A Conceptual Framework for a Digital Circular Built Environment
The Data Pipeline, Passport Generator and Passport Pool

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THE STATE OF CIRCULARITY

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by

Professor Michael Braungart

And the closing words

By

Prof. Andy van den Dobbelsteen

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How Can Digital Technologies Support the Circular Transition of Social Housing Organizations? Empirical Evidence from Two Cases

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Abstract—**The world is facing an alarming housing crisis. The challenge for the construction industry is to find sustainable ways to meet this growing housing demand. The concept of Circular Economy could be an alternative approach as it aims to regenerate, narrow, slow, and close resources loops. Digital technologies are seen as enablers to implementing these looping strategies through their capabilities for managing information and supporting collaboration and new business model creation. In the built environment, many digital innovations have emerged that support the circular transition of the industry at various spatial scales. However, these innovations mainly focus on nano, micro and macro scales and lack perspectives on the meso level (real estate portfolio). This research aims to understand how digital technologies can support circular strategies at the meso level by collecting empirical evidence from the European social housing organisations actively experimenting with circular strategies. We conducted a multiple-case study method and chose two cases from the UK and Belgium. We collected data through desk research and online group interviews. Our results indicate that housing organisations adopt a wide range of circular strategies for managing their housing portfolio. The support of digital technologies to perform the circularity is low. Our findings suggest five potentially enabling digital technologies at the meso level supporting the housing sector towards circularity: circular asset management tools, digital building logbooks, material passports, BIM, and collaboration tools.**

Keywords—Circular economy, built environment, social housing, digital technology, case study; meso level

I. Introduction

The world, particularly some of the European countries, is facing an alarming housing crisis. The United Nations estimates that three billion people will need new housing by 2030 globally [1]. The Netherlands is no exception. Recently, a coalition of housing sector actors proposed an action plan to build one million homes in the next decade to meet the growing housing shortage [2]. While dealing with this great challenge, the industry should also find sustainable methods to minimize its environmental impact when delivering new housing. On the one hand, the sector operates in a linear system, creating the largest waste and emissions [3, 4]; and, on the other hand, increasing material prices put housing production in jeopardy [5]. The concept of Circular Economy (CE) is believed to be an alternative approach to address negative impact of the building industry on the natural environment as it offers resource-effective sustainable ways of building production and management [5].

The CE is a contested concept [6] that is interpreted by many actors differently. Previous research showed that there are at least 96 definitions proposed by academics and practitioners [7]. In its essence, CE aims to sustain our current and future generations through applying four distinct resourcing principles in the built environment (BE) [8-10]: (1) regenerating resource loops: improving human and natural environments with renewable resources, (2) narrowing resource loops: using fewer primary resources when designing, constructing and operating buildings, (3) slowing resource loops: keeping buildings and products in use by extending their service life through repair and maintenance, and (4) closing resource loops: regaining value from the buildings when they reach their end-of-use stage (e.g. urban mining).

Digital technology (DT) is believed to be an enabler for the adoption of CE principles and business models [11] as current advancements in technology support information management [12] and collaboration and offer new opportunities for value creation through business model innovation [13]. To date, several digital innovations have emerged to support circular strategies in the BE. Amongst these, material passports (MPs), building information modelling (BIM) applications and digital platforms received great attention [10]. The concept of MPs is based on the idea of buildings being the material banks [14] for the future resource of raw materials to close the loops. The EU-funded project BAMB [15] and Madaster Platform [16] were some of the pioneers in developing, testing, and disseminating the concept of MPs. In addition, Honic et al. [17] developed a BIM-based MP concept to evaluate the recycling potential and environmental impact of buildings and later on, a method to create MPs for the buildings at their end-of-life stage [18]. Moreover, various BIM plug-ins have been developed to estimate the disassembly performance of building design variants [19] and measure construction waste [20]. Some other enabling technologies include blockchain technology (e.g. Circularise [9]), digital marketplaces (e.g. Insert [12]), the Internet of Things (e.g. lift-as-a-service), and artificial intelligence (e.g. Façade Service Application [21]).

