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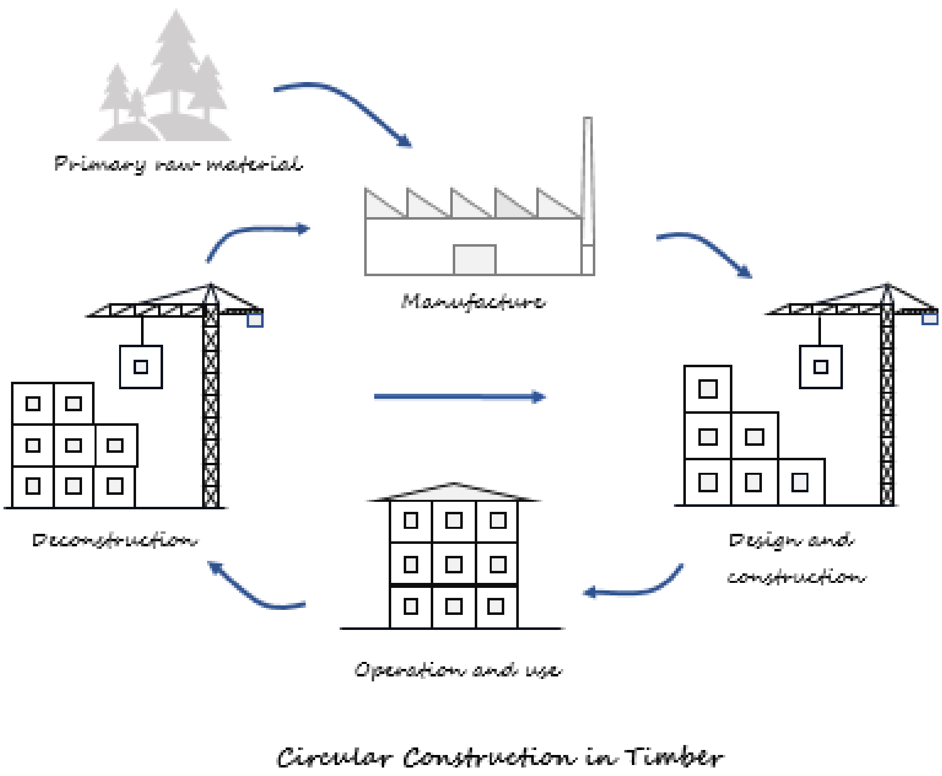

Innovative Design for the **Fut**ure – **U**se and **Re**use of **Wood** (**InFutUReWood**)

Deliverable Report *D3.4* of WP3

Report No.: NUIG-TERG-2022-03

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Traceability protocols for timber construction materials and products

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January 2022

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Foreword

This report is published under the InFutUReWood project - Innovative Design for the Future – Use and Reuse of Wood (Building) Components. Work Package 3.

The InfutUReWood project has seven work packages:

- WP 1 Coordination and management led by Karin Sandberg, RISE, Sweden
- WP 2 Design of timber structures for the future, led by Ylva Sandin, RISE, Sweden
- WP 3 Product design using recovered timber, led by Annette M. Harte, NUI Galway, Ireland
- WP 4 Inventory, deconstruction and quality of recovered wood, led by Mark Hughes, Aalto University, Finland
- WP 5 Properties of recovered wood, led by Daniel Ridley-Ellis, Edinburgh Napier University, UK
- WP 6 Environmental and economic assessment of design for recycling in building construction, led by Michael Risse, TUM, Germany
- WP 7 Dissemination and engagement, led by Carmen Cristescu, RISE, Sweden

ForestValue

Project InFutUReWood is supported under the umbrella of ERA-NET Cofund ForestValue by Vinnova – Sweden´s Innovation Agency, Formas, Swedish Energy Agencythe Forestry Commissioners for the UK, the Department of Agriculture, Food and the Marine for Ireland, the Ministry of the Environment for Finland, the Federal Ministry of Food and Agriculture through the Agency for Renewable Resources for Germany, the Ministry of Science, Innovation and Universities for Spain, the Ministry of Education, Science and Sport for Slovenia. ForestValue has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 773324.

The research and academia project partners are RISE (Sweden), Edinburgh Napier University (UK), National University of Ireland Galway (Ireland), University College Dublin (Ireland), Universidad Politécnica de Madrid, (Spain), University of Ljubljana (Slovenia), Aalto University Helsinki (Finland), and Technical University Munich (Germany).

The industry partners are Kiruna Municipality Technical Service, Swedish Wood, Derome, IsoTimber, Offsite Solutions Scotland, Hegarty Demolition, SIP Energy, Connaught Timber, The Federation of the Finnish Woodworking Industries, Jelovica, The Swedish Federation of Wood and Furniture Industry, Balcas Timber, Stora Enso, Klimark + Nova domus Hábitat, and Brenner Planungsgesellschaft.

Summary

The Innovative Design for the Future Use and Reuse of Wooden building components (InFutUReWood) project aims to examine if secondary wood (wood-salvage) is equally suited for contemporary architecture. This report outlines the aims to develop traceability protocols for construction materials and products to comply with the objectives of Task 3.4.

The lack of information on the recovered timber products hinders their reuse in new products or applications. In this report, practical methods of traceability over the extended lifecycle of timber structural products and systems are discussed. The ultimate goal is to provide reliable data on building products and components at all stages of the life cycle of a building to relevant stakeholders to inform decision-making from design through maintenance and finally end-of-life reuse possibilities. It is widely accepted that should be achieved via digital tools.

Material passports are digital datasets containing all the necessary information on products and components over the lifespan of the building, which can facilitate building management, remodelling and eventually reuse of the components at the end of life. There is currently a lack of standardisation of material passports with a large variation in the structure and data stored. For timber structural products and building components, material information that should be included in a material passport is presented. This includes as-built properties together with information on any deterioration or damage, interventions or treatments and change of use or remodelling during the use phase of the building. The material passports may be generated and stored in a database, such as a materials passport platform, or in a building information model.

Building information modelling (BIM) is a system used in the AEC industry to digitally document and manage information throughout a building project. It is a virtual spatial database that may be updated by the building stakeholders over time. A 3-dimensional model is made in tandem with the building design, and it is amended to reflect the constructed works. The main purpose of the model is to document and communicate all the information of the project. A BIM model could potentially contain all available information about each component of a building. BIM objects contain information about their geometry, their location within the building space, their relation to other objects and a number of different other attributes that describe the object. Information contained in, or needed by, a material passport could also be part of this set of information. BIM objects could potentially include all the material data or, alternatively, they could link to a materials passport platform.

Security and accuracy of the stored data is of paramount importance. As the information stored is updated over the building lifecycle, the data must be accessible without compromising on security. The leading technology in regulating multi-accessible databases is Blockchain. The multi-platform structure of this electronic ledger technology allows a simultaneous view and review of the data input. Its cryptographic data and connection signature, along with the proof-of-work security, safeguards against fraudulent information. Blockchain technology is therefore considered to be an appropriate way to chronicle the lifecycle of building materials from cradle, product provenance, manufacture, use, reuse, and ultimately disposal.

As the pertinent data on the material properties will in the future be stored digitally, a system to permanently connect the digital data with the building component is needed. There are two main emerging technologies to facilitate this link. They are QR coding and RFID-EID tagging. The RFID-EID tagging and scanning equipment are currently more expensive than the QR code method, however the process allows for a more accurate data reading of material inventory in a way that is in accordance

with prevailing AEC work practices. A software connection from tracking to database is necessary with both systems.

Challenges associated with the implementation and use of the traceability system described are presented. One of the key issues is the requirement to share building information across multiple platforms and timeframes. As with any digital repository, changes in technology and systems over time can lead to issues of lack of compatibility. To ensure long-term robustness of building material data over time, the development of platform independent data storage solutions for building information will play a key role. In the context of building information, storing and reading data in these databases will be possible from a variety of hardware platforms and software architectures. Development of these solutions are still at an early stage of development. The other main challenge is the need for training of AEC professionals in the effective use of advanced BIM solutions.

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1. Introduction

1.1. Background

This report is part of the InFutUReWood - Innovative Design for the Future – Use and Reuse of Wood (Building) Components – project which aims to answer two main questions:

- How easy is it to reuse timber from the current building stock, especially as a structural material?
- How can a review of current building practices help in future timber reuse?

To address these questions the project identifies key opportunities and challenges, proposing technical solutions that aim to exploit the opportunities and reduce the challenges identified that may lessen the cascading use (CU) potential of building timber.

