

Chapter 3

Digitising Building Materials for Reuse with Reality Capture and Scan-to-BIM Technologies



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Abstract Effective building component reuse requires specific information about recoverable components. However, 85% of the European building stock predates the building information modelling (BIM) technology that stores and links such information. Digitisation technologies can be used to recover this information. Scanning and scan-to-BIM technologies such as LiDAR and photogrammetry enable us to capture and analyse large amounts of raw geometric data as point clouds to create digital records or BIM models of existing buildings. These digital representations can be used by building owners, inspectors, and deconstruction groups for deconstruction, new design, procurement, and new construction. They help implement closed circular resource strategies linking recovered materials to new projects. In this article, we look at a specific case study of these applications through the circularity consultant Concular. Digitisation technologies are compared based on their range and accuracy in conditions with noisy and cluttered data, as well as their cost and accessibility. Additional sensor technologies may integrate further compositional or structural details to ultimately produce insights beyond surface geometry that can be communicated through integrated digital platforms for data access and exchange. Further technological development will lower the time and labour costs during data collection, processing, and analysis.

Keywords Scanning technologies · LiDAR · Point cloud · Building stock digitisation · Reality capture · Scan-to-BIM

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C. De Wolf et al. (eds.), *A Circular Built Environment in the Digital Age*, Circular Economy and Sustainability, https://doi.org/10.1007/978-3-031-39675-5_3

3.1 Scanning Technologies: An Overview

Digitalised processes in the built environment require large amounts of data to describe an existing environment or new designs. To be useful, this data must be drawn from, or at least informed by, the physical world. This data is often encapsulated in building information modelling (BIM), which combines formal, compositional, and temporal information about a designed or completed building (Quirck 2012; see also Chap. 1 by Koutamanis on BIM and digital twins). The adoption of BIM, however, is incomplete: only 25% of EU countries mandated BIM for new projects as of 2019 (Charef et al. 2019), so many buildings lack models. Since BIM is mostly only used during design and construction, the models that do exist may become outdated (Heaton et al. 2019).

While *digitalisation* as a whole addresses the incorporation of digital processes into the industry, one central process is gathering data through *digitisation*. When working in a data-scarce environment, digitisation injects new information through procedures of measurement, description, and consolidation. One foundational type of digitisation in the field of architecture, engineering, and construction (AEC) is the capture of physical and spatial data, a set of processes often collectively referred to as reality capture. Data from reality capture technologies directly feed BIM and geographic information systems (GIS) (Waters 2018), which often deal with volumes of data for which manual data capture is impossible or inefficient. This technology is used at several stages throughout the building life cycle.

Spatial digitisation technologies – generally either laser-based light detection and ranging (LiDAR) or image-based photogrammetry – are utilised to capture data in large volumes. Both produce dense data in the form of point clouds: collections of individual points in space with associated data such as colour, reflectivity, or surface angle. Depending on the application and hardware, these clouds can cover scales and levels of detail from individual components to landscapes (Fig. 3.1). This data is then analysed using methods specific to its application to produce useful information. Geometrically processing point cloud data in semantically useful ways presents unique challenges compared to, for example, image analysis, because point clouds are inherently irregular, unstructured, and unordered (Bello et al. 2020).



Fig. 3.1 Point clouds at the individual component scale (left: HIR building roof truss, ETH Zurich Hönggerberg Campus), building scale (middle: Kopfbau Halle 118, Winterthur), and landscape scale (right: rehabilitation clinic and grounds, Bettingen)

The relative efficiency, cost, and accuracy of reality capture methods distinguish their use for different situations, as the structure and depth of the data itself is generally standardised. For example, measuring deflection of structural components requires high accuracy, whereas capturing residential interiors for real estate requires communicating the visual experiences in high volume, without the need for millimetre accuracy. Within this range, LiDAR technology can produce very accurate measurements. LiDAR records distance by recording the time of flight (TOF) of a reflection of a laser from a relevant object in a scene. Millions of measurements are taken using different coverage strategies for moving through the site and combined with colour photography to create point clouds realistically coloured for the scene. These systems can be attached to unmanned aerial vehicles (UAVs), mounted on tripods, or operated as part of handheld or smartphone-integrated models. The TOF method can retain an accuracy of 5 mm or better at 100 m distance with contemporary hardware (Wu et al. 2022).

