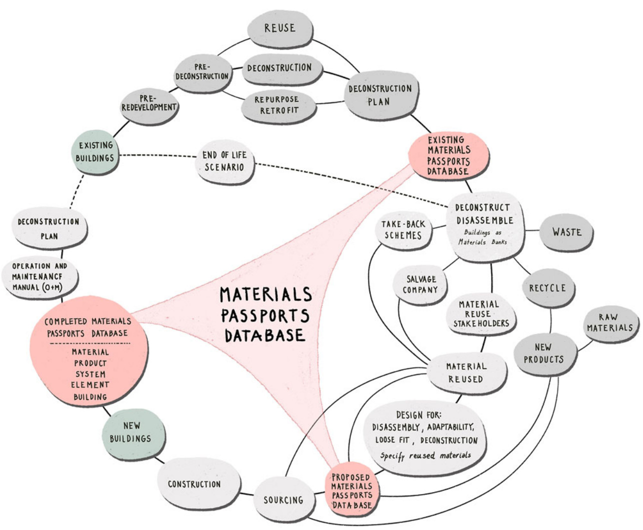

Fig. 2 | The ideal cycle to accelerate material reuse in construction with materials passports, illustration by Ana Rute Costa, adapted from Fig. 3 at (Costa and Hoolahan, 2024).

Aligned with the solution proposal described above, we propose three different iterations of MP databases (existing, proposed and completed materials passports databases) according to the lifecycle of the building. These will be described on recommendation 6.

Recommendation 5: provide a clear standardisation system that allows compatibility and interoperability between MP databases

Due to the lack of standardisation and multiple MP initiatives, we believe that is crucial to provide a clear standardisation system that allows interoperability between different MP databases. This would allow us to access, exchange, interpret and use data in a coordinated manner, and ensure data can flow freely between MP databases, while maintaining its integrity, context and usability. A clear standardisation system would allow MP data to be shared and understood across different platforms, enabling better collaboration and informed decision-making.

The European Union is expected to introduce Digital Product Passports (DPPs), with mandatory implementation set for 2026 to 2030 across all 27member states. As outlined in the provisional agreement under the Eco-design for Sustainable Products Regulation (ESPR) in December 2023, DPPs will initially focus on products with significant environmental impacts and high potential for improvement. The targeted categories include textiles, furniture, chemicals, batteries, consumer electronics, electronic devices, and construction materials. These measures aim to enhance transparency, sustainability, and circularity within these industries[77]. Similar to Digital Products Passports (DPP) currently being developed MP should provide standardisations and specifications to ensure interoperability, security and acceptance by all the stakeholders. Furthermore, MP can act as economic actors through circular value retention and optimisation, generate new job opportunities and businesses focused on reuse, repair, recertificate, remanufacture, repurpose and recycle.

In addition to the extensive, essential and useful guidance provided by the FCRBE project (2023), to increase reclaimed building elements and facilitate circular economy, we argue that MP are a key tool to enhance the reclamation of materials and facilitate material reuse, not only for existing buildings but also for new builds[78]. Some authors propose the creation of a basic material passport database for an existing building and a structured approach for new builds, aligned with the Uniclass classification system[20].

MP terminology is a digital record containing circular economy data relevant to monitoring the lifecycle of the physical material. 'The scope of a materials passport is focused on different hierarchy levels'[37]. According to Luscuere and Mulhall (2018) and referenced by BAMB (2017)[16] the MP can be seen as a part of building documentation with the following hierarchy levels: Material, Component, product, System and Building Passports. MP 'types' are equivalent to MP 'levels' in other frameworks[79]. We prefer to use 'types' instead of 'levels' because it enables us to identify a category with similar characteristics, but that can also be independent and not necessarily integrated into a level hierarchy. These proposed types are aligned with the Uniclass classification system and provide a systematic approach to categorising materials across different projects and specialisms[80].

Uniclass is voluntary standard classification system designed to help organise information throughout the construction processes and aims to facilitate interoperability between different systems. Developed by the Construction Project Information Committee (CPIC) in the UK, this is the most common classification system used in the UK, Italy, France, Australia, and increasingly globally (e.g. adopted by the Building Surveyor's Institute of Japan (BSIJ)). However, there are other similar classification systems used worldwide, e.g. OmniClass (North America), Cuneco (Denmark), CoClass (Swedish), ISO 81346-12:2028 (International Organization for standardization). The International Construction Information Society (ICIS) has made several efforts to advance the globalisation, standardisation, harmonisation and interoperability of construction information[81]. Unfortunately, there is no international consensus to use a common classification system yet[82], therefore, we decided to adopt the most common classification system in Europe. We believe that by adopting an existing standard classification system widely used facilitates the adoption of MP and interoperability between different databases.