Work Package (WP) 3 *Product design using recovered timber* is divided into four tasks, T3.1, 3.2, 3.3, and 3.4. The first task (T3.1) focuses on the specification requirements for timber products and identifies the current range of timber material that is potentially available from demolition. The second task (T3.2) examines the recycling potential of wood in engineered-timber manufacture generally. The third task (T3.3) examines how to improve the design of new products to optimise their deconstruction to optimise the reuse potential of the timber. The fourth task (T3.4) investigates traceability protocols of wood products.

This report is the result of the work carried out within Task 3.4 *Develop traceability protocols for materials and products.*

1.2. Aims and Objectives

The aim of this task is to address the lack of information available for used timber regarding its species, origin, grade, and chemical or heat treatment. The study aims to explore optimum approaches to the recovery of building timber and structural timber products such that key information, that is pertinent to its reuse viability, is available over its extended lifespan.

The main objective of the study is to improve the traceability of building timber and engineered timber products so that designers can have confidence in the origin and work history of reclaimed wooden materials from demolition.

1.3. Scope of the work

This study aims to define the information that is most valuable to promoting the reuse of timber-based building materials. Its aim is to explore key concerns with respect to tracing, cataloguing, and linking the information in a reliable way to facilitate the prolonged use of timber-based products in the construction sector.

1.4. Target group

Primarily, this report is targeted towards the research team of the InFutUReWood project. The findings are aimed at architects, engineers, manufacturers, and national code and regulation authorities, to highlight building procedures that may improve the cascading potential of timber from construction and demolition.

1.5. Short glossary of terms

The most used terms in the report are defined as follows:

Assembly design is used here to refer to the assembly method used at timber product manufacturing and on site.

CE is used here to refer to the circular economy.

CE marking is used here to refer to the EU quality identification, Conformité Européenne marking.

CU is used here to refer to Cascading Use.

Design for Adaptability is used here to refer to the consideration of mixed use and refurbishments of a building at the initial design stage.

DfD is used here to refer to Design for Disassembly.

EID is used here to refer to electronic identification.

EPD is used here to refer to an Environmental Product Declaration.

LCA is used here to refer to a Life Cycle Assessment.

Modular is used here to refer to prefabricated building 3-D units, i.e., comprising rooms rather than individual planar wall and floor elements.

Planar element is used here to refer to 2-dimensional planar prefabricated roof, wall, or floor elements.

Protocol is used here to refer to a set of procedures or steps to be followed for the accomplishment of a given task.

Recycling is any recovery operation by which waste materials are reprocessed into products, materials, or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations. [EC (2008)].

Reuse is any operation by which products or components that are not waste are used again for the same purpose for which they were conceived, with minimal pre-processing, i.e., checking, cleaning, and repairing. (Adapted from EC (2008)).

QR Codes is used here to refer to Quick Response Codes

RFID is used here to refer to radio frequency identification.

2. Circular Economy (CE)

The term circular economy (CE) refers to closing the arc of material flow in manufacturing and production to maximize the use of available resources [Mair & Stern (2017)]. The concept of circular design refers to reusing resources that under current design practices, would be destined for disposal, thereby reducing the current drain on natural resources. A circular building is said to be built and used without impacting negatively on the biosphere [URGE APN (n.d.)]. There are several idioms, labels, or terms used to describe the concept of a circular building design strategy. The two main terms used regarding CE in the built environment at present are Design for Disassembly and Cascading Use.

2.1. Design for Disassembly (DfD)

Design for Disassembly (DfD) is an emerging concept in architecture on how to address the current high material consumption and low recycling practices in the construction sector [Kanters (2018)][Akinade *et al*. (2017)]. The building industry is the world's largest consumer of raw materials [Copeland & Bilec (2020), Mastrucci *et al.* (2017), WEF (2016)]. Its role, therefore, in future sustainable development will be significant.

The concept of DfD refers to a design approach to building assembly that allows for the disconnection of component parts without incurring significant damage. The building elements and constituent materials are thus available for reuse. The premise acknowledges that for a variety of reasons most architecture has a finite lifespan, but that each building comprises a significant store of raw material. Currently much of this valuable resource is destined for landfill or for energy generation. The aim of DfD is to recirculate building stock to maximise its potential before its ultimate disposal. By doing this, the depletion of natural resources and the environmental impact of material extraction, product manufacture, and disposal are reduced.

The intention and commitment to DfD must be established at an early planning phase. Here are some key principles that should be followed:

- Firstly, a comprehensive assembly and disassembly plan is essential to DfD.
- Secondly, the selection of materials is paramount to maintaining the value of the building elements. Suitable materials are robust enough to endure prolonged use and their repeated assembly and disassembly. A Life Cycle Assessment (LCA) of constituent parts may be appropriate. The building elements must be of a size and composition that will weather intermittent transport and storage. They should be non-toxic to ensure compliance with future product standards and to facilitate their ultimate safe disposal.
- Thirdly, the type of connections and their position is fundamental to the successful implementation of a disassembly schedule. It is currently agreed that adhesive bonding is appropriate for the manufacture of large elements that are assumed to be reused whole, such as Cross Laminated Timber (CLT) and glue laminated timber (glulam). However, the general rule in connecting components for disassembly is to use mechanical joints. The use of removable bolts, screws, or nails are preferable to bonding, sealants, or welding. The connection location should be marked clearly on the disassembly schedule and on-site at the appropriate phase of deconstruction and the durability of products at connection locations is critical. The fewer connections to be disconnected the greater efficiency of deconstruction.
- Finally, the tracking of the building components is a significant consideration to DfD.

The application of DfD is not completely straightforward. The lack of standards regarding the material properties of pre-used elements presents a significant challenge to designers in specifying recycled stock. This is especially the case with structural elements. Also, demolition for disposal is assumed to be more time and cost efficient to dismantlement, transport, and storage of building components. However, case studies in the US by the Environmental Protection Agency [EPA (2009)] found that where there was a sufficient store of valuable material-salvage, the increased labour cost was justified. Deconstructed materials are currently separated by the demolition contractors and waste management companies but building material standards limit their scope for reuse, especially in a structural capacity [Niu *et al.*(2021), Szichta *et al.* (2022)].

The potential to return products to the manufacturer is an option being considered in the context of DfD. ABN AMRO and Circle Economy speculate that maintaining the ownership of a product with the manufacturer may be a good way to extend its lifespan [Kubbinga *et al.* (2017)]. In this case, the manufacturer's stake in the material extends from cradle-to-grave. Therefore, its value to the manufacturer continues after its first use. In this scenario, the product disposal remains the responsibility of the producer, so there is a cost incentive also to use recyclable materials. It is suggested by ABN AMRO [Kubbinga *et al.* (2017)] that the traditional roles in the construction industry must overlap to facilitate CE. The demolition contractor, for example, would act as supplier. Figure 1 illustrates their concept graphically.

A common approach to applying DfD is to consider modular design. With modular construction, the sequencing of the building assembly is established at a very early stage in the design process. The assembly schedule is documented, and the transport and storage of the modules is considered at the pre-construction stage. The number of connections is generally optimised to improve assembly time, and the provenance and manufacturing history of the materials used can be tracked from the manufacturing facility to site.

Designing for adaptability enables multiple generational occupancy for varied uses. The adaptability of a structure is improved using DfD as there is better potential for renovation and thus adaptability. Where the disassembly and replacement of the components is factored into the design, so too is its scope for refurbishment. Where the efficient disassembly of component elements is considered, minimal damage to the main building fabric and disruption to the occupiers can be achieved. The potential for simple refurbishment can greatly incentivise extending the building's lifespan. This facilitates a prolonged use of the building in-situ, which is considered the most sustainable type of development. The inherent energy and manpower cost of deconstruction, transport, and reconstruction or disposal is omitted where the building remains substantially intact.