The importance of DTs is also recognized by policymakers. The European Commission referred to "the twin green and digital transitions" in a post-COVID recovery communication [22] that sees DTs as essential instruments for achieving a green and resilient economy and society. The commission has introduced an EU-wide digital building logbook framework on digitizing building information to support several policy initiatives such as Green Deal, Renovation Wave and CE Action Plan [23]. This framework aims to give transparency to building related data and is defined as follows [23] (p.12): " A digital building logbook is a common repository for all relevant building data. It facilitates transparency, trust, informed decision making and information sharing within the construction sector, among building owners and occupants, financial institutions, and public authorities (…) It can include administrative documents, plans, description of the land, the building and its surrounding, technical systems, traceability and characteristics of construction materials, performance data such as operational energy use, indoor environmental quality, smart building potential and lifecycle emissions, as well as links to building ratings and certificates." This concept has many similarities with land registry and material passports and offers key functionalities for circularity.

Although the number of digital solutions for achieving a circular BE is increasing [10], the question remains on how these DTs are implemented in real life by the BE actors. These innovations are typically developed at the building and product scales for designers (architects, engineers, etc.) and demolition contractors (see next section). There are also a few examples of city scale application of DTs, such as GIS (Geographical Information System) [24]. However, there is a lack of understanding in DT implementation at the meso scale of circular BE, which corresponds to housing estates and public real estate portfolios (e.g. public real estate and university campuses).

In this article, we focus on one type of actor who operates at the building and portfolio scales and plays a crucial role in housing production: social housing associations (SHOs). SHOs are non-for-profit enterprises responsible for delivering decent housing to lower-income and disadvantaged groups in societies [25]. They typically own a large housing stock and are considered societal entrepreneurs because they use their resources for the common social interest [26]. In line with their sustainability targets, SHOs in European countries have started experimenting with circular building strategies in new housing and renovation projects (See, for example, NWE Interreg CHARM Project [27] and academic studies [28, 29]). However, depending on country policies, organizational structure, and resources, and among others the size of the building portfolio, SHOs might implement different circular strategies, and therefore, prefer different digital tools for managing their housing stock circularly.

In this research, we (1) investigate which circular building strategies are implemented in real life by SHOs and (2) explore how DTs could be used to support their circular operations at the meso level. The following section sets the background of the study, proving a brief literature review on the fields of circular BE and enabling DTs. Section 3 presents the case study method, introduces the cases and the data collection procedure. Section 4 presents the findings and includes the discussion of results. Finally, Section 5 concludes the study and gives future research directions.

II. Background Literature

A. Circular Built Environment

Scientists estimate that the anthropogenic mass (human-made solid objects) has surpassed overall global biomass in 2020 [30] and the role of BE in this is not hard to depict. The majority of the growing anthropogenic mass is made by concrete, aggregates, bricks, and metals used in buildings [30]. Heisel and Rau-Oberhuber [31] argue that this anthropogenic stock could be seen as material depots that reserve materials for constructing future buildings and cities. Indeed, many studies in the circular BE research focus on how to reuse and recycle materials from urban stocks as well as other industries for producing new construction products [32]. Correspondingly, BE scholars predominantly consider two life cycle stages [33]: (1) end-of-life stage to recover valuable materials for new construction and waste reduction, and (2) design stage for design for modularity, disassembly, reuse and optimization.

Although the number of studies on circular BE is increasing in recent years [33], there is no widely accepted definition of the circular BE. In their seminal article, Pomponi and Moncaster [34] define circular buildings as the ones designed, planned, built, operated, maintained, and deconstructed in line with CE principles. The authors frame circular BE on three spatial scales: macro (cities and neighbourhoods), meso (buildings) and micro (assemblies and components) [34]. Furthermore, Leising et al. [35] view CE as a life cycle approach that optimizes buildings' useful lifetime and creates new ownership models for buildings as material banks. Last but not least, Çetin et al. [10] frame circular BE around four core resource principles defined by previous research [8, 9]: regenerating, narrowing, slowing, and closing resource loops.

As depicted in Figure 1, we understand circular BE as a system consisting of interdependent spatial scales where resources are regenerated, narrowed, slowed, and closed along the lifecycle stages of built artefacts. The scales considered are nano (materials and products), micro (components and buildings), meso (neighbourhoods and real estate portfolios), and macro (areas, cities, and regions). Regenerating resource loops aims to create systems that leaves the natural environment and society in a better state than before [8, 10] by facilitating the use of biobased materials and renewable resources, eliminating the use of toxic materials and improving biodiversity and human wellbeing. Narrowing resource flows is about cutting down the primary resource consumption when producing and operating buildings through design and operational optimization. Slowing resource use addresses the use stage of buildings and resources and aims to keep them in use by extending their lifetime through maintenance, repair and the smart use of space [10]. Finally, closing resource loops is about recovering value from useful materials in urban stocks by reusing or recycling.