The authors propose MP with the following types of MP: materials, products, systems, and (building) elements (Fig. 3).

The materials passports types are:

Material passports (MP) type fall under the Materials (Ma) category of Uniclass and are applicable to all of the individual materials and components that can be isolated and classified in a building. These can be nested under the other types of materials passports.

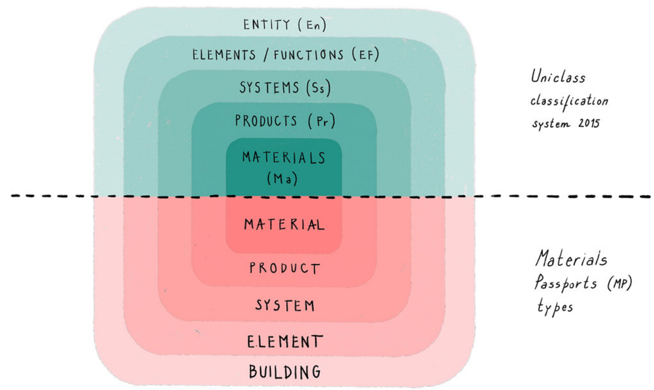

Fig. 3 | Proposed materials passports types, aligned with uniclass, illustration by Ana Rute Costa (Costa and Hoolahan, 2024).

Product passports (PP) types are aligned with Products (Pr) category of Uniclass. Product Passports can integrate multiple MP or be applied to individual products within a building.

System passports (SP) types are aligned with Systems (Ss) category of Uniclass. System Passports normally integrate a combination of MP and PP. SP can be assembled onsite or offsite.

Element passports (EP) types are aligned with Elements/Functions (EF) category of Uniclass. EP can integrate MP, PP and SP and are used for distinct elements with a specific function, e.g. building structure.

Building passport (BP) type is aligned with Entity (En) category of Uniclass and it will integrate all the MP, PP, SP and EP referenced above and have complementary data that refers to the whole building, e.g. Golden thread information, deconstruction plan, energy performance certificate.

The AEC industry is already widely using the Uniclass classification system for structuring specifications and data on BIM projects. By proposing an integrated materials passports classification system, we will be able to optimise the current practice and increase acceptance by all stakeholders.

In a circular and ideal scenario, the raw materials are first extracted and supplied to the manufacturer with a material passport. The manufacturer will then produce a set of components and a final product using the supplied materials. The product is then sent to the contractor for installation on-site with a product passport, linked to the original material passport. When different products are assembled on site or off site, systems and element passports are created. The contractor will then issue a full building passport to the client containing all the product and system passports for the building. The building passport should be retained throughout the building's whole life cycle until deconstruction, to record circular economy metrics and assess the value of re-use and recovery of the products and systems within the building.

Recommendation 6: produce a materials passports database according to the lifecycle of the building – existing, proposed and completed

Existing materials passports database: deconstruction of an existing building

By deconstructing a building and enabling the reuse of deconstructed materials on site or off site (ideally involving nearby sites and stakeholders) we can extend the lifecycle of those materials and reduce carbon expenditure. Currently, in the UK, we don't have any policy that makes this process mandatory. However, as we mentioned before, there are a series of case studies and examples, mainly led by clients and designers (architects and engineers) that consider the cradle-to-cradle principles[83] and deliver a deconstruction process[84].

For an existing building, we argue that a similar structure (materials, products, systems and elements passports) should be created. However, the amount of data collected needs to be aligned with the reuse potential and it would be considerably reduced when compared with a new build. When creating an existing MP, the key information to collect is dimensions, quantity and current condition. MP for an existing building are heavily contextual and affected by local conditions and material's lifecycle. The amount of data required is influenced by different factors, e.g. market needs, stakeholders involved, building regulations and certification standards.

Taking as an example the deconstruction of the Henri Sellier Buildings in Cenon, France, the deconstruction plan, created MP with basic information to enable reuse[85]. After, the MP database was shared with local stakeholders (e.g. architects, contractors, salvage companies, and manufacturers) and used as a digital interface to facilitate the material flows. In this case, MP were used as a system enabler to connect different stakeholders and facilitate a circular economy.

Once the material has been salvaged, the information in the materials passports can be updated. Further testing may be carried out to enable re-certification, demonstrate compliance with regulation and safety standards, or enable warranties to be procured. Materials passports should be seen as live documents that can be expanded or simplified according to the circular economy requirements.

Proposed materials passports database: designing a retrofit/new building

There is a time gap between the design and the construction phases, and this is one of the major challenges to enable material reuse. The reused materials available at design stage may not be available at the construction phase and we need to reduce the storage costs of salvaged materials[86]. To prioritise reuse, at the design stage, every project should include a proposed MP database and account for a certain level of specification flexibility. It is important to design for a loose fit and incorporate the specification of reused materials. The proposed MP database can be composed by MP for materials being reused on site, MP for materials being reused from other sites and MP for any new materials.