In scenarios with many captures over time, the efficiency of each capture becomes more important. This is a key scenario for the usage of mobile LiDAR systems, which continuously capture data over a path through a site, rather than from fixed positions. These systems may be handheld or attached to a variety of autonomous or driven vehicles. On average, these systems involve a trade-off of accuracy for speed (Di Stefano et al. 2021).

Alternatively, photogrammetry compares and triangulates distances from photographs to produce measurements. For the typical ‘structure from motion’ method of photogrammetry, photographs taken during a continuous walk through the site or from many sources over time are used to produce coloured point clouds. Photogrammetry is significantly cheaper than LiDAR, as it can be captured with standard smartphone models, and it can be more efficient, especially if capture is taken with video. Photogrammetry may, however, need additional manual work to correctly set the scale and orientation of a captured scene.

Some applications of reality capture may fuse different data sources depending on the data requirements and context. For instance, reality capture at the city scale may combine an overview of photogrammetry data taken from an aerial source with more detailed street-level LiDAR or photogrammetry, with the goal of maintaining complete coverage while allowing maximum detail in all areas.

3.2 Scanning Technology in the Built Environment

Although the construction industry has been slow to adopt comprehensive digitalisation, digitisation and reality capture have been adopted in applications throughout the building life cycle. As a first example of digitisation used in the industry, scanning is used on raw materials before construction even begins. Stockpiled materials such as sand for concrete production are scanned with extended tripods so they can be better managed and tracked. To avoid the accumulation of errors when only recording amounts of ingoing and outgoing materials, periodic

scans of the entire stockpile can be taken, and volumes can be estimated from the resulting topology (Manish et al. 2022; Zhang and Yang 2019). These volume-based measurements may also be used to estimate excavation volumes for earthworks or the value of used material when working with sprayed concrete.

Many applications of scanning relate to specific BIM representations of buildings. Scans may either be used to compare data to a known existing BIM model, known as *scan-vs-BIM*, or to generate an entirely new model, known as *scan-to-BIM*. A second example of digitisation in construction makes use of scan-vs-BIM for combining and comparing dense spatial and often temporal data to track how buildings develop over time: large-scale progress tracking, for example, can be used in construction monitoring to find which components have already been installed at a particular point in time and to detect errors, such as if components have been installed or fabricated incorrectly. Both goals require a highly detailed BIM model as a goal state for the building. Overlap between the BIM model and the collected datapoints (or point cloud) can be checked to see if a particular component has been installed or to look for differences that reveal incorrect sizes or installation locations.

A third example of digitisation in construction can be found during a building's operational life span, when large-scale reality capture is also applied to monitor for defects or deformations that may affect their safety and usability (Guo et al. 2021). Monitoring deflection is similar to monitoring construction deviations: using an existing BIM model, individual element positions are compared to the local point cloud to detect deflection or rotation over time. The knowledge of the complete structural system allows for the system to detect which deviations represent the greatest immediate danger (Kaartinen et al. 2022). Other types of defects that can be monitored include cracks, spalling, and corrosion visible on the surface of timber, concrete, and steel structures. While these can be detected by comparing them to a BIM model, they can be more specifically identified by the unique geometric effects on the material surface, using techniques similar to 2D image analysis (Tzortzinis et al. 2022). For some materials, these types of digitisation may also involve a direct fusion with image-based techniques, where 3D data is used to broadly locate the critical areas in the component, while the specific defect detection is carried out using accompanying photographic information (see Chap. 4 by Armeni et al. on AI).

Digitisation is also used during the operational phase to maintain up-to-date, as-built modelling for facility management. During a building's life cycle, the digital twin of a building can be used to manage facilities, track changes, and optimise processes. This enables computer-aided facility management.

Monitoring defects by using reality capture has many applications in the fields of building heritage and preservation in particular. Similar techniques to those used for contemporary buildings can help detect and analyse defects in historic structures, though aimed at a wider array of damage and design scenarios in older structures. Assessments often lack existing documentation, so defects can be detected solely by their unique spatial characteristics. In scenarios with obvious damage or missing components, digitisation can also create highly detailed recordings for models used

in the automated production of replacement and repair components (Weigert et al. 2019; see also Chap. 7 by Chadha et al. on additive manufacturing).

Scanning and digitisation can also rapidly capture historical sites as a whole for a complete view of their layout or design. Depending on the scale, ground-based mobile LiDAR systems, aerial systems, connected to low-flying aircraft, and UAVs or other drones might be useful (Adamopoulos and Rinaudo 2021; Rodriguez et al. 2019).

