Towards a circular building industry through digitalisation

Exploring how digital technologies can help narrow, slow, close, and regenerate the loops in social housing practice

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DOI
10.7480/abe.2023.22

Publication date
2023

Document Version
Final published version

Citation (APA)
Çetin, S. (2023). *Towards a circular building industry through digitalisation: Exploring how digital technologies can help narrow, slow, close, and regenerate the loops in social housing practice*. [Dissertation (TU Delft), Delft University of Technology]. A+BE | Architecture and the Built Environment. https://doi.org/10.7480/abe.2023.22

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A+BE | Architecture and the Built Environment | TU Delft BK

23#22

Design | Sirene Ontwerpers, Véro Crickx

Cover photo | Vincent Toprak

ISBN 978-94-6366-786-9
ISSN 2212-3202

This dissertation is open access at https://doi.org/10.7480/abe.2023.22

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Dissertation

for the purpose of obtaining the degree of doctor
at Delft University of Technology
by the authority of the Rector Magnificus, prof.dr.ir. T.H.J.J. van der Hagen
chair of the Board for Doctorates
to be defended publicly on
Monday, 18 December 2023 at 12:30 o'clock

by

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This dissertation has been approved by the promotors.

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This study was financed by INTERREG NWE project CHARM (Circular Housing Asset Renovation & Management—No More Downcycling), project number NWE 760.

To my most loved ones,
Vincent Toprak, Atlas, and Tomris Lente.

Preface

Embarking on a PhD journey is often described as a significant challenge, demanding strength and determination. Over the past four years, my experience has been a mix of fascinating discoveries and emotional struggles.

In 2019, I began exploring digitalisation for a circular building industry—a new and exciting topic. With guidance and freedom from my supervisors, I delved into the digital world to discover solutions. The academic freedom I experienced during this time made these years the most productive and enjoyable of my life.

Amidst the joy of academic exploration, the world underwent significant transformations, marked by the COVID-19 pandemic, echoes of war in Ukraine and Gaza, floods and wildfires around the globe, and seismic shifts in Türkiye. Each event served as a stark reminder of the fragility of human existence, leaving behind ruins and countless loss of lives. This contrast triggered deep contemplation and, at times, a sense of helplessness. While my research aimed to contribute to a sustainable built environment, global events overshadowed these efforts. Real-world complexities seemed distant from the ideals and aspirations I held, and as a parent of two little kids, I grappled with the realisation that my power to effect change on a larger scale was limited.

Throughout these four years, I've learned the value of staying optimistic and advocating for a better, safe, and sustainable future. This book is my first step toward contributing to that future, and I'm dedicated to building upon this research to offer solutions to the part of the world that is less fortunate. In the end, we all share one planet with limited resources and achieving a truly circular and sustainable world requires considering the needs of the entire globe.

Acknowledgments

Reading acknowledgements in a thesis has always been a joy for me—an exploration of the unsung heroes that make a PhD successful alongside the candidate.

Let me begin by expressing my profound gratitude to my supervisors, Prof. Dr. Ir. Vincent Gruis and Dr. Ir. Ad Straub. I feel incredibly fortunate to be your PhD candidate, benefiting from your guidance that allowed me to grow autonomously. Commencing this academic pursuit under your mentorship has been an exceptional privilege, shaping not only my academic trajectory but also fostering the independence that defines my scholarly identity. Thank you, Vincent, for teaching the invaluable skill of pragmatism in navigating complex situations. Thank you, Ad, for consistently offering kindness and gently steering me back to the core focus of our research.

I want to thank the esteemed committee members, Prof. Dipl.-Ing.Dr. Kovacic, Prof. Dr. Ir. Adriaanse, Prof. Dr. Chan, Prof. Dr. Ir. Wamelink, and Dr. Remøy, for generously investing their time in reviewing and participating in the defence of my PhD work.

I consider myself very lucky to have collaborated with significant scholars in our field. Prof. Dr. Nancy Bocken from Maastricht University and Prof. Dr. Catherine De Wolf from ETH Zurich hold a special place, as we wrote papers, established a knowledge platform (DiCE Lab), and co-edited the first comprehensive book of our field—all achieved without ever meeting in person. I've learned a great deal from you. I want to thank my co-authors, Dr. Julia Nussholz, Dr. Meliha Honic, Deepika Raghu, Dr. Boriana Rukanova, Dr. Halima Sacraine, and Jill Vervoort for their collaborative efforts and shared dedication. A special note of appreciation goes to Dr. Julian Kirchherr, Dr. Meliha Honic, and Dr. Daniel Hall, with whom I engaged through editorial activities in the Journal of Circular Economy. I extend my heartfelt thanks to Rory Nuijens from the Dutch Consulate in Istanbul, Prof. Dr. Birgul Colakoglu from Istanbul Technical University, Peter Hoogeweg from EFL, and the DiCE Lab team for their invaluable contributions to organising international events that played a pivotal role in expanding our research field into practical domains.

I extend my sincere appreciation to the housing professionals who anonymously participated in this research. Their valuable insights formed the backbone of this study. Additionally, I am grateful for the support of Henk Korevaar, Ilse van Andel, Jeroen Hollander, Carlijn Stoof, Kevin van der Vliet, Tim van de Kerkhof, and CHARM partners in enriching my research and expanding my network within the social housing sector. I wish to acknowledge the crucial role played by the funding from the Interreg NWE CHARM Project. Without this support, undertaking this PhD would not have been possible.

My time doing PhD, especially with the challenges of COVID-19, was made better by the great people I worked with. Even though I lived in Amsterdam, not Delft, going to the office always felt a bit special. Among the many good memories, some people were extra special. Felipe, a constant presence, was a hug away, offering unwavering support during our frequent meetings in Delft and Amsterdam. Céline, a companion through lonely COVID times, shared her expertise in writing and comfort through video calls. We shared a lot, talking in Turkish and Dutch. Anne (van Stijn), though our paths seldom crossed physically, maintained a profound connection through our extensive phone calls. You are a true warrior, and you inspire me! A big shout-out to Anna (Batallé), who not only worked with me in the DiCE Lab but became a great friend, even a shared one with my son Vincent Toprak. I want to thank Daniel and Paul for their valuable advice on my academic journey. A heartfelt thank you to Tanya, Lu, Lucy, Artur, Bandon, Yifei, Joana, Marc, Alex, Wendy, Bailey, Stijn, Sun Ah, Tan, and others who generously reviewed my papers and/or assumed the roles of mock committee members. Maca, Koray, and Hazal, I want you to know how much your emotional support meant to me after the disastrous earthquakes in Türkiye. Your kindness will always be remembered. A warm thank you to the MBE secretary and HR teams, with special appreciation for Joke and Anuschka. Chatting with them has been a pleasure, and their assistance has been invaluable.

As my PhD journey progresses, so does my integration into Dutch life, having lived in the Netherlands for the past seven years. Several individuals have played a key role in making this country feel like home by generously teaching and sharing the intricacies of Dutch culture and language with us. Jill, you're not just my best friend; you've been a constant pillar of support, always there when I needed it. Your role as "tante" to Vincent and Tomris and the warm addition to our dinner table as our fifth family member has made our bond even more special. Marijke, you're a true inspiration in life, and being around you teaches me so much. I feel incredibly lucky to know you. Our regular coffee and eating sessions with Maarten and Debby, as well as Maarten and Heinz-Josef, have added depth to our Dutch experience and gave us a lot of joy.

Heartfelt thanks to my family and friends. Tunc, Arzu, Serge, and Burcu, thanks for always being there for me. A special mention to my sister Selcen, who lent her designer eye to help create beautiful figures, simplifying complex academic issues for the reader. And to my twin brother Haydar, your mere presence and occasional jokes make me consistently happy. Sevgili Hülya ve Zekoş, eğer sizler olmasaydınız yine doktoramı tamamlayabilirdim; ancak hem Toprak'ın hem de Tomris'in ilk aylarını bu kadar kolay atlatabilir miydim bilemiyorum. Hakkınızı ödeyemem, iyi ki varsınız!

And the final piece of gratitude goes to my husband, Galip Okan. We are two nerds who complement each other so well. Countless sleepless nights were spent either caring for our babies or working tirelessly to achieve our goals in life, all while keeping an eye on the worries in the global news. As you built your own company, I built my own Ph.D. Your hard work and perseverance have been a great inspiration to me. I've learned so much from you, especially in regulating my emotions and becoming a stronger person. I can't thank you enough for your unwavering support. Someday, please take a moment to read one of my papers. I'm sure you'll like it (J).

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Summary

The concept of Circular Economy (CE) has emerged as a promising alternative to the current linear economy, decoupling economic activity from the depletion of natural resources and promoting a restorative and regenerative system. The transition of the building industry to a circular one can be achieved through four core resource principles: ***Narrow*** (minimising the use of primary resources), ***slow*** (extending the lifetime of buildings and products), ***close*** (regaining post-use and construction waste through reuse or recycling), and ***regenerate*** (minimising toxic substances and maximising the use of renewable resources). These principles provide a framework for exploring the role of ***digitalisation*** in the transition of ***social housing organisations*** (SHOs) toward ***circular housing practices***, with a focus on European SHOs, particularly those in the Netherlands. This thesis follows a structured format comprising six chapters, with four of them encapsulating the author's published articles.

Chapter 1 serves as the **introduction**, providing a contextual foundation for the research. It outlines the overarching theme of the thesis, which revolves around the intersection of CE, digitalisation, and the built environment, with a specific focus on SHOs. The chapter sets the stage by identifying the gaps in existing literature, emphasising the need for a comprehensive conceptualisation of this emerging research field. It further delves into essential methodological aspects, the problem statement, and the broader significance of the research.

In **Chapter 2**, the research delves into **an exploration** of the current state of CE implementation in Dutch SHOs and provides insights into the pressing barriers, and potential enablers. A Delphi study conducted with 21 social housing professionals reveals that, as of 2020, SHOs were in an experimental phase, incorporating circular construction techniques in pilot projects. Barriers encompass organisational priorities, operating within a linear system, and a lack of awareness. Also, financial challenges related to the costs of circular materials also emerge as significant hurdles.

Chapter 3 develops **a framework**, the Circular Digital Built Environment Framework, in an exploratory qualitative research approach. This conceptual model integrates CE principles with digital technologies to provide an understanding of their potential applications within the built environment. The framework is constructed through

expert workshops, literature reviews, and evaluations of current research and practices, resulting in the identification of over ten key digital technologies. These technologies encompass a broad spectrum, including big data analytics, blockchain technology, and material passports. The framework not only informs subsequent empirical studies but also serves as a valuable guide for scholars and industry practitioners navigating the intersection of digitalisation and circularity in the building industry.

Chapter 4 presents **an analysis** of how enabling digital technologies ,identified in Chapter 3, are practically employed in real-life practices, specifically within circular new build, renovation, maintenance, and demolition projects of forerunner Dutch SHOs. Employing a multiple-case study approach, the chapter gathers empirical evidence from three large-scale SHOs through semi-structured interviews, desk research, and extensive data analysis. The within-case and cross-case analyses reveal insights into the types of digital technologies being deployed, their impact on circular practices, and the challenges encountered in their adoption. By examining the real-world examples, Chapter 4 contributes to the evolving domain of digitalisation for a circular building industry.

Chapter 5 addresses the challenges associated with data (identified in Chapter 4), with a specific focus on material passports as **a crucial tool** for circularity in existing housing stock. Employing a multiphase mixed-method research design, the chapter utilises the SCOPIS method (Supply Chain-Oriented Process to Identify Stakeholders) for user and data mapping. This approach results in a data template outlining the requirements of users for material passports. Subsequently, the study tests this template through a case study, identifying critical data gaps and proposing a material passports framework to address these gaps. By leveraging both digital technologies and human expertise, Chapter 5 offers solutions to enhance data management in the pursuit of circularity within the building industry. The findings contribute to ongoing industry and policy initiatives.

Chapter 6, the **concluding** chapter, consolidates the exploration conducted throughout the thesis. It presents the overarching contributions of the research, offering a summary of the scientific and practice contributions and recommendations derived from the entire study.

Samenvatting

Het concept van de Circulaire Economie (CE) heeft zich ontwikkeld tot een veelbelovend alternatief voor de huidige lineaire economie. In de CE wordt een economische activiteit losgekoppeld van de uitputting van natuurlijke hulpbronnen en wordt een herstellend en regeneratief systeem bevorderd. De overgang van de lineaire bouwsector naar een circulaire bouwsector kan worden bereikt door vier kernprincipes van hulpbronnen: vernauwen (het minimaliseren van het gebruik van primaire hulpbronnen), vertragen (de levensduur van gebouwen en producten verlengen), sluiten (herwinnen van grondstoffen na gebruik en bouwafval door hergebruik of recycling) en regenereren (minimaliseren van giftige stoffen en maximaliseren van het gebruik van hernieuwbare hulpbronnen). Deze principes bieden een kader voor het verkennen van de rol van digitalisering in de transitie van sociale huisvestingsorganisaties (SHO's) naar circulaire huisvestingspraktijken, met een focus op Europese SHO's in het specifiek in Nederland. De onderzoeksresultaten van dit proefschrift zijn gestructureerd in zes hoofdstukken, waarvan er vier de gepubliceerde artikelen van de auteur betreffen.

Hoofdstuk 1 dient als inleiding en biedt een contextuele basis voor het onderzoek. Dit hoofdstuk draait om de intersectie van CE, digitalisering en de gebouwde omgeving, met een specifieke focus op SHO's. Het hoofdstuk zet de toon door lacunes in bestaande literatuur te identificeren, waarbij de noodzaak wordt benadrukt voor een alomvattende conceptualisering van dit opkomende onderzoeksveld. Het gaat verder in op essentiële methodologische aspecten, het probleemstatement en de bredere betekenis van het onderzoek.

Hoofdstuk 2 duikt dieper in de huidige situatie van CE-implementatie in Nederlandse SHO's en biedt inzichten in de dringende knelpunten en potentiële stimulerende factoren. Een Delphi-studie, uitgevoerd met 21 professionals uit de sociale huisvesting, onthult dat SHO's zich in 2020 in een experimentele fase bevonden, waarbij circulaire bouwtechnieken werden geïntegreerd in pilotprojecten. Knelpunten die naar voren kwamen omvatten onder andere organisatorische prioriteiten, werken binnen een lineair systeem en een gebrek aan bewustzijn. Ook financiële uitdagingen met betrekking tot de kosten van circulaire materialen komen naar voren als significante knelpunten.

Hoofdstuk 3 ontwikkelt een raamwerk, het Circulaire Digitale Gebouwde Omgeving Raamwerk, in een benadering van exploratief kwalitatief onderzoek. Dit conceptuele model integreert CE-principes met digitale technologieën om inzicht te bieden in hun potentiële toepassingen binnen de gebouwde omgeving (breder dan SHO's). Het raamwerk is tot stand gekomen via expertworkshops, literatuurstudies en evaluaties van huidig onderzoek en praktijken, resulterend in de identificatie van meer dan tien belangrijke digitale technologieën. Deze technologieën omvatten een breed scala, waaronder big data-analyse, blockchaintechnologie en materiaalpaspoorten. Het raamwerk informeert niet alleen daaropvolgende empirische studies, maar dient ook als praktische gids voor wetenschappers en bedrijfsprofessionals die de intersectie van digitalisering en circulariteit in de bouwsector verkennen.

Hoofdstuk 4 analyseert hoe de geïdentificeerde digitale technologieën (Hoofdstuk 3) worden toegepast in praktijksituaties, specifiek binnen circulaire nieuwbouw-, renovatie-, onderhouds- en sloopprojecten van vooruitstrevende Nederlandse SHO's. Met behulp van een meervoudige casestudybenadering verzamelt het hoofdstuk empirisch bewijs van drie grootschalige SHO's via semigestructureerde interviews, bureauonderzoek en uitgebreide gegevensanalyse. De binnen-case en cross-case analyses onthullen inzichten in de soorten digitale technologieën die worden ingezet, hun impact op circulaire toepassingen en de uitdagingen die zich voordoen bij hun inpassing. Door praktijkvoorbeelden te onderzoeken, draagt Hoofdstuk 4 bij aan de ontwikkeling van digitalisering voor een circulaire bouwsector.

Hoofdstuk 5 behandelt de uitdagingen die verband houden met gegevens (geïdentificeerd in Hoofdstuk 4), met een specifieke focus op materiaalpaspoorten als een cruciaal instrument voor circulariteit in de bestaande woningvoorraad. Met behulp van een meervoudig gefaseerde mixed-method onderzoeksontwerp gebruikt het hoofdstuk de SCOPIS-methode (Supply Chain-Oriented Process to Identify Stakeholders) voor het in kaart brengen van gebruikersinformatie en materiaalgegevens. Deze aanpak resulteert in een gegevenssjabloon waarin de eisen van gebruikers voor materiaalpaspoorten worden geschetst. Vervolgens test de studie dit sjabloon via een casestudy, waarbij kritieke gegevenslacunes worden geïdentificeerd en een raamwerk voor materiaalpaspoorten wordt voorgesteld om deze lacunes aan te pakken. Door zowel digitale technologieën als menselijke expertise te benutten, biedt Hoofdstuk 5 oplossingen om gegevensbeheer te verbeteren in het streven naar circulariteit binnen de bouwsector. De bevindingen dragen bij aan lopende initiatieven in de industrie en het beleid.

Hoofdstuk 6, het afsluitende hoofdstuk, consolideert de verkenning die gedurende het proefschrift is uitgevoerd. Het onderstreept de relevante inzichten uit het onderzoek en vat de meerwaarde samen ten aanzien van zowel de wetenschap als de praktijk. Dit hoofdstuk sluit af met aanbevelingen voor vervolgonderzoek, die zijn afgeleid uit het gehele promotieonderzoek.

Özet

Döngüsel Ekonomi (DE) kavramı, mevcut lineer ekonomiye umut vaat eden bir alternatif olarak ortaya çıkmıştır; ekonomik faaliyeti doğal kaynakların tükenmesinden ayırarak yenileyici ve yeniden üretilebilir bir sistemi teşvik eder. İnşaat sektörünün döngüsel bir modele geçişi, dört temel kaynak ilkesi aracılığıyla gerçekleştirilebilir: Daraltma (birincil kaynakların kullanımını en aza indirme), yavaşlatma (binaların ve ürünlerin ömrünü uzatma), kapatma (kullanım sonrası ve inşaat atıklarını yeniden kullanma veya geri dönüştürme) ve yenilenme (toksik maddeleri en aza indirme ve yenilenebilir kaynakların kullanımını maksimize etme). Bu prensipler, sosyal konut organizasyonlarının (SKO'lar), özellikle Hollanda'dakilerin, döngüsel konut uygulamalarına geçişinde dijitalleşmenin rolünü araştırmak için bir çerçeve olarak kullanılmıştır. Altı bölümden oluşan bu tez, dördü yazarın uluslararası hakemli dergilerde yayımlanan makalelerini kapsayacak şekilde yazılmıştır.

Birinci Bölüm, araştırmaya bağlam sağlayarak giriş görevi görür. Tezin ana temasını, DE, dijitalleşme ve yapılı çevre kesişimi etrafında dönen bir şekilde tanımlar; özellikle SKO'lar üzerine odaklanır. Bu bölüm, mevcut literatürdeki boşlukları belirleyerek, bu yeni araştırma alanının kapsamlı bir şekilde kavramsallaştırılmasının gerekliliğini vurgular. Ayrıca, temel metodolojik yönleri, problem açıklamasını ve araştırmanın önemini daha ayrıntılı bir şekilde ele alır.

İkinci Bölüm, Hollanda'daki SKO'larda DE uygulamasının mevcut durumunu analiz edip, engelleri ve potansiyel çözümleri anlamamıza katkı sağlar. Sosyal konut organizasyonlarında çalışan 21 profesyonel ile gerçekleştirilen bir Delphi çalışması, 2020 itibariyle SKO'ların deneysel bir aşamada olduğunu, döngüsel inşaat tekniklerini pilot projelerde entegre ettiklerini ortaya çıkarmıştır. Engeller, organizasyonel öncelikler, lineer bir sistem içinde çalışma ve farkındalık eksikliklerini içerir. Ayrıca, döngüsel malzemelerin maliyetleriyle ilgili finansal zorluklar da önemli engeller olarak ortaya çıkmıştır.

Üçüncü Bölüm, keşifsel nitel bir araştırma yaklaşımıyla yeni bir çerçeve geliştirir. Bu kavramsal model, DE prensiplerini dijital teknolojilerle entegre ederek, bu teknolojilerin inşa edilmiş çevre içindeki potansiyel uygulamalarını anlamamıza yardımcı olur. Çerçeve, uzman görüşleri, literatür taramaları ve mevcut araştırma ve uygulamaların değerlendirmeleri aracılığıyla oluşturulur ve on anahtar dijital teknolojinin belirlenmesiyle s onuçlanır. Bu teknolojiler, yapay zeka, blok zincir

teknolojisi ve malzeme pasaportları gibi geniş bir yelpazeyi kapsar. Çerçeve, sadece sonraki ampirik çalışmaları bilgilendirmekle kalmaz, aynı zamanda dijitalleşmenin ve döngüsel bir yaklaşımın inşaat sektöründeki kesişiminde gezinen akademisyenler ve endüstri uygulayıcıları için değerli bir rehber olarak da hizmet eder.

