Digitalization for a circular economy in the building industry: Multiple-case study of Dutch social housing organizations

Çetin, Sultan; Gruis, V.H.; Straub, A.

DOI
10.1016/j.rcradv.2022.200110

Publication date
2022

Document Version
Final published version

Published in
Resources, Conservation and Recycling Advances

15 (2022) 200110

Contents lists available at ScienceDirect

Resources, Conservation & Recycling Advances

journal homepage: www.sciencedirect.com/journal/Resources-Conservation-and-Recycling-Advances

Digitalization for a circular economy in the building industry: Multiple-case study of Dutch social housing organizations

Sultan Çetin *, Vincent Gruis, Ad Straub

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

ARTICLE INFO

Keywords:
Digitalization
Circular economy
Building
Case study
Challenge
Built environment

ABSTRACT

Digital technologies are considered enablers of circular economy implementation in the built environment. Literature mainly focuses on conceptual or review studies examining the role of digital tools (e.g., material passport and building information modelling) to close the material loops. There is a lack of understanding of how digital technologies are implemented in real-life and whether they offer value to the industry actors. This study conducted a multiple-case study to collect empirical evidence from Dutch social housing organizations actively applying circular principles in new construction, renovation, maintenance, and demolition projects. Our findings suggest that artificial intelligence, digital twins, and scanning technologies support data collection, integration, and analysis for slowing the loops strategies (i.e., maintenance), while digital marketplaces facilitate material reuse, enabling narrowing and closing the loops. This study identified 12 challenges that hinder the broader adoption of digital technologies that are associated with the technological, cultural, market, and regulatory factors.

Abbreviations

AI	Artificial Intelligence
BIM	Building Information modeling
BCI	Building Circularity Index©
CE	Circular Economy
DT	Digital Technology
EU	European Union
IoT	The Internet of Things
MP	Material Passport
SHO	Social Housing Organization

1. Introduction

The building industry is one of the largest, most resource- and energy-intensive industries in the European Union (EU) (European Commission, 2020b;, Herczeg et al., 2014), which creates around 36% of the EU's waste (Eurostat, 2018). In the past decade, many governments, organizations, and academics have shown a growing interest in the concept of Circular Economy (CE) as an alternative path to transition toward a resource-efficient and carbon-neutral building industry (Ness and Xing, 2017). The theoretical foundations of the CE can be traced back to several schools of thought (Ellen MacArthur Foundation, 2022), such as Industrial Ecology and Cradle to Cradle. In essence, the CE aims to create a regenerative economy by minimizing resource flows, waste, and energy leakages by narrowing, slowing, and closing the resource loops (Bocken et al., 2016; Geissdoerfer et al., 2017). As outlined by scholars (Bocken et al., 2016; Çetin et al., 2021, Konietzko et al., 2020), narrowing resource loops in buildings aims to curtail primary resource inputs by dematerialization in design, substituting with secondary materials, and operational optimization; slowing resource loops intends to keep buildings and components in use as long as possible by reversible design, repair, maintenance, and reuse; closing resource loops closes the resource cycle at the end of life through reuse or recycling; finally, regenerating resource loops considers using renewable, non-toxic, and biobased resources and improving biodiversity.

The academic discourse on CE in the building industry covers several dimensions and predominantly focuses on strategies for closing the material loops (Benachio et al., 2020). Scholars argue that existing building stock can be a source of raw materials (Heisel and Rau-Oberhuber, 2020) and can serve as a "material bank" in the future for new buildings (Honic et al., 2021). Extracting valuable materials from

* Corresponding author.
E-mail address: s.cetin-ozturk@tudelft.nl (S. Çetin).

https://doi.org/10.1016/j.rcradv.2022.200110

Available online 13 August 2022

anthropogenic stock and reintroducing them into economic processes through reuse and recycling is called "urban mining" (Heisel and Rau-Oberhuber, 2020, Honic et al., 2021, Koutamanis et al., 2018). Urban mining and other value retention interventions depend on the availability of detailed information on the material composition of buildings (Honic et al., 2019; Koutamanis et al., 2018), how component connections are made (Iacovidou et al., 2018), and where and when in the future resources will become available (Heisel and Rau-Oberhuber, 2020). However, accessing such information is challenging as existing buildings are usually poorly documented (van den Berg et al., 2021) and exposed to changes throughout their lifetime that are not reported systematically (Honic et al., 2021, Iacovidou et al., 2018). This challenge, among others, led to the creation of material passports (MPs), digital data sets containing useful information about materials, products, and buildings (Heinrich and Lang, 2019), which have become an essential instrument in realizing circular buildings. Furthermore, it gave an impetus to digitalization for a CE in the industry as an emerging research field.

1.1. Digitalization for a circular building industry

In the past year, a few review articles have been published discussing how digital technologies (DTs) could support circular building strategies (Çetin et al., 2021) and their role in decision-making processes (Yu et al., 2022) and climate change mitigation (Caldas et al., 2022). The literature and practice review of Çetin et al. (2021) identified several DTs that could potentially support implementing circular strategies across the lifecycle stages of buildings, including building information modeling (BIM) and MPs. The application of BIM, as a technology representing a building's data alongside its geometry, is an important research field among researchers. Koutamanis et al. (2018) argue that BIM, by integrating information from different sources like construction documents and on-site investigations, could support urban mining with the precise identification of building components at the end of life. According to Charef and Emmitt (2021), BIM proposes new opportunities for circularity, such as MP development, circularity assessment, and end-of-life model generation. The decision support tool developed by Akanbi et al. (2019) provides designers with insights into the end-of-life performance of design variants aiming to minimize waste and resource consumption. van den Berg et al. (2021) demonstrate the use of BIM in a deconstruction project where valuable elements were labelled in BIM to reuse in another building construction. Recently, BIM-based circularity indicators have been introduced (Khadim et al., 2022), e.g., Zhai (2020) proposed a BIM framework to automate the circularity assessment of buildings from the early design stage.

In addition, BIM is used for creating MPs. There are different types of MPs (Munaro and Tavares, 2021). Early examples of MPs include the prototype developed by the European project BAMB (Heinrich and Lang, 2019), the work of Honic et al. (2019), and commercialized MPs like Madaster (Madaster, 2022) and Cirdax (Cirdax, 2022). The method proposed by Honic et al. (2019) generates the MP based on BIM data and functions as a design-optimization and inventory tool. On the other hand, the MP of the Madaster Platform (Madaster, 2022) operates on an online platform providing industry actors with the registry of building materials and calculating the level of circularity of the buildings (Heisel and Rau-Oberhuber, 2020, Madaster, 2018). Recently, researchers developed a novel method to expand MPs towards existing buildings by incorporating scanning technologies and BIM (Honic et al., 2021).

To trace, track and monitor material flows and increase visibility, scholars proposed the internet of things (IoT)-based systems and blockchain frameworks. One such example is a blockchain- and IoT-based smart product-service system developed for housing prefabrication in China (Li et al., 2021). Similarly, Shojaei et al. (2021) introduced a blockchain infrastructure that acts as a network for recording, storing, and sharing material/component information to enable reuse and recycling.

Some other advanced DTs such as artificial intelligence (AI), virtual reality, and digital platforms have also been explored. Płoszaj-Mazurek et al. (2020) developed a regenerative design model that simplifies the environmental assessment of architectural design variants based on machine learning techniques. Building on deep learning models, Akanbi et al. (2020) created a tool that predicts the volume of reusable materials prior to demolition. Raghu et al. (2022) presented a data collection method based on image processing techniques using publicly available street views that identifies reusable elements in the existing building stock. Similarly, a Dutch startup, Spotr (Spotr, 2022), offers an AI-based product inspecting building skin with drones and satellite images and gives insights into maintenance needs. Furthermore, O'Grady et al. (2021), combining game design and BIM, built a virtual reality tool that visualizes reusable materials and components.

Digitalization has also become an important topic in the European policy landscape, particularly for the EU's green transition (European Commission, 2022). The EU's recent Circular Economy Action Plan stresses that DTs will play a driving role in circular innovation, especially for tracking resource flows, dematerialization, and realizing circular service business models (European Commission, 2020a). Furthermore, the EU promotes MPs, tags, and watermarks for sustainable products and encourages establishing digital logbooks for the buildings (European Commission, 2020a). These developments are followed by the EU's post-COVID recovery plan which aims to reinforce sustainability efforts by accelerating investments in the "twin"- green and digital- transitions (European Commission, 2021).

1.2. Literature gaps and research objective

Notwithstanding the promising potential of DTs, several critical points regarding their implementation remain underexplored. First, current academic discourse assumes that DTs are key enablers of the CE. However, with the majority of the studies being theoretical or conceptual (Çetin et al., 2021, Yu et al., 2022), this claim is poorly substantiated how DTs are implemented in real-life and whether they provide building industry actors with value. In particular, the industry is known for its slow technology adoption and this challenge is associated with cultural aspects such as resistance to technological change (Shojaei et al., 2021) rather than the availability or capability of DTs (Chan, 2020). A similar gap also exists in the broader literature on the DT-CE intersection (Cagno et al., 2021, Ranta et al., 2021, Rosa et al., 2019). Many scholars (see, e.g., (Awan et al., 2021, Lopes de Sousa Jabbour et al., 2018, Munaro and Tavares, 2021, Ranta et al., 2021, Rosa et al., 2019)) called for empirical studies such as case studies to expand scientific knowledge through the lens of primary actors who are implementing circular strategies in practice and identify the challenges that emerge when they deploy DTs.

Second, as indicated in (Caldas et al., 2022, Çetin et al., 2021, 2021), current digital innovations predominantly consider closing the loops strategies during design or end-of-life stages for reusing and recycling building materials. Given the long lifetime of buildings, life extension strategies such as repair and maintenance, which have a higher priority at the EU level (Ingemarsdotter et al., 2021), are surprisingly overlooked in the circular built environment literature, particularly from a DT perspective (Caldas et al., 2022).

Third, in terms of target groups, extant literature mainly prioritizes designers, architects, or engineers for decision support in the design stage (Çetin et al., 2021), and material suppliers or demolition managers during the end-of-life stage for the waste reduction (Yu et al., 2022). Little is known about the actors who manage or own a sizeable portfolio of buildings, such as public clients and commercial real estate owners. As Chan et al. (2020) point out, these actors hold strong market power and could play an acceleratory role in the DT adoption for the circular building industry.