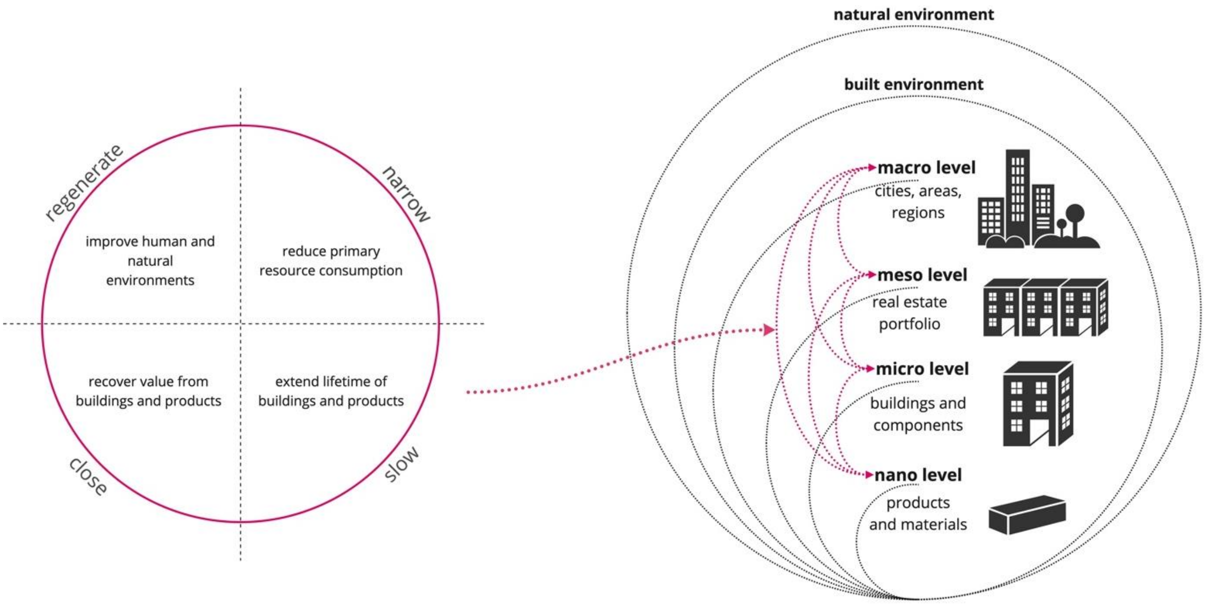

FIGURE I. Framing of the circular built environment. Built on previous research [8-10, 34].

B. Enabling Digital Technologies for a Circular Built Environment

A comprehensive review and mapping of the enabling DTs for a circular BE was recently done by Çetin et al. [10]. The authors identified ten enabling DTs and mapped them onto the Circular Digital Built Environment framework (CDB Framework). See Figure 3. This framework was developed based on the four core resource principles with a supporting strategy on collaboration. Although the CBD framework gives an extensive overview of the digital innovations, it has limitations when it comes to demonstrating spatial scales of the BE and target groups that these DTs are developed for.

Table 1 presents academic studies in the intersection between DTs and circular BE, based on CE principles, scales, lifecycle stages, and target groups. Academic studies predominantly focus on closing resource loops principle to support designers about recycling and reuse potential of various building design alternatives and material choices through BIM [19, 36]. This technology seems to be a powerful tool not only for designing circular buildings but also for evaluating the environmental performance of design options. Furthermore, BIM is used to create MPs [17, 37] as BIM models contain notable amount of data regarding buildings and material compositions of building components. In addition, scholar developed a BIM-based web tool for a material and component bank to facilitate reuse in future [38], a BIM-based framework and databank to estimate future reuse of structural elements [39], and a cloud-based BIM platform linking physical building components with BIM counterparts for life cycle information management and enabling reuse of components with lease and buy and sell business models [40].