Dördüncü Bölüm, Üçüncü Bölüm'de belirlenen etkinleştirici dijital teknolojilerin, özellikle de Hollanda'daki öncü SKO'ların döngüsel yeni inşa, renovasyon, bakım ve yıkım projelerinde nasıl pratikte kullanıldığını analiz eder. Çoklu vaka çalışması yaklaşımı kullanarak, üç büyük ölçekli SKO'dan empirik kanıtlar toplar. Metodoloji, yarı yapılandırılmış görüşmeler, masaüstü araştırma ve kapsamlı veri analizini içerir. İç durum ve çapraz durum analizleri, kullanılan dijital teknolojilerin türleri, döngüsel uygulamalara olan etkileri ve benimsenmelerinde karşılaşılan zorluklar hakkında içgörüler sunar. Dördüncü Bölüm, gerçek dünya örneklerini inceleyerek döngüsel bir yapı endüstrisi için dijitalleşmenin gelişen araştırma alanına katkıda bulunur.

Beşinci Bölüm, veri ile ilişkilendirilmiş zorluklara odaklanarak (Dördüncü Bölüm'de belirlenenler), özellikle mevcut konut stogunda döngüsellik için kilit bir araç olarak malzeme pasaportlarına odaklanmaktadır. Çoklu aşamalı karışık yöntem araştırma tasarımını kullanarak, bölüm, kullanıcı ve veri haritalama için SCOPIS yöntemini (Tedarik Zinciri Odaklı Paydaşları Tanıma Süreci) kullanmaktadır. Bu yaklaşım, malzeme pasaportları için kullanıcı gereksinimlerini belirten bir veri şablonu oluşturmada kullanılır. Daha sonra, çalışma bu şablonu bir vaka örneği üzerinden test eder, kritik veri boşluklarını belirler ve bu boşlukları gidermek için bir malzeme pasaportları çerçevesi önerir. Beşinci Bölüm, hem dijital teknolojileri hem de insan uzmanlığını kullanarak, döngüselliği hedefine yönelik olarak yapı sektöründe veri yönetimini artırmak için çözümler sunmaktadır. Bulgular, devam eden endüstri ve politika girişimlerine katkıda bulunmaktadır.

Altıncı Bölüm, tez boyunca gerçekleştirilen keşifleri bir araya getirir. Araştırmanın genel katkılarını sunarak, çalışmanın bilimsel ve uygulama katkılarını özetler ve tüm çalışmadan elde edilen önerileri sunar.

1 Introduction

1.1 From a linear to a circular building industry

Today's building industry is based on a linear system where natural resources are extracted from the Earth, transformed into construction materials, and turned into waste once buildings are no longer needed. This model is highly resource- and carbon-intensive and causes serious environmental, social, and economic problems. In the European Union (EU), for example, the built environment accounts for about 50% of all materials extracted (European Commission, 2022a). In parallel, buildings consume 40% of the EU's energy and produce around one-third of its greenhouse gas emissions and waste (European Construction Sector Observatory, 2018; Eurostat, 2020). With a projected 35 % population growth in European cities by 2030 (European Commission, 2022d), the building industry faces massive adversity to produce new housing and improve the ageing housing stock. Besides the growing housing need, the industry is also confronted with a rapidly increasing demand and a scarcity of construction-related raw materials as a result of supply chain disruptions due to the COVID-19 pandemic and climate change effects (i.e., low water levels) as well as rising energy prices amid the Russian invasion of Ukraine (Housing Europe Observatory, 2022). It is, therefore, fair to claim that this linear take-make-use-waste model of the building industry is failing. An alternative sustainable model is urgently needed to meet the demands of society while respecting the natural environment.

A promising alternative model to this linear approach is a circular economy. The Circular Economy (CE) decouples economic activity from the exhaustion of natural resources by designing a restorative and regenerative system (Ellen MacArthur Foundation, 2013b).

It minimises resource inputs, waste, emissions, and energy leakages and maximises the value of products and materials over time (Geissdoerfer et al., 2017). Having roots in various schools of thought, such as industrial ecology, Cradle to Cradle (Braungart & McDonough, 2009) and Biomimicry (Benyus, 1997), the CE has revived and gained interest in the last decade (Kirchherr et al., 2017). Particularly, CE has become an essential element of the EU's environmental policy for resource efficiency and waste reduction (Domenech & Bahn-Walkowiak, 2019), wherein construction and buildings were prioritised to take prompt actions (European Commission, 2020b). Simultaneously, academia and practice have increasingly embraced this momentum in the policy landscape as the number of academic research articles and circular construction projects have rapidly grown in the last few years (Circular Construction Economy Transition Team, 2020; Munaro et al., 2020).

The building industry can apply numerous strategies to transition from a linear to a circular building industry. These strategies can be summarised under four core resource principles (Bocken et al., 2016; Çetin, De Wolf, et al., 2021; Konietzko et al., 2020):

- *Narrow:* minimise the use of primary resources in buildings by, e.g., improving design and operational efficiency and substituting new materials with secondary ones.
- *Slow:* extend the lifetime of buildings and products through repair and maintenance and keep them in use as long as possible.
- *Close:* regain the post-use and construction waste through reuse or recycling.
- *Regenerate:* minimise toxic substances, maximise the use of renewable resources (energy and materials) and improve biodiversity and the human-nature interaction in buildings.

An illustration summarising these core CE principles is given in FIG.1.1 To implement these strategies, collaboration is needed across the building industry value chain, from material suppliers to real estate owners, throughout the life cycle stages of the buildings (Leising et al., 2018). Because the built environment consists of multiple interdependent layers, i.e., nano (materials), micro (buildings), meso (neighbourhoods), and macro (cities), where resources flow from one scale to another and considering the building industry as a fragmented industry, where actors work in silos, collaboration is surely a big challenge.

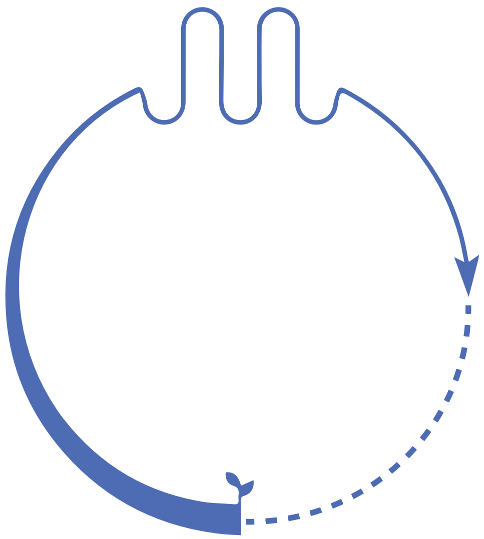

FIG. 1.1 Narrow, slow, close, and regenerate framework (Source: Konietzko et al., (2020)).

1.2 European social housing organisations in the circular transition

Social housing organisations (SHOs) are one of the crucial actors in the building value chain. Social housing refers to a non-profit or limited-profit sector that provides decent and affordable housing to disadvantaged groups in society (Elsinga & Wassenberg, 2014). SHOs typically own a large portfolio of buildings in Europe and are managed by a group of professionals. For example, in some European countries like the Netherlands, Austria, and Denmark, social housing makes up around 29%, 24%, and 21% of the total national housing stock, respectively (Housing Europe, 2021). In the Netherlands, SHOs have a core task of delivering new housing and maintaining and improving existing buildings and neighbourhoods. These improvements have been concentrating on energy efficiency in the last two decades to curb carbon emissions (Ministerie BZK, 2019). Following the Dutch government’s ambition to transition to a CE by 2050 (Rijksoverheid, 2016), Dutch housing providers have begun experimenting with circular building strategies to expand their sustainability efforts. According to a practice-based study published in 2020, 70 circular housing projects (e.g., new build and renovation) across the Netherlands have been realised (Kersten, 2020). This shows a growing interest among SHOs towards this new sustainability paradigm.

In the circular transition of the building industry, SHOs can play an important role for several reasons. First, they own a large part of the existing building stock and have a powerful position in the building value chain due to the considerable volume of housing activities and investments. Adopting circular approaches in new build, maintenance, renovation, and demolition operations could make a positive impact on an extensive share of housing stock and a network of stakeholders involved in these operations, such as architects, material suppliers, software providers, demolition contractors and tenants. Second, SHOs are social entrepreneurs, and they are expected to use their resources in line with the collective social interests (Nieboer & Gruis, 2014; Roders & Straub, 2015; van Overkeener, 2014). Besides implementing carbon reduction measures, applying circular principles could support them in minimising construction and demolition waste, toxic contents, and whole life cycle carbon emissions (Nussholz et al., 2023) while maximising resource efficiency and longevity of their housing stock. Third, European SHOs provide affordable housing for millions of economically disadvantaged people from different social backgrounds (Housing Europe, 2021). Implementing circular building strategies could potentially improve the living environment of these people and address the missing social dimension of the CE (Padilla-Rivera et al., 2020).

1.3 Towards digitalisation for a circular building industry

Looking back to CE in the building industry, a general trend can be seen in the current academic discourse that considerable attention is paid to *close* strategies through reusing and recycling products and materials at the end-of-life stages of buildings (Benachio et al., 2020; Munaro et al., 2020). One common idea is that the existing building stock can be an alternative source of materials for the buildings which will be constructed in the future (buildings-as-material-banks) (Benachio et al., 2020; Matthias Heinrich & Werner Lang, 2019; Heisel & Rau-Oberhuber, 2020;

Honic et al., 2021). Reclaiming valuable products and materials from existing stock, more broadly from anthropogenic stock, can be done through urban mining (Cossu & Williams, 2015; Heisel & Rau-Oberhuber, 2020). Like natural resource mining (e.g., coal mining), urban mining is an activity to extract materials from buildings that reach their end-of-life. Deconstruction, demolition, and destruction are some of the main approaches to recovering materials through urban mining at the end-of-life stage (Arora et al., 2021). Compared to others, deconstruction is the most beneficial method in terms of material recovery, as it follows a carefully planned process resulting in various products or materials ready to be reused in the next cycles (Arora et al., 2021). Deconstruction is profoundly connected to design concepts that ease the reuse of building parts, such as design for disassembly and reversibility. These design strategies concern reusing building parts by incorporating element connections that allow easy disassembly (Durmisevic, 2019).

Interventions aimed at *closing* material loops are highly dependent on the availability of building information. For example, it is crucial to know the material composition of building products (Honic, Kovacic, & Rechberger, 2019; Koutamanis et al., 2018), the type and quantity of connections they have (Iacovidou et al., 2018), and their location in a building (Heisel & Rau-Oberhuber, 2020). However, accessing such information is challenging as buildings are usually poorly documented (van den Berg et al., 2021). Also, they are exposed to changes during their lifetime, which are not reported systematically (Honic et al., 2021; Iacovidou et al., 2018). These challenges, among others, led to the creation of material passports to enable industry actors to access reliable data when reusing or recycling building products and materials at their end-of-life.

A material passport is a digital data set containing detailed qualitative and quantitative information about materials or products embedded in a building (Çetin, De Wolf, et al., 2021; Heisel & Rau-Oberhuber, 2020; Honic, Kovacic, & Rechberger, 2019). It is a new instrument in the industry that is defined and developed differently by different actors. The EU Horizon 2020 project BAMB[1] developed one of the first prototypes of a material passport to support the concept of buildings-as-material-banks. Concurrently, the Madaster Foundation[2] introduced a material passports platform and turned it into a commercial product which made the foundation a forerunner in disseminating the concept in the market. In addition,

1 https://www.bamb2020.eu/

2 https://madaster.com/

some public and public-private initiatives, such as the Dutch Platform CB'23[3] and the Ministry of The Economy of Luxembourg (Mulhall et al., 2022) launched action groups for defining and standardising material passports for the building industry.

Furthermore, academic researchers expanded the field towards combining material passports with BIM (building information modelling) and proposed design support tools estimating the end-of-life recyclability performance of building design options (see, e.g., (Akanbi et al., 2018; Honic et al., 2021; Honic, Kovacic, Sibenik, et al., 2019)). Other researchers, such as van den Berg et al. (2021) investigated the use of BIM in deconstruction planning, and Akanbi et al. (2019) developed a deconstruction analytics tool. In the meantime, several European projects started focusing on other technologies, such as blockchain technology, digital platforms, and scanning technologies alongside BIM and material passports, for realising circularity in buildings (see, e.g., CHARM[4], Digital Deconstruction[5] and Reincarnate[6]). Overall, these developments in practice, policy, and research gave an impetus to digitalisation for a CE in the building industry as an emerging research field.

The terms digitisation, digitalisation, and digital transformation are often confused, and it is important to clarify their meaning within the context of this research. Digitisation refers to transferring a process from an analogue form to a digital one (Gartner, 2023). Digitalisation can be defined as the outcome of applying digital technologies on a company's offerings (products or services), such as increased efficiency through automation (Gong & Ribiere, 2021). Digital transformation, on the other hand, is a broader concept that encompasses the integration of digital technologies into a business, as a whole new form, function, or structure, leading to fundamental changes in the business model that a company offers (Gong & Ribiere, 2021; Verhoef et al., 2021). It involves rethinking business models, processes, and customer experiences to leverage the opportunities created by digital technologies. Digital transformation differs from digitalisation in terms of scope of improvement and end-results. Digitalisation revolves around incremental enhancements at the operational level, whereas digital transformation aims to implement a series of digitalisation projects that profoundly transform elements within a system at the strategic level (Gong & Ribiere, 2021). As it will be seen in the following sections, the building industry, particularly SHOs, are at an experimental stage in CE

3 https://platformcb23.nl/

4 https://www.nweurope.eu/projects/project-search/charm-circular-housing-asset-renovation-management/

5 https://www.nweurope.eu/projects/project-search/digital-deconstruction/#tab-1

6 https://www.reincarnate-project.eu/

implementation and the use of digital technologies for circularity is mainly restricted to pilot projects. Therefore, "digitalisation," instead of "digital transformation," is preferred in this thesis as the terminology to refer to the use of digital technologies that enhance circular building strategies in these early stages.

1.4 Problem definition

Researchers, practitioners, and policymakers have just started understanding the opportunities digitalisation might bring to the building industry to apply circular strategies. Previous work has predominantly focused on certain technologies (e.g., BIM) to enable *close* strategies and has not sufficiently addressed other CE principles of *narrow, slow*, and *regenerate* or explored other potentially enabling digital technologies (e.g., artificial intelligence). Considering their market position and scale and role in stimulating circular practices in the industry, it is surprising that very little attention has been paid to European SHOs (especially the Dutch ones) and how they implement CE principles in their housing practices. Moreover, there is a lack of knowledge on the data requirements of SHOs and their stakeholders regarding circularity and in what areas and ways digital technologies could support their decision-making in circular projects. In addition, there has been no empirical investigation of how enabling technologies are implemented in real life by the forerunner[7] SHOs and whether they face challenges when deploying digital technologies in circular housing projects.

7 It is meant early adopters by the term “forerunners” in the context of this research.

1.5 Research aim and key questions

This thesis therefore aims to explore potentially enabling digital technologies and how they can support SHOs in adopting Circular Economy principles of *narrow, slow, close,* and *regenerate* material loops in housing practices. Four key research questions are formulated to address the outlined research gaps and achieve the research aim:

RQ 1: What are the current state, barriers, and enablers of Circular Economy implementation in Dutch social housing organisations? (Chapter 2)

The first key research question is formulated to establish the research background, placing the research in a broader academic context. Given the Netherlands' position as a forerunner in CE implementation (Khadim et al., 2022; Marino & Pariso, 2020) and the influential roles of Dutch SHOs in the construction sector, the initial research question focuses on the Dutch context. Chapter 2 addresses this research question, providing an exploration of CE in SHOs.

RQ 2: What digital technologies can potentially enable a CE in the built environment, and in what ways? (Chapter 3)

The second key research question aims to investigate the potential of digital technologies in supporting CE principles within a broader context of built environment research and practice, extending beyond the social housing sector. Chapter 3 addresses this research question and develops a framework, providing a comprehensive overview of enabling technologies, which in turn informs the subsequent two studies in this thesis (Chapter 4 and 5).

RQ 3: How are digital technologies deployed in the circular projects of forerunner Dutch social housing organisations, and what challenges emerge in their adoption? (Chapter 4)

The third key research question utilises the framework developed in Chapter 3, integrating it with the analytical capabilities of digital technologies to analyse whether and how the identified enabling digital technologies are employed in real life by forerunner SHOs. Furthermore, it explores the types of barriers that arise when applying these technologies in circular new build, maintenance, renovation, and demolition projects of SHOs. Consequently, Chapter 4 responds to this question with a multiple-case analysis.

RQ 4: What are the data requirements of users from material passports for the existing housing stock? Are these data available? If not, how can digital technologies support fulfilling the data gaps? (Chapter 5)

The empirical evidence and challenges presented in Chapter 4 underscore a significant research gap concerning the creation and management of material passport data for existing housing stock. Subsequently, the final key research question dives into material passports as a pivotal tool for circularity, addressing these challenges related to data issues and seeking to provide a solution based on the capabilities of digital technologies in Chapter 5.

1.6 Research approach

When addressing a research problem, researchers make certain decisions on research methodology, procedural and theoretical choices to justify their choice of methodology, and methods of data collection, analysis, and interpretation. The choice of a research approach reflects a researcher's understanding of the world (Feilzer, 2009), which is informed by the paradigm (Morgan, 2007) or worldview (Creswell, 2009) assumptions. These choices are usually influenced by the nature of the research problem, the researcher's previous experiences or the larger research community or society in which the researcher is involved (Creswell, 2009; Morgan, 2014). Based on the conceptualisations of Crotty (1998) and Creswell and Clark (2011), as illustrated in FIG.1.2, this section elaborates on the main research elements that the researcher considered when conducting this research.

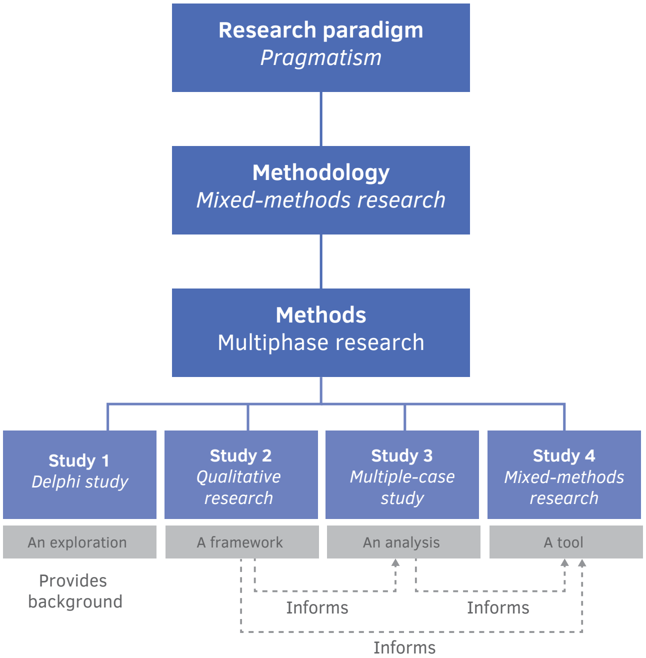

FIG. 1.2 Main elements of this research (Based on Creswell & Clark, (2011); Crotty, (1998)).

This research deals with issues rooted in real life, i.e., digitalisation for a circular building industry, and aims to offer a better understanding of the phenomena along with potential solutions to improve the current situation. Accordingly, it uses *pragmatism* as the underlying philosophical framework to guide the research process. *Pragmatism*, as a research paradigm, prioritises the practical application of ideas as the pursuit of solutions to real-world problems (Feilzer, 2009), rather than dealing with contentious metaphysical debates about the nature of truth and reality (Feilzer, 2009; Kaushik & Walsh, 2019; Kelly & Cordeiro, 2020) or division between positivism and constructivism (Creswell & Clark, 2011). In fact, in a given set of circumstances, *pragmatism* treats prior beliefs equally (Morgan, 2014) and admits that there are singular and multiple realities that are open to empirical inquiry (Feilzer, 2009). According to research methodologists (Creswell, 2009; Creswell & Clark, 2011), *pragmatism* orients itself towards practice, focusing on the research problem and consequences of research rather than the methods, giving researchers the freedom to choose appropriate quantitative and qualitative approaches to address the research problem most appropriate way.

Methodology is the second research element that connects philosophical considerations to actual methods. This research uses *Mixed-methods research* (Creswell & Clark, 2011) as an overarching research methodology that embodies four core studies undertaken throughout the PhD trajectory (FIG. 1.2). *Mixed methods research* combines quantitative and qualitative approaches over a single or series of studies providing a comprehensive understanding of the research problem by utilising the strengths of both approaches (Creswell & Clark, 2011). A *multiphase mixed methods design* is chosen, consisting of four sequential studies that inform each other to address the research aim. Each study has a different research design based on the key research question addressed and uses several qualitative, quantitative, or mixed data collection and analysis methods, as summarised in TABLE 1.1.

TABLE 1.1 Four core studies encompassing the research and their associated research questions, research design and methods deployed.

Study	Research questions	Research design & methods	Chapter
1	RQ 1: What are the current state, barriers, and enablers of Circular Economy implementation in Dutch social housing?	***Delphi study*** - Literature review - Interviews - Online survey - Quantitative data analysis	2
2	RQ 2: What digital technologies can potentially enable a CE in the built environment, and in what ways?	***Exploratory qualitative research*** - Framework development - Expert workshops - Literature and practice review	3
3	RQ 3: How are digital technologies deployed in the circular projects of forerunner Dutch social housing organisations, and what challenges emerge in their adoption?	***Multiple-case study*** - Semi-structured interviews - Desk research - Within-case analysis - Cross-case analysis	4
4	RQ 4: What are the data requirements of users from material passports for the existing housing stock? Are these data available? If not, how can digital technologies support fulfilling the data gaps?	***Multiphase mixed-method design*** - User & data mapping (SCOPIS method) - Literature and practice review - Interviews - Case study - Framework development	5

The first study (Chapter 2) sets an underlying understanding of the overall research context, i.e., CE implementation in SHOs. The state-of-the-art CE practices of 19 forerunner Dutch SHOs and emanating barriers and enablers are explored through a *Delphi study*. A three-phase data collection process was performed based on a literature review, interviews, and an online survey, and a quantitative approach was followed to analyse the collected data. The research revealed the most pressing barriers to CE implementation experienced by the practitioners as well as potential enablers to address identified barriers.