Different types and depths of digitisation are used throughout the building life cycle to manage construction, ensure its correctness, and check for problems over time. BIM information is often compared to the captured data, but the results often do not make it beyond the stage of capture to be communicated to other relevant parties, as the industry has not adopted comprehensive digitalisation.

3.3 Scanning Technology for a Circular Built Environment

The measurements and data that scanning technologies and digitisation collect are often not new in construction; human workers could collect (and historically have collected) similar data. The true value of digitisation technology comes from the large volume and efficiency of gathering digital data. Since the technology enables the rapid capture of entire buildings and structures, digitisation of the entire active built environment becomes a possibility. This technology could help close material loops in the built environment by efficiently tracking and working with the uniqueness of individual material components at a large scale after their initial life span.

Post-demolition material reuse is the primary method for closing material loops today. Historically, balancing supply and demand with uncertainty from the procurer regarding the history (and, thus, reliability) of a specific reused component has hindered post-demolition material reuse (Hobbs and Adams 2017). These challenges could be mitigated by thorough and data-rich inventories of components that are available or will soon become available (Chap. 5 by Honic et al. on material passports).

Scanning and digitisation can provide a source for these inventories in the form of automated inventory making or scan-to-BIM, primarily making use of techniques for identification and description, in contrast to the connection and comparison performed for scan-vs-BIM. BIM documentation of existing structures hinges on the connection between physical measurements and digital representations. Traditionally, human workers would draft from a series of manual measurements; more recently, they have drawn BIM elements over a point cloud, using their own judgement in response to noise and misalignments. Nowadays, contemporary research is increasingly enabling automated assistance in the generation and construction of BIM models.

Analysis techniques of construction verification and defect detection (as described in Sect. 3.2) require scan-to-BIM to combine noise handling, component detection, measurement, and material description concurrently. The complexity

of techniques needed to identify building components and features depends on the components they handle. Some features may be identified through simple statistical analysis – for instance, the level of each floor may be identified by determining the highest concentrations of points from a series of horizontal slices through the building cloud. Individual elements with minimal surface detail (such as interior walls) may instead use a geometric approach – algorithms such as random sample consensus (RANSAC), which finds patterns in high-noise environments, are used to identify simple geometry primitives such as planes and cylinders within a dataset, which can then be further refined to locate doors or windows. Alternatively, the system may handle all interior components and objects simultaneously using techniques borrowed from 2D computer vision (which generally deal with image pixels). Here, each point is individually classified using deep learning techniques as one of several common classes for the type of site, which may be further instance-segmented into individual components (see also Chap. 4 by Armeni et al. on AI).

In all cases, the identified points are condensed into a single BIM element, at minimum containing information on the component's position and dimensions (such as the wall thickness or structural profile). From here, additional relevant information is extracted and integrated. Descriptions of the connections between elements are particularly relevant for making decisions about reuse. This may be at the fine-grain level – such as in determining details about a structural connection – or at a larger scale, such as for extracting the larger web of relationships between elements in a structural system. This BIM model can then be used as the basis of a component inventory for the building. Depending on the level of detail, these records can be used to estimate the economic value of or potential for reducing emissions by reusing the building's components, assisting deconstruction groups in planning removal operations, or helping designers and contractors estimate the amounts of local materials that will soon be available.

Scanning and digitisation may also be applied to material streams after demolition or deconstruction has occurred. In these cases, the system only has to consider a single component at a time, so analysis can be focused on capturing specific dimensional information or various types of defect detection, as described in Sect. 3.2. On an urban scale, scanning technologies such as airborne or satellite data can also be used to construct or enrich existing digital models. In addition to applications of 3D urban models ranging from solar potential analyses to a wide variety of environmental analyses (microclimate, flooding, etc.) to dynamic thermal simulation of buildings (Malhotra et al. 2022), they can be used to predict future trends for reuse. By combining geometric data with data on materials, material stocks can be identified on a larger scale and used as a basis for a material flow analysis.

By using scanning and digitisation techniques, scan-to-BIM can connect reality capture to reuse operations. While assistive modelling tools are increasingly being used in practice, fully automated methods have not yet seen commercial implementation. Active research is continuing for addressing finer details (Zhou et al. 2021; Yan and Hajjar 2022) and overcoming gaps and noise in data (Park et al. 2022).