This research aims to address these gaps by examining how large-scale social housing organizations (SHOs) deploy DTs in their circular

Table 1
Main characteristics of the selected cases. Numbers are extracted from organizations' 2020 reports.

Case	Location	Total properties	Real-estate market value	Primary data (interviews)	Secondary data
Alpha	Amsterdam	56,319 homes	€12,7 billion	Senior sustainability advisor; project developer renovation & maintenance; technical advisor; project developer new build	News articles, research reports, presentations, media interviews, videos, company website and releases, yearly public reports
Beta	Amsterdam and surrounding areas	56,964 homes	€11,7 billion	Strategic advisor; innovation manager; senior area developer	News articles, research reports, media interviews, company website and releases, videos, yearly public reports
Gamma	Rotterdam	51,274 homes	€7,2 billion	Portfolio advisor circularity; portfolio advisor maintenance, asset manager, project manager, real estate developer, consultant digital innovation and transformation	News articles, media interviews, videos, company website and releases, yearly public reports

new build, renovation, maintenance, and demolition projects and what challenges emerge when they implement DTs in circular processes. A multiple-case study was carried out with three pioneer SHOs at the forefront of circularity implementation in the Netherlands. Dutch SHOs are non-for-profit organizations that deliver affordable homes to low-income and disadvantaged groups in society. They typically own a large portfolio of buildings and are responsible for keeping their building stock in good quality (AEDES, 2016). They are involved in all life-cycle phases of buildings, from initiation to demolition stages. Consequently, a multiple-case study of forerunner SHOs is a fruitful source for collecting practice-based evidence to expand academic knowledge. More specifically, we address the following research questions:

RQ1: How are DTs deployed in circular projects of forerunner SHOs?

RQ2: What challenges do SHOs perceive in the broader adoption of DTs to facilitate circular approaches?

The following section explains the research design and methods. Section 3 presents findings and Section 4 discusses findings and concludes the study.

2. Methodology

2.1. Research design

Given the emergent nature of the research field, this study deployed a qualitative multiple-case study method to expand theoretical knowledge by integrating new empirical insights derived from real-life cases. The case study method is prevalent in social sciences and is used by many researchers and practising professionals, which allows for retaining in-depth, holistic, and real-world perspectives from a case in the focus (Yin, 2018). We chose a multiple-case study design as it is more robust than a single-case design allowing in-depth investigation of individual cases while examining processes across two or more cases through a cross-case analysis (Eisenhardt, 1989). It reveals similarities and differences between individual cases, unearths novel findings from collected data (Eisenhardt, 1989), and strengthens the precision, stability, and validity of the research (Miles et al., 1994; Yin, 2018).

2.2. Case selection

We followed the methodological procedures defined by Yin (2018) and applied the literal replication logic when selecting cases. Our sampling was purposive and focused on similar cases as establishing typical cases helps improve confidence in findings (Miles et al., 1994). The principal criteria for selecting SHO cases were as follows:

- Forerunner in circularity: cases should actively implement circular principles in housing projects or portfolio policy.
- Location: cases should operate in the same country since housing systems, regulations, and interest in circularity vary by country. We chose to focus on the Netherlands as the country has a long-term national strategy for transitioning to a CE by 2050 (Rijksoverheid, 2016) and is considered a pioneer country in CE implementation (Marino and Pariso, 2020) and research (Khadim et al., 2022, Munaro and Tavares, 2021). Also, The Netherlands has the largest share of social housing in the EU (with around 30%) (Housing Europe, 2021).
- Size: approximately 300 SHOs operate in the Netherlands (AEDES, 2022) with varying sizes, managing from as small as hundreds of dwellings to over 50,000 homes. Based on the assumption that large organizations are more likely to adopt DTs than smaller ones (see (Çetin et al., 2021)), we concentrated on large-size SHOs. This criterion helped to keep cases comparable in their institutional settings.

Based on these criteria, we investigated web sources and created a preliminary list of potential case SHOs. We sent invitations to the employees of potential organizations by using the snowballing technique, our network and publicly available contact information. Subsequently, three SHOs operating in the largest two Dutch cities, Amsterdam and Rotterdam, accepted to participate in the research. Table 1 presents the main characteristics of the selected cases.

2.3. Data collection

We collected data from multiple sources from October 2021 to February 2022. First, we examined secondary data sources such as case organizations' yearly reports. Then, building on the preliminary findings, we formulated a semi-structured interview protocol with open-ended questions (see Table A.1 in the appendix). We invited key informants who were directly involved in circular projects, policymaking, or digitalization processes. The selection of interviewees was purposive and considered different organizational levels (Table 1). For example, we included strategic advisors who inform policymaking at the portfolio level as well as project managers who implement circular strategies in the pilot projects. In total, 13 semi-structured interviews were conducted in an online setting due to the COVID-19 pandemic restrictions. Interviews lasted typically between 40 and 60 min and were recorded, transcribed verbatim, and anonymized (Interview data is openly available). Later, these interviews were substantiated with secondary data for data triangulation as this improves the validity of the results (Yin, 2018).

2.4. Data analysis

Data analysis consisted of two phases. In the first phase, we conducted within-case analyses by coding collected data to identify and classify circular and digital elements as well as challenges that the interviewees mentioned. We created a theory-based framework by combining two previous CE-DT-related works. The Circular Digital Built Environment Framework (CDB Framework) (Çetin et al., 2021) gives a comprehensive overview of circular building strategies and enabling DTs, built on prior CE conceptualizations (Bocken et al., 2021, 2016, Konietzko et al., 2020). It helped us categorize circular strategies implemented in circular new build, maintenance, renovation, and demolition projects. We used the data flow processes and analytic capabilities defined in the Smart CE Framework (Kristoffersen et al., 2020) to

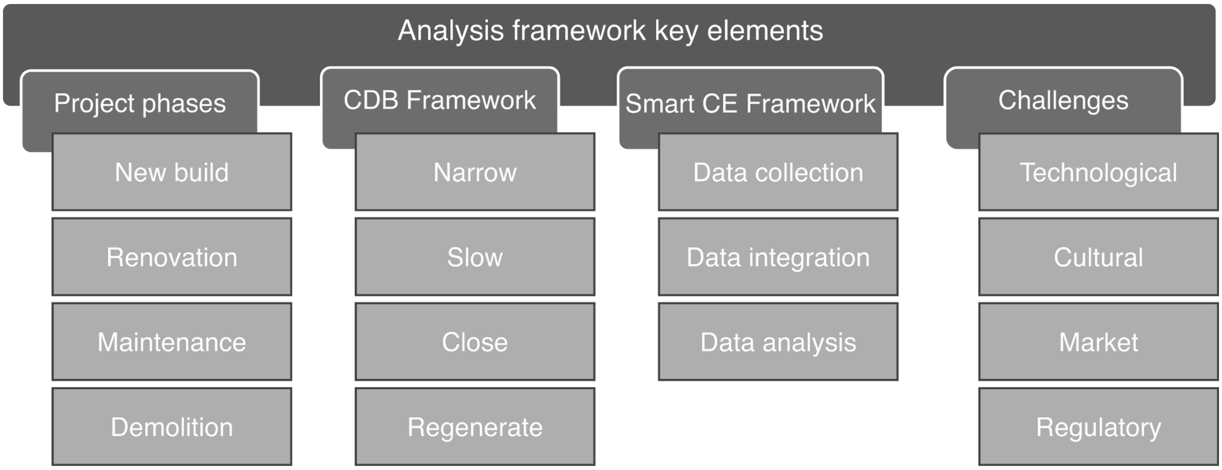

Fig. 1. Key elements of the frameworks used in case analysis (Bocken et al., 2021, 2016; Çetin et al., 2021; Kirchherr et al., 2018; Kristoffersen et al., 2020).

Table 2
Circularity and digitalization targets/projects of the cases.

Case	Long- and mid-term circularity ambitions	Circular pilot projects	Digitalization and real-estate data
Case Alpha	-CO_2-neutral housing stock and operating fully circular by 2050 -Circular roadmap -Green Deal Timber Construction	-Demolition/new construction -Renovation -Circular energy renovation -Transformation (from office to housing) -Maintenance -Marketplace for furniture -Circular nest boxes for biodiversity -Product-as-a-service with white goods	-BIM models exist for new build and renovation projects -Data-in-order program
Case Beta	-CO_2-neutral housing stock and operating fully circular by 2050 -Circular living (for tenants) -Green Deal Timber Construction	-Demolition/new construction -Maintenance -Renovation -Shared laundry rooms -Marketplace for furniture	-BIM models exist for new build and renovation projects -Digital twin of the housing stock (external surfaces only) -Digital house of the future -Data lake
Case Gamma	-CO_2-neutral housing stock -Circularity program	-Demolition/new construction -Maintenance -Renovation	-Digital organization strategy 2019 -Real-estate information program (digital twin of the housing stock) -Data lake

categorize identified DTs. Building on Siow et al. (2019), Kristoffersen et al. (2020) suggest a 3-step hierarchical structure of data flow processes. *Data collection* is the process of data generation and collection from various sources such as the IoT systems (Kristoffersen et al., 2020, Pagoropoulos et al., 2017). *Data integration* represents the process of organizing, maintaining, and sharing collected data for further analysis (Kristoffersen et al., 2020, Pagoropoulos et al., 2017), while *data analysis* is about the process of interpreting data and acquiring actionable decisions (Kristoffersen et al., 2020). We further identified the data requirements of actors for achieving identified circular strategies and whether and how DTs are used for meeting specified needs.

The second phase of the analysis concerned the cross-case analysis. We compared cases by mapping their similarities and differences and identified emerging patterns. Furthermore, cross-case analysis was useful to determine and categorize common challenges for broader DT adoption. Following Kirchherr et al. (2018), we grouped the main challenges into four categories: technological, cultural, market, and regulatory. Kirchherr et al. (2018) initially formulated these categories for identifying barriers to CE implementation across EU countries. While we did not adopt the sub-barriers authors proposed, we translated their conceptualization of four main categories to DT implementation. Fig. 1 displays the key elements of the frameworks that are used for the case analysis.