The second study (Chapter 3) expands the research focus towards digitalisation and investigates potentially enabling digital technologies for a circular built environment. Due to the underdeveloped nature of the research field and a lack of a thorough overview of the enabling technologies, an *exploratory qualitative research* design was adopted. The study followed an iterative process consisting of developing a literature-based framework, data collection through expert workshops and literature and practice review of enabling technologies and presenting results on an emergent framework. The study identified ten digital technologies that support industry actors to *narrow, slow, close*, and *regenerate* the loops along the life cycle stages of buildings.

The third study (Chapter 4) builds on the findings of the second study and analyses how enabling digital technologies are used in real-life settings, namely, in circular new build, renovation, maintenance, and demolition projects of SHOs. A *multiple-case study* was conducted to gather empirical evidence from three large Dutch SHOs that have been at the forefront of CE implementation in the Netherlands. Data were collected from various sources (e.g., interviews, annual reports, etc.) and examined through within-case and cross-case analyses. The study also identified challenges for adopting enabling technologies, which informed and motivated the fourth study.

The fourth study (Chapter 5) responds to the data-related challenges, such as creating and managing material passports for the existing housing stock, emerged from the preceding chapter. The study conducted a *multiphase mixed-method research* design consisting of two main parts. The first part was dedicated to mapping data and users of material passports through SCOPIS method (supply chain-oriented process to identify stakeholders) (Fritz et al., 2018), resulted in a data template where data requirements of the users are presented. And the second part identified critical data gaps by testing the data template on a case study. By analysing the findings, the fourth study proposed a material passports framework to address the identified data gaps that leverages the capabilities of digital technologies along with humans.

1.7 Research relevance

At the start of the PhD trajectory, in 2019, digitalisation for a CE was a new scientific area mainly debated by scholars from the manufacturing industry (see, for example, Lopes de Sousa Jabbour et al., (2018)), which was embraced by the built environment scholars in time. Material passports and BIM have been the two major tools that the research concentrated on providing solutions for mainly *closing* the material loops at the end-of-life of buildings. This research builds on this emerging body of knowledge and advances it in multiple ways.

First, by developing the novel *Circular Digital Built Environment Framework (CDB Framework)* (Chapter 3), this research establishes a much-needed and underexplored link between three research areas, namely, CE, building industry, and digital technology, with a holistic approach. Second, the CDB framework not only uses the main life cycle stages but also considers the overlooked strategies *slow* and *regenerate* and maps more than ten enabling digital technologies that have not been explored in previous research, such as big data analytics and robotic manufacturing. To this end, it provides scholars and practitioners with an extensive overview of the potential use cases of digital technologies towards circularity and conceptualises the emerging research field. Third, the extant CE literature remains mainly theoretical and lacks perspectives from real-life applications. By conducting empirical studies (Chapters 4 and 5), this thesis advances the emerging theory by providing evidence from forerunner SHOs. Accordingly, it sheds light on what digital technologies are feasible to implement in real-life and what value they offer to the industry actors. Finally, this research complements the circular built environment research by providing evidence from SHOs that manage a large portfolio of buildings, which is an underdeveloped research area in this field.

CE is an important topic for policy and practice at the EU level as well as at the national level, and data and digitalisation are the two integral parts of the discussions (see, for example, the Twin Transitions agenda of the EU (EU Science Hub, 2022)). The knowledge generated in this research is highly relevant for the industry actors who want to use digital innovations to transform their current practices into circular processes. The CDB Framework (Chapter 3) provides a fruitful guide for practitioners when deciding what CE principles are suitable and what digital possibilities are available for their operations. The material passport framework developed for existing buildings (Chapter 5) contributes to ongoing industry and policy efforts (e.g., Platform CB'23 initiative and EU's Digital Product Passport legislation) from a scientific point of view. Furthermore, this study analyses the practices of forerunner SHOs and provides a comprehensive overview of the CE principles and digital tools deployed in circular new build, renovation, maintenance, and demolition projects. To this end, it helps novice organisations leverage the insights from forerunners and take concrete steps in transitioning towards a CE.

1.8 Thesis structure

This is a paper-based dissertation composed of six chapters. Chapter 1 introduces the research rationale and main research elements. Chapters 2, 3, 4 and 5 are based on the researcher's published academic articles as listed in TABLE 1.2. The manuscripts are kept in their original form as published, only referencing style, figures and tables are adjusted according to this book's style. Also, small grammar corrections and conversion to British spelling are made. Finally, Chapter 6 answers research questions and concludes the thesis with reflections on science and practice.

TABLE 1.2 Outline of the thesis.

Chapter	Chapter titles/ Publications
1	**Introduction**
2	**Circular Economy in social housing practice: An exploration** *Çetin, S., Gruis, V., & Straub, A. (2021). Towards Circular Social Housing: An Exploration of Practices, Barriers, and Enablers. Sustainability, 13 (4).*
3	**Circular digital built environment: A framework** *Çetin, S., De Wolf, C., & Bocken, N. (2021). Circular Digital Built Environment: An Emerging Framework. Sustainability, 13 (11).*
4	**Digitalisation for circular social housing practices: An analysis** *Çetin, S., Gruis, V., & Straub, A. (2022). Digitalisation for a circular economy in the building industry: Multiple-case study of Dutch social housing organizations. Resources, Conservation & Recycling Advances, 15, 200110.*
5	**Material passports for social housing stock: A tool** *Çetin, S., Raghu, D., Honic, M., Straub, A. & Gruis, V., (2023). Data requirements and availabilities for material passports: A digitally enabled framework for improving the circularity of existing buildings. Sustainable Production and Consumption, 40, 422-437.*
6	**Conclusions**

2 Circular Economy in social housing practice

An exploration

This chapter delves into the implementation of Circular Economy strategies by 19 forerunner Dutch social housing organizations in circular housing projects and their portfolio policies. It identifies fundamental barriers associated with circular practices and proposes potential enablers to address them. By offering background information, this chapter sets the stage for subsequent chapters to build upon.

Recap key research question 1: What are the current state, barriers, and enablers of CE implementation in Dutch social housing organisations?

Publication: Çetin, S.[1], Gruis, V.[1], & Straub, A.[1] (2021). Towards Circular Social Housing: An Exploration of Practices, Barriers, and Enablers. Sustainability, 13 (4).

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ABSTRACT

The concept of Circular Economy (CE) and its application in the built environment is an emerging research field. Scholars approach CE from various perspectives covering a wide range of topics, from material innovation to city-scale application. However, there is little research on CE implementation in housing stock, particularly that which is managed or owned by social housing organisations (SHOs), and which offers opportunities to generate circular flows of materials at the portfolio level. This research focuses on Dutch SHOs and uses the Delphi method to examine CE practices in their asset management, as well as the main barriers to and potential enablers of its uptake. The analysis of two iterative rounds of expert questioning indicates that Dutch SHOs are in the early experimental phase of CE implementation. From the results, it is evident that organisational, cultural, and financial barriers are the most pressing ones that hinder the wider adoption of CE in their asset management. Building on the panel input, this study suggests potential enablers to overcome these

barriers, such as CE legislation, best practice case studies, commitment and support from the top management, and the creation of a clear business case.

KEYWORDS Circular Economy; social housing; Delphi method; barriers; enablers; practices; built environment

2.1 Introduction

The built environment is a critical sector in terms of its influence on the economy, society, and natural environment, as construction activities are estimated to form about 9% of the European gross domestic product (European Commission, 2016b) and are the major consumer of natural resources (Giljum et al., 2016). Research suggests that this industry is responsible for 39% of global energy-related emissions (World Green Building Council, 2019) and 46% of the total waste generation in the European Union (EU) (Gálvez-Martos et al., 2018). Thus, there is an urgent need to transform the built environment into a resource-effective one to address these challenges.

The concept of Circular Economy (CE) has been embraced as an approach for minimising resource inputs and outputs by introducing cyclic principles (Bocken et al., 2016), avoiding waste and pollution, and creating regenerative systems (Ellen MacArthur Foundation, 2019). The concept gained traction in Europe in the early 2010s with the efforts of the Ellen MacArthur Foundation (EMF) along with the introduction of the first Circular Economy Action Plan (Eberhardt et al., 2020; Merli et al., 2018). Indeed, many European countries (Marino & Pariso, 2020), including the Netherlands (Rijksoverheid, 2016), have developed several strategies and action plans, in which the construction sector takes a pivotal role as one of the main priorities in the transition towards a CE.

Research on CE in the built environment covers various dimensions, with some researchers focussing on material innovation while others address CE implementation at the city scale. For example, Marie and Quiasrawi (Marie & Quiasrawi, 2012) studied the properties of recycled aggregates that are reintroduced in the concrete life cycle multiple times; van Stijn and Gruis A. van Stijn and V. H. Gruis (2019) proposed a circular housing retrofit strategy for modular building components; Eberhardt and colleagues (Eberhardt et al., 2020) conducted a systematic literature review to determine which building design and construction strategies are associated with circularity for new buildings; and, Prendeville and colleagues (Prendeville et al., 2018) investigated how six European cities are implementing CE as a strategy. Furthermore, several researchers have proposed tools (Cambier et al., 2020; Leising et al., 2018; A. van Stijn & V. Gruis, 2019) and assessment methods (Sassanelli et al., 2019) to support circular building processes, while others conducted systematic literature reviews to demonstrate the state-of-the-art of CE research (Benachio et al., 2020; Munaro et al., 2020) and identified barriers (Bilal et al., 2020) for CE implementation in the built environment.

However, only a very few of the reviewed studies explicitly examine the circular transition of the housing sector, with a notable example (Eikelenboom et al., 2021). This can be considered somewhat surprising, given that the housing stock constitutes a significant part of the built environment. Moreover, especially in North-Western Europe, a large part of the housing stock, varying from 3% to 30% of the total housing stock (Pittini et al., 2019), is managed by professional institutes, social housing organisations (SHOs), with substantial portfolios that offer opportunities to generate circular flows of materials at the portfolio level. For a wider adoption of the CE in the built environment, therefore, understanding of SHO's experiences with the circular practices is critical.

The sustainability of social housing is one of the five top priorities of Aedes, the umbrella organisation of Dutch housing associations (AEDES, 2020). Dutch SHOs own 29% of the national housing stock (CBS, 2020) and provide services to approximately 4 million low-income residents (AEDES, 2016), which makes them prominent actors in the Dutch construction sector. Based on this background, this article aims to identify (1) circular practices of the early adopter Dutch SHOs; (2) main barriers that hinder CE implementation; and (3) potential enablers to address the most pressing barriers by conducting a Delphi study with 21 sector professionals across the Netherlands.

The remainder of this article is organised as follows. Section 2.2 presents the background of the study, discussing relevant literature on CE in the built environment, the main characteristics of Dutch SHOs, and CE implementation barriers and enablers in the construction sector. Section 2.3 demonstrates the execution of the Delphi method and elaborates on the data collection and data analysis phases. Further, Section 2.4 presents the research results highlighting priority issues, while Section 2.5 includes the discussion and concluding remarks.

2.2 Research background

2.2.1 Circular Economy in the built environment

Circular Economy (CE) has emerged as a paradigm that originated from several theoretical backgrounds, such as Industrial Ecology and biomimicry (Ellen MacArthur Foundation, 2013a; Ghisellini et al., 2016) and has been interpreted in numerous ways by different players (Blomsma & Brennan, 2017). The literature review of Kirchherr and colleagues (Kirchherr et al., 2017) resulted in 95 different academic and practitioner definitions of the concept, illustrating the conceptual confusion around the topic (Kirchherr et al., 2017). In a field where circularity is still in its infancy, only a limited number of scholars attempted to define CE for the built environment, as reported by Benachio et al. (Benachio et al., 2020).

Pomponi and Moncaster (Pomponi & Moncaster, 2017, p. 711) conceptualised the building research from a CE perspective by proposing a research framework and made a brief definition of circular buildings: *"… a building that is designed, planned, built, operated, maintained, and deconstructed in a manner consistent with CE principles*" (p. 711). One of the limitations of this definition is that it does not elaborate on the circular principles to which it refers. Leising and colleagues (Leising et al., 2018), on the other hand, defined circular buildings from a broader perspective by incorporating ownership issues: *"A lifecycle approach that optimises the buildings' useful lifetime, integrating the end-of-life phase in the design and uses new ownership models where materials are only temporarily stored in the building that acts as a material bank"* (p. 977). They emphasise the importance of supply chain collaboration in closing the material loops throughout the lifetime of buildings.

Moreover, some non-academic actors, such as EMF, described a circular built environment as *modular* and *flexible by design,* where resource loops are closed, and human well-being is promoted (Ellen MacArthur Foundation, 2017). Similarly, but more thoroughly, a comprehensive definition of circular construction is presented for the Dutch construction industry in the Circular Construction Economy Transition Agenda as follows: *"… the development, use and reuse of buildings, areas and infrastructure without unnecessarily exhausting natural resources, polluting the living environment, and affecting ecosystems. Construction in a way that is economically sound and contributes to the well-being of humans and animals. Here and there, now and later."* (De Circulaire Bouweconomie, 2018) (p. 10).

For the implementation of CE, several strategies, frameworks and tools have been suggested by academicians, practitioners and consultants. Ness and Xing (Ness & Xing, 2017) reviewed a wide range of resource efficiency principles and discussed whether these could be extended beyond industrial applications to the built environment. They concluded that industrial closed-loop strategies aiming to extend the lifetime of products could be translated for the building sector by strategies like *reuse*, *remanufacture* and *maintenance* as well as by offering service models for building parts (Ness & Xing, 2017). Indeed, some circular principles are assumed to be known already to the construction sector, particularly the R principles. Recent research showed that 'recycle', and 'reuse' are the strategies that have been predominantly used (Munaro et al., 2020), especially for recovering construction and demolition waste (Ghisellini et al., 2018). Arguably, the most extensive R framework is the one proposed by Potting et al. (Potting, 2016) for measuring the progress of CE transition (FIG. 2.1), which also applies to construction processes.

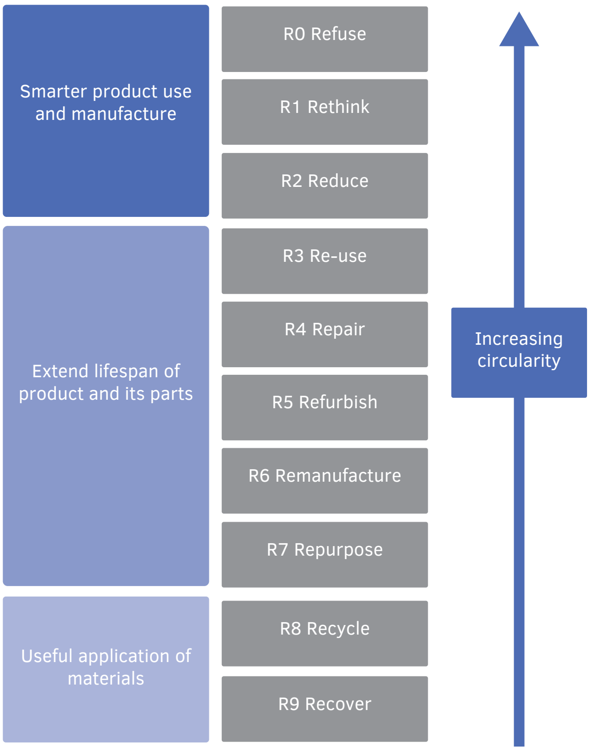

FIG. 2.1 R framework proposed by Potting and colleagues (Potting, 2016). Own illustration.

R strategies are also intertwined with the famous ReSOLVE framework of the EMF (Zimmann, 2016). Although developed for products and services in other sectors, the ReSOLVE framework is believed to be relevant for various spatial levels of the built environment (Zimmann et al., 2016). For instance, *share* strategy can be applied to reuse reclaimed building products and to pool available assets in the cities, such as cars and office spaces, while with *optimise* strategy efficiency and performance of buildings can be increased during the design phase (Zimmann et al., 2016).

We used the R framework of Potting et al. (Potting, 2016) in this study as it is a well-known framework for the Dutch construction sector (see, for example, a recent report of the Dutch circular construction economy transition team (Transitieteam Circulaire Bouweconomie, 2020)), which made it easier to communicate the survey and collect data during the Delphi sessions amongst our respondents.

2.2.2 Dutch social housing organisations

Dutch housing associations have a long tradition and are considered to be major actors in the Dutch construction industry (Boelhouwer et al., 2014). The first housing organisations were established in the mid-1800s to construct labour houses, and they became critical during the post-war era due to the role they played in reducing the enormous housing shortage at that time (Boelhouwer & Priemus, 2013; Elsinga & Wassenberg, 2014). They remain an essential part of Dutch housing provision to date. Aedes, the umbrella organisation of the Dutch housing associations, describes the Dutch SHOs as "*non-profit enterprises that pursue social goals within a strict framework of national laws and regulations by involving local government, tenants and other stakeholders in their policies and are accountable to the society*" (AEDES, 2016)(p. 3). Their primary responsibility is to construct, rent and manage social homes for the target group of low-income households as well as to maintain a good quality of homes and neighbourhoods (AEDES, 2016; Rijksoverheid, n.d.).

When delivering these housing services, Dutch SHOs work closely with other market actors. Although some Dutch SHOs have an in-house maintenance department responsible for daily maintenance services, most of them outsource planned maintenance work. Typically design activities for renovation and new construction are outsourced as well. Over ten years ago, Dutch housing associations began to develop supply chain partnerships in new-build, maintenance and refurbishment projects (Straub, 2009). In recent years, collaborative relationship models and partnering agreements for maintenance and renovation have been introduced, although traditional procurement processes are still used for the majority of projects.

The main characteristic of the Dutch social housing sector, compared to the other European countries, is the large share of the social rented segment within the housing stock, which is the highest in Europe. As of 2020, approximately 2.3 million dwellings, constituting 29% of the national housing stock, are owned by the Dutch housing associations [24]. Currently, there are 312 SHOs actively operating in the Netherlands [44], some of them owning more than 50,000 dwellings [45].

In the past decade, energy transition, particularly energy renovation of the existing housing stock, has been the central sustainability aspiration for the housing associations to contribute to reaching national climate targets of reducing carbon emissions by 95% by 2050 (Aedes). More recently, interconnected with the climate targets and also with the government-wide CE programme (Rijksoverheid, 2016), CE is becoming a new sustainability paradigm in their agenda. In response to these developments, several SHOs across the country have started experimenting with circular strategies in pilot projects.

One such initiative, adopted by the province of Drenthe, is “Drenthe Woont Circulair” (Drenthe lives circularly). To generate affordable, repeatable and scalable circular homes, six experimental projects, so-called “proeftuinen” (experimental ‘playgrounds’), have been developed that will result in 110 social rental homes (Drenthe Woont Circulair, n.d.). Similarly, another circular proeftuin has started by employing a living lab approach in the province of Overijssel. This initiative involves many actors, from architects to a demolition company, to learn dismantling techniques and using biobased materials to increase the reuse potential of the building components in future (Corporatie Media, 2020). In the province of Limburg, as part of the Super Local Estate project, three circular homes have been constructed by reusing more than 90% of the materials from a 10-story apartment dating back to the 1960s (Durmisevic, 2020). A few housing associations have gone beyond experimentation and announced ambitious targets in their policies to be carbon-neutral and fully circular in the coming decades (Eigen Haard, 2018; Renda, 2017).

2.2.3 Barriers and enablers for a circular built environment

Next to the conceptualisation of CE across the disciplines, scholars also focus on its operationalisation and interrogate factors hindering its wider adoption. For example, Geng and Doberstein (Geng & Doberstein, 2010) took an exclusive approach to identifying challenges associated with China’s long-term CE program. Similarly, Kirchherr and colleagues (Kirchherr et al., 2018) investigated the EU-wide barriers interrupting the transition towards a CE. In their comprehensive review, de Jesus and Mendonça (de Jesus & Mendonca, 2018) outlined the main CE barriers and enablers in a framework from an innovation studies point of view. Other researchers focused on the topic from supply-chain (Bressanelli, Perona, et al., 2018; Govindan & Hasanagic, 2018; Ozkan-Ozen et al., 2020), firm (Masi et al., 2018; Rizos et al., 2016) and circular business models (Vermunt et al., 2019) perspectives.

The research on barriers and enablers of CE implementation in the built environment is limited. Current studies either focus on a particular country context or a specific subset of the building sector. Adams and colleagues (Adams et al., 2017) examined the industrywide CE awareness, challenges and enablers in the UK. Their results showed that the most pressing barriers are *a lack of incentive to design for end-of-life issues, the lack of market mechanisms to aid greater recovery, and an unclear financial case.* On the other hand, *a clear business case, assurance arrangements for reused materials*, and *best practice examples* are seen as important enablers for the construction sector (Adams et al., 2017). In another study (Bilal et al., 2020), researchers address this issue in developing countries. In contrast, their findings reveal the absence of various social and regulatory aspects, such as public awareness, financial resources and support from public institutions as the key obstacles. Moreover, Jugend et al. (Jugend et al., 2020) focused on a building component manufacturer and pointed out that the infrastructure systems might become a significant challenge in achieving intended circularity on the product level, meaning macro-level problems could hinder CE adoption on the micro-level (Jugend et al., 2020). In connection with that, the fragmented structure of the building industry and the complexity of buildings become critical obstacles when introducing innovative ideas. As pointed out by Leising and colleagues (Leising et al., 2018), successful supply chain collaboration might address these issues. Within the construction supply chain, architects are at the centre of the design processes. Kanters (Kanters, 2020) investigated the barriers and drivers that architects and consultants encounter when designing circular buildings. His interview results showed that the absence of a definition of circular building design causes varying approaches within the sector. Furthermore, lack of flexibility in trying new methods alongside the limitations of current building codes, financing of buildings and high labour costs are identified as barriers for designers, while the intention of the client towards circular building is seen as the main driver (Kanters, 2020).