Similar to BIM, the concept of MPs has taken a great interest not only in academia but also in practice. MPs are digital datasets of products that contain useful information describing their characteristics, location, history and ownership status, in a varying level of detail based on the scope they are created [10]. They can be created at different aggregation levels ranging from materials to buildings [41]. Academic studies typically consider them as decision support tool and include life cycle analysis as an essential part [17, 37] whereas commercial versions, such as Madaster Platform [16], see the technology as digital registry of building and product data and calculate circularity level of buildings [31]. Both BIM applications and MP technologies are developed for material or products (nano) and component or building (micro) levels.

TABLE I. Overview of the academic studies in the intersection of digital technology and circular built environment. (BIM: Building information modelling; AI: Artificial intelligence; IoT: the internet of things; AM & RM: Additive and robotic manufacturing; GIS: Geographic information system)

Authors	Digital technology	Enabling function	CE Principle	Scale	Life cycle stage	Target group
Akanbi et al. [36]	BIM	Estimating the recycle and reuse potential of design alternatives from the design stage	Close	Micro (Component)	Design	Architects, designers
Akanbi et al. [19]	BIM	Supporting decision making for efficient end-of-life sustainability performance of buildings	Close	Micro (Building)	Design	Architects, engineers
Akanbi et al.[42]	AI (Deep learning)	Estimating end-of-values of buildings after demolition	Close	Micro (Building, Component)	End-of-use	Demolition engineers, surveyors, planners
Akinade & Oyedele [20]	BIM; AI	Improving collaboration within construction supply chain to design out waste	Close	Micro (Building)	Design	Construction supply chain
Atta et al. [37]	Material passports; BIM	Redeveloping material passports to support sustainability	Close	Micro (Building, Component); Nano (Product)	Design	Architects, engineers, environmental agencies, sustainability assessment providers
Bertin et al. [39]	BIM; Material bank; IoT	Enabling structural engineers to anticipate the future reuse potential of structural elements (supported by LCA)	Close	Micro (Component)	Design	Structural engineers
Bruce et al. [43]	AM & RM	Manufacturing building products from recycled plastics	Narrow; Close	Nano (Material; Product)	Manufacture; End-of-use	Not defined
Heisel& Rau-Oberhuber [31]	Material passports	Calculating circularity level of buildings through Madaster platform; enabling better decision making	Narrow; Slow; Close	Micro (Building); Nano (Product)	Construction; Use; End-of-use	Private, industrial, and governmental users
Honic et al. [18]	Material passports; BIM; Laser scanning	Extending material passports model towards existing buildings	Close	Micro (Building)	End-of-use	Not defined
Honic et al. [17]	Material passports; BIM	Optimizing design options for better recycling and environmental performance; inventorying embedded materials in buildings	Close	Micro (Building, Component); Nano (Product)	Design	Architects, planners
Hoong et al. [44]	AI (Deep learning)	Automating identification of recycled aggregate composition through deep learning-based image analysis	Close	Nano (Material)	End-of-use	Recyclers
Jayasinghe & Waldmann [38]	BIM; Database; Web	Documenting and storing building information for better waste management, future reuse, and deconstruction	Close	Micro (Building, Component); Nano (Material)	Construction and end-of-use	Contractors, designers

Kleeman et al. [45]	GIS	Enabling continuous monitoring of a city's building stock and material flows for urban mining	Close	Macro (City)	End-of-use	Not defined
Mogas-Soldevila et al. [46]	AM & RM	Additive manufacturing of regenerated biomaterials	Narrow; Regenerate	Nano (Material); Micro (Component)	Design; Manufacture	Not defined
Oezdemir et al. [24]	GIS	Identification of secondary material stock in an area for urban mining	Close	Macro (Area)	End-of-life	Not defined
Płoszaj-Mazurek et al. [47]	AI (Machine learning)	Evaluating architectural design options in terms of total carbon footprint	Regenerate	Micro (Building)	Design	Architects
van der Berg et al. [48]	BIM	Analysing existing conditions, labelling reusable elements, and planning deconstruction	Close	Micro (Building)	End-of-use	Demolition contractors
Xing et al. [40]	BIM; IoT; Digital marketplace	Linking physical building components with BIM counterparts for life-cycle information management and enabling reuse of components	Slow; Close	Micro (Component)	End-of-use	Suppliers; architects, builders, developers

Other technologies such as artificial intelligence (AI) is used for assessing regenerative architectural design options for improved carbon performance [47]; deep learning techniques are developed for estimating the amount of building materials that would be made available after demolition [42] or for the identification of recycled aggregate compositions through deep image analysis [49]. Additive manufacturing and robotic manufacturing (AM & RM), on the other hand, is explored for material level innovation. For example, researchers manufactured building products from recycled plastic using 3d printing and developed a robotically controlled AM system for producing biodegradable composite elements from regenerative biomaterials [46]. IoT is used for tracking and tracing building components [40]. Both DTs address nano and micro scales of the circular BE.