3. Findings

3.1. Overview of the cases

Case Alpha is one of the early adopters and pioneers of circularity in the sector, aiming to operate fully circular by 2050 by minimising material use, choosing renewable resources that do not harm the natural ecosystem and keeping materials in use as long as possible. The CE is seen as an opportunity to address embodied carbon in buildings to achieve a carbon-neutral stock by 2050. Since 2018, Case Alpha has carried out a wide range of circular pilot projects and initiated in-company and external collaboration groups to increase the awareness and technical know-how of CE implementation. Informed by the experiences of pilots, the organization is working toward setting up a policy roadmap that will enforce employees to include circular elements in their common processes. For example, the roadmap introduces circular design guidelines and a circular materials list so that project managers can make informed decisions when selecting materials or contractors. Case Alpha is also exploring alternative methods to monitor and measure the circularity level of its buildings, such as the Building Circularity Index© (BCI) (BCI, 2022). This index is a new assessment instrument that determines the circularity level of a building based on material compositions, disassembly factors, and the functional lifetime of a

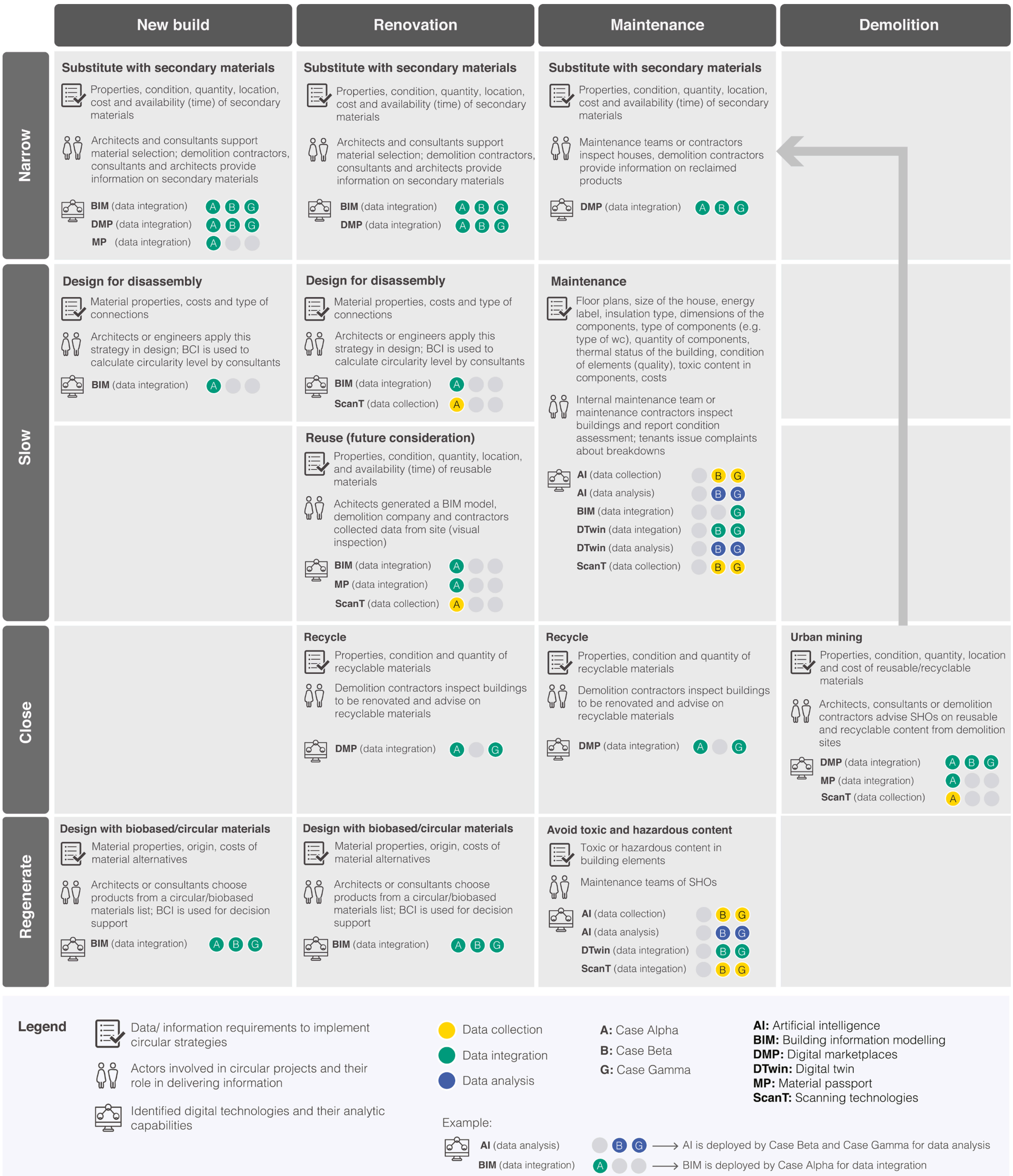

Fig. 2. Summary of the cross-case analysis of identified DTs mapped according to CE principles (y-axis) and project types (x-axis).

building (BCI, 2022, Khadim et al., 2022, Zhai, 2020).

The case SHOs have no common definition of CE. This is in line with more general findings that CE is interpreted in many different ways amongst academics, practitioners and policymakers (e.g., (Kirchherr et al., 2017)). Accordingly, and related to the early stage of development, the SHOs emphasize different aspects of their circular strategies, as can also be seen in Table 2.

Digitalization of the real-estate data is at an immature stage in Case Alpha. Most of the data, such as architectural drawings, are stored in an enterprise resource planning system, typically in PDF format, and maintenance data are fed into a maintenance planning system. Although BIM models are made for new build and renovation projects by involved architects, these models are hardly used or updated upon project compilation. Recently, Case Alpha has begun a new program called "data-in-order" to organize and make accessible real-estate data that will be expanded towards circularity.

Similarly, Case Beta also has long-term circularity and carbon reduction ambitions toward 2050 and sees circularity as an opportunity to curb the carbon footprint of its housing stock. CE is considered a construction method that is based on the reuse of building materials, homes, and areas without depleting natural resources and polluting the environment. Moreover, the organization informs and encourages tenants about CE and supports them with reusing furniture and separating waste. Starting with a circular bathroom renewal project in 2019, where tiles from around 3400 recycled plastic bottles were installed, the organization has experimented with several circular projects (See Table 2). One of the core steps was mapping out material flows and developing decision support frameworks for circular interventions, which are based on the BCI (BCI, 2022).

Case Beta mainly uses an enterprise resource planning system and connected applications for handling real estate data. It has recently introduced a digitalization package for creating a digital twin of its building stock. Case Beta collaborates with a startup that uses AI to generate a 3D model of the housing stock and gives insights into when and where maintenance is required. In addition, Case Beta, together with other SHOs, is developing a digital house that is monitored in real-time to predict maintenance and renovation needs. Lastly, in 2020, the organization set up a data lake with supply chain partners to share data efficiently in carbon reduction projects.

Case Gamma introduced a circularity program in 2019 aiming to integrate a threefold strategy in the construction cycles: (1) reusing materials and choosing biobased materials, (2) keeping buildings in use as long as possible, and (3) circular procurement, encouraging contractors to work circularly. This organization is also preparing a roadmap building on learnings from pilot projects. among pilots, urban mining has been the focal point as the organization formed new collaboration networks with several demolition contractors and architects to use valuable materials coming from their demolition sites. In addition, considering the high costs of maintenance operations, Case Gamma sees circularity as an opportunity to curtail material spending by incorporating secondary products in maintenance operations.

In parallel to circularity, the organization started developing a digital transformation strategy focusing on customers, employees, and real estate data. As part of the real estate information program, a digital twin of the entire building stock has been generated with the help of scanning technologies, drones, BIM, and AI. The buildings were scanned from the inside and outside where possible, and image recognition was used for digitizing architectural drawings. The main goal of generating a digital twin was to improve work processes, data access and sharing, and maintenance operations.

3.2. *Identified digital technologies*

This section presents the findings from the cross-case analysis. A synopsis of the results is given in Fig. 2 where each box illustrates a circular building strategy (e.g., recycle) under a project type (e.g., renovation) and showcases what DT is used to realize this strategy. Furthermore, information requirements defined by interviewees are displayed alongside other actors involved in the processes. In order to demonstrate the analytical capabilities of DTs (i.e., data collection, integration, and analysis), a colour code is used (see legend in Fig. 2). Table A.2 in the appendix supplements Fig. 2 with a selection of interviewee quotes and secondary data.

3.2.1. *Narrow*

Substituting with secondary materials is the narrow strategy that was applied by all cases in the design phase of circular new housing and renovation projects and in maintenance operations, particularly in void repairs. Instead of sourcing new products from the market, project managers of cases, together with other project stakeholders such as architects and consultants, investigated what materials and products could be reused from their to-be-demolished buildings (also called "donor buildings" by the SHOs) so they could reduce primary resource input.

One general trend observed in all cases was the use of digital marketplaces in searching for suitable materials and products from the secondary market or demolition operations (see also Section 3.2.3). These platforms are typically operated by demolition companies that collaborate closely with SHOs. For example, a digital marketplace company developed a special dashboard for Case Beta where reusable elements from circular demolition operations are listed to supply materials to the new construction project of 400 new rental homes. In a circular renovation project, Case Gamma worked with a specialised architecture firm with extensive expertise in reusing materials in design. This firm also operates a digital marketplace, which was the main data source for finding reclaimed products for renovating a building that contained 46 rental homes and six flexible spaces.

BIM is the primary technology used by architects and engineers in the design process, which stores valuable data on building design and material properties and allows design communication between project stakeholders. Our respondents emphasized that BIM models are hardly used or updated upon project compilation. However, BIM is believed to offer a data foundation to generate MPs and support data exchange between project stakeholders, not only for narrowing but also for slowing, closing, and regenerating the resource loops. Project developers and architects of a new housing project of Case Alpha used MPs that were created for reclaimed materials. These MPs were helpful when selecting reusable elements from demolition sites (the process is explained further in Section 3.2.3).