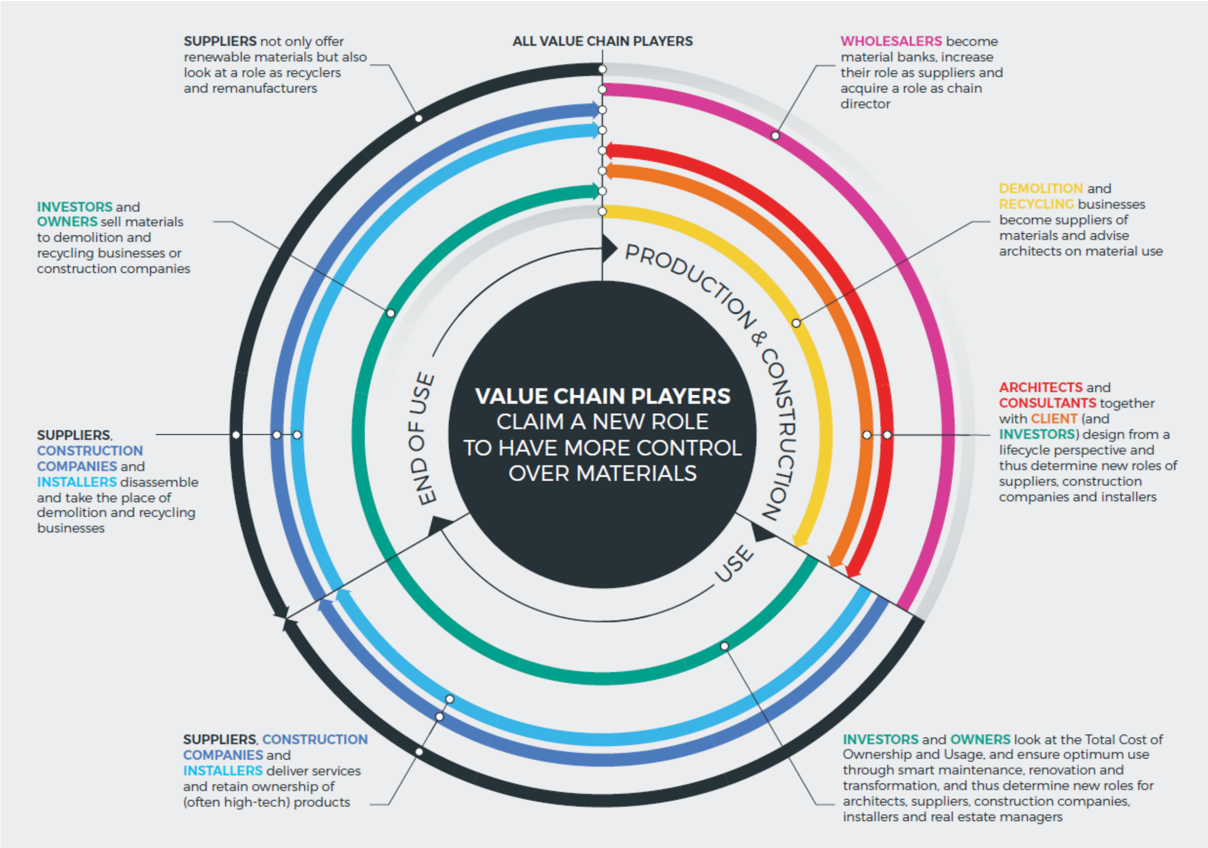

Figure 1*: Value chain members in construction circle* [*Kubbinga* et al. *(2017)*]

2.2. Cascading Use (CU)

A concept which extends from DfD is that of cascading use (CU). The term refers to the repeated use of bio-based materials before their ultimate end-of-life. The definition provided for CU by the European Commission is "*the efficient utilisation of resources by using residues and recycled materials for material use to extend total biomass availability within a given system*" [Vis *et al.* (2016)]. In the case of timber, it is processed into a product which is reused at least once for material or energy purposes before ultimate disposal [Vis *et al.* (2016)]. It has been found that replacing construction materials with timber could reduce carbon dioxide and fossil fuel consumption worldwide by up to 31% and 19%, respectively [Oliver *et al.* (2014)]. To facilitate multiple CU of a building product, a material hierarchy is applied with respect to size and processing. Elements are kept as close to the original or preceding product form as is practical for the subsequent applications thereby extending the number of times a material can be used before it is reduced to energy or landfill biomass.

To achieve circularity of a building, a buy-in from key stakeholders with respect to DfD and CU at the design stage is required [Pomponi & Moncaster (2017), URGE APN (n.d.)]. However, the tracing and management of data on material resources requires appropriate technological solutions with respect to supply and demand necessary over time for CE of the building and CU of the materials [Oliver *et al.* (2014)].

3. Traceability

The term traceability in building can refer to processes, systems, or materials. In the case of materials, the term generally refers to tracing data on the sourcing, processing, and manufacturing of products and their component elements as the products move along their supply chain from raw goods to use. The information recorded may include suppliers, purchasing practices, and material provenance. A more succinct definition is provided by the International Organization for Standardization (ISO) as the *"ability to trace the history, application, or location of an object"* [ISO (2015)]. The concept is straightforward, however the logistics of recording and storing pertinent information for the lifespan of a building material is more complex. This becomes more difficult when multiple reuses of a material are also proposed.

Katenbayeva *et al.* (2016) suggest that a theoretical framework of traceability for sustainability in the Architecture, Engineering, and Construction (AEC) sector should be developed. However, the focus in research on traceability in AEC is still only emerging [Katenbayeva *et al.* (2016), Pomponi *et al.* (2017)]. There is no universal agreement on which information is most significant nor is it clear, even in International Management Standards [Mair & Stern (2017)], at what stages traceability should commence and conclude. This absence of clear guidance is regarded as a key factor in low-value engagement in sustainability by key AEC sector stakeholders until a traceability protocol is defined [Akinade *et al.* (2017)].

Fabbri *et al.*'s (2016) analysis of the energy use in the European residential building stock explored the use of a logbook to the track energy efficiency and any retrofitting of buildings. It included case studies from Germany, Flanders, and France. It was proposed that a logbook be populated by trained auditors, or the building occupants, and linked to a web-platform along with the relevant files. It was suggested that the web-platform be private, with anonymised data made available on a public link. The expected lifespan of the logbook was in the range of 20 years. It was noted that the current method to record a buildings performance in Germany of using *'Energy Performance Certificates'* (EPC) is generally considered an administrative obligation. It was postulated that the EPCs, with accompanying very detailed auditor reports, are usually unread. Therefore, a more manageable tool, not necessarily a logbook, is recommended for future energy performance tracking.

A logbook, albeit stored on a web-platform, that is filled intermittently over 20 years by various parties may be sufficient to track the energy performance of a building. The tracing of the source, use, treatment, and location of timber elements at different stages of CU over a prolonged timeframe may require a more complex solution that is securely linked to each element.

3.1. Building Information Model (BIM)

Building information modelling is a system used in the AEC industry to digitally document and manage information throughout a building project. It is a virtual spatial database that may be updated by the building stakeholders over time. A 3-dimensional model is made in tandem with the building design, and it is amended to reflect the constructed works. The main purpose of the model is to document and communicate all the information of the project. It comprises the following main features:

- BIM is a method to coordinate and share information. All the data produced over the lifecycle of a building, from the draft feasibility stage, through detailed design, building construction, use, and demolition, are stored to facilitate efficient information retrieval. The drawings, schedules, and manuals that are required to issue instruction on construction, operation, performance, and maintenance can be generated from the BIM instead of preparing the documentation separately for each purpose.

- The data is stored and labelled in a conventional and consistent way. Therefore, all contributors to the model must follow a similar procedure which enables straightforward coordination of the varied information.
- The creation of a BIM is a multi-disciplinary collaborative process. The model is updated by many stakeholders at the various stages of development and the data is integrated and repeatedly updated. Therefore, any spatial clashes between building systems, an overlap of the ventilation system with structure for example, can be resolved at the virtual stage. Thus, waste and delays on site are reduced.
- A BIM provides a shared dynamic record of the location and the attributes of every component.
- The model will automatically update the revision to a base element for all the copied elements throughout the building, a window type for example.
- Building performance indicators and analytical models can be produced from the model. Therefore, the implications of a design choice can be provisionally assessed and amended as necessary.
- The constituent elements and materials of the building may be tracked from procurement to disposal.

The concept of creating a computer-generated spatial model in tandem with actual design and development was taken from the car manufacture and aviation industry. In these industries the machines are built, assembled, and tested virtually often before any actual prototype is made. Therefore, material waste is reduced. Product and manufacturing in these industries are sourced internationally. The use of virtual modelling allows for continued progress in research and development without relying on the timely manufacturing or delivery from around the globe.

The creation of BIM is a follow-on from electronic 2-dimensional drawings (AutoCAD, etc.). It is a logical progression in the capacity of computer added design to store all the related data with the digital building drawings and then to develop 3-dimensional models. Thus, the sharing of the electronic data simultaneously with all the building stakeholders becomes possible. Figure 2 shows the progress in BIM advancements over time.