CE implementation strategies, barriers and enablers and their importance differ according to the stakeholders in the construction value chain. Thus, previously discussed factors might not be recognised by Dutch SHOs. Given their unique position in the Dutch building sector, it is timely to investigate their experiences with circular strategies in asset management. Therefore, this article aims to identify circular practices, as well as barriers and enablers associated with the CE implementation of early adopter Dutch SHOs. The next section elaborates on the Delphi study conducted with 21 sector professionals.

2.3 Delphi method

Delphi is a method for aggregating opinions from a group of knowledgeable individuals for a wide variety of purposes, including issue identification, concept development, group decision-making, and forecasting future trends (Dalkey, 1967; Dalkey, 1962; Okoli & Pawlowski, 2004). Early applications of Delphi concern forecasting in the military context; later, it became a popular method, both in academia and the corporate world, for reaching consensus, decision-making or policy-making (Landeta, 2006; von der Gracht, 2012). This technique is considered convenient for several scientific domains as many scholars applied it in social sciences (Brady, 2015; Landeta, 2006; Remøy, 2007), housing studies (Mullins, 2007; Mullins et al., 2017; Nieboer & Gruis, 2013; Zeeman et al., 2016) and also in CE related inquiries (Bui et al., 2020; de Jesus & Mendonca, 2018; Janik & Ryszko, 2019; Padilla-Rivera et al., 2020; Prieto-Sandoval et al., 2018; Sharma et al., 2019). Furthermore, some researchers used the Delphi technique, similar to this study, to determine barriers and enablers for implementing successful CE-based food supply chains (Sharma et al., 2019), and for the application of sustainable purchasing and supply management (Giunipero et al., 2012).

The Delphi method has four key characteristics that make it suitable as the core method of this study. Based on the literature (Dalkey, 1967; Dalkey, 1962; Landeta, 2006; Okoli & Pawlowski, 2004; Rowe, 1991; von der Gracht, 2012), these features can be summarised as follows: (1) *Anonymity*: During the execution, participants do not confer with each other as the facilitator controls the process. The aim is to reduce the impact of dominant individuals in group decision-making. Additionally, anonymity allows respondents to express their opinions freely without feeling group pressure. (2) *Iteration:* The questioning of the participants occurs in several rounds of written questionnaires or interviews so that the panellists can adjust their opinions based on the feedback they get from the facilitator. Throughout the process, participants are actively involved in the debate and influence the questions and outcome. (3) *Controlled feedback*: The facilitator regularly transfers information between panellists. After each Delphi round, the facilitator delivers feedback in a summary of the statistical values of the group judgements. (4) *Statistical group response:* At the final stage of the process, participant responses are formulated statistically and presented numerically, graphically or sometimes qualitatively to indicate the degree of consensus or disagreement.

We performed a two-round Delphi study between December 2019 and October 2020, comprising three overarching phases, as shown in FIG.2.2 The preparation phase concerned the panel recruitment and the preparation of a list of barriers and enablers. The execution phase dealt with the data collected through interviews and questionnaires, and the final phase dealt with the analysis of the collected data.

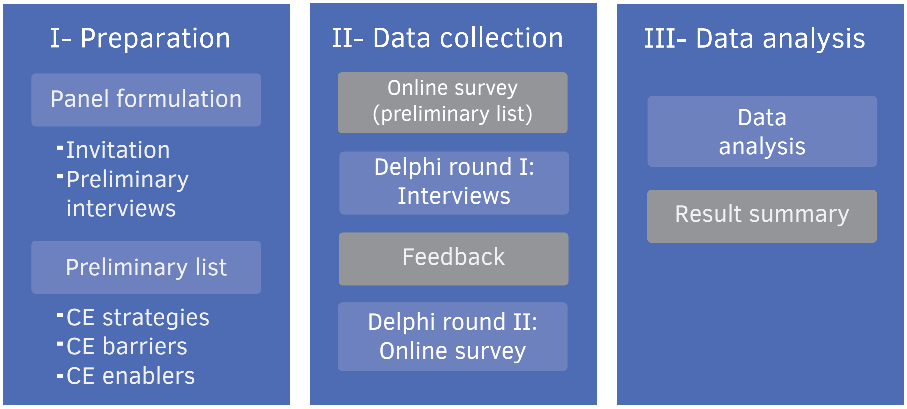

FIG. 2.2 Three phases of the Delphi study.

2.3.1 Preparation

Panel formulation

Scholars stress two crucial aspects of the panel formulation in Delphi surveys: the expertise of the panellists and the size of the panel. The former is related to the selection of experts who have sufficient knowledge and experience in a specific domain (Rowe, 2001), whereas the latter concerns the ideal number of participants in a Delphi panel. Sossa and colleagues (Sossa, 2019) observed a tendency towards using a fewer number of panellists in academic research. Although there is no unique rule for the panel size, it is suggested to keep the participant number between five and 20 (Rowe, 2001).

At the beginning of the study, we sent invitations to 64 sector professionals across the country who work for the forerunner SHOs that have explicit ambitions to implement circular principles and preferably have conducted pilot projects in which they have experimented with circular construction approaches. The selection of forerunner SHOs was made based on reviewing professional journals and sector-related websites, our own knowledge, and the snowball technique. In return, 26 of the invitees responded to our call positively, a response rate of 40%. Following a round of introductory conversations, a panel was formed with 21 professionals representing 19 different housing associations owning approximately 21% of the social housing stock in the Netherlands. The size and locations of the participating SHOs are shown in TABLE 2.1 and FIG.2.3, respectively, and the overview of the panel members is presented in TABLE 2.2.

TABLE 2.1 The size of the represented SHOs in the Delphi panel.

SHO	Size (Dwellings Owned)
1	35,800
2	43,000
3	50,000
4	69,400
5	55,800
6	15,000
7	25,000
8	33,000
9	4500
10	4000
11	56,000
12	4000
13	28,200
14	9000
15	11,000
16	15,200
17	4100
18	11,000
19	15,000
Total dwellings	489,000

FIG. 2.3 The locations of the represented SHOs on the Dutch map.

Extensive list of barriers and enablers

Prior to the first Delphi round, we prepared an initial set of CE implementation barriers and enablers, based on the relevant literature (Adams et al., 2017; de Jesus & Mendonca, 2018; Hart et al., 2019; Kirchherr et al., 2018; Kok., 2013; Mahpour, 2018; Masi et al., 2018; Shahbazi et al., 2016), to stimulate the discussions with the panel members during the interviews. Similar issues identified by different scholars were merged and sometimes adapted to the context of this study. For example, we combined “Limited awareness across the supply chain” (Adams et al., 2017), “Lack of interest, knowledge/skills and engagement throughout the value chain” (Hart et al., 2019) and “Lack of awareness, understanding, knowledge and experience with environmental issues” (Shahbazi et al., 2016) into “Lack of awareness, knowledge and experience with the CE”. A total of 56 issues were grouped under six categories, namely, *social and cultural, organisational, financial, sectoral, technical and technological,* and *regulatory*.

2.3.2 Data collection

Delphi round I

The purpose of the first Delphi round was to explore the CE implementation issues that early adopter housing associations experience with their pilot projects. Before the online interviews, panellists were sent a list of barriers and enablers in a questionnaire format and asked to score each of the matters by importance on a 5-point Likert scale, 1 being “not important at all” to 5 being “extremely important”.

As outlined in TABLE 2.2, 19 out of 21 members of the Delphi panel responded to the online questionnaire and participated in the online interviews. At the beginning of the interviews, panellists were asked open questions regarding circular practices in their organisations. Following this, barriers and enablers in each category were refocused, and panellists’ initial ratings were discussed in-depth. In the meanwhile, panellists reflected on their responses and supplemented additional points that were not covered in the list. These points were then mentioned in the subsequent interviews to validate whether they were relevant to be brought to the second round. Further, panellists were given a chance to adjust their answers upon discussions before the interviews ended. Upon completion of the first round, a summary of the first cut results, demonstrating the mean scores, the highest and the lowest ratings, and additional notes of the panellists were reported to all participants.

TABLE 2.2 Overview of the Delphi panelists.

Profession	Professional Experience (Years)	Delphi Round 1	Delphi Round 2
Advisor	34	x	x
Advisor	7	x	
Advisor	24	x	x
Advisor	22	x	
Advisor	22	x	x
Director	25	x	x
Director	25	x	x
Director	36	x	x
Innovation manager	10	x	x
Program manager	18	x	x
Program manager	20	x	x
Project leader	15	x	x
Project leader	16	x	
Project leader	18		x
Project manager	30	x	x
Project manager	20	x	x
Project manager	14	x	x
Real estate manager	7	x	x
Real estate manager	25	x	
Real estate manager	20	x	x
Real estate manager	20		x
Total participants		**19**	**17**

Delphi round II

There were two underlying objectives of the second Delphi round: (1) to determine circular principles used in business-as-usual practices and circular pilot projects and (2) to prioritise barriers and identify enabling factors. For the former, we used the R framework proposed by Potting and colleagues (Potting, 2016) and asked panel members to indicate which of the R principles apply to both their regular activities and circular pilot projects. For the latter, panel members ranked 13 barriers, chosen from the previous round, in line with the priority given by their organisations. The selection of these barriers was made according to the top-rated two scores per category, including an additional issue raised by the panel members ("The building code, rules and regulations hinder reusing building materials"). The reader must note that some of the barriers from the first round were combined to keep the list concise. For instance, "High purchasing costs of new circular materials" and "High purchasing costs of recycled materials" were combined into "High purchasing costs of circular materials (new and recycled)." Finally, participants were requested to propose enablers to address the top 5 barriers they ranked. With this, we aimed to build meaningful correlations between the most pressing five barriers and potential enablers.

2.3.3 Data analysis

For the first cut summary, a quantitative analysis was performed to summarise the panel ratings by calculating minimum, maximum, mean scores, and standard deviation values. Standard deviation was used to demonstrate the distribution of responses, in other words, the degree of consensus. A lower standard deviation value indicates a higher consensus. We did not seek a consensus among panel members but focused on exploring CE implementation issues. Therefore, a consensus criterion was not defined when analysing the results. Similarly, for analysing the second-round results, mean, and median scores of the rankings were used to measure central tendency, standard deviation and interquartile range were calculated for quantifying the amount of variation in rankings. After finalising the data analysis, a summary of the results was reported to all panellists.

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2.4 Results

2.4.1 Circular Economy practices of the Dutch social housing organisations

The Current state of the CE implementation

The analysis of the Delphi rounds reveals that CE is a new topic for the Dutch social housing sector, and its implementation is in an experimental phase. As presented in FIG.2.4, none of the represented housing associations has completed a circular project up until now. However, almost 80% of them are currently carrying out their first circular pilot projects, which are expected to be completed in a short period of time. Most panel members regard these projects as the first experimental steps to generate practical knowledge, or as one panellist put it, “learning by doing.” In addition, we found that two-thirds of the SHOs have implemented a few circular strategies in renovation and demolition activities. These include collecting old building components, for instance, bathroom fixtures, reusing them upon cleaning and repairing in another location, using biobased insulation materials in energy renovation projects, and reusing old roof tiles in renovation projects. Moreover, the majority of the represented organisations have incorporated CE in their policy documents or explicitly expressed it as one of their long-term sustainability targets.

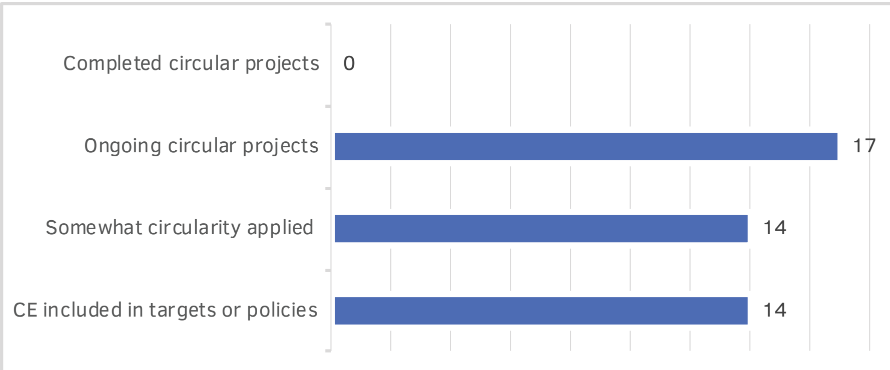

FIG. 2.4 The current state of the CE implementation in 19 early-adopter Dutch SHOs.

Circular Economy strategies and business models

In the second Delphi round, participants were asked what circular strategies are used in their business-as-usual activities and in what ways circular pilot projects differ from them. FIG.2.5 shows the total counts of the responses on each R strategy. “Repair” is the dominant approach in both business-as-usual and circular operations, as maintaining homes is one of the core tasks of the SHOs, as mentioned previously. Particularly in demolition projects, “recycling” is a norm as there is a lack of urban mining experience among social housing associations. One of the panel members elaborated on this: *“We are not aware of the value that could be captured from the existing buildings. We do not have the tools to measure it. Therefore, we prefer to recycle building components instead of seeking upcycling options.”*

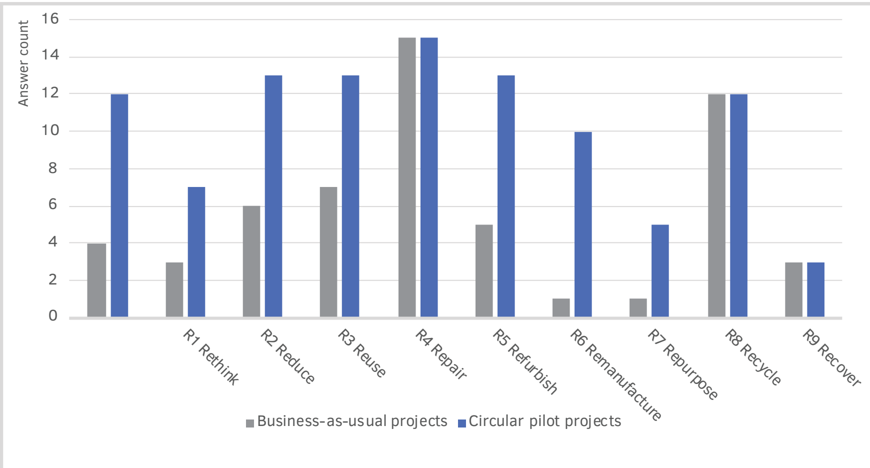

FIG. 2.5 Response counts on R strategies (Potting, 2016) by 19 participating Dutch SHOs.

Maybe the most apparent trend in circular practices is the growing attention to the pre-use phase-related strategies (*refuse, rethink, and reduce*) that aim to reduce and, if possible, eliminate resource use when designing buildings. Another remarkable finding is that SHOs consider applying new circular strategies during the use phase of buildings, such as *remanufacturing* and *repurposing*.

The typical business model of the Dutch SHOs has several links with the circular business archetypes defined by Bocken and colleagues (Bocken et al., 2016). For example, Dutch SHOs own the properties in their housing portfolio and provide rental services to their tenants, which corresponds to the “Access and performance model” [5], and also their housing stock has a long lifespan thanks to the regular repair and maintenance activities, which can be linked to the “Classic long-life model” (Bocken et al., 2016). As for the circular pilot projects, there have been a few experiments with the new business models: Only one participating SHO applied the material-as-a-service model, and two tested sharing economy and take-back guarantee models.

2.4.2 Barriers and enablers for the Dutch social housing organisations

In the first round, panel members were asked to rate and discuss 56 barriers and enablers, subdivided into six categories. The scores were given on a 5-point Likert scale, one being “not important at all” to five being “extremely important.” The analysis of the ratings is demonstrated in minimum, maximum, mean, and standard deviation values in TABLE 2.3. The following sections discuss these findings in depth and present the mean scores of the barriers and enablers in brackets.

TABLE 2.3 The extensive list of CE implementation barriers and enablers

Category	Barriers and Enablers	Min	Max	Mean	Standard deviation	Mean category
Barriers						
Social and Cultural Barriers	Lack of awareness, knowledge and experience with the CE	2	5	3.84	0.87	3.27
	Resistance from stakeholders	2	5	3.42	0.94	
	Tenant preference for new building products	2	4	3.32	0.8	
	Lack of willingness to collaborate across the supply chain	1	4	3.26	0.85	
	Lack of consumer (tenant) awareness and interest	1	4	2.53	0.88	

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TABLE 2.3 The extensive list of CE implementation barriers and enablers

Category	Barriers and Enablers	Min	Max	Mean	Standard deviation	Mean category
Organisational Barriers	Giving higher priority to other issues, e.g., energy transition	3	5	4.11	0.72	3.62
	Operating in a linear system	2	5	3.68	0.8	
	Limited top management commitment and support for circularity	1	5	3.58	1.23	
	Lack of time and human resources	2	5	3.47	0.99	
	Insufficient technical training and education on circularity	1	5	3.26	1.02	
Financial Barriers	High purchasing costs of new circular materials	3	5	4	0.46	3.8
	High purchasing costs of recycled materials	2	5	3.95	0.69	
	Unclear business case	2	5	3.95	0.94	
	High upfront investment costs	3	5	3.89	0.72	
	High costs for collecting, dismantling, urban mining	2	5	3.84	0.59	
	Limited funding for circular projects	1	4	3.16	0.93	
Sectoral Barriers	Conservative and uncooperative nature of building industry	2	5	3.79	0.95	3.42
	Lack of standardisation	2	5	3.68	0.86	
	Uncertainty in building end-of-life issues	2	5	3.42	0.82	
	Long product life cycles	1	5	3.37	1.13	
	Poor partnership formation with supply chain	2	5	3.26	1.07	
	Complexity of buildings	2	5	3	0.92	
Technical and Technological Barriers	Lack of an information exchange system	2	5	3.68	0.86	3.5
	Lack of circular design guidelines	2	5	3.53	0.82	
	Lack of relevant tools for material reuse	2	4	3.47	0.68	
	High costs of implementing new technologies	2	5	3.32	0.8	

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TABLE 2.3 The extensive list of CE implementation barriers and enablers

Category	Barriers and Enablers	Min	Max	Mean	Standard deviation	Mean category
Regulatory Barriers	Circularity is not effectively integrated in regulations	2	5	3.68	0.8	3.51
	Limited circular procurement	2	5	3.68	0.8	
	Uncertainty regarding future legislation	2	5	3.42	0.82	
	Lack of global consensus on CE	2	5	3.26	0.91	
Enablers						
Social and Cultural Enablers	Leadership	3	5	4.21	0.61	3.84
	Collaborating with other social housing organizations	3	5	4.05	0.6	
	Circular economy training, education and workshops	2	5	3.84	0.67	
	Social awareness and shifting tenant preferences	3	5	3.79	0.61	
	Awareness raising events	3	4	3.32	0.46	
Organisational Enablers	Commitment and support from the top management	3	5	4.58	0.59	4.09
	High priority on circularity within the organisation	2	5	3.95	0.89	
	Collaboration of internal teams	2	5	3.74	0.64	
Financial Enablers	Clear business case for CE	3	5	4.05	0.83	3.91
	Lower costs for circular materials	3	5	4.05	0.6	
	Financial incentives to use secondary materials	2	5	3.84	0.93	
	Lower costs for collecting, dismantling, urban mining	2	5	3.84	0.87	
	Sufficient funding for circular projects	2	5	3.79	0.83	
Sectoral Enablers	R&D and innovation	3	5	4.05	0.69	3.99
	Best practice case studies	3	5	4	0.56	
	Better collaboration with sector parties	3	5	3.95	0.6	
	Development of standards	2	5	3.95	0.83	

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TABLE 2.3 The extensive list of CE implementation barriers and enablers

Category	Barriers and Enablers	Min	Max	Mean	Standard deviation	Mean category
Technical and Technological Enablers	Development of enabling technologies	3	5	3.95	0.6	3.87
	Development of tools and guidelines	2	5	3.84	0.74	
	Development of digital marketplaces for secondary material	2	5	3.84	0.93	
	Development of circular procurement systems	2	5	3.84	0.81	
Regulatory Enablers	Incentives for CE	2	5	4.11	0.72	3.96
	Circular economy legislation	3	5	4.05	0.69	
	Policy support	3	5	3.95	0.51	
	Waste management directives	2	5	3.95	0.83	
	Global agreement on circular economy	2	5	3.74	0.85	

Based on Adams et al. (2017); de Jesus & Mendonca (2018); Hart et al. (2019); Kirchherr et al. (2018); Kok. (2013); Mahpour (2018); Masi et al. (2018); Shahbazi et al. (2016) and authors' interpretations.