3.2.2. *Slow*

Maintenance is the core slowing intervention in case organizations. Generally, SHOs differ in their maintenance processes between planned maintenance, responsive maintenance, and void repairs. Planned (preventive) maintenance means that activities are scheduled at regular intervals mainly based upon condition assessments, using maintenance planning software filled with data on the condition of buildings, maintenance activities, and costs. Responsive maintenance is done upon residents' complaints, often after breakdowns. Void repairs are realized in between tenancy periods. In-house maintenance departments and contractors are responsible for planning and executing responsive maintenance and void repairs using software integrated into enterprise resource planning systems. Recently, case organizations have taken a more progressive approach by incorporating circular strategies in maintenance processes, particularly for reducing raw material consumption (Section 3.2.1) and avoiding toxic material use (Section 3.2.4).

Both Case Beta and Gamma have collaborated with a technology startup to remotely inspect their housing stock for condition measurement and ease maintenance processes. This startup helped both organizations to produce up-to-date outer skin image models of the entire housing stock. The employees of Case Beta were taught to use drones to scan buildings. The drone images were coupled with satellite images and analyzed by the startup's image recognition system to generate a well-organized and searchable database. This eventually led to reduced time and travel of maintenance personnel, thus less fuel consumption through the fleet. The AI-based system can recognize building elements, measure dimensions, and spot defects on the building skin. It can also detect toxic or hazardous contents and identify energy leakages on the façade.

On the other hand, several image sources such as publicly available street views, inspection photos, and satellite images were used when producing the exterior model of Case Gamma's housing stock. These data were then fed into a BIM model, completing the digital twin of the

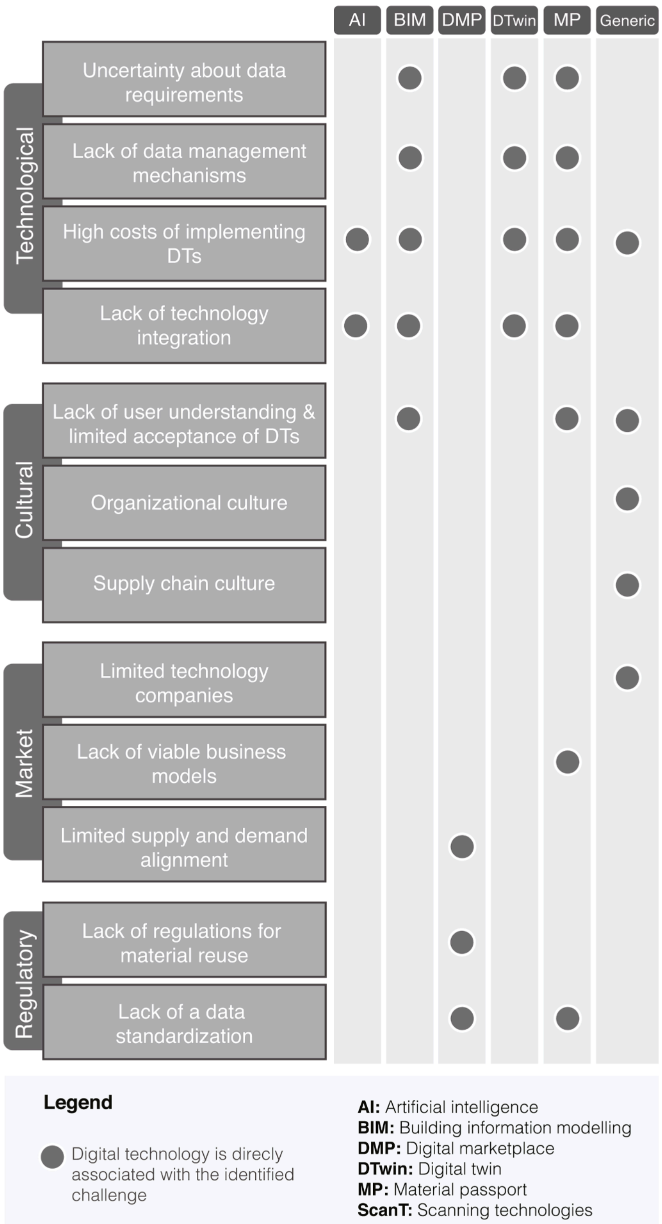

Fig. 3. Challenges emerged from the interview data.

building stock. Case Gamma combined several technologies to generate the digital twin of its housing stock, including machine learning for modelling interior spaces from 2D architectural drawings. The digital twin was developed based on the information delivery specification drawn up with other SHOs that contain the relevant specifications for the management and maintenance of housing. In sum, for both cases, adopting DTs for maintenance provided advantages with work processes, decision-making, and cost reduction and allowed them to get predictive insights into maintenance works.

Design for disassembly is another design strategy applied by architects or engineers in new build and renovation projects to slow the loops. Some of the examples include steel structure design in Case Gamma's renovation project where component connections were made with bolts instead of welding. Although BIM is a core design tool for new build and renovation projects, our findings do not suggest a direct link between BIM and *design for disassembly*.

However, in two circular renovation projects of Case Alpha, BIM was used to store and exchange material data and create MPs. Contractors and demolition partners of Case Alpha used point cloud laser scanners to generate a BIM model of the site and updated the model with a list of reusable materials generated through visual inspection. Later, Case Alpha tested the usability of an MP platform. Some material data from the BIM model were transferred to the MP platform. The process was time-consuming as the MP platform demanded more detailed data than the BIM model had. This process required extra manual work from the technicians. In addition, project managers mentioned that they could not get sufficient output regarding the circularity level of the project from this platform.

3.2.3. Close

Urban mining has become an essential strategy for cases to deal with waste and reduce raw material consumption. All cases have formed partnerships with demolition companies, which now label their business as a harvester or urban miner. These companies usually own a digital marketplace that lists reclaimed materials to match supply and demand sides.

Case Alpha collaborated with a software company that also gives consultancy services for the circular demolition of three apartment buildings. Donor buildings were inspected by the company's experts and scanned with 3D laser scanning technology to create a detailed inventory of materials. The software automatically generated MPs for reusable elements and provided Case Alpha with guidelines on reusing reclaimed materials in other projects. In the circular demolition projects of Case Beta and Case Gamma, demolition contractors performed site inspections, mainly through visual inspection, to create material inventories. These inventories and MPs were useful for architects to design with secondary materials. All cases used digital marketplaces to recycle materials that come out from renovation, maintenance, and demolition operations.

3.2.4. Regenerate

All case SHOs incorporated regenerating the loops strategies in new build and renovation projects by *designing with biobased or circular materials* (e.g., timber as a biobased material and recycled bricks as circular products). Case Alpha developed a list of circular materials and a database of trusted suppliers, which has become an in-company tool for material or contractor selection. Both Case Alpha and Beta tested the BCI (BCI, 2022) in their circular new build and renovation pilots. Two consultancy companies developed a decision support tool (i.e., a menu card) for Case Beta that combines the BCI method (BCI, 2022) with material prices, allowing obtaining environmental impact and circularity level of design alternatives. Besides the circularity performance, a product's price is paramount for SHOs for decision-making. Several interviewees expressed the need for a decision-making tool that gives rapid insights into different design options' financial and circularity performances. Case Alpha is currently investigating how to link the BCI method (BCI, 2022) with BIM to measure the degree of circularity of alternative scenarios in the design stage.

Another regeneration strategy that was employed in the maintenance operations by all case organisations was *avoiding toxic and hazardous contents* in building components. The AI-based inspection system embedded in the digital twins of Case Beta and Gamma can identify anomalies on the building surfaces and detect hazardous contents (e.g., identification of hexavalent chromium in walls) by using an image recognition system.

3.3. Challenges

Previous sections explained how SHOs deployed several DTs in circular projects. This section presents the challenges that emerged from the interview data. Some of the challenges remain generic, indirectly impacting DT adoption in the case organizations, whilst many of them are directly linked to a specific DT, as shown in Fig. 3. A selection of interviewee quotes is presented in Table A.3 in the appendix.