3.4 Industrial Implementations of Scanning and Digitisation for a Circular Building Environment: Concular

While industry use of LiDAR and digitisation began with applications for detecting defects and manual drawings from scans, the importance of inventories and large-scale scan-to-BIM is prompting further practical implementation. The German start-up Concular is a primary example of a company that is applying scan-to-BIM to the circular built environment. To improve resource efficiency within the construction sector by closing material loops, Concular has developed a platform for matching the supply and demand of reusable materials (Concular 2021).

High reuse and recycling rates are crucial to achieve a circular construction sector. The reuse of materials and products must be considered in the design and building process, especially in anticipation of the end of the building life cycle. To this end, Concular is developing a platform storing material, component, and building passports to represent and reintroduce the materials used in a building throughout its life cycle. The dataset storage method for the building passports can be continuously updated during the material, component, and building life cycle. The resulting database of reusable material and components is utilised for estimating amounts of available resources and finding appropriate circular sources. An essential function of Concular's database is the ability to connect digitised 3D models to the platform. Existing and new buildings can be added through open-source interfaces (IFC or CSV file formats). However, there is often little or no digital information available on buildings built before 1978 (which account for 75% of all structures), meaning most of our built environment is only accessible via analogue plans if at all (Metzger et al. 2019).

An ideal dataset would include digital plans, an overview of the current renovation or planning status, and information on building materials and their suitability for reuse. Scanning technology offers an accurate and potentially efficient way to digitise the built environment and provide applications such as Concular with the necessary BIM data. Within this context, Concular focuses on the technical development of a unique database model that combines relevant data formats in the building industry with the capture as well as tracking of building elements. A scan/capture phase first evaluates 2D plans and records, including recognising the building envelope or envelope elements from floor plans. Then, 3D scans capture rooms to accurately locate building elements within a floor plan. This is primarily accomplished with photogrammetry, which leverages the image data to gain information on materials and qualities of single products and building elements during building assessments. The data generated by these capture methods is stored within a building life cycle passport on a platform provided by Concular.

Additional technical details relevant to further connections, such as GIS data and product-specific sustainability information, are also mapped to the building elements within the passport. To deal effectively with many elements at scale and verify the quality of the data input of the relevant file standards, an artificial intelligence (AI)

application is trained through test projects to assign this sustainability information to the materials, products, and components.

Building life cycle passports store updatable information on trackable materials and products contained at the building level. As a result, they provide project managers and building owners with an overview of the materials and products used in their buildings, as well as the ability to evaluate buildings by carbon footprint, recyclability, or circularity. A ‘living’ building passport allows for changes during a building’s life cycle, by updating information on products transferred between buildings or replacing and digitally renewing defective products. Linking building passports to external product passports enables detailed information (such as service cycle, replacement duration, circularity, and availability) about products and components to be retrieved, compared, or exchanged. Trackable technical details can be stored within a building product, material, and property table (Chap. 5 by Honic et al. on material passports).

Scanning and capture technologies help create the volume of data necessary to digitise the built environment. Subsequently generated BIM data is then available to analyse and evaluate the aspects of sustainability and reusability on an adequate scale. Data collection is supported by AI automation in relevant areas while supplemented by additional external data collected in traditional ways. While a fully automated scanning process is technically feasible, the costs of both manual and automation-assisted intensive building assessments, plus the need to transform and standardise data formats, are still prohibitive to fully automating the process. Nevertheless, providing clear use cases to a variety of stakeholders, such as building owners and planners, encourages further adoption.

Obtaining data about the built environment is essential for urban mining and reusing materials and building components in a circular manner. Concular’s platform allows this data to be stored and made accessible in order to close material loops and reduce the amount of new resources needed for construction.

3.5 Business Models for Scanning in a Circular Built Environment

The circular economy retains and maintains the embedded value of products by creating continuous closed loops of materials or product parts and reclaiming value lost to waste. Today, the lack of available data through secure, quality assured, and automated methods is one of the main obstacles that industry actors point to when creating new circular value networks (Deloitte 2019). There is usually no digital information available on buildings predating the adoption of digital planning and tracking tools – information that is necessary for judging the suitability of reusing components for specific new uses. In addition, information is lacking on sustainability factors (e.g. embodied carbon emissions), and open interfaces to existing historical information often do not exist. Thus, evaluating a building’s circularity

potential and the necessary deconstruction according to ecological or sustainability measures remains a challenge, and doing so requires great manual effort by experts and reviewers. Data digitisation and capture via scanning can significantly reduce that effort and has relevance for stakeholders across the entire building sector.