Social and cultural barriers

Our results indicate that panellists identified "Lack of awareness, knowledge, and experience with CE" as the most influential cultural barrier (with an average score of 3.84), while "Lack of tenant awareness and interest" was considered the least important (2.53) in this category. The panel unfolded the reason behind this distinction: "*Tenants are not involved in the project development phase. Thus, their knowledge and awareness in CE would not influence the way we develop housing.*" However, "Tenant preference for new building products over reclaimed ones" was considered moderately necessary (3.32) as some of the participants experienced resistance from their clients in situations where reclaimed toilet components from an old hospital were thought to be unsanitary. Moreover, another panel member pointed out that tenant acceptance could be an essential obstacle when initiating new circular business models. She further explained: "*Tenant acceptance becomes a major issue when we want to introduce laundry rooms since tenants need to say goodbye to their personal washing machines and adopt a new behaviour. This is more difficult than accepting reclaimed materials in their homes.*"

Organisational barriers

As mentioned in the previous chapters, increasing the existing building stock's energy efficiency has been a critical task for Dutch housing associations in the past decade. The panel confirms this tendency as "Giving higher priority on other issues", rated 4.11 being the most pressing organisational barrier. Although the represented SHOs are forerunners in circularity, they are operating in a linear way, which is found to be the second most pressing institutional barrier (3.68). A divergence in participant opinions is noted on the "Limited top management commitment and support for circularity initiatives", which has the highest standard deviation among all questions (s.d. 1.23). Although the majority of the panel considered it as a significant obstacle (3.58), some of the panel members rated it "not at all important" *by claiming that the higher management in their organisations has "an innovative mindset and convincing them is not an issue for sustainability-related matters."*

Financial barriers

Throughout the categories investigated, financial barriers possess a crucial place in CE implementation. Five of the six financial barriers identified scored more than 3.80, meaning "very important." High purchasing costs associated with new and reclaimed circular building materials are considered the most pressing economic barriers. One of the panel members reflected on this as follows: *"For social housing companies, it is extremely difficult to realise new housing due to the high construction costs and the lack of good locations… when extra material costs are added, it may not be financially possible to deliver the desired number of homes."* Furthermore, another panellist claimed that *"…the value-added tax (VAT) on top of labour and storage costs makes secondary materials even more expensive. We should be exempted from the tax on the materials recovered from old buildings."*

The second-most important financial factor appears to be the "Unclear business case" (3.95) for the housing sector. Panel members expressed the need for experimentation to test and learn how circularity aids value creation with the supply chain partners. One panellist compared this process with the energy transition: *"A decade ago, during the experimental phase, solar panels were expensive, but now they have become a part of our core business case. We have to find out ways for the circular materials as well."*

Interestingly, "Limited funding for circular projects" was considered less important (3.16) than the other financial barriers. Although various institutions fund a large proportion of the pilot circular housing projects, some of the panel members believe that receiving funding is a short-term solution. Panellists express the importance of pilot projects in testing new ideas; however, concrete financial models are needed for the long-term implementation of CE.

Sectoral barriers

Our results suggest that sectoral barriers related to the construction sector are the least significant within distinguished categories (3.42). The building industry is known for its fragmented and conservative characteristics that hamper innovation. In a field like CE, innovation is needed at an ecosystem level throughout the sector. Although acknowledging the “Conservative and uncooperative nature of the building industry” as the most critical sectoral barrier (3.79), panel members perceive “Poor partnership formation with supply chain” as a reasonable obstacle (3.26). This could be explained by the dominant role of SHOs in the construction sector. As one panellist claimed: *“If one supplier does not agree with our approach, we will proceed with another interested innovative company. Our position in the market makes us an important player.”* Furthermore, “Lack of standardisation”, especially for the design of buildings and end-of-life practices along with material passports, is expressed as a significant barrier (3.68), whereas “Complexity of buildings” is considered less significant (3.0).

Technical and technological barriers

As noted in several studies (Ellen MacArthur Foundation, 2016b; Väisänen et al., 2019; Wilts, 2017), information management, in terms of data exchange between stakeholders regarding products’ quality, quantity and location, is critical when applying circular strategies and introducing new business models. Indeed, interviews with the panel members made it explicit that there is a need for an information exchange system among SHOs and their stakeholders. Thus, the “Lack of an information exchange system” is seen as the most critical technological barrier (3.68) in this category. Another significant technical barrier has been found to be the “Lack of circular design guidelines” (3.53). During the interviews, we noticed that there is an immediate demand for guidelines, not only for design but also for implementation, management, and measurement of the circular construction, renovation, and maintenance projects. The lack of measurement tools to assess the circularity level was echoed in multiple interviews. Further, some panel members, although acknowledging the existence of several innovative technologies such as resource management platforms, material passports, and digital marketplaces, expressed the confusion around missing the “time” dimension in these tools: *“…*

buildings have long life cycles; it is confusing how to keep material passports for 50 years." Another panellist commented: *"Current marketplaces fail to offer time arrangements for building parts that will become available from planned demolition sites. This hinders reusing reclaimed materials in design projects."*

Regulatory barriers

According to the calculated ratings, two of the identified regulatory barriers came forward. The first one is "Circularity is not effectively integrated into regulations", which scored 3.86. The major issue raised by the panellists was the strict building code, hindering the reuse of reclaimed building components in new construction projects. For instance, a panel member complained: *"We could not reuse a modular concrete staircase that we dismantled from an old building because the dimensions of the risers will not comply with the current building code. It was a lost opportunity."* Likewise, many panellists shared similar practical obstacles when applying for a building permit for their circular pilot projects. The second barrier, which also scored (3.86) is "Limited circular procurement." According to the panel, there is a lack of understanding regarding the circular procurement procedures within the supply chain, which result in low demand and supply of circular products and services.

Social and cultural enablers

"Leadership" with a clear vision and commitment is believed to be the most driving cultural factor for the CE implementation (4.21). Following this, "Collaborating with other social housing organisations" to share knowledge and experiences scored as the second influential enabler (4.05). This enabler was echoed multiple times during the interviews. One panel member representing an SHO that has recently started the piloting process commented: *"We did not know how to start. Luckily, there are other housing associations that share their knowledge and experiences with us."* Knowledge generation and distribution are not limited to collaboration with the companions, as panel members pointed out the driving power of "CE training, education, and workshop" (3.84) for a well-informed ecosystem creation. Moreover, to stimulate a more extensive adoption of circularity, a shift in consumer (tenant) preferences and raising awareness in public are seen as essential enablers.

Organisational enablers

Among all enablers throughout the categories defined, “Commitment and support from the top management” received the highest score (4.58). Some of the panellists mentioned that the organisational structure of the Dutch SHOs is still very hierarchical as one of the panel members put it: *“If the top management is enthusiastic about circularity and open for innovation, we are one step closer towards achieving carbon-neutral housing stock; otherwise, we have to convince them for all the steps we are taking which, at times, is hindering the adoption of CE.”* As mentioned in previous sections, increasing the energy efficiency of the existing stock or transforming towards natural-gas-free homes have higher priority for Dutch SHOs in the current state. Along these lines, prioritising circularity is thought to be an essential enabler (3.95). In addition to the listed enablers, some panellists suggested “Creativity, openness for innovation, and new ideas” as an enabler.

Financial enablers

Not surprisingly, “Lower costs for circular materials” is considered the most crucial enabling factor (4.05), along with “Clear business case for CE” (4.05). During the interviews, we noticed that lowering material costs is linked with several elements discussed in other categories, for instance, R&D in biobased materials, market ecosystem creation for secondary materials, and policy support for lower taxes on reclaimed materials. Further, due to the labour-intensive nature of urban mining, dismantling building products becomes expensive. Panel members expect lower costs for urban mining to be a driving force for following a more circular business model. An additional enabler suggested by one panellist, “carbon tax on materials”, was agreed to be a critical enabler by other participants. In addition, panellists scored “Sufficient funding for circular projects” (3.79) vital for CE implementation by acknowledging the need for a viable business model: *“Funding is essential during the experimentation phase. For the long-term implementation, we need a successful business case.”*

Sectoral enablers

Our results suggest that “R&D and innovation” is a very significant sectoral enabler (4.05) in proposing new ways of thinking for production and consumption systems in the sector. These could be in the form of introducing new circular materials, proposing new business models for closing the loops or developing new technologies for ecosystem creation. “Best practice case studies” scored as the second critical enabler (4.00). Panel members echoed this driving factor frequently during the interviews. One interviewee claimed that *"…if there is a platform where the best practice cases and experiences are demonstrated, it could be beneficial for the rest of the sector."* "Better collaboration with sector parties" is believed to be essential (3.95) to create a circular ecosystem where, as one of the panellists put, *"… all stakeholders from architects to suppliers sit at the same table …"* Last but not least, "Development of standards" for circular construction methods, circular procurement, and material passports is seen as a vital factor (3.95).

Technical and technological enablers

Many scholars agree that technology plays an enabling role in the implementation of circular strategies and business models (Antikainen et al., 2018; Neligan, 2018; Wilts, 2017). Our results show that this is valid for the Dutch housing associations as well. Overall, by category, technical and technological enablers scored 3.87, where "Development of enabling technologies" is thought to be an essential enabler (3.95). Exactly what "enabling technology" entails was an essential aspect of the discussions with the panel members: Data collection from the existing stock, data registration, measuring circularity, managing repair and maintenance operations, collaboration, and trading building components between the stakeholders were some of the qualities mentioned. In addition, tools and guidelines for circular design, implementation, deconstruction, and procurement are urgent requirements for the practitioners, according to the panel. In addition, panellists stressed the importance of digital marketplaces to stimulate the use of secondary building materials (3.84). Such platforms are not used primarily in housing projects, as some of the respondents noted. Finally, circular procurement tools and associated databases are seen as being necessary when delivering circular building projects (3.84).

Regulatory enablers

One of the frequently mentioned enabling factors was regulatory support from the policy environment for innovation and the development of circular practices. In line with this, panel members stressed the driving influence of "Incentives for CE" (4.11). Especially adapting the current building laws to circular strategies and creating "CE legislation" (4.05) are considered essential for circular building projects. "Policy support" is another urgent aspect (3.95), which mainly refers to tax and procurement issues by the panel members. For better handling of construction and demolition waste, strict waste management legislation is seen as a driving factor (3.95).

2.4.3 High-priority issues and potential enablers

In the second round of the Delphi inquiry, panel members were asked to rank 13 top-scored barriers according to their importance and requested to suggest enablers to overcome the most critical five barriers. TABLE 2.4 shows the calculated minimum, maximum, mean, median, standard deviation, and interquartile range values of the rankings, and TABLE 2.5 presents the potential enablers. According to the results, the most pressing five barriers appear to be: (1) higher priority in other issues; (2) operating in a linear system; (3) lack of awareness, knowledge, and experience with the CE; (4) high purchasing costs of circular materials (new and recycled); and (5) unclear business case.

TABLE 2.4 Results of the second-round Delphi rankings. Lower numbers indicate higher priority.

Rank	High-priority issues	Min	Max	Mean	Std Dev	Median	Inter. Range
1	Higher priority in other issues, e.g., energy transition	1	9	3.60	2.50	3	4
2	Operating in a linear system	1	11	3.80	3.21	3	5
3	Lack of awareness, knowledge and experience with the CE	1	8	4.00	2.07	4	4
4	High purchasing costs of circular materials (new and recycled)	1	13	4.93	3.66	4	5
5	Unclear business case	2	11	5.53	2.55	5	4
6	Conservative and uncooperative nature of building industry	1	13	5.87	3.56	7	6
7	Lack of standardization in circularity	2	9	6.60	2.18	8	3
8	Lack of an information exchange system	3	13	8.67	2.44	9	3
9	Resistance from stakeholders	3	13	8.73	3.86	12	5
10	Lack of circular design and implementation guidelines	6	13	9.20	2.10	10	4
11	The building code, rules and regulations hinder reusing building materials	4	13	9.33	2.98	10	5
12	Circularity is not effectively integrated in innovation policies	1	13	10.27	3.28	12	4
13	Limited circular procurement	8	13	10.47	1.26	10	1

TABLE 2.5 The top five high-priority barriers and potential enablers.

Rank	High-priority issues	Potential enablers
1	Higher priority in other issues	Giving higher priority on circularity within the organisation
	(Organisational)	CE Legislation
		Leadership in circularity
		Commitment and support from the top management
		Combining energy efficiency and CE targets *
2	Operating in a linear system	Best practice case studies
	(Organisational)	Collaborating with other housing organizations
		CE Legislation
		Leadership in circularity
		R&D and innovation
		Better collaboration with sector parties
		Introduction of change management practices *
3	Lack of awareness, knowledge and experience with the CE	Best practice case studies
	(Social and cultural)	Development of circular design and implementation guidelines
		Giving higher priority on circularity within the organisation
		CE training, workshops, education
		Making experiments with supply chain actors *
		Introduction of clear measurement methods for circularity *
		Lobbying for CE *
4	High purchasing costs of circular materials (new and recycled)	Clear business case
	(Financial)	Development of enabling technologies to recover materials
		R&D and innovation
		CE Legislation
		Development of circular procurement systems
		Lower costs for circular materials
		CE training, workshops, education
		CO_2 tax on materials *
		Considering life-cycle costs *
		Making experiments with circular materials and products *
5	Unclear business case	Clear business case
	(Financial)	Best practice case studies
		R&D and innovation
		Commitment and support from the top management
		Incentives for CE
		Development of circular procurement systems
		Development of standards
		CO_2 tax on materials *

The two top barriers concern the way housing providers shape their strategic priorities in terms of sustainability, where energy transition has been the central theme. Regulatory frameworks played an essential role in steering energy efficiency measures in the housing stock in the past decade. Similarly, panel members consider the introduction of a binding “CE legislation” as an important driver to give circularity more attention in their organisations. Additionally, panel members suggested combining CE with energy efficiency targets as an alternative solution.

Our findings show that the linear, as one participant put it, *hierarchical* structure of the SHOs makes it challenging to introduce innovative thinking in strategic and daily activities. This could be addressed with the leadership and commitment from the top management. “Operating in a linear system”, although we consider it an organisational barrier in this study, is a systematic obstacle that impacts all supply chain actors. In that sense, engaging in a collaborative ecosystem with other SHOs and sector parties is very critical not only to steer circular construction models but also to create new business opportunities. In connection, previously mentioned, “proeftuinen” (experimental playgrounds) play a key role in this, as many panellists expressed the importance of successful case studies in convincing top management of their organisations as well as other sector parties towards circular practices.

“Lack of awareness, knowledge, and experience with the CE” was the third most significant barrier. In terms of attainment of skills and experience for circular construction methods, successful “Best practice case studies”, where alternative circular strategies and business models are tested, are considered essential. Such experiments are critical not only for SHOs but also for their stakeholders in the supply chain. Concerning this, the need for circular design and implementation guidelines was thought to be necessary, particularly for the new starters. Furthermore, measurement methods and standardisation of circular processes and materials are believed to be very crucial for catalysing a wider adoption of the concept in the housing sector.

The fourth and the fifth most pressing CE implementation barriers are related to the financial constraints: the high costs of circular materials and ambiguity around a viable circular business case for the housing sector. A few solutions were proposed for the former, including introducing a CO_2 tax on construction materials, developing circular procurement systems, and considering lifecycle costs in financial calculations. Among them, the CO_2 tax on construction materials gained considerable attention from the panel members, reflecting the ongoing discussions regarding the demand for a structural shift for taxing labour, raw materials, pollution, and emissions for the construction sector in the Netherlands (*Manifest Belastinghervorming voor de Circulaire Bouweconomie*, 2020). We noticed that generating a viable business case has connections with lowering circular material prices as well; however, it is not limited to it. A few of the participating SHOs have experimented with product-service models by taking an innovative approach. Similar experimentations with circular business models showcased in "Best practice case studies" are assumed to be an essential driver for CE implementation in the sector.

Overall, to address the most urgent CE implementation issues in the Dutch social housing sector, four enablers come to the forefront: First, "CE Legislation" for the introduction of new tax schemes on construction materials and for construction methods; second, "Best practice case studies" to demonstrate successful experimentations with circular construction strategies and new business models; third, "Commitment and support from the top management" to make circularity a priority item on SHOs' agenda; and finally, "Clear business case" to boost the market for wider adoption of the CE concept.

2.5 Discussion and conclusions

Despite the emerging body of literature on CE in the built environment, existing research has mostly overlooked the housing stock, especially the one managed or owned by the social housing organisations (SHOs), while this offers tremendous opportunities to generate circular flows of resources in the built environment. This article sheds light on the CE practices of the early-adopter Dutch SHOs and presents the main barriers and enabling factors associated with implementing circular principles, employing a Delphi study with 21 sector professionals.

Seen from a wider implementation of CE approaches in their maintenance, renovation and construction activities, our findings indicate that Dutch SHOs are at the early stage of development in which they experiment with new circular strategies by involving sector stakeholders from the beginning of the construction process. In doing so, we found a tendency to apply higher-level circular strategies, such as "refuse", "rethink", and "reduce" in pilot projects.

From the circular business models perspective, Dutch SHOs are "service providers" who keep the ownership of the housing stock they operate and offer rental properties to their tenants. This system coincides with the "Access and performance model" of Bocken et al. (Bocken et al., 2016), which was interpreted differently by Eikelenboom et al. (Eikelenboom et al., 2021) as delivering an all-inclusive service package to the tenants through a single contract. They argue that such a model could cause an extra burden on low-income households. SHOs also regularly repair and maintain their housing stock, slowing the resource loops by offering long-lived buildings, as in the "Classic long-life model" (Bocken et al., 2016). Therefore, elements of a CE are already implicit in their business operations. However, there is a noticeable gap in new business model creation in circular pilot projects. Among 19 represented SHOs, only two of them employ the take-back system, and one of them tests a materials-as-a-service model with a supplier.

Our Delphi research has identified five critical barriers to a wider implementation of CE in the Dutch SHOs, namely, (1) higher priority in other issues; (2) operating in a linear system; (3) lack of awareness, knowledge, and experience with the CE; (4) high purchasing costs of circular materials (new and recycled); and (5) unclear business case.

In general, the main barriers that Dutch SHOs encounter are closely related to their organisational structure and company culture. This finding coincides with Kirchherr and colleagues' EU-wide study (Kirchherr et al., 2018). According to their results, other businesses also suffer from "Hesitant company culture" when introducing CE as a strategic goal in their organisations. On the other hand, Adams and colleagues (Adams et al., 2017) discuss organisational issues mainly from the sectoral perspective. Their study with the UK construction industry indicates that the sector's fragmented nature hinders the application of circular principles throughout the supply chain. The panellists also acknowledged this view in the first round of our Delphi survey. However, we have not observed a direct relationship between the sectoral and organisational barriers.

Similar to our study, several studies highlight that developing a viable business case for circular construction processes is challenging (Adams et al., 2017; Akinade et al., 2020); and high costs of circular materials hampers the CE implementation (Densley Tingley et al., 2017; Jugend et al., 2020). Challenges for new business model creation have ties with the traditional ownership models in the building sector. Several scholars discuss the need for a shift in the way of ownership of buildings and their components is structured for the circular flows of resources (Adams et al., 2017; Kanters, 2020; Pomponi & Moncaster, 2017; van den Brink et al., 2017). As discussed previously, Dutch SHOs retain ownership of their building stock and deliver services to their tenants, which correspond to circular models. However, for renovation and newly built projects, there is room for experimentation with other circular business models to increase the level of circularity.

Many reviewed studies identified a lack of awareness as one of the most critical barriers to CE implementation (Adams et al., 2017; Bilal et al., 2020; Jugend et al., 2020; Kirchherr et al., 2018). Consistent with the literature, our study also found this barrier very important; however, there is a marked difference in our findings that panel members consider lack of ‘tenant’ interest and awareness as a minor issue, whereas other studies, for example, Kirchherr and colleagues (Kirchherr et al., 2018) found ‘Lacking consumer interest and awareness’ as the most pressing barrier in the European context.

Several enablers are proposed to overcome these key obstacles. These include a binding CE legislation allowing innovation in circular construction practices and reforming existing tax schemes on construction materials, systematic exchange of best practices, development of enabling technologies and circularity measurement tools, a more prominent role for leadership and priority setting at the top-management level, and clear business models for SHOs and their supply chain partners. Particularly for new starters, developing CE design and implementation guidelines and collaborating with other SHOs are important enabling factors.

Overall, our study shows that, although the Dutch SHOs may have been dealt a good hand in terms of their fundamental business model and societal objectives, they also face significant barriers to a wider implementation of CE principles. The main challenge now seems to be setting in place the enablers that will allow circular asset and construction to become common practice.

When interpreting our findings, it must be kept in mind that the Delphi panel members were chosen from SHOs that have explicit goals for the CE. Other SHOs, who have no explicit CE goals yet, may be expected to face similar barriers and enablers when they do start to adopt CE goals, but this cannot be stated with absolute certainty. Moreover, as CE in the construction sector itself evolves over time, the experienced barriers and enablers are likely to shift as well.

This article contributes to the rapidly expanding field of circular built environment research by providing insights from the SHOs, who own a large part of the housing stock, particularly in Northwestern Europe. Our work appears to be one of the first attempts to examine housing associations’ CE practices thoroughly and lays the groundwork for future research into CE implementation in the sector. This study’s findings will be used in further research on developing a framework to address identified barriers through enabling digital technologies.

Author contributions

Conceptualization, S.Ç., V.G., and A.S.; methodology, S.Ç., V.G., and A.S.; formal analysis, S.Ç.; investigation, S.Ç.; resources, S.Ç.; data curation, S.Ç.; writing—original draft preparation, S.Ç.; writing—review and editing, S.Ç., V.G., and A.S.; visualisation, S.Ç.; supervision, V.G. and A.S.; project administration, S.Ç.; funding acquisition, V.G. All authors have read and agreed to the published version of the manuscript.

Funding

This research is funded by INTERREG NWE project CHARM (Circular Housing Asset Renovation & Management—No More Downcycling), project number NWE 760. Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Human Research Ethics Committee of the Delft University of Technology.

Informed consent statement

Informed consent was obtained from all subjects involved in the study.

Data availability statement

The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy and traceability to individual housing associations, combined with the promise of anonymity of respondents.

Acknowledgements

We would like to thank all panel members for their valuable contribution to the Delphi study and the reviewers for their constructive feedback.

Conflicts of interest

The authors declare no conflict of interest.