When materials are being reused on site, the existing MP database can be updated and integrated into a proposed MP database. Once the building is under construction, early procurement may be required to ensure that the design team has appropriate time to review and sign off sourced materials against the specification. At this stage, contractors may consult designers to validate reused materials selected.

Completed materials passports database: conclude a retrofit/new building

During construction, the contractor should take on responsibility for the completed MP database. Detailed information should be collected from sub-contractors and materials catalogued. Once the building is completed, the contractor should provide a completed MP database, with a comprehensive level of information. This information can be integrated into the Operation and Maintenance manual and inform the deconstruction plan. Once the building reaches the end-of-life stage, the completed MP can be used to plan the reuse/deconstruction process.

If we already have an as-built bill of materials, this data can be used to create the completed MP database, especially when we do not have an existing or proposed MP database produced during the design stages.

A collective effort from the industry, research and policy

It is recognised that many local authorities, clients, designers, retailers and manufacturers are already adopting and encouraging the implementation of MP and accelerating material reuse in construction. However, additional resources to support the implementation of the recommendations, and enable upskilling to support the adoption of MP is critical. We need a collective effort across the industry, including further research and policy, along with a systemic change to provide additional opportunities around MP and material reuse.

Recommendation 7: incorporate reused materials

While much has been done in academia and industry to advance current reuse practices in the construction sector, there are still some major challenges and barriers to be addressed[87,88], According to an Australian study[89], these are: lack of interest and demand from clients, lack of training, lack of legislation to support the reuse practices. According to Swedish clients[90], the three most significant barriers are: a lack of measurable economic incentives, the absence of a professional reuse market, and obsolete project management. The reuse of reclaimed building elements from an obsolete building at its end of life was deemed critical for circular construction and material's value retention[91]. Bellini et al.[91] propose a three-step process for reuse of building elements in a case study project that are aligned with the recommendations proposed above: 1. Collect Information, 2. Information-driven evaluation, 3. Plan for reuse. To accelerate material reuse in construction, clients and design teams need to explore and accept a degree of flexibility in both the aesthetic potential and performance of materials[92]. The incorporation of reused materials in construction needs to be a collective effort and every industry stakeholder has a key role to play on this circular construction process.

Recommendation 8: create a regulation that supports a cultural shift to address value the economic, social and environmental value of materials

This recommendation can facilitate the reuse of existing materials and reduce extraction of raw materials. The most sustainable materials are the ones that consider their environmental, economic and social impact[93]. We need a cultural shift among the AEC industry that values existing materials despite their low economic value when compared to new materials. Some studies suggest the economic valuation or monetisation of life cycle assessment (LCA) results as a weighting step that can make it easier for non-practitioners to use LCA results to support decision-making[94]. We recommend that future regulations need to consider the balance of economic, social and environmental value[95] of materials to support a circular economy and reduce the extraction of raw materials.

Final remarks

The following eight recommendations to adopt materials passports and accelerate material reuse in construction, are built upon current research, practices and knowledge. These recommendations identify the key barriers to material reuse in construction, and defines a route to increase the lifecycle of materials:

1. Prioritise the reuse of the whole building.
2. Complete a pre-redevelopment and a pre-demolition audit.
3. Prioritise deconstruction over demolition.
4. Prepare a deconstruction plan.
5. Provide a clear standardisation system that allows compatibility and interoperability between MP databases.
6. Produce MP database according to the life stage of the building: existing, proposed and completed.

   Furthermore, the industry, research and policy need to join forces and:

7. Incorporate reused materials
8. Create a regulation that supports a cultural shift to address the economic, social and environmental value of materials.

These recommendations enable a systematic approach throughout the life cycle of materials, preserve material's values, measure embodied carbon of materials, reduce waste and provide accurate circular economy metrics. The AEC Industry needs to collaborate and work collectively towards a more sustainable future, where we are frugal about the resources spent and we take decisions that will preserve our planet for future generations.

The proposed eight recommendations present a strategy to value materials already in use, adopt MP at different scales and as appropriate to the context. We argue that MP can adopt a standardised approach by using an existing standardised classification system, record the existing data available and ensure interoperability with future platforms and policy requirements. We don't need to have a full MP with all possible data; we just need to gather enough data (now) to avoid existing materials becoming waste.

Data availability

No datasets were generated or analysed during the current study.

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Author contributions

A.R.C. Data Collection, Analysis, Article Structure and Conceptualization. R.H. Data Collection and Analysis. A.R.C. Illustrated Figs. 1–3. All authours wrote and reviewed the manuscript.

Competing interests

The authors declare no competing interests.

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