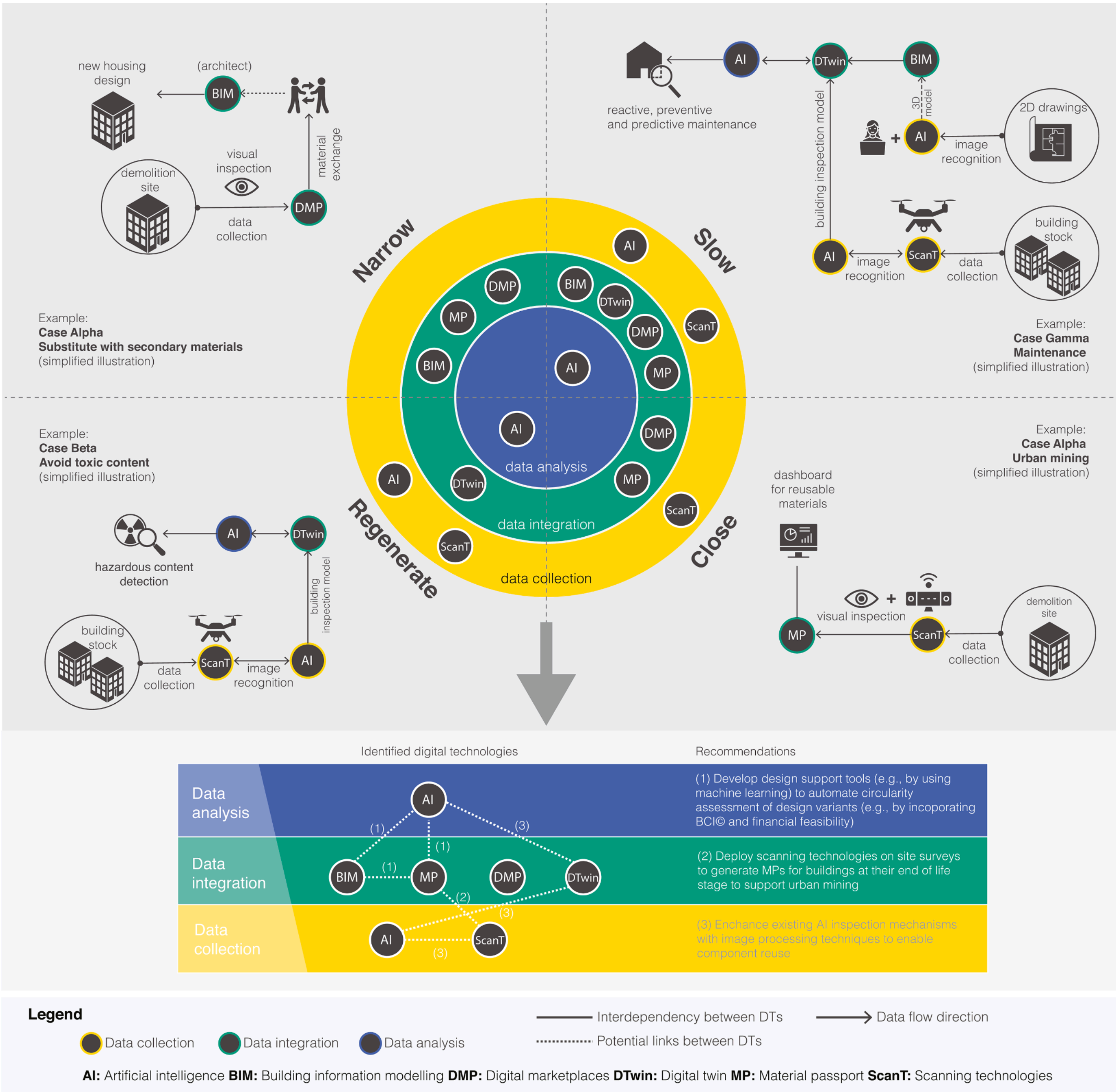

Fig. 4. DTs supporting circular building strategies in SHOs are illustrated with examples and interlinks between each other.

3.3.1. *Technological challenges*

Incorporating DTs in circular processes creates new technology-related challenges for SHOs. One of the major issues that all case organizations mentioned was the uncertainty regarding the data requirements for circular strategies. Although SHOs possess a large volume of real estate data stored in their systems or digital twins, there is a lack of an instrument to organize and translate these data for the purpose of circular strategies. Early attempts to measure the circularity level of circular pilots through the BCI method are thought supportive of defining these data needs. Further steps should be taken to critically identify the data requirements of key stakeholders to allow them to make informed decisions.

Another pressing issue with DT implementation, particularly for MPs, is the lack of a data management mechanism. Theoretically, MPs are created to store material documentation, and track material flows throughout life cycle stages. However, the real-life implementation shows that this process requires updating MPs manually every time a change is made in buildings. As highlighted in interviews, creating and maintaining MPs demand considerable resources from SHOs. They lack the financial and human capacity to sustain such a system for a long time. In addition, interviewees stress the importance of technology integration into their existing systems. Using multiple DTs based on different languages and standards makes interoperability and data sharing challenging. Also, there is a concern about different versions of BIM models as software is usually upgraded, and newer file formats might not be compatible in the future.

3.3.2. Cultural challenges

Our findings suggest that employees of SHOs are reluctant to use advanced technologies in daily practice. For example, an interviewee from Case Alpha indicated that although they obtain BIM models from architects, they prefer to work with 2D drawings. In addition, other interviewees highlighted that even though new technologies are introduced in their organizations, some of their colleagues would resist using these tools because they have been used to working with the same programs and processes for so many years. This cultural behaviour causes hindrance to the entry of new technologies within organizations. A systemic change is needed that goes beyond SHOs. However, such a systemic change is difficult to achieve in an industry characterized by slow technology adoption and a fragmented supply chain. Interviewees expressed that running pilot projects is helpful for learning in organizations. However, to expand the use of DTs in circular operations, a supply chain integration is needed, particularly for efficient data sharing. Another challenge we identified is the hesitant organizational culture. Both CE and digitalization are restricted to the broad corporate vision and pilot projects, lacking a comprehensive adoption of DTs in day-to-day operations. Therefore, DT implementation for circularity becomes a niche area that requires convincing many people in the organization to make investment decisions.

3.3.3. Market challenges

Although there have been numerous DT solutions, their application in practice is restricted due to market or economic limitations. Our respondents were aware of enabling DTs for circular buildings. Still, it was difficult for them to find technology companies in the market that could digitalize their building stock or implement MPs. Case Beta and Gamma, therefore, formed new types of collaborations with young technology firms to develop digital twins, inspection, and advanced analytics tools for maintenance. All cases ran pilot projects with two different MP providers: one generates MPs based on BIM data and manual data entry, and the other has a team of experts scanning buildings and creating an inventory of reusable components with guidelines. The case organizations emphasized the unpractical business model for the former MP provider. SHOs perceive no value in investing time and money today to generate MPs that will only be used decades later. Instead, as the experience of Case Alpha shows, inspecting existing buildings prior to demolition and creating MPs for reusable components seem to be a viable option. However, there is still a question of how to offer a workable business model for MPs targeting circular new build and renovation projects.

Furthermore, our findings suggest that digital marketplaces play a crucial role in narrowing and closing the loops as materials that come out from maintenance, renovation, and demolition operations find a new home by means of these platforms. However, interviewees raised an important issue that these platforms lack a sufficient volume of listed materials, hampering the supply and demand matching on time.

3.3.4. Regulatory challenges

Interviewees associate DT adoption challenges with a few regulatory issues that are closely related to CE implementation. For example, reusing secondary materials through marketplaces raises the issue of meeting quality requirements as measuring the physical quality of secondary products is a tedious task and requires expert inquiry. Materials listed on a marketplace usually lack sufficient information regarding their material properties. Another challenge raised by an interviewee was the lack of a nationwide standardization for data exchange. As mentioned earlier, SHOs are confused about how to measure and monitor circularity and lack a standardized method to perform calculations. There is also uncertainty regarding data requirements for generating MPs. Therefore, an (inter)national data standardization could address these challenges in data management and sharing.

4. Discussion and conlusions

By conducting a multiple-case study of forerunner Dutch SHOs, this study demonstrated empirical evidence from real-life practices extending the existing body of knowledge through the lens of social housing providers that are managing a large portfolio of buildings. The findings of this research shed light on how DTs are deployed in circular new build, renovation, maintenance, and demolition projects for narrowing, slowing, closing, and regenerating the resource loops and what challenges emerge for their broader adoption. To the best of the authors' knowledge, this study contributes to the emerging research field at the intersection of digitalization, CE and the building industry and is one of the few studies displaying practice-based evidence.

Our findings show that even though the case organizations are at the forefront of circularity implementation in the sector, they have only taken initial steps towards digitalization, particularly for circularity. Some of the enabling technologies identified in previous research (Çetin et al., 2021, Heisel and Rau-Oberhuber, 2020, Honic et al., 2019; Munaro and Tavares, 2021, Yu et al., 2022), such as MPs, are typically tested in pilot projects but have not been extensively augmented for day-to-day operations. On the other hand, other emerging technologies like AI-based inspection systems and digital twins offer organizations value through their capabilities in resource optimization and data-driven maintenance operations.

4.1. Discussion of findings

In addressing the first research question, Fig. 4 summarizes how DTs are deployed by the case organizations in circular housing projects. From a CE perspective, case organizations deployed DTs mainly for lifetime extension interventions in maintenance activities (i.e., reactive, preventive, and predictive maintenance). This outcome, to some extent, differs from previous studies that link DTs with mainly reusing or recycling materials (Çetin et al., 2021) and can be explained by the primary responsibilities of Dutch SHOs as they have a long-term perspective on keeping housing available for their target groups with decent quality (AEDES, 2016).

A combination of DTs was used to develop a data-driven maintenance system linked to a digital twin (see example Case Gamma in Fig. 4). AI seems to be a promising technology for data collection and analysis through computer vision techniques. A novel way of digitization was applied to generate the digital twin of the housing stock by modelling inner spaces from archived architectural drawings through AI and coupling it with the exterior models developed through scanning technologies (e.g., point cloud scanners and drones). AI-based inspection systems further enrich the digital twin, giving insights into the physical condition of the skin elements by detecting anomalies and harmful content. This helps also eliminate hazardous content from building stock, thus, supporting the regeneration actions. This innovative way of using AI somewhat differs from the exploratory work of Raghu et al. (2022), which deploys similar image processing techniques to enable component reuse from the existing stock. SHOs could further explore expanding these AI-based inspection systems to identify reusable materials in their portfolio. Such an innovation, as argued by Koutamanis et al. (2018), could enable acquiring precise and accurate data, thus fostering urban mining activities in cities.

DT adoption for narrowing and closing the loops strategies is limited in the case organizations and their project stakeholders. BIM, as a central building data integration technology (Yu et al., 2022), is mainly used by architects and engineers for design coordination in circular new build and renovation projects, while its use in circular demolition projects is absent, confirming arguments of van den Berg et al. (2021). Despite the increasing number of BIM-based decision support tools (Yu et al., 2022), our study found no evidence of their use in practice.

Similarly, the implementation of MPs is restricted to pilots, although case organizations acknowledge the idea behind creating MPs to close the loops. Practitioners perceive MPs as a data inventory system for building materials rather than a design support tool as proposed in previous research (Honic et al., 2019, Munaro and Tavares, 2021). A possible explanation for this might be that SHOs prioritize the financial feasibility of a design option alongside its circularity level, and MPs and BIM frameworks that are available on the market fail to give financial insights into design alternatives. Therefore, incorporating economic factors in decision support tools could boost their use in practice.

Interestingly, to measure and monitor the circularity level of design variants, the BCI (BCI, 2022) from a consultancy company is used by all case organizations. This indicator is not only complementary to the design process but can also inform real estate owners about circularity level of their portfolio. Extension of the BCI or other circularity indices in BIM or MPs could provide opportunities to automate the circularity assessment and support practitioners in the decision-making (Zhai, 2020). Such an extension can be developed using machine learning techniques similar to the tool developed by Płoszaj-Mazurek et al. (2020) for the environmental assessment of architectural designs in the early design stage.