3 Circular digital built environment

A framework

This chapter broadens research focus from the social housing sector to the entire built environment, exploring the application of digital technologies to facilitate circular strategies that aim to narrow, slow, close, and regenerate resource loops throughout various life cycle stages. By doing so, it provides a comprehensive overview of potentially enabling digital innovations. The chapter answers the second key research question by developing a novel framework, the Circular Digital Built Environment Framework, which identifies and maps ten enabling technologies. The framework, established in this chapter, serves as a foundational guide for the subsequent two chapters (Chapter 4 and 5).

Recap key research question 2: What digital technologies can potentially enable a CE in the building industry, and in what ways?

Publication: Çetin, S.[1], De Wolf, C.[2], & Bocken, N.[3] (2021). Circular Digital Built Environment: An Emerging Framework. Sustainability, 13 (11).

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The framework introduced in this chapter has been made accessible online as an interactive tool for researchers, students, and practitioners. You can find it at: *https://miro.com/miroverse/digital-circular-economy-framework/*

ABSTRACT

Digital technologies are considered to be an essential enabler of the circular economy in various industries. However, to date, very few studies have investigated which digital technologies could enable the circular economy in the built environment. This study specifically focuses on the built environment as one of the largest, most energy- and material-intensive industries globally and investigates the following question: what digital technologies potentially enable a circular economy in the built environment, and in what ways? The research uses an iterative stepwise method:

(1) framework development based on regenerating, narrowing, slowing and closing re-source loop principles; (2) expert workshops to understand the usage of digital technologies in a circular built environment; (3) a literature and practice review to further populate the emerging framework with relevant digital technologies; and (4) the final mapping of digital technologies onto the framework. This study develops a novel Circular Digital Built Environment framework. It identifies and maps ten enabling digital technologies to facilitate a circular economy in the built environment. These include (1) additive/robotic manufacturing, (2) artificial intelligence, (3) big data and analytics, (4) blockchain technology, (5) building information modelling, (6) digital platforms/marketplaces, (7) digital twins, (8) geographical information system, (9) material passports/databanks, and (10) the internet of things. The framework provides a fruitful starting point for the novel research avenue at the intersection of circular economy, digital technology and the built environment and gives practitioners inspiration for sustainable innovation in the sector.

KEYWORDS circular economy, digital technology, digitalisation, built environment, construction, buildings, framework, circular strategies, circular business models, circular design, sustainability

3.1 Introduction

By 2050, roughly two-thirds of the world's population will be living in cities (United Nations Department of Economis and Social Affiars, 2018). By 2030, three billion people will need new housing (UN-Habitat, 2018). However, today's construction sector is the most resource-intensive sector in industrialised countries (Giljum et al., 2016), using 50% of all materials used in Europe (Márton Herczeg et al., 2014), creating 36% of the total waste in the European Union (EU) (Eurostat, 2018a), and emitting 39% of our global energy-related greenhouse gas emissions (Abergel et al., 2019) due to its linear model: we extract, produce, use, and dispose of building materials and resources. The challenge for all stakeholders of the built environment (BE) is to respond to global housing needs while reducing environmental impacts. However, this is no easy task. Considering that the construction industry forms about 9% of the European gross domestic product (European Commission, 2016a), it is essential to drive the paradigm shift from a linear to a circular BE. Indeed, to address the emissions, resource depletion and waste caused by this industry, a transition to a circular model is urgently needed.

The Circular Economy (CE) concept is not new, and some would refer to it as old wine in new bottles (Potting & Kroeze, 2010). Indeed the work by Boulding on Spaceship Earth (Boulding, 2013), Commoner's Four Laws of Ecology (Sears, 1973) and later work on the cradle-to-cradle (McDonough & Braungart, 2010), biomimicry (Benyus, 2002) and slowing and closing loops (Stahel, 1994) form some of the foundations of what is now known as the CE (Bocken et al., 2017). Organisations such as the Ellen MacArthur Foundation (EMF) helped popularise the concept, and it is now embedded in business goals as well as various (inter)national policies, such as in the Circular Economy Promotion Law in China and the Circular Economy Package in the EU (Bocken et al., 2017).

The CE concept has been discussed by many scholars and practitioners and interpreted differently (Kirchherr et al., 2017). Building on Nancy Bocken et al., (2021); Bocken et al., (2016); Konietzko et al., (2020); World Commission on Environment and Development, (1987), we consider the CE as a system that supports sustainable development to secure the resources to sustain our current and future generations by minimising resource inputs and waste, emissions, and energy leakage of products over time, which may be achieved through four distinct resource strategies:

1. Narrowing the loop: using fewer resources through efficiencies in the production and design process.
2. Slowing the loop: using and consuming less, through long product life, product life extension and avoiding unnecessary consumption.
3. Closing the loop: reusing materials, or, post-consumer recycling.
4. Regenerating the loop: focused on leaving the environment (and society) in a better state than before, e.g., through improving biodiversity.

Promoted by the EMF, CE principles applied to the BE sector have been illustrated in different industry reports (ARUP, 2016; Ellen MacArthur Foundation, 2018). Iacovidou and Purnell (Iacovidou & Purnell, 2016) demonstrated that mining the physical infrastructure through the reuse of building components leads not only to the conservation of resources but also the development of new business models and the creation of environmental, technical, and social value. Formed by a multistakeholder consortium, the Buildings as Material Bank (BAMB) project (BAMB, n.d.) has been one of the pioneers in developing and testing circular strategies and tools to recover value from buildings. Other examples of such pioneers include Rotor (Rotor, n.d.), Cycle Up (cycle up, n.d.), and Baubüro In Situ (baubüro in situ, n.d.). However, the lack of cross-sector communication and coordination tools needs to be addressed to enable the broad implementation of a feasible circular design strategy in the current construction practice (De Wolf et al., 2020). Digitalisation could offer some of the tools needed.

Digital transformation, next to the CE transition, has been proclaimed as one of the priority areas of the EU in a recent announcement of “Europe’s Digital Decade” (European Commission, 2021a). This vision aims not only to empower people and businesses but also to support the transition to a climate-neutral, circular, and resilient economy (European Commission, 2021a). Likewise, in the 2020 EU CE Action Plan (European Commission, 2020d), innovation and digitalisation are seen as drivers for tracking, tracing and mapping resources and dematerialising the economy for less dependency on natural resources. Thus, we can see a clear link between digitalisation and CE in the policy environment within the European context.

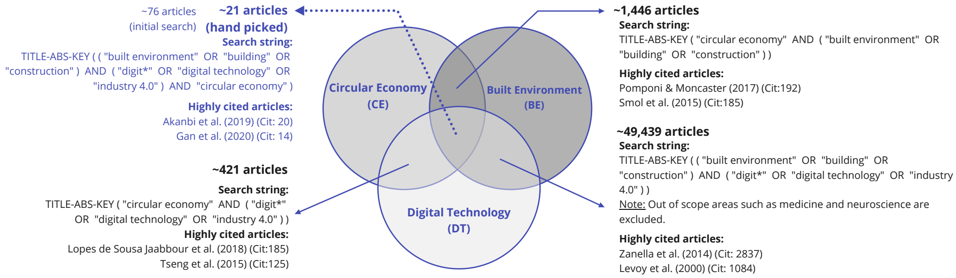

FIG. 3.1 Literature search results on the intersections among Circular Economy (CE), Built Environment (BE) and Digital Technology (DT). The results were extracted from the Scopus database (February 2021). See TABLE S1 in the Supplementary Materials for 21 articles on the intersection between CE, BE and DTs.

Furthermore, digital technologies (DTs), which some scholars refer to as Industry 4.0 technologies, are thought to be essential for the transition to a CE in various industries (Bressanelli, Adrodegar, et al., 2018; Ingemarsdotter et al., 2019; Lopes de Sousa Jabbour et al., 2018; Okorie et al., 2018; Pagoropoulos et al., 2017; Rosa et al., 2019). The research concentrating on the intersection between the CE and DTs is still immature as the number of publications started to grow from the mid-2010s onwards (Okorie et al., 2018; Rosa et al., 2019) (See also FIG.3.1). Several researchers sought to identify suitable DTs for supporting the transition to a CE or introduced integrative frameworks (Lopes de Sousa Jabbour et al., 2018; Okorie et al., 2018; Rosa et al., 2019), while others focused on their role in circular business models, particularly in product-service systems (Bressanelli, Adrodegar, et al., 2018; Pagoropoulos et al., 2017). Within the context of the CE, frequently referred DTs are additive manufacturing (AM), cyber-physical systems, the internet of things (IoT), as well as big data, and analytics (BDA) (Bressanelli, Adrodegar, et al., 2018; Lopes de Sousa Jabbour et al., 2018; Pagoropoulos et al., 2017; Rosa et al., 2019).

These DTs are found to be supportive of varying circular strategies such as enhancing the product design (Bressanelli, Adrodegar, et al., 2018), sustainable operations management (Lopes de Sousa Jabbour et al., 2018), resource efficiency (Rosa et al., 2019), optimisation of resource flows (Pagoropoulos et al., 2017), and tracking and tracing of post-use products (Lopes de Sousa Jabbour et al., 2018).

Compared to other sectors, digital transformation has been slow in the BE industry, but there have been considerable developments in the last few decades (Chan et al., 2020). The focus has been mainly on the relatively new uptake of Building Information Modelling (BIM) and digital twins (ARUP, 2019b), sometimes exploring the link to the blockchain technology (Hunhevicz & Hall, 2020) and the Internet of Things (IoT) (Dave et al., 2016; Tang et al., 2019) to manage buildings. Pilot projects have also demonstrated the feasibility of the digital fabrication (National Centre of Competence in Research, n.d.). Geographical Information System (GIS) is used at an urban scale in the decision-making process (Wang et al., 2019). The construction sector's value chain is known to be fragmented (Akinade & Oyedele, 2019; Pomponi & Moncaster, 2017), which is why digital platforms are being developed more and more (Akinade & Oyedele, 2019; Kovacic et al., 2020). Research is also being conducted about using Artificial Intelligence (AI) (Darko et al., 2020) in different fields in the sector.

From a CE perspective, some of these technologies have received great attention from both practice and academia. Several material passport concepts have emerged, e.g., Madaster (Madaster, n.d.); BIM platforms and add-ins have been developed to estimate the recoverability of materials in various design alternatives (Akanbi et al., 2018; Akanbi et al., 2019; Honic, Kovacic, & Rechberger, 2019), and to facilitate efficient data flows and supply chain collaboration (Akinade & Oyedele, 2019; Honic, Kovacic, Sibenik, et al., 2019); recycled materials are tested in concrete mixes with AM (Álvarez-Fernández et al., 2021); IoT systems have been designed for tracking materials for reuse across the life cycle stages (Li et al., 2021; Turner et al., 2021; Xing et al., 2020).

Despite broadly acknowledged opportunities that these DTs offer, no articles have been identified by the authors that comprehensively investigate which DTs could potentially support a CE throughout the life cycle stages of buildings. As shown in FIG.3.1, a literature search on the Scopus database yielded 21 articles on the intersection between BE, CE and DTs (after eliminating papers that are not relevant). These articles, similar to the abovementioned examples, focus on the development or implementation of a particular technology for a certain circular strategy in a specific life cycle stage. Therefore, there is a lack of a thorough overview of the DTs, which could enable the circular transition of the BE. To contribute to the building of knowledge on this matter, this chapter addresses the following research question: what digital technologies potentially enable a Circular Economy in the built environment, and in what ways? The study adopts an iterative stepwise approach, consisting of four steps: framework development; expert workshops; literature and practice review; and mapping of enabling DTs.

The remainder of this article is structured as follows. Section 3.2 displays the research design and methods. Section 3.3 introduces the Circular Digital Built environment framework (CDB framework) that was developed based on life cycle stages in buildings and the four core CE principles of regenerating, narrowing, slowing and closing resource loops. Furthermore, Section 3.4 presents the empirical findings from the expert workshops, while Section 3.5 focuses on the literature and practice to explore the enabling functions of the identified DTs. Based on the findings from the previous sections, Section 3.6 maps ten enabling DTs onto the CDB framework and demonstrates the interdependencies of these technologies. Finally, Section 3.7 elaborates on the research contributions, implications for practice, and limitations.

3.2 Research design and methods

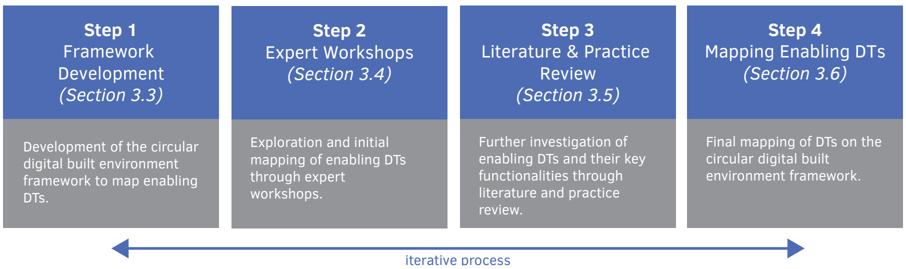

FIG. 3.2 Research design.

Given the emerging characteristics of DTs in the CE, an exploratory qualitative research approach was chosen based on an iterative stepwise method. The four overarching research steps presented in FIG.3.2 are (1) the development of a framework for mapping enabling DTs; (2) the identification and initial mapping of DTs through expert workshops; (3) the literature and practice review; and (4) the final mapping of the identified DTs onto the framework. In a sense, our work can be considered to be an integrative review of three research domains (CE, BE, and DTs) that formulates an initial conceptualisation of an emerging research field (Snyder, 2019).

3.2.1 Step 1—Framework development

In order to map the enabling DTs, the CDB framework was developed, similarly to Ingemarsdotter et al., (2019); Lopes de Sousa Jabbour et al., (2018); Rosa et al., (2019), based on life cycle stages and circular building strategies. For the former, we looked at the life cycle stages of different resource loops—i.e., water, land, energy, and materials—and combined them with the building project development stages. Eventually, three overarching life cycle stages are considered: pre-use phase, use phase, and next-use phase. For the latter, we reviewed academic and grey literature on circular building and business model strategies and categorised them under four core CE principles: (1) regenerate, (2) narrow, (3) slow, and (4) close. These core principles were built on previous research (Bocken et al., 2016; Bocken et al., 2021; Konietzko et al., 2020). In the meantime, we created a list of potential enabling DTs for a circular BE to be used at the next stage. After the expert sessions, the framework was updated and used for the final mapping of enabling DTs. Section 3.3 explains the framework development process in detail.

3.2.2 Step 2—Expert workshops

In the second research step, we conducted three workshops with 16 experts in March 2021. The purpose of the expert workshops was threefold: (1) to explore potential enabling DTs; (2) to map the identified DTs onto the framework; and (3) to find out whether the framework needs further revisions. The two main criteria for the selection of the experts were: having significant built environment industry or academia experience and having worked in circular building projects or developed digital construction tools (preferably for circular construction). TABLE 3.1 presents the occupational background, professional experience, and field of expertise of the participating experts. All of the experts came from Europe. We initially sought professionals with skills in both DTs and circular BE fields. However, it was difficult to find both types of expertise in one person (only three out of the 16 participants had expertise in both fields). Thus, the expert groups were formulated from three pools—experts in CE, circular BE or digital construction technology—by ensuring that at least one from each pool was present in each session.

TABLE 3.1 Overview of the participating experts. CE: Circular Economy in general; CBE: Circular Economy in the built environment; DCT: Digital construction technologies.

Groups	Occupational Background	Years of Experience	Field of Expertise
Workshop 1	Academic	20	Design and construction management
	Practitioner	25	CE; CBE
	Practitioner	10	DCT
	Academic	20	DCT
	Practitioner	40	DCT
Workshop 2	Academic	10	DCT; Biomaterials
	Practitioner	20	CE; CBE; Waste management
	Architect/Practitioner	25	CE; CBE; Reversible building design
	Academic	15	DCT; Sustainable design strategies
	Architect/Practitioner	32	CBE; Design philosophy
	Practitioner	15	CE; CBE
Workshop 3	Consultant	15	CE; CBE; DCT
	Practitioner/Consultant	17	CE; CBE; DCT
	Engineer	14	DCT; Prefab timber system design
	Academic	16	CBE
	Consultant	15	CE; CBE; DCT

Prior to the workshops, the experts were given information regarding the research and workshop protocol and were asked to mention enabling DTs for a circular BE. This input was then used to update the preliminary list of enabling DTs, which was presented to the participants during the online sessions. All of the sessions were organised online through a video conferencing platform and took approximately 60 min. An online interactive whiteboard application was used to record the experts' input on the framework. The primary researcher facilitated the sessions and took notes. These notes are reported as a summary of each workshop in Section 3.4. The following workshop procedure was followed in all of the sessions:

- Introduction (10 min): Upon welcoming the participants, the primary researcher briefly introduces the workshop's goal and explains the main elements of the CDB framework. The participants are allowed to add notes and suggest new circular building strategies or enabling DTs.
- Questions and discussion (45 min): The researcher poses a set of questions: "What DTs can enable CE in the BE? Where would you place them on the framework?" and initiates discussions when needed.
- Closing (5 min): The researcher receives feedback from the participants and closes the session.

3.2.3 Step 3—Literature and practice review

In the third step, we conducted a literature and practice review to determine the ways in which the identified DTs enable a circular BE. For the literature review, we used the Scopus database and searched for articles using a number of search strings. The scope of the search was limited to articles that explicitly referred to "circular economy". We also included subfields of some DTs. For example, when searching for articles relating to Artificial Intelligence, we used the following search string: "circular economy" AND (AI OR "artificial intelligence" OR "machine learning" OR "deep learning") AND ("construction" OR "building" OR "built environment"). See Appendix A for the search strings used in the literature review.

The initial query resulted in 265 articles and conference proceedings as of March 2021 (no timeframe was applied). However, the articles containing terms and expressions which were semantically different but homonyms (e.g., "construction" is used as "model construction") were eliminated. This led to 77 relevant articles, which were then analysed to select the ones that demonstrate a structured relationship between the DTs and circular building strategies. We excluded papers that were too broad in scope and which did not give a clear indication of DTs' enabling functionalities. The resulting papers were then used to map DTs onto the CDB framework.

To complement the literature review, we also reviewed practice, similar to Konietzko et al., (2020), and used pertinent literature beyond CE, e.g., energy efficiency in buildings. The purpose of the practice review was to exemplify the applications of enabling DTs in real-life. We used two search engines, Google (Google, n.d.) and Ecoasia (Ecosia, n.d.), and reports from consultancy firms (e.g., ARUP) to retrieve the examples. However, it was not possible to find examples for all of the DTs, as some of them are studied at the theoretical level by academics.

3.2.4 Step 4—Mapping of enabling digital technologies

In the last step, we synthesised the findings from the preceding steps and mapped the enabling DTs onto the CDB framework in order to better understand how DTs relate to the circular BE. The final mapping of the DTs was based mainly on the literature and practice review findings, whereby the main trends observed during the expert workshops were incorporated. TABLE S2 in the Supplementary Materials presents the references used in the CDB framework in detail.

3.3 Framework development

3.3.1 Life cycle stages

The BE consists of several interconnected sub-systems (e.g., cities, infrastructure, buildings) which are exposed to varying degrees of use (Durmisevic, 2019) and numerous actors (Eberhardt et al., 2020; Pomponi & Moncaster, 2017). Within each system, multiple resources coincide, including material, land, energy, water, and nutrients (from here onwards, 'resource' is used to refer to all). These resources have different characteristics, functions and lifespans; therefore, their recovery in a circular system requires individual attention (Eberhardt et al., 2020) (See FIG.3.3). Moreover, buildings are exposed to a large number of stakeholders from design until end-of-life stages, such as architects, developers, occupants and demolishers (Leising et al., 2018). The number, combination, and timeframe of the stakeholders vary by project, as each building is considered a unique entity (Pomponi & Moncaster, 2017).

Given the complexity of buildings and associated resources, it can be acknowledged that simplifying life cycle stages for framework development is a challenging task. Commonly used building life cycle stages consider four main phases: production stage, construction process, use stage, and end-of-life stage (see, for example, European standard EN 15978:2011 (NEN, 2011)). This approach is based on material flows and associated water and energy consumption and overlooks the "design process", which is a fundamental phase for developing circular buildings where DTs play a critical role. A recent review article highlighted that project design was the second most considered life cycle stage in the circular BE research (Benachio et al., 2020). Therefore, in our framework, we also include the design stage in buildings' life cycle stages. Overall, as illustrated in FIG.3.3, we consider three main lifecycle phases by taking into account material (De Wolf et al., 2020), water (ARUP et al., 2018; Mannan & Al-Ghamdi, 2020; Pimentel-Rodrigues & Siva-Afonso, 2019), energy (Cabeza et al., 2014), and land (Amenta & van Timmeren, 2018) cycles: pre-use phase, use phase, and next-use phase.