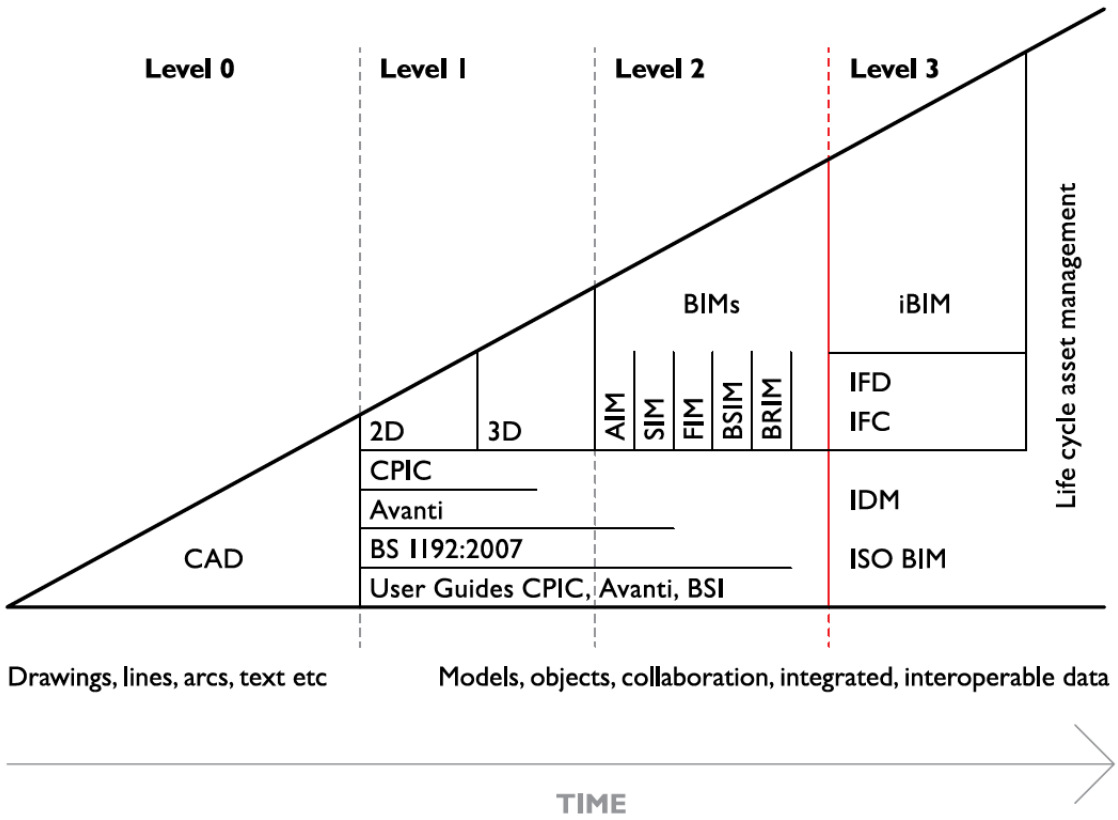

Figure 2: *BIM maturity model* [Gelder *et al.* (2013)]

Where a BIM is done well, with all information and variations recorded, a virtual blueprint of the whole structure is available, thus, providing a record of the materials, products, and their performance. Timely maintenance can be scheduled based on material LCAs that are input to the model and material performance indicators can be tracked for analysis and review.

However, there are three main caveats to bear in mind when endorsing BIM in the context of material traceability protocols. They are:

1. The reliability of the information obtained from a BIM is determined completely by the detail and accuracy of the model created and whether it is updated to reflect on-site amendments to the design, renovations, and maintenance.
2. The availability of the data stored on a BIM relies on the continued availability of the software used to build the model and its compatibility with future technology.
3. The trustworthiness of the BIM depends on the secure management of the files.

However, BIM is a significant tool that is evermore integrated into in the AEC industry [ARUP (2016)]. The UK government is mandating that data at key stages during construction are submitted to the '*Construction Building Information Exchange'* (COBie) [Corps of Engineers USA (2015)]. The objective of this is to support ownership and operations after building handover. This data may be submitted in simple electronic datasheets, but it has been widely observed that the availability of an accurate BIM will make the administration of this process simple and efficient to all concerned [Gelder *et al.* (2013)]. Strategies to implement DfD and CU also now include the application of BIM technology.

However, regardless of how documentation is stored, confidence in the verification of certification of a building, including its design, products, and materials, is based on the reliable accreditation of the certifier. Distributed Ledger Technology (DLT) is emerging as the most trusted method to permanently log accreditation and documentation in the digital world; DLT is outlined in the following section.

3.2. Distributed Ledger Technology (DLT)

An important consideration in reliable traceability is the principle of unique identification. The leading technology universally endorsed to provide stable and secure identification in the virtual space is *'distributed ledger technology'* (DLT). DLT comprises regulated databases of replicated updated records which are simultaneously stored in multiple locations. Figure 3 provides a visual overview of the attributes of DLT. The most secure branch of DLT is blockchain which is the basis of the cryptocurrency, Bitcoin.

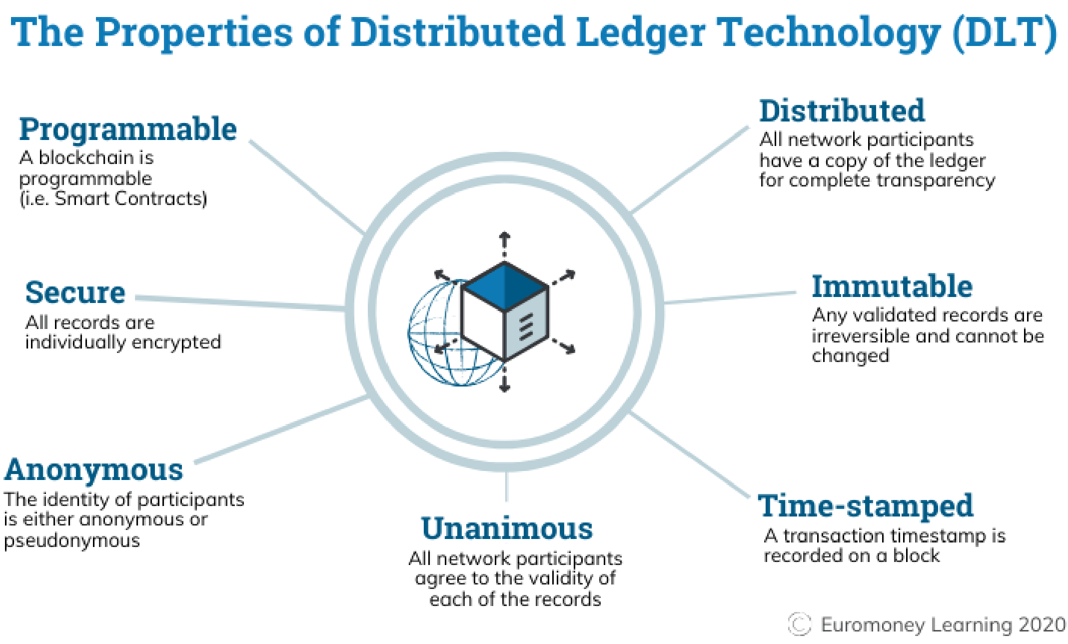

Figure 3: *The attributes of DLT [Euromoney Learning (2022)]*

3.2.1. Blockchain

Blockchain is a virtual ledger of transactions with the digital proof duplicated and distributed over the network of contributors [Komdeur & Ingenbleek (2021)]. The digital record is simultaneously updated with each new transaction in all copies. The key components of blockchain DLT are:

- Blocks: Each new transaction is represented by a block of data. Every block is identified by a unique cryptographic number and the connection between each two blocks is identified by a unique cryptic signature. The blocks are connected in series. There is an initial genesis block and then each subsequent block contains an identifier of the previous block.

- Hash: The hash is a security safeguard that uniquely identifies each block. The hash of each new block starts with the hash of the preceding block. Therefore, if any block along the chain is changed, the hash also changes and all subsequent blocks on the chain are corrupted and thus, invalidated.
- Proof-of-work: The proof-of-work is an intrinsic defence against simultaneously changing the hash identifiers of all blocks to cover-up the corruption of one or more. It is a mechanism written in to delay the creation of each new block. The proof-of-work for Bitcoin, for example, is approximately 10 minutes.
- P2P Network: Another security safeguard with blockchain is that rather than managing the chain from a central location, it is managed on a peer-to-peer (P2P) network. All members, referred to as nodes, on the network are provided with a copy of the blockchain. When a new block is proposed for addition to the chain, it is distributed to all nodes for verification. Usually, only if there is consensus on the validity of the block by more than 51% the nodes, is it added to all the duplicates.

A Building Research Establishment (BRE) Report [Cooper & Ghumra (2018)] observed that blockchain technology could combine certification and verification of elements with regard to physical and chemical characteristics. Komdeur and Ingenbleek's (2021) study of the potential for blockchain technology in the procurement of sustainable timber products found that the application of blockchain technology can improve trust in the timber product particularly when combined with certification along the chain.