Finally, at the macro scale, geographical information system (GIS) is deployed for analysing material stocks in urban areas for urban mining. Kleeman et al. [45], for example, analysed overall material stock in Vienna by using available GIS data from municipal authorities to generate a basic form of resource cadastre at the city scale. Similarly, Oezdemir et al. [24] calculated anthropogenic stock of an urban area in Germany with GIS to create a resource cadastre.

Our brief literature analysis showed that there is no single study focusing on enabling DTs for the meso level of circular BE, which corresponds to the real estate portfolio or neighbourhood scales. Also, the majority of the articles presented in Table 1 are theoretical studies lacking empirical evidence from the real-life implementation of DTs, with the exception of [31, 48]. Therefore, this study aims to address these gaps by examining European SHOs who are actively experimenting with CE principles. As mentioned in the introduction, SHOs manage large housing portfolios and are responsible for maintaining the good quality of homes and neighbourhoods. Thus, they are suitable candidates to discover which circular strategies are relevant and how DTs could support the circular transition of the BE at the meso level.

III. METHODS

This study adopted an exploratory multiple-case study to allow a deeper understanding of how DTs could support SHOs. Two cases from European SHOs were chosen to collect empirical evidence. We chose two cases because two or more cases in case study method is considered more robust compared to single-case design [50].

The cases were selected based on (1) location they operate (Europe) and (2) circular ambitions in housing construction. The main characteristics of the cases are presented in Table 2.

TABLE II. Main characteristics of the cases.

	Case Alpha	Case Beta
Location	Belgium	The United Kingdom
Total housing units	2,350	25,000
Total employees	32	4,000

Case Alpha is a small Belgian housing provider operating in the Northern side of the country. Case Alpha considers CE as a way of thinking and applies circular building methods in the daily operations for years, even before the concept became popular, by following a six-step approach:

1. Decrease the demand for all resources
2. Use renewable resources
3. Efficient use of resources
4. Measure and monitor the progress
5. Coach users
6. Share the results with others

The second case study, Case Beta, is a medium sized housing company from England who delivers not only housing but also care services to their residents. They have an off-site manufacturing facility producing timber-framed homes as well as in-house design, construction, and maintenance teams. As shown in Figure 1, Case Beta uses Waste Hierarchy [51] in their operations and sees CE as the reuse element, especially considering resources' future use. That's why they are currently experimenting with a virtually plastic-free housing production concept. Case Beta is committed to a zero-carbon target at the strategic level.

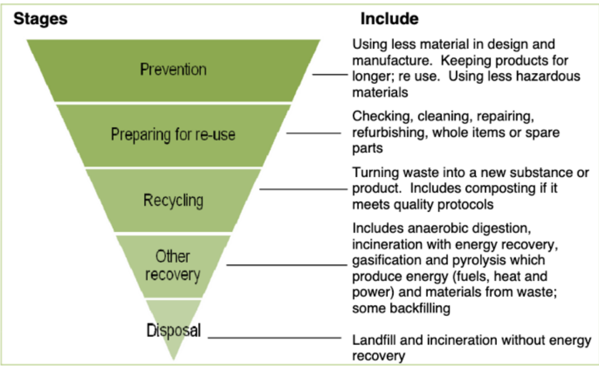

FIGURE II. Waste Hierarchy. Source: [51]

We collected data from multiple sources such as company websites, news, and publicly available reports, and conducted online group sessions with key informants. Table 2 presents the workshop protocol. We used the CDB Framework [10] during the online sessions to map respondents' inputs. The first online session with Case Alpha took around 55 minutes and was attended by one sustainability consultant, one project manager, and the managing director of the SHO. The second workshop with Case Beta lasted around 65 minutes and was attended by an architect, two project administrators, and an assistant director of the SHO.

TABLE II. Group discussion protocol.