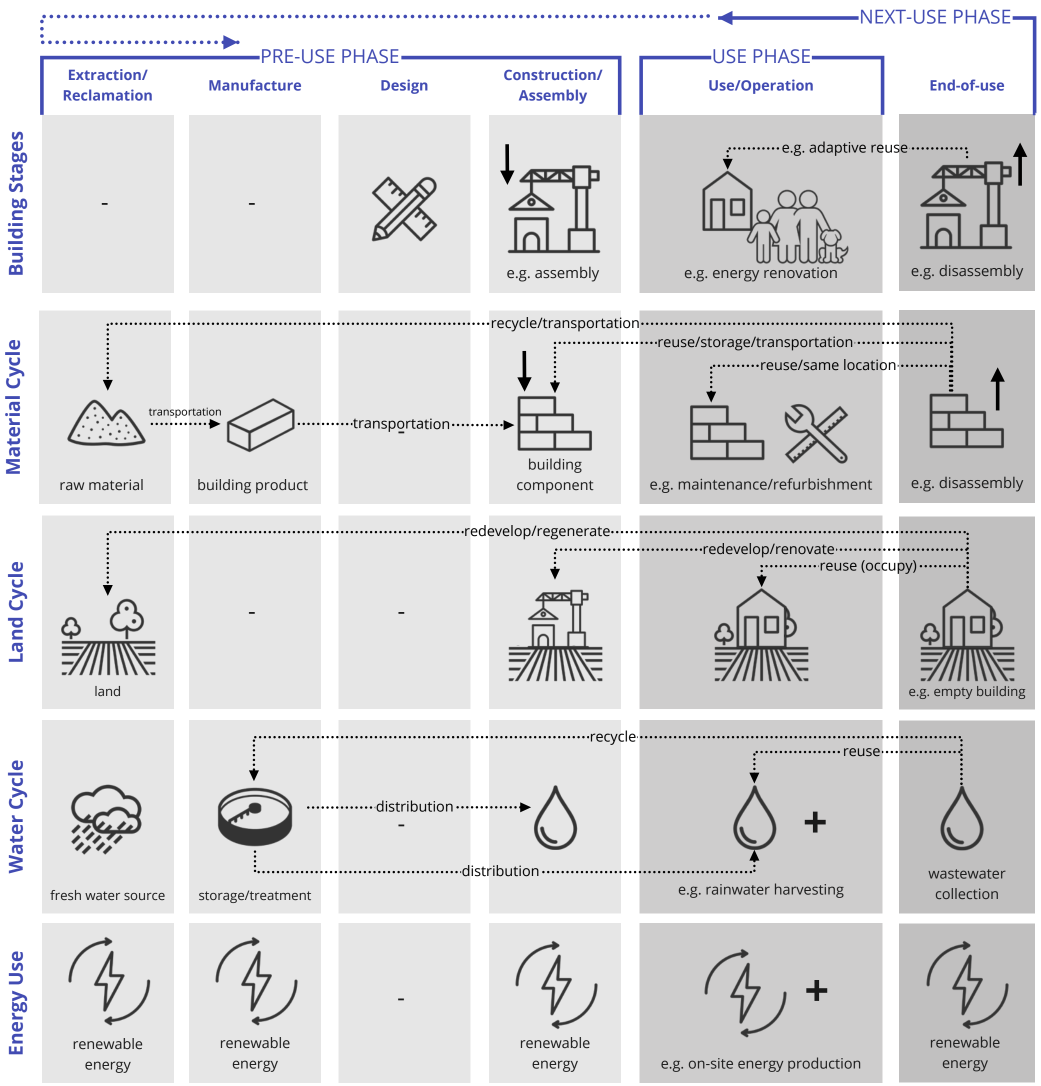

FIG. 3.3 Life cycle stages in a circular built environment (Own illustration). Note. The life cycle stages of resources are shown in a simplified way. Resource cycles are built on previous research (Amenta & van Timmeren, 2018; ARUP et al., 2018; Cabeza et al., 2014; De Wolf et al., 2020; Mannan & Al-Ghamdi, 2020; Pimentel-Rodrigues & Siva-Afonso, 2019). "+" signs on the water and energy cycles indicate potential surplus resource production.

The pre-use phase concerns activities that take place before buildings are occupied by users. These activities include mining raw materials or reclaiming resources from existing buildings, manufacturing building components, design, transportation, and construction or assembly. Depending on the construction method, the order of these activities may change. The pre-use phase activities play a critical role in reducing the resource inputs and increasing the operational performance of buildings, leading to a lower carbon BE. The use phase often constitutes the longest period of a building's life cycle, when a significant environmental impact is created (Cabeza et al., 2014; Gan et al., 2020). Therefore, it is very crucial to design buildings in such a way that their operational performance is also optimised. In addition, the use phase is critical to extending the lifetime of buildings and building products through activities such as repair and maintenance. Finally, the next-use phase refers to reintroducing buildings and associated resources when they reach their end-of-use stage. We envision a circular system in which there is no end of life; instead, all of the resources are reintroduced to the system multiple times by reuse or recycling with minimum resource inputs (see Section 3.4 for further arguments on this topic).

3.3.2 Circular building strategies

CE is an emerging concept in BE research that has received significant recognition in the past decade (Benachio et al., 2020; Hossain et al., 2020; Munaro et al., 2020). Scholars focused on various research areas from material reuse to urban planning (Munaro et al., 2020), where end-of-life activities, e.g., waste management, were the central issue in most of the studies (Benachio et al., 2020; Hossain et al., 2020; Munaro et al., 2020). As noted by Hossain et al., (2020), a holistic evaluation of CE principles that embrace all life cycle stages of buildings is missing. Several comprehensive framings of circular strategies have been proposed for the building components (van Stijn & Gruis, 2019); prefabricated buildings (Minunno et al., 2018); industrialised housing construction (Kedir & Hall, 2021); new building design and construction (Eberhardt et al., 2020); sustainable building construction (Hossain et al., 2020); material and product flows in buildings (Geldermans, 2016), and CE in the real estate sector (Kyrö, 2020). These frameworks look at either one particular life cycle stage (e.g., design phase) or production method (e.g., prefabrication) or consider a specific resource flow (e.g., material flow), lacking a holistic approach.

By building on previous research, we propose a comprehensive approach to group existing circular building strategies under four core CE principles (Nancy Bocken et al., 2021; Bocken et al., 2016; Konietzko et al., 2020): regenerate, narrow, slow, and close resource loops. We also add "collaborate" as a supporting strategy to address the inefficiency issues in the construction supply chain, which are fundamental in transitioning towards a circular BE. The following sections elaborate on the details of each principle and the associated circular building strategies.

Regenerate

The *terms "regeneration" and "restoration" are frequently* used in CE definitions interchangeably; yet, their meanings were poorly discussed (Morseletto, 2020). In technical cycles, products are reintroduced to the economy through restorative activities such as repair and remanufacturing (Morseletto, 2020), while regeneration aims at upgrading the state of systems by pursuing a net positive impact on the environment (Bocken et al., 2021). In architectural design, regenerative design is believed to be the highest level of sustainability, going beyond green and sustainable building concepts, generating continuous flows of resources in a self-sufficient manner (Attia, 2018; Lyle, 1996) where co-evolutionary systems are initiated between humans and nature based on the characteristics of the place (Mang & Reed, 2012). It shifts the mindset from "doing things to nature" to "being part of nature" (Reed, 2007). Within the scope of this study, we consider regeneration as one of the core principles of a circular BE, which aims at creating a positive impact in human and natural systems by co-creating with local communities and using renewable and healthy resources. The following strategies are proposed:

- "Stimulate human nature co-habitation and local biodiversity": Creation of shared spaces where humans interact with each other and with nature, accommodating green space and promoting biodiversity (Attia, 2018; Craft et al., 2017; Kubbinga et al., 2018). Examples include urban farming (Thomaier et al., 2014) and green roof ecosystems (Calheiros & Stefanakis, 2021). A real-life project is Resilio (RESILIO, n.d.) which implements blue-green roofs in Amsterdam.

- "Use healthy and renewable resources": Avoiding hazardous contents in building products (Attia, 2018); using bio-based renewable building materials, for instance, using mycelium (vegetative structure of fungi) to produce building components (Strunge, 2020); and producing with renewable energy (Konietzko et al., 2020). For example, British start-up Biohm is producing insulation panels from the mycelium (Biohm, n.d.).

- "Enhance indoor and outdoor environment": Providing high-quality healthy spaces for people in terms of lighting, air and place organisation (Attia, 2018; Kubbinga et al., 2018), and enhancing outdoor space, i.e., public and urban areas. An example is the transformation of misused or unused areas (wastescapes) into public spaces for local communities (Amenta & van Timmeren, 2018).

- “Exchange excess resources”: Capturing economic value from regenerative building operation. Positive buildings are equipped with advanced technologies that allow them to share surplus resources with their surroundings (energy, water, food and others) (Craft et al., 2017). Particularly for energy, recent years have seen tremendous advancements in smart grid technology that allow prosumers (consumers who also produce and sell energy) to trade surplus energy within their neighbourhoods (Mengelkamp et al., 2017). An example is Pando (Lo3 Energy, n.d.), a platform that empowers users to buy and receive local renewable energy within their neighbourhoods through a mobile application.

Narrow

As described in Bocken et al., (2016), narrowing resource flows refers to resource efficiency and fewer inputs in products. Translating it to the circular BE, narrow indicates using fewer resources throughout a building’s lifetime. In that sense, the early design phase plays a critical role as design decisions influence the performance of buildings and operations in later stages (Akinade & Oyedele, 2019; Kedir & Hall, 2021). Also, upgrading systems in existing buildings might lead to reductions in water and energy consumption during the use phase. Narrow strategies are summarised into three groups:

- “Reduce primary resource inputs”: This strategy is based on the dematerialisation approach (Kedir & Hall, 2021; Skillington & Crawford, 2020) and aims to minimise primary resource inputs in buildings and building products. Some examples include optimising lightweight structures (Block et al., 2017), using renewable energy in production, designing water circulation systems for sanitary hot water (Pimentel-Rodrigues & Siva-Afonso, 2019), and avoiding extra rooms in the space planning by assessing their added functions (Geldermans, 2016), i.e., avoiding the second bathroom. Designing from reclaimed materials rather than new materials is also another way to reduce primary resource inputs.

- “Design for high performance”: This design strategy aims to optimise building performance for fewer resource consumption before, during, and after the use phase of buildings. For instance, by considering building characteristics such as geometry, site, materials, and orientation, design optimisation provides considerable energy savings during the operational phase (Gan et al., 2020; Konis et al., 2016) or by optimising the transportation distance, resource consumption could be reduced during construction and end-of-use stages.

- “Improve efficiency”: Enhancing pre-use, operational, and next-use phase activities for lowering resource consumption, such as improving manufacturing systems for high performance, introducing rainwater collection systems in existing buildings or upgrading building facades for higher energy performance. For example, the Rennovates project implemented a technology-based renovation concept in 249 old single-family houses and upgraded their energy performance to zero-energy level (Enervalis, n.d.).

Slow

The slowing resource loops principle intends to slow down the speed of resource flows by intensifying their use and extending their valuable service life (Bocken et al., 2016; Stahel, 1994) through design and operational strategies as listed below:

- "Design for long life": Originally introduced for short-lived consumer products, e.g., mobile phones (Bocken et al., 2016), design for long-life aims to extend the utilisation period of buildings and building products. This can be achieved by creating an emotional connection with users (Bocken et al., 2016); increasing the physical durability of building components (Eberhardt et al., 2020); and considering ease and frequency of maintenance work during the design phase (Wood, 2012), i.e., considering easy access to technical building services (Eberhardt et al., 2020).

- "Design for reversibility": Reversible building design incorporates several design strategies that enable multiple resource life cycles until resources become irreversible. The circulation of resources occurs at spatial, structural, and material levels, and it has two main domains (Durmisevic, 2019): (1) Spatial reversibility refers to the ability of functional transformation of spaces without causing significant resource consumption, e.g., transforming an office into a classroom, while (2) technical reversibility addresses how structural and material arrangements are made allowing reuse of building parts in future, e.g., designing interlocking connections between components so that they can be easily dismantled (Durmisevic, 2019). The set of strategies that enable reversibility include the design for disassembly, design for reuse, modular design, flexible design, adaptable design, design for standardisation, design for upgrades and adjustment, prefabrication, and off-site construction. An example of a reversible building design is the UMAR (Urban Mining and Recycling) project built for disassembly in Switzerland (Heisel & Rau-Oberhuber, 2020).

- "Lifetime extension": This strategy targets the use phase of buildings and is concerned with prolonging the service life of buildings and building products through predictive, preventive or reactive maintenance and repair (Bocken et al., 2016; Ingemarsdotter et al., 2019).

- “Smart use of space”: The main purpose of flexibility and adaptive reuse strategies is to capture value from the existing buildings or land by introducing new functions; otherwise, they will remain underutilised and lose value. These strategies might exist in different forms, including the transformation of vacant office spaces into housing units (Olivadese et al., 2017); modification of building layout for a different function (Durmisevic, 2019); retrofit, rehabilitation and redevelopment of cultural heritage buildings (Foster, 2020); building modular buildings temporarily on a vacant land (Acharya et al., 2020); and, utilisation of empty spaces for short-term use through lease agreements (Acharya et al., 2020). An example is Workfrom, an online platform that lists available cafes, co-working spots, and alternative spaces for users, making use of under-occupied spaces in cities (workfrom, n.d.).

- “Deliver access and performance”, or, more broadly, Product-Service Systems: This business model strategy is focused on providing services instead of the ownership of products (Bocken et al., 2016; Bressanelli, Adrodegar, et al., 2018). This could be achieved in three ways: (1) the customer receives services based on per-time use (use-oriented), (2) the customer pays for a contractually-set performance or outcome (result-oriented), (3) the customer keeps ownership of the product but receives high warranty and maintenance services (product-oriented) (Bressanelli, Adrodegar, et al., 2018; Fargnoli et al., 2019). (NB. The latter is an example of a Product-Service-System where the product is still owned). Examples include co-working spaces, which provide workplaces for enterprises as a service, or Signify’s pay-per-lux model for lighting (formerly known as Philips Lighting) (Philips Lighting, n.d.).

- “Reuse”: Reuse is concerned with reintroducing buildings and resources back into the system without needing major transformation and resource consumption. Reuse may occur in the same or different location, and the function of the product may remain or change (De Wolf et al., 2020). Strategies such as ‘reduce primary resource inputs’, ‘design for reversibility’, ‘smart use of space’ and ‘urban mining’ are partially built on reuse. Reuse as a separate strategy can also go beyond these strategies, for example, reusing greywater in buildings (Pimentel-Rodrigues & Siva-Afonso, 2019) or reusing old window frames to construct indoor partitions in the same place during façade renovation.

Close

The closing resource loops principle aims to bring resources back into the economic cycle when buildings reach their end-of-use stage. Within the context of BE research, four closing resource loops strategies can be seen at the end-use-phase:

- “Recycle”: Recycling is concerned with remanufacturing resources into equivalent or lower-value resources and usually requires energy and water for the processes (e.g., glass melting) (De Wolf et al., 2020). This strategy has been dominantly used in BE for treating construction and demolition waste, e.g., recycling concrete aggregates (Ghisellini et al., 2018).

- “Urban mining”: Heisel and Rau-Oberhuber define urban mining as *“the reactivation of materials accumulated in the urban environment, which were not specifically designed for re-use or recycling (thus mining)” (Heisel & Rau-Oberhuber, 2020,* p. 2). The process requires the identification, quantification, and mapping of materials in cities and determining their recycling potential (Oezdemir et al., 2017). Urban mining in practice can be seen in the Dutch city of Rotterdam, which has the goal of reducing primary resource use by 50% before 2030 (Metabolic, n.d.). The municipality of Rotterdam identified and mapped buildings that are scheduled to be demolished in order to harvest materials in the future (Metabolic, n.d.).

- “Industrial symbiosis”: Industrial symbiosis is a concept of benefiting from the waste or by-products of different industries by building collaboration and synergetic interactions (Yu et al., 2021). For example, researchers demonstrated an industrial symbiosis model between a recycling factory and a concrete production factory based on recycled concrete aggregates (Yu et al., 2021).

- “Track and trace resources”: Tracking and tracing resources throughout the lifetime of buildings enables us to capture embodied value when they reach their end-of-use phase.

Collaborate (supporting strategy)

A higher degree of collaboration among supply chain actors is needed to achieve circularity in the BE. The construction industry is known for its highly fragmented and inefficient nature (Akinade & Oyedele, 2019), which was seen as one of the major barriers in CE transition (Leising et al., 2018). Therefore, we propose two collaboration strategies to support the circular transition of the BE:

- "Support supply chain collaboration": The first level of collaboration may occur at the level of single materials and technologies and reverse logistics, e.g., to reclaim building materials in a demolition project, or to implement a new technology (Brown et al., 2019) in a new-built project to increase energy efficiency. This can be done mainly within the existing supply chain network without too much disruption.

- "Create knowledge and value networks": The more transformative CE projects start with an ambitious vision of the future (Brown et al., 2019; Leising et al., 2018) that may require different types of partners to regenerate, narrow, slow, and close the loops. These partners would share the same vision, bring in new experience, and also support the creation of a new circular ecosystem. A wider sector-engagement is also needed for a broader transition in the sector (Brown et al., 2019) and there is evidence for such engagement already. For example, a buyer group initiative was established by the contracting authorities in the public and private sector to stimulate circular procurement in the Netherlands (Pianoo, n.d.).

A summary of the circular building strategies and examples is given in TABLE 3.2.

TABLE 3.2 Summary of the circular building strategies and examples.

Core Principle	Circular Building Strategy	Description and Example
Regenerate	Stimulate human nature co-habitation and local biodiversity	Create spaces for human nature interaction and biodiversity, e.g., green roof project in Amsterdam (RESILIO, n.d.).
	Use healthy and renewable resources	Eliminate toxic contents, use bio-based materials, and produce with renewable energy, e.g., producing insulation panels from mycelium (Biohm, n.d.).
	Enhance indoor and outdoor environment	Improve the indoor environment and regenerate degraded outdoor spaces, e.g., transformation of misused urban areas into public spaces (Amenta & van Timmeren, 2018).
	Exchange excess resources	Exchange surplus resources produced by regenerative buildings, e.g., exchanging renewable energy within the neighbourhood (Lo3 Energy, n.d.).
Narrow	Reduce primary resource inputs	Minimise primary resource use and waste, e.g., optimisation of lightweight structures (Block et al., 2017).
	Design for high performance	Optimise buildings and systems for fewer resource use, e.g., early design optimisation for passive performance (Konis et al., 2016).
	Improve efficiency	Enhance performance of building systems and operations to minimise resource consumption, e.g., deep energy renovation of old houses (Enervalis, n.d.).
Slow	Design for long life	Design buildings with durable materials, consider ease of maintenance and repair, and design for emotional attachment.
	Design for reversibility	Design buildings and products for multiple life cycles with deconstruction and transformation strategies, e.g., the UMAR Project (Heisel & Rau-Oberhuber, 2020).
	Lifetime extension	Extend the service time of buildings and components by restorative activities such as repair, maintenance and refurbishment.
	Smart use of space	Deliver new functionalities to underutilised buildings, and land through adaptive reuse and flexibility, e.g., flexible office spaces (Deloitte, n.d.).
	Deliver access and performance	Provide access, functionality or services without offering ownership of buildings and building products, e.g., pay-per-lux model for lighting (Philips Lighting, n.d.).
	Reuse	Bring resources back into the economy with a minimum of resource input, e.g., construct indoor partitions from old windows during façade renovation.

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TABLE 3.2 Summary of the circular building strategies and examples.

Core Principle	Circular Building Strategy	Description and Example
Close	Recycle	Convert reclaimed resources into similar or lower quality ones with considerable energy and water input, e.g., recycling concrete aggregates (Ghisellini et al., 2018).
	Urban mining	Extract materials from the urban environment that are not designed for reuse or recycling, e.g., urban mining project in the city of Rotterdam (Metabolic, n.d.).
	Industrial symbiosis	Initiate synergistic interactions between different industries to recover waste and by-products, e.g., an industrial symbiosis for recycled aggregates (Yu et al., 2021).
	Track and trace resources	Track and trace resources from extraction/reclamation until end-of-use stages and in further cycles.
Collaborate (as supporting strategy)	Support supply chain collaboration	Work with partners in the existing supply chain to slow, close, narrow and regenerate resource loops, e.g., for reverse logistics.
	Create knowledge and value networks	Identify and develop new networks for collaboration to implement ambitious CE visions, e.g., a buyer group is established to foster circular procurement in the Netherlands (Pianoo, n.d.).

3.3.3 Circular Digital Built Environment Framework (CDB Framework)

Combining the literature findings presented in FIG.3.3 and TABLE 3.2, we developed the Circular Digital Built environment Framework (CDB Framework) to map the enabling DTs for a circular BE. The building life cycle stages are demonstrated on the x-axis against the circular building strategies on the y-axis. Furthermore, potential enabling DTs are presented with colour coding. This framework was used in the expert workshops (next section) and was updated in line with the feedback given by the experts. FIG.3.4 demonstrates the revised version of the framework.