3.3. Dynamic Digital-to-Physical link

It is now the conventional view in most industries that information should be stored electronically in such a way that the relevant data can be easily accessed by many but updated by the authorised few. The challenge to find ways to secure this data is the focus of the most influential bodies globally and is a well-resourced and multifaceted field of study. BIM and DLT are emerging as the leaders in technology to store data from the AEC industry [Alsafouri & Ayer (2018), Cooper & Ghumra (2108), Corps of Engineers USA (2013), Czmoch & Pękala (2014). Gelder *et al.* (2013), Katenbayeva *et al.* (2016)]. The main challenge to developing a traceability protocol for use with CU materials is to permanently link this virtual dynamic file to the actual materials which are intended for reuse in different applications and in potentially different physical forms. The following sections outline some methods that are currently employed in the AEC industry and elsewhere that may be applicable or adapted to track and trace AEC timber over CU into the future.

3.3.1. Environmental Product Declaration (EPD)

An *'Environmental Product Declaration'* (EPD) is an internationally verified document which is registered in the framework of a programme based on ISO 14025 [ISO (2006)]. The basis of an EPD is an LCA that evaluates the products environmental performance over its whole life cycle, from material extraction, manufacturing, use, and disposal. The EPD documents are registered and stored in the EPD library [EPD Portal, nd] where they are freely available to download.

An EPD consists of two parts:

1. A background report giving a detailed account of an LCA by a third-party verifier. The report is not publicly available.
2. The publicly accessible EPD document that outlines the LCA results.

The registration of a product EPD is voluntary on the part of the manufacturer or supplier and does not imply any grade of environmental standard. It serves only to give a comparable and transparent review of its credentials.

3.3.2. CE Marking

Any product that is marketed in the European Union (EU) requires the attachment of a '*Conformité Européenne marking (CE marking')'* [Your Europe, n.d.]. This quality marking system is fixed to the product. A CE marking represents a declaration of conformity with the safety, health, and environmental standards set out by the EU. It is mandatory since 1985, but the obligation to affix a CE marking only applies where there is a relevant EU specification. It is unlawful to include a marking without the existence of an appropriate standard. However, in some cases, several standards are applicable. The product must comply with all the applicable standards before affixing the CE marking. The assessment of the product and declaration of conformity with the relevant standards is the responsibility of the product manufacturer. The attachment of a CE marking to a product requires:

- Technical documentation outlining the product's compliance with the applicable EU standards, and
- A signed EU declaration of conformity.

A specific licence is not required to attach a CE marking, but it may be the case that the product must be tested independently by a notified body to validate its accord with the required criteria. The requirement of a notified body to validate conformity is in some instances outlined in the relevant EU specification. The identification of the notified body must accompany the CE marking where an independent assessment was made.

There are also criteria outlining the legibility and permanence of the actual marking. In addition to guidelines and templates on size and script of the lettering, it is mandated that the marking is:

- Visible,
- Legible, and
- Indelible.

A CE marking may be fixed to accompanying documentation or packaging, where it is not feasible to attach the marking to the product itself. Figure 4 shows a sample CE mark.

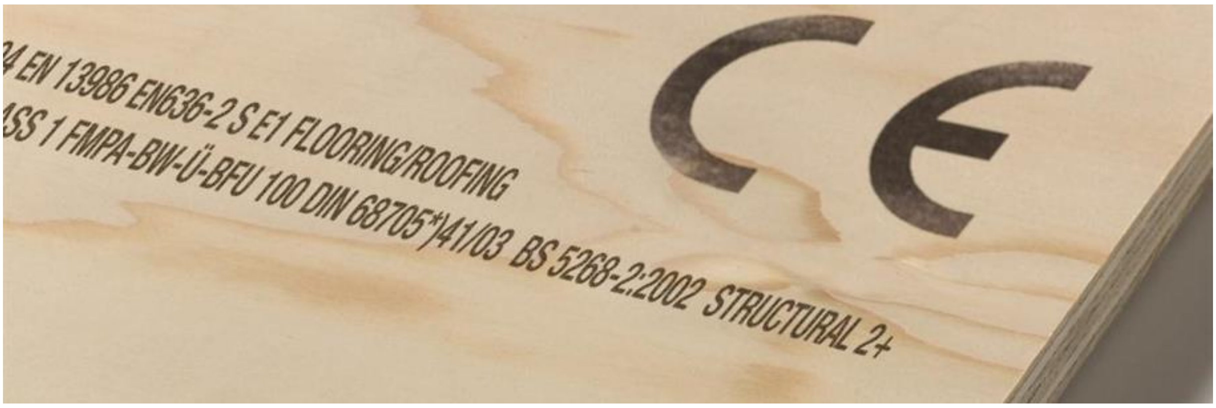

Figure 4: *CE Mark example* [*MetsäWood (2022)*]

While this system has served to link quality criteria to a very wide range of products for over 35 years, there are some obvious limitations to its continued viability in the context of timber CU. They are:

- Firstly, the CE marking may be cut away. This is very possible, in the case of in-situ carpentry for example, even before its first use and continues to be a possibility with every cascading application of a structural timber member.
- Secondly, the marking may be covered or coated, or planed off at any stage of the materials life cycle.
- Thirdly, it is a once only physical marking. It is not updated to reflect any revisions to standards or product criteria.
- Finally, any link between the manufacturer or independent certifier is likely to be lost before the end of the first use of a cascading lifespan.

Where a material was certified for use in one application, as was the case in the past, these limitations to the CE marking system were not especially significant. However, where an extended lifecycle is proposed in the context of material circularity, a more robust and versatile identification of the product, its provenance, history, and certification are required going forward.

Convenience and accessibility is a key requirement when developing any data tracking system for universal use [Fabbri *et al.* (2016)]. The more accessible and inclusive the technology, the more it is applied.

3.3.3. Quick Response (QR) Codes

Quick Response (QR) Codes are a 2-dimensional update of the traditional 1-dimensional barcode which have been used for generations to track key information on a variety of consumer products. Like the traditional barcode, they are generally printed onto documents and packaging. Each QR code is unique. Both the conventional barcode and QR code are quick to scan, but the advantage to using a QR code is that it can be scanned by an everyday smartphone or other mobile devices with an integrated imaging device, so simply assessable to most. Also, the QR code has a larger storage capacity. The main disadvantage to using this simple 2-dimensional method is:

- The marking profile is most suited to application onto clean and clear surfaces (or digital devices). While it may be printed on packaging, it is not currently designed for application directly onto an uneven material such as sawn timber, although laser cutting of QR codes into smooth timber surfaces is relatively commonplace.

The use of this code scanning method may be applicable for use in tandem with specific label types that are durable and smooth [Vasilyev *et al.* (2020)]. However, a key disadvantage that pertains to CE marking still applies:

- It is very possible that the physical marking will be lost due to trimming, coating, adhesion, or weathering over time.

Figure 5 shows the use of a QR code on site.

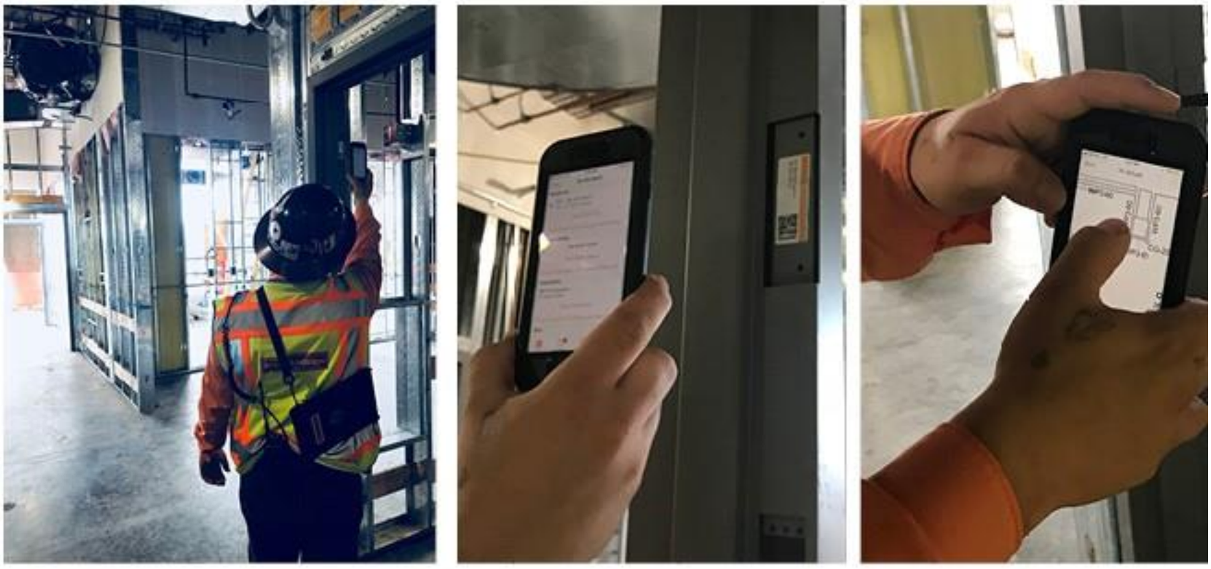

Figure 5: *QR code in use in construction* [Morton (2022)]