The representations of existing buildings created by digitisation technology can be used to generate BIM models as a basis for renovations, retrofittings, or assessing reuse potential. For project developers as well as building owners, scanning can provide an overview of current building conditions as well as information on building elements. A detailed assessment of material and products is then possible through digital capture, and scan-to-BIM offers additional possibilities for analysis and evaluation of the building mass both in terms of economic calculations and sustainability and compliance. Calculating the material worth of materials and products for reuse or recycling increases the potential economic value of buildings and offers a more productive use of leftover materials.

BIM data is used as the basis for life cycle analyses, which enable the assessment of a building's compliance with sustainability standards and reveal areas for improvement. This also has implications for investors and property owners. Project developers and building owners who want to access 'green finance', for example, must ensure that their projects are resilient to climate change and resource scarcity. These requirements impact the financial market of sustainable investment but also the work of planners. As the demand for taxonomy-compliant properties increases in the future, sustainable investing will become relevant for private investors and governmental funding alike. Capture and scan-to-BIM technology contributes to demand for resource efficiency and creates measurable sustainability standards relevant for investors.

Companies offer digital BIM models for different project purposes such as renovations or retrofittings. Companies such as Plan3D, for example, offer as-built surveys of listed buildings and technical installations, deformation studies, and visualisations for marketing purposes (Plan3D 2021). Concular's services are an example of a complementary platform model that stores the resulting data and provides analysis tools in a subscription-based software-as-a-service model.

Scanning and capture technology can also provide a connection between digital planning and physical reality during the construction process. By monitoring the progress and placement of building elements, scan-vs-BIM supports planners and construction companies in planning new building projects and identifying potential construction issues. Components may also be tracked individually, for example, with embedded radiofrequency identification (RFID) chips or codes from production to gate to on-site application, where data can be updated in real time (Strabag 2023). This also allows manufacturers to track their products over an entire life cycle, thereby establishing takeback or refurbishment processes and diversifying material resource flows.

Scan-to-BIM can also capture necessary information as a basis to create inventories of reuse components for the planning process, including information on their availability or material makeup and on the geometry of building elements. In order to provide predictive information on material availability and flows, building-specific

capture has the potential to be supplemented with large-scale datasets. For example, large-scale 3D building models are made freely available by surveying agencies as open data or are available for a fee as a file or as a web service (Geiger et al. 2022).

During the process of deconstruction, similar advantages can be gained: digital capture makes it possible to collect the necessary structural information as well as more detailed assessments on the location of pollutants. Building surveys and audits can quickly and accurately portray existing building conditions, including dimensions, structures, and finishes to generate BIM models for assessing reuse potential. As a basis for urban mining, this can be used for informing the planning process and resource availability.

These use cases provide an outlook on the possibilities to offset the current costs of labour- and time-intensive digitalised processes by establishing new applications, especially within the framework of urban mining and circular construction. Key factors for the application of scan-to-BIM within the built environment are high-quality, accurate results with concrete economic benefits. Adoption of circular principles is further fuelled by current political developments to reduce CO₂ emissions and diversify resource flows. For example, the European Commission has stated its intention to make Europe the first climate-neutral continent by 2050 and to create a nearly climate-neutral building stock (European Commission 2018). The necessary analysis of our built environment as a basis for reuse is only possible with large-scale digitisation – which can be reached by using large-scale methods such as capture and scan-to-BIM technology.

3.6 Discussion

Digitisation technology addresses an immediate gap in material recovery and reuse today – it provides an efficient, effective, and available way to fill a lack of knowledge about the location and quality of relevant materials. The density and coverage of models created by digitisation technologies contribute to the geometric side of digital twins (Chap. 1 by Koutamanis discussing BIM and digital twins), more complete and up-to-date building records, and building an initial record of pre-digital buildings. These technologies are increasingly being applied in different stages throughout the standard building life cycle and by reuse actors, such as in the case of Concular outlined here.