Steps	Description	Time (minutes)
Opening	The researchers explain the goal of the workshop and the main elements of the CDB Framework	10
Step 1	The researchers ask the first question and mark participants inputs onto the CDB framework. Q1: "What circular building strategies are being implemented in your organization currently, and which of them are your targets for the future?"	25
Steep 2	The researcher asks the second question and marks participant inputs onto the CDB framework. Q2: "What digital technologies are you currently using when implementing these circular building strategies?"	15
Step 3	The researchers ask participants about ideal digital solutions they would prefer to use for circular building operations and who would take responsibility for developing such tools/technologies.	15
Closing	The researchers close the session.	5

IV. Findings and discussion

A. *What circular strategies do case SHOs implement?*

As displayed in Figure 2, Case Alpha usually involves circularity in the design phase and wants to expand their circular operations towards the operational/use phase. As for regeneration, Case Alpha provides an improved indoor environment to their tenants as a business-as-usual task and incorporate renewable resources (i.e., materials and energy) in housing production. For example, they implemented roof-integrated solar panels in some of the dwellings, where tenants could share their excess energy production with their neighbours. As mentioned previously, decreasing demand for primary resources at the heart of their operations as they use secondary materials in new construction and renovation and make use of rainwater recovery systems. Also, they apply reversible design methods for future reuse of resources. Some of the buildings operated by Case Alpha are designed with common laundry rooms, and tenants are enabled to access washing machines with a small payment through coins. Finally, Case Alpha will be involved in a heat network in the region soon, where they will receive heat from other industries for their housing stock.

Case Beta has a strong focus on regeneration and narrow strategies as they have a factory to produce lightweight timber-framed housing units. They aim to maximise renewable resource use across the life cycle stages, for example, through increasing the use of electric fleet and optimising manufacturing and assembly processes. As for slowing resource loops, they apply a design standard based on flexible space design principles allowing their tenants to adapt their homes according to their changing needs. Reuse as a strategy remains an ambition for Case B because they are only reusing some of the heating and plumbing items in the current state. Finally, in line with their waste management strategy, they apply recycling actions more frequently than reuse.

Our findings indicate that case SHOs are involved in almost all life cycle stages of buildings and implement a range of different circular strategies when producing new housing as well as managing their existing building stock. In that sense, our findings consistent with those of previous studies [28, 29]. However, there is a significant difference when looking at the regenerate principle. According to Kyrö [52], the research on circular BE predominantly focusses on design and end-of-life stages and neglects regeneration. In contrast, as shown in