3.3.4. Electronic Identification (EID)

The use of *'electronic identification'* (EI, or EID) tagging is widely employed over a multilateral range of industries and the possibility of combining this technology with Blockchain is considered viable [Lanko *et al.* (2018)]. The most common current use of this tracking technology is in the context of traceability of livestock (EID tags). It has been widely adopted in place of conventional visual ear-tags that are marked and recorded manually. The use of EID tagging is now mandatory for specific livestock by government authorities [Forde (2021)]. The technology involves the use of a microchip that is embedded in a durable tag which is fixed to the animal. It is used to identify the animal. The technology is based on low-frequency radio waves, termed *'radio frequency identification'* (RFID) which are emitted from a transponder or scanner. The waves are picked up by the microchip in the tag prompting the issue of a unique identification number. This number is feed to a database where each file is stored and updated. The tags can be scanned at a distance and both the tags and tag-readers are totally water and dust proof. There are different types of scanners used depending on the application. Two that comply with ISO standards are FDX and HDX transponders, full- and half-duplex transponders, respectively. The HDX transponders can scan the tag at greater distance.

The procedure of tagging livestock is obligatory in the regulation of some agriculture [34]. Here are some reasons given for their use:

- Applying this system has been found to improve the speed, accuracy, and reliability of the data collection.
- Mismatched tracing and administration errors were found to be reduced using this system.
- It was found to reduce the administration burden of tracking stock.
- The automated reporting of product movement is facilitated by this technology.
- This system was deemed efficient and safe to employ.
- The EID system allows for up to daily monitoring of animal welfare and medical treatment.

Many of the benefits to the agricultural trade are also applicable to the AEC industry. The change and movement of product over time and place, is comparable with the proposed CU of AEC material, albeit over an extended timeframe. The benefits to adapting this technology to timber product tracing are:

- The technology is widely established and commonly used in the challenging outdoor working environment that is similar to that of the construction industry.
- The data can be accessed without direct or very near proximity to the tag. Thus, materials can be scanned in-situ or already loaded for storage or transport. This allows for speedy accumulation of product inventory in a way that is appropriate to current health and safety procedures.
- The information is transferred and stored electronically in a way that it can be accessed and updated repeatedly.

The tags can be manufactured for single use or for reuse. The reliability of the correct association of the data with the product is better achieved where a non-reusable tag is used.

This technology overcomes the challenges identified with using the CE marking system and has been found to be more time efficient to QR code scanning [Chin *et al.* (2017)]. However, the cost for individual timber sections could be prohibitive [Lin *et al.* (2014), Valero *et al.* (2015)]. The cost may be justified however, for manufactured elements, such as composite wall-panels, CLT panels, glulam beams and columns, windows, and doors.

4. Building Material Passports

The importance of information sharing and collaboration is now accepted as being key to implementing circular construction in practice [Wijewickrama *et al.* (2021)]. Tracking construction products along their life cycle from cradle to cradle is necessary to ensure optimum reuse and recycling. This, however, is not straightforward due to the fact that different stakeholders are involved in the different stages of the lifecycle and no one stakeholder is engaged over the whole life cycle. Figure 6 illustrates the broad range of circular economy practices along the building lifecycle. Communication links between different stakeholders is complicated by the fact that they often use different information and digital tools. While information tracking in from project design, manufacture and construction phases are readily available up to the time of construction, this information is often lost and is not available at the end-of-life stage. Also, the operation and end-of-life stages are not currently well linked with the earlier stages. Closing the loop between end-of-life and product design or manufacturing has not yet been properly considered [Ali, 2019].

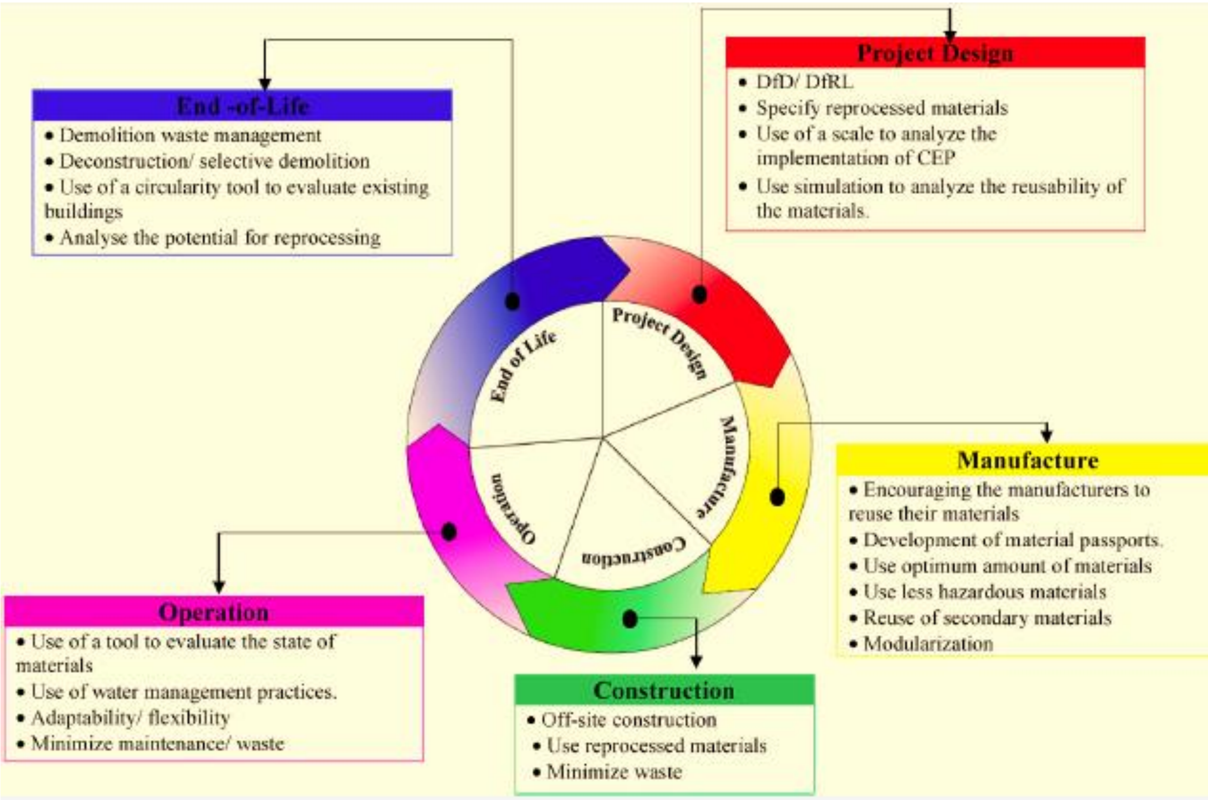

Figure 6: *Circular economy practices across building life cycles[Wijewickrama et al. (2021)].*

4.1. Material Passports

The development of building material passports, which track the characteristics of materials, products or building components over their lifespan, has been the focus of much research in recent years [Atta *et al.* (2021), Mulhall *et al.* (2018), Munaro and Tavares (2021)]. Material passports provide stakeholders with product information from source to manufacture to assembly in a building, during the building lifespan and reuse at the end of life. In the EU-funded Buildings as Material Banks (BAMB) project [EPEA and Sundahus (2017)], which considered circularity within the construction sector, material passports were defined as '*sets of data describing defined characteristics of materials in products that give them value for recovery and reuse'*.

Use of building passports increases the potential to reuse or recycle the building products or components. As part of the BAMB project, an overview of the value propositions associated with material passports was presented. These include supporting:

- the transition from waste management costs to materials recovery revenue
- management efficiencies through identification of location, quantity, type and reuse potential building products and components
- the provision of instructions on safe deconstruction of the building to maximise product recovery levels
- more accurate estimation of residual value of building components
- the provision of a basis for calculating carbon savings from using recycled materials and carbon trading credits that may apply to a building.