Going forward, automation and ease of access will be major factors in the further adoption of these technologies. Effective automation will be dependent on the development of focused models and machine learning systems for the reuse context. Existing machine learning work using 3D scans often focuses on natural features, geographic applications, or furniture and fit-out features in the building domain. Identification and analysis of construction components require the compilation of entirely new datasets. The specific needs of these models create unique challenges for analysis. The geometry of products and components may vary heavily, especially by region, leading to possible unexpected difficulties in generalising information

about products. Additionally, the ability to recognise and process components from a variety of vernaculars and styles speaks to the design effects of circularity, where, for instance, a region may want to maintain a historic style while utilising components from nearby areas or alternatively create new combinations.

The contemporary adoption of scanning and scan-to-BIM technology still faces some existing challenges. Immediately relevant is the high entry cost for the capture hardware, with building-scale terrestrial models often costing more than 50,000 Euros. While accessible models are becoming widely available, the best resolution and accuracy may still be inaccessible for smaller groups interested in utilising digitisation, especially in scenarios requiring many captures over a period of time. Additionally, safe and efficient long-term storage of the huge volume of data required for a large portfolio of sites presents new operational challenges. These concerns may be mitigated through collaboration with specialised groups providing scanning services and with expertise in large-scale data processing and data storage. Finally, contemporary scanning technology can only gather a limited amount of detail about each component. Information about possible interior damage, the composition of multilayer parts, or even the materiality of painted surfaces must still be gathered through other technology or through manual means.

Going forward, technological advancements in scanning and capture technology will directly allow for a continuous record of buildings. While higher-end models will always be necessary in high-accuracy scenarios, the form factor and cost of LiDAR technology are already becoming accessible at the smartphone scale. Furthermore, image-based reconstruction is increasingly merging with deep learning techniques, fostering more accurate reproductions from smartphone hardware capture (Heipke and Rottensteiner 2020). As these tools become appropriate for full building reconstruction, they will become better integrated in the ongoing operations of building managers and owners, thus extending life cycles through target repair and ultimately more informed reuse of building components.

There are also paths for adapting the role of scanning technology in the building life cycle. Scanning and scan-to-BIM are often employed currently as a single explicit step, as a static representation of the building state. These same increases in accessibility will allow for regular or even continuous recording and updating of associated BIM models as part of the digital twin concept (Chap. 1 by Koutamanis on BIM and digital twins). In the context of circular construction and urban mining, it is also possible to provide up-to-date information on large-scale inventories of material and components, which are instrumental to closing material loops. These continuous and integrated models will be further enhanced with varied data sources. Alternative hardware, such as thermal imaging, has been studied to overcome noisy and uncertain lighting conditions in building sites, as well as its potential for locating hidden mechanical, electrical, and plumbing engineering components (Pazhoohesh et al. 2021; Penzel et al. 2019). Understanding the interior of components may be addressed by several tomography technologies, such as those using electrical resistance or ultrasonic audio for studying structural conditions in wood and concrete (Karhunen et al. 2010; Zielińska and Rucka 2021).

Digitisation via scanning technologies and scan-to-BIM is a key facilitator in a digitalised system for circularity in the built environment and is crucial for achieving the target of zero-carbon buildings by 2050. Presently, practitioners often lack precise pre-demolition information to understand the existing building stock. Scanning, geometry assignment, and material analysis together address this need. Centrally, they allow for the large-scale creation of BIM models and geometry for digital twins. This information can also aid in creating sharable material passports that compile the linked data describing a component's characteristics, location, history, and ownership status in previously non-digitised contexts. Automated techniques for capture and analysis are also a central application for AI and computer vision in reuse operations. Together, they are a key source of information that powers the subsequent systems for material tracking and design in a circular built environment as well as improving accuracy, efficiency, and collaboration in the built environment.

3.7 Key Takeaways

- Effective material reuse requires data about many available sites and components to close the loop into new projects.
- Reality capture technologies record large amounts of spatial data as point clouds, collecting useful information about as many relevant components as possible and contributing to the digital representation of the built environment ultimately needed for circular construction.
- Point cloud data can inform material passports and qualitative checks throughout the life span of a building, facilitating repair operations to slow the life span of individual buildings and enabling the analysis and tracking of materials and components throughout their life cycle.

Acknowledgements The associated research includes funding by Vlaanderen Circulair – Call Circulaire Bouweconomie – Vlaams Agentschap Innoveren and Ondernemen (VLAIO).

Declaration of Competing Interests Authors von Zimmerman, Haradhun, Campanella, and Bräutigam are or were employees of Concular, a Berlin-based start-up using digitalisation to further circular construction.

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