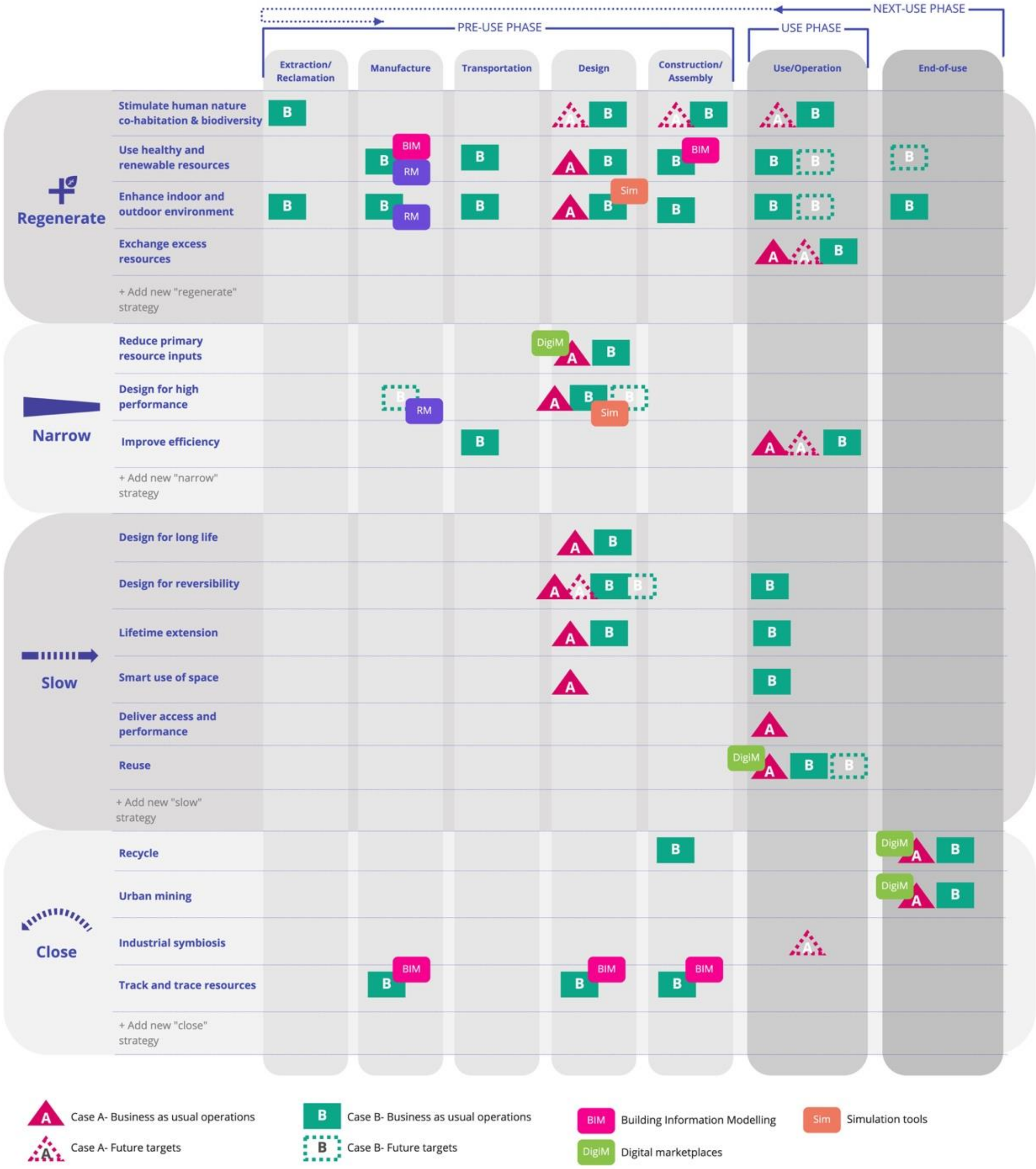

Figure 3, our findings suggest that SHOs implement regenerate strategies in their business-as-usual operations.

FIGURE III. Online group session findings mapped on the CDB Framework [10].

B. *What digital technologies do case SHOs deploy when implementing circular strategies?*

Participants of Case Alpha mentioned that their financial situation does not allow them to use advanced digital solutions for circular operations. Thus, they handle most of the tasks with essential office tools such as spreadsheet software. However, some of their contractors use BIM in construction works, although there is no clear link with BIM use in circular asset management. They also stated that the architecture team that they usually work with does not use BIM for architectural design. On the other hand, Case Alpha uses digital marketplaces to exchange or trade secondary materials in their daily operations and own a warehouse to store reclaimed materials.

Compared to Case Alpha, Case Beta deploys more digital tools to manages their assets and manufacturing processes. Their in-house design team uses BIM for constructional design and manufacturing (CNC machines) of timber frames and as a collaboration tool. Also, they track timber elements through BIM models. Although the use of BIM is limited in the current state, Case Beta aims to implement BIM in the whole business processes. Project and asset managers of Case Beta uses a housing information management system for monitoring properties and life cycle information. Also, they use simulation tools for energy performance calculations (Se Figure 4).