4.2. Material Passports for Timber Buildings

Within this report, the building products and components considered relate to the structural timber products and built-up components that include structural timber products. The material passport for a specific product, such as a CLT panel, can also be part of the material passport for a composite multi-layer wall or floor component. The material passport provides a means of storing product information so that this material remains with the component during first and subsequent uses thereby facilitating safe design of new structures or design for change of use of existing buildings using these components.

As the information stored in the material passport will be required for the reuse of the product or components, it must include not only information the as-built properties but also the history of use during the building life. It is essential that a record is available of any damage to the building elements over their service life is recorded together with any remedial interventions in order to be able to evaluate the reuse potential.

The information required for the design of new timber structures today is likely to remain largely unchanged in future design for reuse. This information includes:

- Physical Properties
- Mechanical Properties
- Acoustic Properties
- Fire Properties
- Environmental Properties

The data for the product or component can be stored directly in the material passport or accessed via links to other documents, such as Technical Approvals, Environmental Product Declarations (EPD), and Deconstruction Plans. Some current materials link to data provided on suppliers' websites; this may not be a reliable source of data over the life of a building as product lines may change or the company may no longer be in business. It is recommended, therefore, that the relevant data at the time of construction be downloaded and stored with the material passport.

By way of illustration, a sample record of properties for timber structural elements, such as solid timber or engineered wood products, is shown in Table 1. The reference number for the element provides information on the location within the building. It links with a BIM model and/or an identifier on the physical object, such as an EID tag. Basic dimensions and mass are important for estimating reuse quantities and to facilitate deconstruction. Information on the use of preservatives, fire retardants or other chemical treatments is essential to determine compliance with environmental regulations at the time of reuse. A structural timber element, such as a CLT panel, provides not only mechanical resistance but also may contribute to the acoustic, thermal and fire performance. Where appropriate the relevant properties must be available for design for reuse. As material standards change over time, it is also important to record the standard used to measure or calculate the relevant property. To facilitate deconstruction of the element, information on how the element is connected to the rest of the structure should also be provided, where relevant.

Table 1: *Sample of information contained within proposed material passport for structural timber element including history of use and repair*

Structural Timber Element		Reference #
AS-BUILT PROPERTIES (Date: 28 Jan 2022)		
General Properties		
Type	e.g. external wall, floor, roof	
Product type	e.g Solid timber, GLT, CLT, LVL	
Key dimensions	e.g. 6 m x 5 m x 0.1 m	
Lay-up	e.g. for CLT : 40-20-40 mm	
Mass	e.g. 600 kg	
Location of lifting points	Shown on dwg #	
Manufacturer:	e.g. Stora Enso, KLH, etc	
Design Life:	e.g. 50 years	
Service class:	e.g. 2	
Species:	e.g European spruce, beech	
Adhesive:	e.g. 1K-PUR	
Treatments:	e.g. details of preservative, fire retardant, heat treatment	
Deconstruction manual	Link	

Technical approval	Provide reference code and Link	
EPD	Link	
Other Element Properties		
Mechanical	**Value**	**Standard**
Strength class	e.g. C24	e.g. EN338
$E_{m,0,mean}$, $E_{m,90,mean}$	e.g. 12 000 MPa; 370 MPa	e.g. EN338
$G_{090,mean}$, $G_{9090,mean}$	*e.g. 690 MPa; 50 MPa*	e.g. EN338
$f_{m,k}$	*e.g. 24 MPa*	e.g. EN338
$f_{t,0,k}$	*e.g. 14.5 MPa*	e.g. EN338
$f_{t,90,k}$	*e.g. 0.4 MPa*	e.g. EN338
$f_{c,0,k}$	*e.g. 21 MPa*	e.g. EN338
$f_{c,90,k}$	*e.g. 2.5 MPa*	e.g. EN338
$f_{v,090,k}$	*e.g. 4 MPa*	e.g. EN338
$f_{v,9090,k}$	*e.g. 1.1 MPa*	
$f_{h,k}$	*e.g. fastener dependent value in MPa*	
Acoustic		
Airborne sound insulation	e.g. $R_w(C; C_{tr})$ = 34 (-1,-3) dB	e.g. ISO 10140-2, ISO 717-1
Impact sound insulation	e.g. $L_{n,w}(C_I)$ = 88 (-5) dB	e.g. ISO 10140-3, ISO 717-2
Sound absorption	e.g. α_s v freq	e.g. ISO 354, ISO 11654
Thermal		
Thermal conductivity	e.g. 0.12 W/(mK)	e.g. ISO 10456
Air permeability	e.g. Class 4	e.g. EN 12207
Fire		
Fire resistance class	e.g. REI 60, REI 90	e.g. EN 13501-2

Charring rate	e.g. 0.65 mm/min	e.g. EN 1995-1-2
Reaction to fire		
Environmental		
GWP	$kgCO_2e/m^3$	ISO 14025 & EN 15804+A2
ODP/AP/EP etc.		
Connections		
Connection type	e.g. Floor to wall	
Fastener description	e.g. Rothoblaas self-tapping screws	
Size and spacing	8 mm x 250 mm @ 450 mm centres	
Connection type	e.g. Wall to wall	
Fastener description		
Size and spacing		
HISTORY OF USE		
Record of deterioration/damage		
Date:	Description	Intervention
	Water damage due to burst pipe	
	Fire damage	
Record of change of use/change in regulation requiring upgrade/remodelling		
Date:	Description	Details

Many building components comprise a number of different materials in addition to the structural timber, which contribute to the overall performance of the component. For example, a wall or floor may have layers of gypsum board for fire resistance and acoustic layers for sound insulation. Where it is intended that the component will be reused in component form, then a material for the component is appropriate. Table 2 shows a sample of the type of record that could be used for component material passports. It gives the overall properties of the component similar to those given in Table 1 but also includes information of the different layers and/or materials used to make up the component.

Table 2: *Sample of information contained within proposed material passport for building components*

Building Component		Reference #
	AS-BUILT PROPERTIES (Date: XX/XX/XXXX)	
General Properties		
Component type	e.g. external wall, floor, roof	
Layer build-up	e.g. 12.5 mm gypsum plasterboard/100 mm CLT/ 12.5 mm gypsum plasterboard.	
Key dimensions	e.g. 6 m x 5 m x 0.125 m	
Mass	e.g. 1725 kg	
Location of lifting points		
Deconstruction manual	Link	
Technical approval	Provide reference code and Link	
EPD	Link	
Component Properties		
Acoustic	Value	Standard
Airborne sound insulation	e.g. $R_w(C; C_{tr})$ = 48 (-5,-12) dB;	e.g. ISO 10140-2, ISO 717-1
Impact sound insulation	e.g. $L_{n,w}(C_I)$ = 53 (3) dB)	e.g. ISO 10140-3, ISO 717-2
Sound absorption	e.g. α_s v freq	e.g. ISO 354, ISO 11654
Thermal		
U-value		

Air permeability	e.g. Class 4	e.g. EN 12207
Fire		
Fire resistance class	e.g. REI 60, REI 90	
Environmental		
GWP etc.		
Layer Properties		
Layer #	e.g. 1	
Type	e.g. Gypsum plaster board	
Description	Type DF	e.g. EN 520
Key dimensions	12.5 mm thick	
Mass (or density)	e.g. 720 kg/m^3	
Manufacturer		
Date manufacture		
Design life		
Technical approval	Link	
EPD	Link	
Etc.		

4.3. Material Passport Platforms

As part of the BAMB project, a Material Passport Platform (MPP) was developed. The MPP is the software and linked database for creating material passports and contains structured and unstructured data on buildings and building materials. The platform allows building stakeholders to generate material passports and to access the data during all phases of the life cycle of the building. Figure 7 shows the structure of the MPP. The expectation is that the availability of this platform will incentivise manufacturers and suppliers to consider and record the circularity potential of their products.