Digital marketplaces for secondary materials are relatively easy to adopt as most platforms are operated by third-party actors (i.e., demolition companies or architects), requiring hardly any investment from SHOs. These platforms are crucial to matching supply and demand sides during the design and demolition phases to narrow and close the material loops. Another interesting finding is that case organizations usually access insightful information through architects, engineers, consultants, and demolition contractors rather than insights gained from analytics, mainly when reusing building materials. For example, demolition companies typically have sufficient expertise in identifying and harvesting materials from donor buildings. At the same time, architects and consultants provide insights into how and where to use these reclaimed materials in renovation or new housing projects. Thus, it is not only a matter of having information available by the SHOs but the value of the information is also linked to specific competencies of supply chain partners. Kristoffersen et al. (2020) suggest that DTs could support these processes for the smart use of resources by, e.g., deploying image recognition for reusable elements in donor buildings.

The second research question relates to the challenges that emerge from the practice for a broader DT adoption in circular processes. The cultural challenges witnessed by the cases are mainly in line with common barriers perceived in the building industry when adopting new technologies (Chan, 2020, Munaro and Tavares, 2021). For instance, as pointed out by Munaro and Tavares (2021), the industry is known for its fragmented supply chain, and the lack of knowledge about circular tools hinders their broader adoption within the sector.

Nevertheless, the case organizations also experience some more specific barriers. An example is the lack of resources for managing lifecycle data in BIM or MPs for an extended period as SHOs maintain their buildings for decades. Keeping data precise and up to date requires skills, time, and investment. Moreover, the business model of current commercialized MP platforms is not viable for SHOs as investing in such a digital infrastructure today to benefit from it after decades raises questions regarding their added value. However, new types of MPs emerged from recent research, such as the one developed by Honic et al. (2021) for existing buildings, could be beneficial for SHOs. Our findings indicate that business-as-usual site surveys are done by demolition contractors or consultants through visual inspection to recover materials. Incorporating scanning technologies in field surveys could enhance the data collection process as well as allow the creation of MPs for buildings that are at their end of life, as proposed by Honic et al. (2021).

Another market-related challenge is the misalignment of supply and demand sides in the secondary material market. Platform literature emphasizes the network effect, the more users and suppliers join a platform, the more attractive the platform becomes, as an essential feature of successful platforms (Gawer and Cusumano, 2014). Digital marketplaces, therefore, should increase their users from both supply and demand sides to deliver secondary materials in adequate quantity and on time.

A pressing challenge regarding governance is the lack of data standardization for circularity. In this respect, the efforts of, for example, Platform CB' 23 (national initiative for circular construction) to develop a framework for circularity indicators and standards (Platform CB'23, 2020) are valuable and should be incorporated into BIM and MP methods.

4.2. Limitations

Of course, the generalizability of our results is subject to certain limitations. For instance, our research depended on data collected from purposefully chosen cases, i.e., large-scale Dutch SHOs. Our data set was restricted to three cases, and more research is needed to confirm our findings in varying organizational sizes, such as in small and medium SHOs. Further research should investigate private owners and other key actors, such as other public clients, architects, construction and demolition contractors, building product suppliers, and other countries advancing in digitalization and circularity.

4.3. Recommendations for practitioners and policymakers

Based on our study, we recommend that SHOs initiate pilots to explore using DTs in managing their building stock, systematically evaluate these and alter standard processes with proven DTs. Considering the barriers we identified, we recommend DT developers and suppliers develop products that are easy to integrate into existing systems and processes, user-friendly, and financially viable. Also, current business models and data management mechanisms of DTs should be arranged in such a way to ease their implementation in large organizations. Lastly, we recommend policymakers and branch organizations stimulate standardization in both circularity measurement and data exchange, which will also increase trust in the long-term value of DTs and adoption by SHOs and their supply chain partners.

Data availability statement

The data presented in this study are openly available in 4TU. Research Data at https://doi.org/10.4121/19732975.v1.

CRediT authorship contribution statement

Sultan Çetin: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization, Project administration. **Vincent Gruis:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition. **Ad Straub:** Conceptualization, Writing – review & editing, Supervision.

Declaration of Competing Interest

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

Acknowledgements

This research is funded by INTERREG NWE project CHARM (Circular Housing Asset Renovation & Management—No More Downcycling), project number NWE 760. The authors would like to thank the housing professionals who participated in the case study, Sebastian Lawrenz for his support in formulating the digitalization part of the case analysis framework, Tanya Tsui and Du Ling for revieweing the first draft of the manuscript and the anonymous reviewers for their careful reading of the manuscript and their many insightful comments and suggestions.

Appendix A

Table A.1
Interview guide for data collection.

Context	Questions
General	• What is your role in your organization? • What CE projects or policy processes have you been involved in?
CE objectives *(For policy advisors)*	• How is CE incorporated into your organization's sustainability objectives? • How does your organization understand/define CE? • What is the level of (maturity) CE implementation in your organization?
CE in strategic decision making *(For policy advisors)*	• How does your organization include CE in the portfolio policy? • How do you measure circularity progress at the portfolio level? • What kind of information/data do you need to make decisions at the portfolio level (for sustainability and CE)? • How do you access the required data/information? • What digital tools do you use for data collection/analysis etc.? • Have you used any specific tools for circularity? • How was your experience with that tool? • What kind of digital tools could support you in implementing CE strategies and decision-making? • Are you familiar with the digital tools that you could use for CE at the portfolio level? • What challenges do you face when implementing new digital tools for CE?
Maintenance and repair	• What kind of maintenance activities does your organization deliver? • What kind of data/ information do you need for that? • How do you access the required data/information? • What digital technologies do your employees use in daily maintenance activities? • What kind of digital tools could support you in implementing CE strategies and decision-making? • What challenges do you face when introducing new digital tools for CE?
Circular pilot projects *(For project managers)*	• What circular principles are applied in the circular new housing/renovation/ demolition projects you are involved in? • How do you access the required data/information? • What digital tools do you use for data collection/analysis etc.? • Have you used any specific tools for circularity? • How was your experience with that tool? • What kind of digital tools could support you in implementing CE strategies and decision-making? • Are you familiar with the digital tools that you could use for CE? • What challenges do you face when implementing new digital tools for CE?
Digitalisation and innovation *(For ICT managers)*	• How does your organization understand and use digitalization? • What is the level of maturity of digitalization in your organization? • How far is your organization's housing stock digitalized? • What kind of technologies are used to manage housing stock data\information? • What kind of data/information is collected from the housing stock? And, how? • How are these data stored and monitored by the employees? • Have you used any specific tools for circularity? • How was your experience with that tool? • What kind of digital tools could support you in implementing CE strategies and decision-making? • Are you familiar with the digital tools that you could use for CE? • What challenges do you face when implementing new digital tools for CE?

Table A.2
Selection of interviewee quotes and secondary data on how DTs are used to implement CE strategies.

CE Principle	Project type/CE Strategy	Digital technology	Example quote/ secondary data
Narrow	New build/ (Substituting with secondary materials)	Digital marketplaces	*"…Yes, you need to know what kind of other materials, not only from our three projects that we demolished but also what is available elsewhere… So that's why we found out, for example, the toilets, we could reuse from a hospital. So, those marketplaces can give us information as well."* -Interviewee A4 (Case Alpha)
	New build/ (Substituting with secondary materials)	Digital marketplaces	*Our demolition/new construction project of 400 new rental homes has been designated as a pilot project for circular construction. That is why we will reuse as much demolition waste as possible as raw material or offer a new life. All reusable (building) materials from buildings to be demolished are offered on a digital marketplace, so that supply and demand can be linked.* -Company website (Case Beta)
	Renovation/ (Substituting with secondary materials)	Digital marketplaces	*"We designed the building and with the technical design, we had lists of stuff we need like glass, wood, all those kinds of stuff. < <Architecture firm> > as an advisor, they looked at a < <digital marketplace> >. I think that's their own platform, but I'm not sure…"*-Interviewee G5 (Case Gamma)
	Maintenance/ (Substituting with secondary materials)	Digital marketplaces	*"Maintenance is a big operation in our organization where a lot of materials and money are spent… And we can relatively easily put reclaimed materials between tenancy periods (interviewee means void repairs) … We started to work with one demolition contractor (who also operates a digital marketplace) in September and now we have four partners helping us reuse elements in maintenance operations."* -Interviewee G1 (Case Gamma)
	New build/ (Substituting with secondary materials)	Material passports	*"… So, < < material passports & consultancy company> > … – We hired them to do this inventory and they made a dashboard of all the materials and the quality of them. Together with the architect, they looked at the timber, for example… – How long would that be used, in what kind of formats, and where can we use it for? etc."* -Interviewee A4 (Case Alpha)
Slow	New build/ (Design for disassembly)	n/a	*"… I mean it's not only the construction where you're looking at but also the skin, of course, the building, facade and the layers of the floor – you will put after. So, we try to make them demountable. So that will give us a higher score (interviewee means BCI score)."* -Interviewee A4 (Case Alpha)
	Renovation/ (Design for disassembly)	n/a	*"…what was very apparent in this project was the steel structure had bolts instead of welding. We use bolts to connect everything so you can take it out again… I don't think that so much has to do with circular activity because you know BIM is just what they use. What I know is that the steel structures are actually being designed in 3D by the producing company…"* -Interviewee G.4 (Case Gamma)
	Renovation/ (Design for disassembly, reuse)	BIM, Material Passports, Scanning technologies	*I have two projects: One is with the extension, and the other one is < <a project name> > in Amsterdam. It's a high apartment building. We also made a BIM project of it. We looked at all the materials that were in the building and these were put into < <a material passports company> > as well to check how accessible < <a material passports company> > really is… It was already scanned and put in a BIM file in the project. And they also incorporated all the materials that are in the building and make a list … We let the architect do this. So now we know how many doors there are or how much wood, concrete, windows … Now we can make a file [of the materials] that we can use in another place or in maintenance… And we created some new parts and there were completely circular as well, so there was nothing glued or something, always screwed. You can take it away and put it somewhere else with the same value as it is here."* -Interviewee A.2 (Case Alpha)
	Maintenance	AI, BIM, Digital twin, Scanning technologies	*"…all PDFs are also scanned (interviewee means architectural drawings) … < <BIM software company> > scans the PDFs and with image recognition, they make BIM models … we started with < <BIM software company> > and then we said what if we give the ILS to < <AI-based tool> > which does the image recognition and say to them deliver all the objects which are exterior objects. If you can do that and then add it to our BIM model from < <BIM software company> >… So basically, we have three ways, just the traditional way of modelling, scanning and modelling, and image recognition and modelling.* *… So if there's a use case like for the exterior we made with a dashboard which says these are old objects which need painting… I guess this summer we have all the data and I hope we can then do some predictive maintenance …"*-Interviewee G.6 (Case Gamma)
Close	Demolition/ (Urban mining, recycle)	Digital marketplaces	*"Think of locks, heaters and in the following residential blocks also kitchen units, toilet bowls and washbasins that still look and work well. We use them to refurbish existing homes. We also reuse bricks, concrete and wooden beams. For example, by grinding bricks to make new bricks…"* -Website of a harvester (Project manager, Case Gamma)
	Renovation (Recycle)	n/a	*"…We had a strategy – Everything that comes out must have a second life or be recycled."*-Interviewee A.2 (Case Alpha)
Regenerate	New build and renovation	n/a	*"… And, then turning the common system into a circular system … We have a list of materials that we use… So, now, we have to look at that list of materials and use more circular materials in it."*-Interviewee A.1 (Case Alpha)
	New build	n/a	*"By informing our colleagues about circularity, we also plan to have the regular situation that every project has a circular target extra … For example, the facade has to be made from more biobased or recycled materials."*-Interviewee B.1 (Case Beta)
	New build and renovation/(BCI)	n/a	