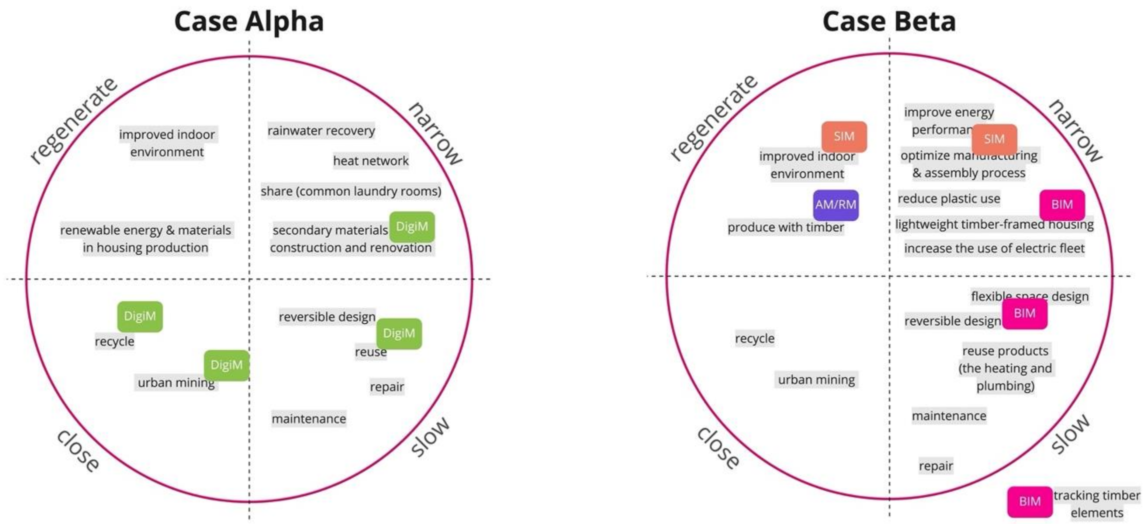

FIGURE IV. Digital technologies used for circular strategies by the case social housing organisations.

C. *How can digital technologies support the circular transition of SHOs?*

At the last stage of the online sessions, we asked participants about an ideal digital solution that they might want to have to support their circular ambitions. Participants of Case Alpha conveyed that a user-friendly circular asset management tool that contains material passports for all their buildings, which help them reuse resources in later stages would be useful. This digital tool must also provide the circularity level of each building and should be connected to an open market to exchange reclaimed materials in the local region. According to the participants, a strong player in the market should develop such a tool, instead of SHOs, such as the local government or a software company.

Participants of Case Beta mentioned two ideal digital solutions for circularity: first, a collaboration tool to keep important tasks recorded in a common platform; and second, an improved cloud-based asset management tool connecting asset management tool to the BIM environment for displaying the attribute data. Such a digital tool would allow different stakeholders access to necessary information and help to reduce paper use. Participants of Case Beta expressed that developing such a digital product is not part of their tasks and they would prefer to buy this software from the shelf.

These findings confirm that digital technology is needed to manage information flows and collaboration effectively in circular housing projects. An expected outcome was that the small size case, Case Alpha, is not able to deploy digital innovations due to the financial constraints whereas the medium sized case, Case Beta, is able to use advanced technologies in their manufacturing facility. That is why digital software services might be interesting for small scale organisations. Particularly, marketplaces seem to be interesting for reintroducing excess resources in the market and create new business opportunities. The findings suggest that MPs, BIM, digital marketplaces, and collaboration tools might support the circular transition of SHOs. Also, a digital asset management is believed to be helpful. Although not mentioned specifically by the participants, however, digital logbooks for buildings could be a suitable technology for housing providers because, as explained in the framework, these logbooks are suggested to be user-friendly and contain important information regarding building's physical building characteristics, environmental performance information and real estate transaction data.

V. Conclusion

This study adopted an exploratory multiple-case study to collect empirical evidence on the digital technology implementation at the meso scale for achieving a circular built environment. We focussed on European social housing organisations because they manage large housing stocks and can be considered as suitable candidates to investigate the meso level of the circular built environment. Two cases from Belgium and the UK were chosen, who actively experiment with circular building strategies. Data were collected from multiple sources like company reports and online group discussions with key informants. Our findings indicate that SHOs are applying a wide range of circular building strategies and are using very few digital tools to assist their circular operations. There is a need for a circular asset management tool that supports creating and managing building information that is user-friendly and accessible by various project stakeholders. This tool would boost the reuse of secondary building materials if connected to a digital marketplace. In many ways, this tool resembles to newly introduced digital building logbook. Furthermore, four digital technologies could potentially support SHOs in their circular operations, namely, BIM, material passports, digital marketplaces, and collaboration platforms.

We argue that organisations operating at the meso level could potentially deploy DTs that are developed for micro and macro scales. As our findings suggest, BIM and material passports could also be used for managing building portfolios circularly. GIS is used for determining material stocks at the city scale. A further study could look at how GIS data could be integrated in decision making processes of housing organisations. The scope of this study was limited in terms of search terms used to explore enabling DTs as we only focussed on circular economy related articles. Therefore, other potentially enabling technologies such as big data analytics could be explored for predictive maintenance of real estate portfolios.

A limitation of our work is the generalizability of our findings, as we examined only two cases. A further study could assess SHOs in different countries, particularly where social housing is dominant. Also, technology implementation of SHOs might vary by company size. This study examined one small and one medium sized organization. Further research could look at larger organizations as well as other public and commercial real estates. Our further research will focus on the circular transition of large forerunner housing associations operating in the Netherlands and explore how digital innovations could support their circular ambitions.

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