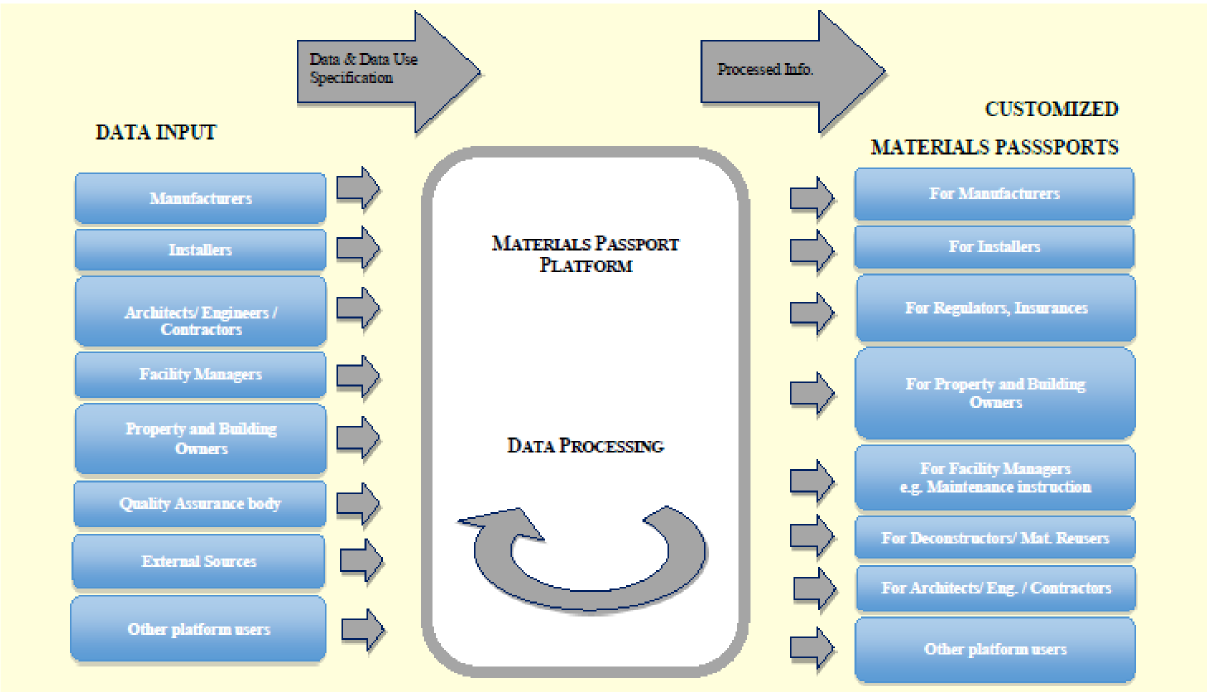

Figure 7: *Structure of Material Passports Platform from BAMB poject [EPEA & Sundahus (2017)]*

4.4. Material Passports and BIM

A BIM model could potentially contain all available information about each component of a building. BIM objects contain information about their geometry, their location within the building space, their relation to other objects and a number of different other attributes that describe the object. Information contained in, or needed by, a material could also be part of this set of information. However, the potential to use BIM for material passports only been exploited to a limited extent. One factor is that there is still a lack of standardisation of the approach to be used to implement this in the AEC industry.

While the current level of BIM is growing in the AEC industry, it tends to be used mainly for larger projects. These mostly operate at BIM level 2, where each design team member has their own model with information sharing between them. The move to Level 3 BIM where the design team works simultaneously on a single project model is hampered by a lack of portability across different versions of BIM software. The use of BIM today is in many cases limited to 3D including architectural, structural and mechanical and electrical services. The use for facility management is limited, although developments in knowledge management aim to support this [(Wang et al, 2018)]. Solutions are currently on the market that facilitate the use of BIM beyond the design phase to construction, handover and maintenance, which have the potential to greatly enhance circular construction practices. One example is the Zutec range of BIM-enabled solutions.

4.4.1. Zutec BIM-Enabled Solutions

Zutec provides a range of BIM solutions for the design, construction, hand-over and maintenance phases of a building [www.zutec.ocm/ie/#]. These include:

- Common data environment (CDE) enabled for BIM brings together 3D models, structured data and project data into a single platform and is ISO 19650 [ISO (2018)] compliant. ISO 19650 is an international standard for managing information about the whole life cycle of a building using BIM.
- Digital handover solution combines geometric, As Built and Field Data, which facilitates tracking of the construction process and the creation of a complete as-built visual index of the completed building. It also allows additional attributes to be added to the model data.
- Quality management solution allow data on location information from inspections to be entered directly into the BIM model together updating of BIM objects and photographic evidence of products used.

Further development of systems such as these can provide the level of traceability of materials and products to support circularity in the AEC sector.

5. Conclusions

It is generally accepted that AEC building design and operational information should be documented electronically and that the leading technology platform to implement this is BIM. It is therefore necessary to store this data long-term in such a way that it can be easily accessed for reference. However, in order that the files are accurate they also need to be accessible to make amendments - security would demand that accessibility is limited and these amendments must be reviewed by suitably qualified personnel. The leading technology in regulating multi-accessible databases is Blockchain. The multi-platform structure of this electronic ledger technology allows a simultaneous view and review of the data input. Its cryptographic data and connection signature, along with the proof-of-work security, safeguards against fraudulent information. Blockchain technology is therefore considered to be an appropriate way to chronicle the lifecycle of building materials from cradle, product provenance, manufacture, use, reuse, and ultimately disposal.

Currently AEC timber in the EU is physically marked by the manufacturer in accordance with regulation and standards. However, as the pertinent data on the material properties will in the future be stored remote to the product, virtually, the next obstacle is establishing a system to permanently connect the digital data with the physical material. There are two main emerging technologies to facilitate this link. They are QR coding and RFID-EID tagging. The data that is linked using QR coding can be assessed by most modern handheld mobile devices. Therefore, the current cost of implementing this technology is confined to the labelling of the material. However, the accuracy of the reading can be compromised by environmental, weather, and physical conditions that are very common in the AEC work environment. These conditions include poor lighting and the obstruction of the code due to dirt or other parts of the fabric of the building. RFID-EID tagging requires specialised transponders, but the data can be recorded without direct or very near proximity to the tag. The RFID-EID tagging and scanning equipment are currently more expensive than the QR code method, however the process allows for a more accurate data reading of material inventory in a way that is in accordance with prevailing AEC work practices. A software connection from tracking to database is necessary with both systems. A challenge to be addressed in parallel with the wider adoption of material passports will be guaranteeing the long-term robustness and viability of such technological solutions to maintain accessibility.

Material passports are digital datasets containing all the necessary information on products and components over the lifespan of the building, which can facilitate building management, remodelling and eventually reuse of the components at the end of life. These can be associated with specific BIM objects in the building digital twin or contained in a material passport platform that links with the BIM model. Many different forms of material passports have been developed each with different data stored depending on the stakeholder focus. There is a need to standardise the structure and content of material passports to provide a holistic dataset that covers all stakeholder requirements over the lifespan of a building. If necessary, stakeholder specific passports can be generated from the overarching material passport. The updating of BIM models and material passports during the use phase of a building is essential to support the evaluation of the reuse potential and should reflect (i) damage or deterioration and any interventions to address these issues or (ii) treatments, remodelling, or change of use .

There is a need for fully-integrated, standardised digital building information systems to be developed, including BIM and material passports, to ensure widespread adoption across the AEC sector. However, the widespread implementation and use of these systems will not be without its challenges.

- One of the key challenges is the requirement to share building information across multiple platforms and timeframes. As with any digital repository, changes in technology and systems over time can lead to issues of lack of compatibility. This is currently a problem with design teams using different versions of BIM software. To ensure long-term robustness of building material data over time, the development of platform independent data storage solutions for building information will play a key role. This problem is not unique to the AEC industry but is an issue that faces a wide variety of communities wishing to share information over an extended timeframe. To address this problem, research is currently underway within the IT community to develop databases with platform-independence [Murillo et al. (2022)]. In the context of building information, storing and reading data in these databases will be possible from a variety of hardware platforms and software architectures. Development of these solutions are still at an early stage of development.
- Currently, BIM is not universally adopted across the AEC community. However, the present drive toward digital transformation of the construction sector in Europe should see this change over coming years. A recent report by the European Construction Sector Observatory published by the European Commission [European Commission (2021)] identified a lack of skilled human resource and lack of awareness and understanding of the technology as the most important challenges to the digitisation of the sector. Training of building professionals is a key priority.
- As highlighted earlier, the importance of tracking the materials through the use phase of a building is key to having accurate information on the end-of-life properties. This will require updating of material passports and/or BIM models. However, facilities managers, in general, do not currently have the ability to update BIM models to reflect changes to products or during use phase of building. This will require either training or recruiting of specialists to carry out the updates.
- The additional costs associated with the adoption of new technology and platforms, including staffing and training. Policy incentives may be required to reduce this financial burden.

In conclusion, the ultimate goal is to provide reliable data on building products and components at all stages of the life cycle of a building to relevant stakeholders to inform decision-making from design through maintenance and finally end-of-life reuse possibilities. The most likely solution for this is a combination of BIM with integrated or linked material passports. The associated data should be stored in platform-independent databases to ensure long-term robustness. While the path to achieving material traceability is understood, current challenges remain for the sector to achieve this goal.

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