(*continued on next page*)

Table A.2 (*continued*)

CE Principle	Project type/CE Strategy	Digital technology	Example quote/ secondary data
			According to <<Interviewee B.1>>, the first step to arrive at a circular housing stock is to collect information. "That is why we asked <<Consultancy Firm A>> and <<Consultancy Firm B>> to first map out our material flows up to 2050. You need this information to inform colleagues. They cannot act circularly without information." But those choices cannot yet be made with insights into the current material flows alone. That is why <<consultancy firm A>> and <<consultancy firm B>> make menus, which provide insight into the circular options that are available per building section. -Company website of Consultancy Firm A (Case Beta)
	Maintenance/ (Avoid toxic and hazardous content)	AI, Digital twin	*"The AI system can identify materials, from wood to steel, on the surface of our buildings. Chromium 6 (hexavalent chromium), that resides in paint of certain fencing or walls, this system can also identify that. Therefore, we have 60,000 homes and we do not need anymore our personal to go to the location and check these issues…"* -Interviewee B.2 (Case Beta)

Table A.3
Selection of interviewee quotes on challenges.

Challenge	Sub-challenge	Example quote
Technological	Uncertainty about data requirements	"… So, what we're basically looking for is if we've got these goals in sustainability and circularity, what would be the digital assets we need? So, what does that need from us? Like data-wise, what do we have to register from now on to give those insights? … That's still not very clear." -Interviewee G.6 (Case Gamma) *"Why do have to put too much energy into the BIM model to have all the information in it and then we are not going to use it. And I think that we must see the BIM model as a tool that stores only basic information so that we can use it for the maintenance and reference book."*-Interviewee A.3 (Case Alpha)
	Lack of data management mechanisms	*"What I see a lot in the world of data is that it all depends on the people to put the right source into the data system… Data is not up to date. Maintaining and refreshing data, that's where everything goes wrong in organizations."* -Interviewee B.3 (Case Beta) *"I don't see the value of using material passports. Because as I told you that a system does not work if nobody is responsible for updating the data. Imagine we build a house and let it out for 50 years, in those 50 years, all kinds of things are changed, also by the tenants. How do you take of what changes in buildings?… The benefit is only there if you only dismantle the building…"* -Interviewee B.3 (Case Beta)
	High costs of implementing DTs	*"We did one pilot with a material passport platform. It's interesting for us when we are going to do something with the building, not before that. Because it's a lot of work and a lot of costs… You need to put all the information yourself and this requires time.* -Interviewee A.1 (Case Alpha) *"…what my colleagues see about material passports is an extra thing to do, but not as something they can really use."* -Interviewee B.1 (Case Beta)
	Lack of technology integration	*"We also did a pilot with a passport company to see if it's compatible. And it is. But it needs a lot more detail and we can't deliver that now. So, we did the main materials which are in the BIM models but not everything. (New) Tools need to fit into our current tools."* - Interviewee G.1 (Case Gamma) *"No one talks the same language, standards, exchanging data based on standards, open systems…"*-Interviewee G.6 (Case Gamma)
Cultural	Lack of user understanding and limited acceptance of DTs	*"We still don't do enough with BIM. We have programs to review the model that actually we don't use on daily basis. We still look at 2D drawings."* -Interviewee A.4 (Case Alpha) *"We have different programs (software) for digitalization, but not everybody uses them."* -Interviewee A.2 (Case Alpha) *"There are so many tools that we can use so that the level is going up. But Case Alpha is not ready for that because people are not used to … they are not flexible with the systems. They are working for so many years and are stuck on one tool. It is difficult to teach those people to innovate and so that will make it easier for them."*-Interviewee A.3 (Case Alpha) *"… When I started working here, I was not able to find my information and I know now. You really need to start working with programs to get a profit. And I'm still young, so I will. But I know that some people won't do it that fast."* -Interviewee G.5 (Case Gamma)
	Organizational culture	"… if I ask to have a program (software) that isn't supported by our organization, it can take a year because of certificates and then the board has to find something about that…" -Interviewee G.5 (Case Gamma) *"New digital tools will always be difficult to implement because of the organization. We need to change the organization and sometimes that can be hard because many people are working with the same processes. So, if you want to change something in that, it will cost a lot of time for convincing people a lot of people."* -Interviewee A.4 (Case Alpha)
	Supply chain culture	"*If you really want to make it work, you have to have your employees use it. You have to get some volume in using it. Not only one project to pilots is easy, but everyone can also do a pilot. How do you scale up to really using it? And then you have the whole chain. So not only us but also the party who has to use the data in a project, so the circular partners. And how do you exchange data? And so, it's the whole information chain. Which need to be aligned, and that's really a challenge."* -Interviewee G.6 (Case Gamma)
Market	Limited technology companies	"*… We want to build a digital twin of our housing stock, like BIM. But there were very little businesses who could do that."* -Interviewee B.2 (Case Beta)
	Lack of viable business models	

(*continued on next page*)

Table A.3 (*continued*)

Challenge	Sub-challenge	Example quote
		"I see that theoretical model behind material passports is really nice but practically I don't see us maintaining that data for 80 years before it's used… Because it is a long time and a lot can go wrong in maintaining the data… I am more on the side that maybe we should decide when we demolish a building, that's four years in advance, then we go through the building and see what's in it and we can see what we can use for other projects, or we can put it on a marketplace…" - Interviewee G.1 (Case Gamma)
	Limited supply and demand alignment	*"…What is really important for contractors is that materials are really there on time because we cannot stop the whole construction process because of materials that don't show up and you know then there's not going to be successful, and we will not do it."* -Interviewee G.5 (Case Gamma)
Regulatory	Lack of regulations for material reuse	*"Well, the thing is the tools don't say enough. It's good to know which materials there are and maybe when they were installed. But still, I don't know if we can meet all the regulations with those windows."* -Interviewee G.4 (Case Gamma)
	Lack of a data standardization	*"It would really helpful if you have an ILS, a data standard for circularity for sustainability for just maintenance for attachment."-Interviewee G.6* (Case Gamma)

References

AEDES. (2016). Dutch social housing in a nutshell.
AEDES. (2022). De woningcorporaties die lid zijn van Aedes Retrieved 9-May-2022 from aedes.nl/vereniging/de-woningcorporaties-die-lid-zijn-van-aedes.
Akanbi, L.A., Oyedele, A.O., Oyedele, L.O., Salami, R.O., 2020. Deep learning model for demolition waste prediction in a circular economy. J. Clean. Prod. 274 https://doi.org/10.1016/j.jclepro.2020.122843.
Akanbi, L.A., Oyedele, L.O., Omoteso, K., Bilal, M., Akinade, O.O., Ajayi, A.O., Davila Delgado, J.M., Owolabi, H.A., 2019. Disassembly and deconstruction analytics system (D-DAS) for construction in a circular economy. J. Clean. Prod. 223, 386–396. https://doi.org/10.1016/j.jclepro.2019.03.172.
Awan, U., Sroufe, R., Shahbaz, M., 2021. Industry 4.0 and the circular economy: a literature review and recommendations for future research. Bus. Strategy and the Environ. 30 (4), 2038–2060. https://doi.org/10.1002/bse.2731.
BCI. (2022). Retrieved 18-April-2022 from bcigebouw.nl/.
Benachio, G.L.F., Freitas, M.d.C.D., Tavares, S.F., 2020. Circular economy in the construction industry: a systematic literature review. J. Clean. Prod. 260 https://doi.org/10.1016/j.jclepro.2020.121046.
Bocken, N., Stahel, W., Dobrauz, G., Koumbarakis, A., Obst, M., & Matzdorf, P. (2021). Circularity as the new normal. Future fitting Swiss business strategies.
Bocken, N.M.P., de Pauw, I., Bakker, C., van der Grinten, B., 2016. Product design and business model strategies for a circular economy. J. Ind. Prod. Eng. 33 (5), 308–320. https://doi.org/10.1080/21681015.2016.1172124.
Cagno, E., Neri, A., Negri, M., Bassani, C.A., Lampertico, T., 2021. The role of digital technologies in operationalizing the circular economy transition: a systematic literature review. Appl. Sci. 11 (8) https://doi.org/10.3390/app11083328.
Caldas, L.R., Silva, M.V., Silva, V.P., Carvalho, M.T.M., Toledo Filho, R.D., 2022. How different tools contribute to climate change mitigation in a circular building environment?—a systematic literature review. Sustainability, 14 (7). https://doi.org/10.3390/su14073759.
Çetin, S., De Wolf, C., Bocken, N., 2021a. Circular digital built environment: an emerging framework. Sustainability 13 (11). https://doi.org/10.3390/su13116348.
Çetin, S., Straub, A., Gruis, V., 2021b. How can digital technologies support the circular transition of social housing organizations?. In: Empirical Evidence from Two Cases. 2nd International Conference of Circular Systems for the Built Environment-Advanced technological and Social Solutions for Transitions. ICSBE2, Eindhoven, the Netherlands.
Chan, P.W., 2020. Briefing: industry 4.0 in construction: radical transformation or restricted agenda?. In: Proceedings of the Institution of Civil Engineers - Management, Procurement and Law, 173, pp. 141–144. https://doi.org/10.1680/jmapl.20.00036.
Charef, R., Emmitt, S., 2021. Uses of building information modelling for overcoming barriers to a circular economy. J. Clean. Prod. 285 https://doi.org/10.1016/j.jclepro.2020.124854.
Cirdax. (2022). Retrieved 1-April-2022 from cirdax.com/.
Eisenhardt, K.M., 1989. Building theories from case study research. The Acad.Manag. Rev. 14 (4), 532–550. https://doi.org/10.2307/258557.
Ellen MacArthur Foundation. (2022). Schools of thought. Retrieved 5-October-2021 from guides.co/g/mv5ue63s0a/165170.
European Commission. (2020a). Circular Economy Action Plan: for a cleaner and more competitive Europe.
European Commission. (2020b). In focus: energy efficiency in buildings. ec.europa.eu/info/news/focus-energy-efficiency-buildings-2020-lut-17_en.
European Commission. (2021). Recovery plan for Europe. Retrieved 7-October-2021 from ec.europa.eu/info/strategy/recovery-plan-europe_en.
European Commission. (2022). Shaping Europe's digital future- Green digital sector. Retrieved 4-April-2022 from digital-strategy.ec.europa.eu/en/policies/green-digital.
Eurostat. (2018). Waste statistics. Retrieved 27 August 2021 from ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics#Total_waste_generation.
Gawer, A., Cusumano, M.A., 2014. Industry platforms and ecosystem innovation. J. Prod. Innovation Manag. 31 (3), 417–433. https://doi.org/10.1111/jpim.12105.
Geissdoerfer, M., Savaget, P., Bocken, N.M.P., Hultink, E.J., 2017. The circular economy – A new sustainability paradigm? J. Clean. Prod. 143, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048.
Heinrich, M., Lang, W., 2019. Material Passports-Best Practice: Innovative Solutions For a Transition to a Circular Economy in the Built Environment. Technische Universität München i. a. w. B.
Heisel, F., Rau-Oberhuber, S., 2020. Calculation and evaluation of circularity indicators for the built environment using the case studies of UMAR and Madaster. J. Clean. Prod. 243 https://doi.org/10.1016/j.jclepro.2019.118482.
Herczeg, M., McKinnon, D., Milios, L., Bakas, I., Klaassens, E., Svatikova, K., & Widerberg, O. (2014). Resource efficiency in the building sector.
Honic, M., Kovacic, I., Aschenbrenner, P., Ragossnig, A., 2021. Material passports for the end-of-life stage of buildings: challenges and potentials. J. Clean. Prod. 319 https://doi.org/10.1016/j.jclepro.2021.128702.
Honic, M., Kovacic, I., Rechberger, H., 2019. Improving the recycling potential of buildings through Material Passports (MP): an Austrian case study. J. Clean. Prod. 217, 787–797. https://doi.org/10.1016/j.jclepro.2019.01.212.
Housing Europe. (2021). The state of housing in Europe 2021.
Iacovidou, E., Purnell, P., Lim, M.K., 2018. The use of smart technologies in enabling construction components reuse: a viable method or a problem creating solution? J. Environ. Manag. 216, 214–223. https://doi.org/10.1016/j.jenvman.2017.04.093.
Ingemarsdotter, E., Kambanou, M.L., Jamsin, E., Sakao, T., Balkenende, R., 2021. Challenges and solutions in condition-based maintenance implementation - A multiple case study. J. Clean. Prod. 296 https://doi.org/10.1016/j.jclepro.2021.126420.
Khadim, N., Agliata, R., Marino, A., Thaheem, M.J., Mollo, L., 2022. Critical review of nano and micro-level building circularity indicators and frameworks. J. Clean. Prod. 357 https://doi.org/10.1016/j.jclepro.2022.131859.
Kirchherr, J., Piscicelli, L., Bour, R., Kostense-Smit, E., Muller, J., Huibrechtse-Truijens, A., Hekkert, M., 2018. Barriers to the circular economy: evidence from the european union (EU). Ecol. Econ. 150, 264–272. https://doi.org/10.1016/j.ecolecon.2018.04.028.
Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005.
Konietzko, J., Bocken, N., Hultink, E.J., 2020. A tool to analyze, ideate and develop circular innovation ecosystems. Sustainability 12 (1). https://doi.org/10.3390/su12010417.
Koutamanis, A., van Reijn, B., van Bueren, E., 2018. Urban mining and buildings: a review of possibilities and limitations. Resour. Conserv. Recycl. 138, 32–39. https://doi.org/10.1016/j.resconrec.2018.06.024.
Kristoffersen, E., Blomsma, F., Mikalef, P., Li, J., 2020. The smart circular economy: a digital-enabled circular strategies framework for manufacturing companies. J. Bus. Res. 120, 241–261. https://doi.org/10.1016/j.jbusres.2020.07.044.
Li, C.Z., Chen, Z., Xue, F., Kong, X.T.R., Xiao, B., Lai, X., Zhao, Y., 2021. A blockchain- and IoT-based smart product-service system for the sustainability of prefabricated housing construction. J. Clean. Prod. 286 https://doi.org/10.1016/j.jclepro.2020.125391.
Lopes de Sousa Jabbour, A.B., Jabbour, C.J.C., Godinho Filho, M., Roubaud, D., 2018. Industry 4.0 and the circular economy: a proposed research agenda and original roadmap for sustainable operations. Ann. Oper. Res. 270 (1–2), 273–286. https://doi.org/10.1007/s10479-018-2772-8.
Madaster. (2018). Madaster circularity indicator explained. docs.madaster.com/files/Madaster_Circularity_Indicator_explained_v1.1.pdf.
Madaster. (2022). madaster.com/.

Marino, A., Pariso, P., 2020. Comparing European countries' performances in the transition towards the circular economy. Sci. Total Environ. 729, 138142 https://doi.org/10.1016/j.scitotenv.2020.138142.

Miles, M.B., Huberman, A.M., Saldaña, J., 1994. Qualitative Data Analysis: An Expanded Sourcebook. Sage Publications.

Munaro, M.R., Tavares, S.F., 2021. Materials passport's review: challenges and opportunities toward a circular economy building sector. Built Environ. Project and Asset Manag. 11 (4), 767–782. https://doi.org/10.1108/bepam-02-2020-0027.

Ness, D.A., Xing, K., 2017. Toward a resource-efficient built environment: a literature review and conceptual model. J Ind Ecol 21 (3), 572–592. https://doi.org/10.1111/jiec.12586.

O'Grady, T.M., Brajkovich, N., Minunno, R., Chong, H.-.Y., Morrison, G.M., 2021. Circular economy and virtual reality in advanced BIM-Based prefabricated construction. Energies 14 (13). https://doi.org/10.3390/en14134065.

Pagoropoulos, A., Pigosso, D.C.A., McAloone, T.C., 2017. The emergent role of digital technologies in the circular economy: a review. Procedia CIRP 64, 19–24. https://doi.org/10.1016/j.procir.2017.02.047.

Platform CB'23. (2020). Guide- passports for the construction sector - working agreements for circular construction.

Płoszaj-Mazurek, M., Ryńska, E., Grochulska-Salak, M., 2020. Methods to optimize carbon footprint of buildings in regenerative architectural design with the use of machine learning, convolutional neural network, and parametric design. Energies 13 (20). https://doi.org/10.3390/en13205289.

Raghu, D., Markopoulou, A., Marengo, M., Neri, I., Chronis, A., De Wolf, C, 2022. Enabling component reuse from existing buildings through machine learning - using google street view to enhance building databases. In: 27th International Conference of the Association for Computer- Aided Architectural Design Research in Asia (CAADRIA) 2022. Sydney, Australia.

Ranta, V., Aarikka-Stenroos, L., Vaisanen, J., 2021. Digital technologies catalyzing business model innovation for circular economy-Multiple case study [Article]. Resour. Conserv. Recycl. 164 https://doi.org/10.1016/j.resconrec.2020.105155. Article ARTN 105155.

Rijksoverheid. (2016). Nederland circulair in 2050. www.rijksoverheid.nl/onderwerpen/circulaire-economie/nederland-circulair-in-2050.

Rosa, P., Sassanelli, C., Urbinati, A., Chiaroni, D., Terzi, S., 2019. Assessing relations between Circular Economy and Industry 4.0: a systematic literature review. Int. J. Prod. Res. 58 (6), 1662–1687. https://doi.org/10.1080/00207543.2019.1680896.

Shojaei, A., Ketabi, R., Razkenari, M., Hakim, H., Wang, J., 2021. Enabling a circular economy in the built environment sector through blockchain technology. J. Clean. Prod. 294 https://doi.org/10.1016/j.jclepro.2021.126352.

Siow, E., Tiropanis, T., Hall, W., 2019. Analytics for the Internet of Things. ACM Comput. Surv. 51 (4), 1–36. https://doi.org/10.1145/3204947.

Spotr. (2022). Retrieved 4-April-2022 from www.spotr.ai/.

van den Berg, M., Voordijk, H., Adriaanse, A., 2021. BIM uses for deconstruction: an activity-theoretical perspective on reorganising end-of-life practices. Construction Manag. Econ. 39 (4), 323–339. https://doi.org/10.1080/01446193.2021.1876894.

Yin, R.K., 2018. Case Study Research and Applications: Design and Methods, 6th edition. SAGE Publishing.

Yu, Y., Yazan, D.M., Junjan, V., Iacob, M.-.E., 2022. Circular economy in the construction industry: a review of decision support tools based on Information & Communication Technologies. J. Clean. Prod. 349 https://doi.org/10.1016/j.jclepro.2022.131335.

Zhai, J., 2020. BIM-based Building Circularity Assessment from the Early Design stages: a BIM-based Framework For Automating the Building Circularity Assessment from Different Levels of a Building's Composition and Providing the Decision-Making Support On the Design of the Circular Building from the Early Design Stages Eindhoven University of Technology]. Eindhoven, The Netherlands research.tue.nl/en/studentTheses/bim-based-building-circularity-assessment-from-the-early-design-s.