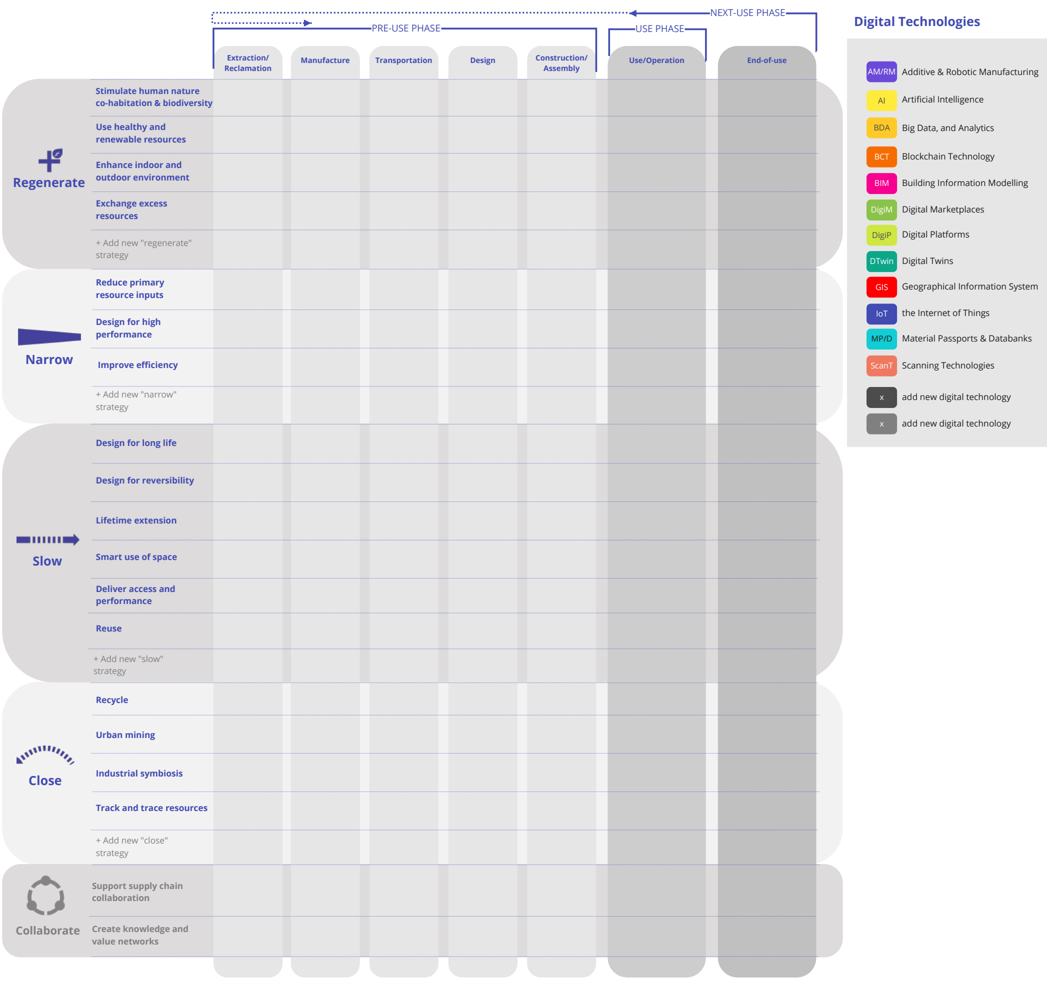

FIG. 3.4 Circular Digital Built Environment Framework (CDB Framework).

3.4 Workshop findings

The main purpose of the expert workshops was to explore potential DTs for enabling a circular BE and to map them onto the CDB framework. The experts were given a list of DTs in advance, as shown in FIG.3.4, and were asked to link the listed DTs with circular building strategies on the framework. Moreover, the experts were allowed to suggest new strategies as well as new DTs. In each session, different key discussion points emerged based on the experts' backgrounds. These insights helped us to finetune the mapping of the DTs in the next step.

In the first expert session, the discussions were concentrated on three technologies: BIM, digital twins and digital platforms. BIM is considered an essential collaboration tool throughout the entire lifespan of buildings; however, in practice, it is not mature in all of the life cycle stages. Furthermore, the use of digital twins is believed to be an integrative platform on which different technologies are combined to represent the real world at the building, portfolio and urban levels, enabling the monitoring and management of resource flows in the BE. The experts stress the importance of creating a platform ecosystem for circular flows of materials. The major challenge for this seems to be the low number of users in both the demand and supply side in current marketplaces.

In the second workshop, the experts discussed the life cycle stages of the framework (the pre-use, use and post-use phases) and suggested the amendment of the "end-of-life" stage to "end-of-use" or "next-use" because, in a circular system, resources have multiple life cycles. Even though buildings reach their end-of-life, the materials embedded in buildings have the potential to be reused in other applications. Another point raised by one of the experts was the missing time dimension. In order to address this issue, the "material availability calendar" was proposed to deliver designers with timely information regarding the availability of materials (See FIG.3.5). In addition, the experts highlighted the role of parametric design tools in generative building design and their connection with AI in terms of making sense of large data sets in design practice.

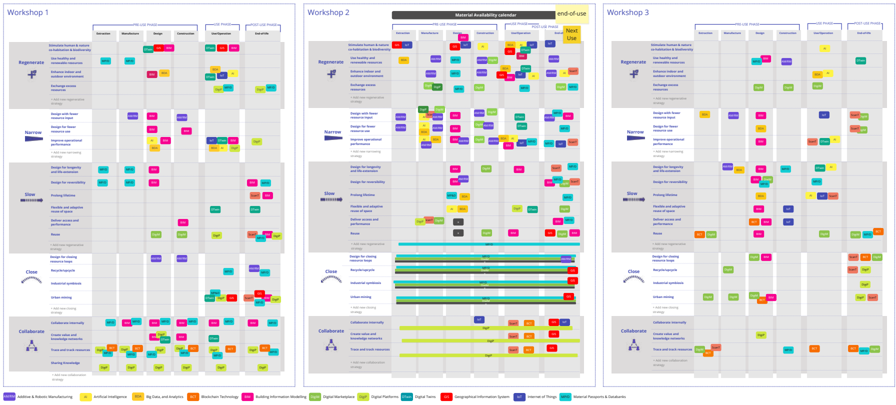

FIG. 3.5 Workshop findings. Note. Full-size versions of the workshop screenshots can be found in the Supplementary Materials.

In the final workshop, material passports were at the centre of attention. Although several material passports have been developed recently, uncertainty about data governance seems to be a big obstacle. Compared to digital twins, the current material passport applications remain static in terms of life cycle data management. In that sense, the digital twin concept was found to be important for managing resources in commercial buildings and infrastructure throughout the entire lifetime. Finally, a platform environment was mentioned to be useful for material passports in which all of the parties could communicate from the design until the end-of-use stages.

The overall impression of the experts on the framework was positive. However, one notable issue was raised in all of the workshops: in most cases, the listed technologies work together, and placing each DT separately on the framework was challenging. We address this issue in Section 3.6 by illustrating the linkages between different technologies. Furthermore, on top of our list of enabling DTs, no additional DTs were proposed. The experts recommended a few tools, such as simulation and parametric design tools, to support the design process, which is discussed in connection with the identified ten potential enabling DTs (see FIG.3.5).

3.5 Enabling digital technologies for a circular built environment

Based on the findings from the previous steps, we identified ten enabling DTs that support the transition of the BE towards a CE. Some tools (e.g., simulation and LCA tools) and supporting technologies (e.g., scanning technologies) are not separately explained as they are briefly discussed in connection to the identified DTs. The following sections present the enabling DTs in alphabetical order by highlighting their potential roles in a circular BE.

3.5.1 Additive and robotic manufacturing (AM/RM)

The two main digital fabrication methods discussed in the BE are: additive manufacturing (AM), also known as 3D printing, and robotic manufacturing (RM), or, more broadly, automated manufacturing. AM is a manufacturing technology that enables the fabrication of complex 3D objects by adding materials together layer upon layer (Gibson et al., 2015). It has been predominantly used to produce parts in various sectors such as the aerospace and automotive industries, and by product designers to produce rapid prototypes of their designs. Its application in the construction industry mainly concerns the concrete printing (Albar et al., 2019; Álvarez-Fernández et al., 2021) and the fabrication of building components from the metals and polymers (Paolini et al., 2019). RM is a manufacturing technology that enables robots to do part of the work previously done by humans, especially repetitive, dangerous, or precision-requiring tasks, such as assembly, lifting, or welding. It is related to Computer Aided Manufacturing (CAM) and Computer Numerical Control (CNC). In the BE, its main applications are the complex assembly of timber or metal elements (Devadass et al., n.d.; Huang et al., 2018), the digital casting of concrete or plaster (de Soto et al., 2018; Ercan Jenny et al., 2020), and precise milling or drilling (Robeller et al., 2014).

Compared to conventional construction methods, AM/RM provide several opportunities for a circular BE.

- First of all, 3D printing with, e.g., concrete can be used to reduce resource use and waste through the design optimization (De Schutter et al., 2018; Oberti & Plantamura, 2015; Rippmann et al., 2018) and minimise transportation distance (Hager et al., 2016; Oberti & Plantamura, 2015). AM/RM from, e.g., lightweight PET material fibre enables both lightweight building structures and the use of recycled materials (Wang, 2020). Researchers demonstrated the potential energy saving of the digital fabrication of a wall or floor component (Agustí-Juan & Habert, 2017; He et al., 2020). An example from real-life practice is the design of a 3D-printed steel bridge that used a software to generate the most material-efficient shape (MX3D, n.d.).

- Second, AM/RM indeed can be done by recycling materials in the concrete mixes (Oberti & Plantamura, 2015), using the mining tailings (Álvarez-Fernández et al., 2021), and reusing (waste) materials (Baiani & Altamura, 2018; Bier & Nazzarri, 2020).

- AM/RM also allows designers to tailor connection pieces for the reuse of truss and frame elements (Brütting et al., 2021). The modular design of printed structures enables the reuse of building parts at the end-of-life stage (Oberti & Plantamura, 2015). Digital deconstruction is also being researched, e.g., reversible timber beams can be robotically manufactured and disassembled (Kunic et al., 2021). Digital reuse is gaining attention in general (Kuzmenko et al., 2020).

- Moreover, AM/RM often provides a safer working environment and reduces injuries on site (Hager et al., 2016; Oberti & Plantamura, 2015), contributing to the well-being of construction workers.

- Finally, the emerging research field of bio-based 3D printing has applications in the construction industry, potentially increasing the regenerative aspect of buildings. Examples include 3D printing with biomass-fungi/mycelium bio-composite material (Robertson et al., 2020) and other bio-based materials (Smith et al., 2019).

3.5.2 Artificial intelligence (AI)

Artificial Intelligence (AI) is a broad scientific domain covering a large terrain of fields ranging from general-purpose areas to specific tasks, such as diagnosing diseases (Stuart & Norvig, 2003). Therefore, many definitions of AI exist. At a basic level, AI refers to "the ability of a computer or machine to mimic the capabilities of the human mind" (IBM, n.d.-b) and consists of several subbranches using different techniques. For example, Machine Learning trains algorithms to learn from data and identify patterns for decision-making with minimum supervision, while Deep Learning is capable of training itself for leveraged tasks (IBM, n.d.-a). Some of the example applications of AI in everyday life are chatbots, face recognition systems, voice-controlled digital assistants and online language translators.

According to EMF and Google (Ellen MacArthur Foundation & Google, 2019), AI capabilities offer a number of opportunities for transitioning to a CE, including design improvement, infrastructure optimisation and operating circular business models. Similar AI competencies can also be applicable in a circular BE. We group enabling functions of AI and its subfields into three groups:

- With design optimisation, designers aim to find the perfect solution for predefined performance criteria. Data-driven approaches, such as neural networks (a subset of Machine Learning), provide advanced solutions for generating multiple design alternatives and selecting the most optimal design solution (Arcadis, 2020; Gan et al., 2020). For example, researchers developed and tested a machine learning model to support architects during the early design phase, which can predict the total carbon footprint of regenerative building design alternatives (Płoszaj-Mazurek et al., 2020).

- Combined with other technologies such as big data and IoT, AI techniques and algorithms provide capabilities to predict defects in systems and determine resource needs in buildings. For the former, for example, computer vision detection models reinforced with deep learning techniques are used to detect the state of an asset, learn from past data and predict future failures (Arcadis, 2020), and for the latter, researchers highlight the capabilities of machine learning algorithms for predicting energy demand of buildings (Mehmood et al., 2019). An example from practice is the FaSA project (Façade Service Application) (Facade Service Applicatie, n.d.). The FaSA application maps the current state of buildings and predicts the maintenance requirements of façade elements with the help of AI, drone and sensor technologies (Facade Service Applicatie, n.d.).

- AI techniques are also believed to be useful for end-use phase activities. Akanbi et al., (2020) developed deep learning models based on national demolition records to predict the amount of recyclable, reusable and waste materials generated from deconstruction and demolition projects (Akanbi et al., 2020). Rakhshan et al. (2021) proposed a predictive model using machine learning techniques to estimate and evaluate the economic reusability of structural elements. Furthermore, Davis et al. (2021) designed an on-site waste classification system using a deep learning method that can classify different categories of waste based on digital photographs taken from construction site bins. Similarly, other researchers also used deep learning-based image analysis to obtain composition details of recycled aggregates to improve the recycling performance (Lau Hiu Hoong et al., 2020).

3.5.3 Big data and analytics (BDA)

With the advancement of the internet and digital technology in the last few decades, data generated by people, machines, and their interactions has grown tremendously. The term “Big data” is used to define large-size data sets which cannot be handled by typical software tools (Manyika, 2011). These data can be found in diverse formats such as text, audio, video or social media (Gandomi & Haider, 2015). Although the term “big data” evokes “size” as its main attribute, other characteristics have also been highlighted recently. For example, the framework of Five Vs describes five aspects of big data (Yin & Kaynak, 2015): volume (amount of data), variety (heterogeneity of a data set), veracity (authenticity of data), velocity (speed of data processing), and, value. Capturing the value potential of big data lies in translating big data into valuable insights through analytics, as Gandomi and Haider put (Gandomi & Haider, 2015, p. 140): “Big data are worthless in a vacuum”. Thus, big data analytics deals with analysing and interpreting acquired data to extract insights for better decision making (Gandomi & Haider, 2015) by incorporating many techniques such as statistics, data mining, predictive analysis, and machine learning (Bilal et al., 2016).

According to Bilal et al. (2016), the construction sector progresses slowly in adopting BDA even though an enormous amount of data is generated throughout the lifespan of a building through BIM, embedded devices and sensors. The authors highlight several opportunities that this technology offers for the sector, which might be considered within the context of the CE: resource and waste optimisation, generative design, performance prediction, personalised services, energy management, BIM and IoT applications, and intelligent buildings. Building upon these, the following roles are identified for BDA in a circular BE:

- Big data are used to train machine learning algorithms for designing low-carbon regenerative buildings (Płoszaj-Mazurek et al., 2020), support generative design tools (Bilal et al., 2016), and assist decision-making in design processes (Bressanelli, Adrodegar, et al., 2018). Moreover, data mining techniques are employed for improving building energy performance during the operational phase, leading to less use of resources (Fan & Xiao, 2017).

- As highlighted by Bressanelli, Adrodegar, et al. (2018), BDA might play a vital role to prolong the lifespan of the products by providing insights into sustainability-oriented decision-making during the operational phase. For example, Katona and Panfilov (Panfilov & Katona, 2018) designed and tested a smart maintenance framework on a real-life heating, ventilation and air conditioning unit to detect and prevent failure with the help of sensing technologies and BDA.

- Finally, as we will explain in Section 3.5.10, together with IoT, BDA is seen as essential in realizing smart buildings and cities (Nobre & Tavares, 2017).

3.5.4 Blockchain technology (BCT)

Since the publication of the famous whitepaper "Bitcoin: A Peer-to-Peer Electronic Cash System" in 2008 (Nakamoto, 2019), Blockchain Technology (BCT) has received significant interest from both academia and practice. The concept is based on a distributed peer-to-peer system that is cryptographically secured, enabling transparent value transactions without needing central authorities and intermediaries such as banks and government agencies. IBM defines five disruptive elements of the BCT (Arun et al., 2019): transparency (end-to-end visibility of the transactions); immutability (records cannot be altered or deleted); security (blockchain is secured by cryptographical techniques making it very difficult to hack); consensus (consensus of network participants is needed to validate transactions); and, smart contracts (automation of business logic).

Although the initial focus has been on cryptocurrencies, a range of different application areas have emerged as BCT allows any form of registry, inventory, and exchange of tangible and intangible assets (Swan, 2015). For instance, Hunhevicz and Hall (Hunhevicz & Hall, 2020) identified twenty-four potential use cases of BCT in the BE, which include: using smart contracts to automate transactions between external actors; tracking supply chain logistics; timestamping changes in BIM models; recording ownership of assets; maintaining material passports; and, automating building maintenance based on IoT interactions (Hunhevicz & Hall, 2020). The following functions are identified for BCT in a circular BE:

- From a CE perspective, BCT is considered an enabling technology, particularly for managing complex information networks in the supply chain management (Böckel et al., 2021; Shojaei, 2019). In a sector that is characterized by low productivity and a fragmented supply chain (Hunhevicz & Hall, 2020), BCT might offer opportunities for leveraging efficiency and transparency to keep the value of resources along their lifecycle. Li et al. (Li et al., 2021) proposed a smart product-service system for prefabricated housing production based on IoT and blockchain technologies. A blockchain system was employed to control cash flow autonomously through smart contracts and perform data exchange between relevant stakeholders acting as a shared database (Li et al., 2021). Another example from the practice is Circularise (*Circularise, n.d.*), a start-up operating a blockchain information exchange platform for enabling circular value chains that protects the competitive advantage of companies while sharing necessary information with relevant stakeholders (Licht et al.).

- According to the literature and practice review of Böckel et al. (Böckel et al., 2021), the most frequently mentioned use case of BCT in CE is enabling material passports as the technology offers transparency and reliability of data flows across the supply chain network (ARUP, 2019a) from extraction until end-of-use phase and further in subsequent use cycles. For example, Tata Steel (Tata Steel, n.d.), one of the largest steel-producing companies globally, has piloted a material passport system whereby each of the steel components was given a unique identification and registered on a blockchain allowing project stakeholders to follow the life cycle data of steel products (Penzes, 2018).

- BCT enables secure peer-to-peer trading networks (ARUP, 2019a). This is especially interesting for local renewable energy exchange where intermittency is a big obstacle. Mengelkamp et al. (2017) demonstrated a concept of a decentralised local renewable energy market based on a blockchain system to address this issue. Their results suggested that BCT offers secure, transparent and cost-efficient energy trading (Mengelkamp et al., 2017). An example from the practice is a community energy marketplace called Pando (Lo3 Energy, n.d.). Pando empowers users to buy and receive local renewable energy within their neighbourhoods through a mobile application (Lo3 Energy, n.d.).

3.5.5 Building Information Modelling (BIM)

Building Information Modelling (BIM) is the digital representation of a built asset (Charef & Emmitt, 2021), containing relevant information, such as building geometry, material properties, and quantities of elements (Honic, Kovacic, Sibenik, et al., 2019). BIM has been used by many actors in the architecture, engineering, and construction sector for various purposes, including design, design visualisation, design optimisation, cost estimation, construction planning, maintenance, and facility management. Won and Fan (2013) highlight two major contributions of BIM to sustainable building design: first, the BIM method can reduce inefficiencies in traditional construction processes by allowing integrated project delivery through effective information sharing between all project stakeholders; second, it can help optimise building design to reduce natural resource use and waste creation (Wong & Fan, 2013). The use of BIM for CE goes beyond these two main benefits. Charef and Emmitt (2021) investigated existing BIM uses in the BE and revealed their potential to support CE implementation. Their study showed that all current BIM uses influence achieving a CE, e.g., structural design directly impacts the disassembly potential of a building. The authors further identified seven new uses of BIM for a circular BE: a digital model for sustainable end-of-life, material passport development, project database, data checking, circularity assessment, materials' recovery processes and materials' bank (Charef & Emmitt, 2021) (see also Section 3.5.9). Building on these, enabling functions of BIM are presented below:

- Within the context of sustainable building design, BIM software and extension tools (add-ins) are used for analysing and optimising building performance (e.g., indoor climate, energy, daylighting, and site) (Habibi, 2017) and for integration of life-cycle analysis (LCA) into the building design process (Xue et al., 2021). Recent studies expand the capabilities of BIM towards early design considerations for slowing and closing resource loops. For example, Akanbi et al. (2018) developed a BIM-based tool to predict the reusability and recyclability potential of design alternatives, and Akanbi et al. (2019) proposed a disassembly and deconstruction analytics system to assess the end-of-life performance of building design. Furthermore, Akinade and Oyedele (2019) designed an add-in to BIM software using machine learning techniques to estimate the potential construction waste of design alternatives.

- BIM technology can be used from design until the end-use phase as an asset's whole life cycle model (Aguiar et al., 2019), where resource flows can be traced and monitored. During the use phase, BIM is used to operate and maintain assets (Gao & Pishdad-Bozorgi, 2019), and monitor the operational performance of systems (Davila Delgado & Oyedele, 2020). Emerging sensing technologies integrated into the BIM models provide new capabilities to increase system efficiency. For example, Jianli (2014) developed a dynamic BIM model by embedding real-time sensor data and monitoring accurate information from the asset. Although rarely seen, BIM can also be used in deconstruction activities where the digital copy of the building does not exist. To this end, van der Berg et al. (2021) demonstrated in a case study that BIM could be used for analysing existing conditions of the site, labelling reusable elements and performing deconstruction planning simulations.

- As discussed in Section 3.3, collaboration is believed to be essential in creating circular supply chain networks to narrow, slow and close the resource loops in the construction sector (Leising et al., 2018). BIM, as a collaboration platform, brings project stakeholders together for effective information sharing and transparent project coordination (Akinade & Oyedele, 2019; Chan, 2019; Honic, Kovacic, Sibenik, et al., 2019; Wong & Fan, 2013). Akinade et al. (2019), for example, developed a BIM-based construction waste analytics tool by putting supply chain integration at the core. The tool assists material producers and suppliers in estimating waste creation so that they can consider the environmental impact of their products during the manufacturing phase (Akinade & Oyedele, 2019).

- Finally, BIM supports material passports and databanks by providing necessary information regarding buildings and their components. Most of the material passports and databanks reviewed in this study use BIM either as a source of material data or as a platform to operate on (See Section 3.5.9).

3.5.6 Digital platforms

Platform concepts, either digital or non-digital, have been discussed from different worldviews and are dispersed across a wide range of fields, making them challenging to study (de Reuver et al., 2018). From the technical perspective, a digital platform is understood as a software-based system providing core functionalities which derivative applications can be developed upon, while non-technical perspectives see it as a multi-sided network, matching different groups of users to exchange goods and services (Asadullah et al., 2018). To date, very few studies focused on digital platforms in the BE. Chan (2019) points out two main approaches in BE literature regarding digital platforms: tool-based platforms that target the building production processes, where BIM plays a central role, and collaboration platforms that bring different actors together for better engagement with the BE. From a CE point of view, Konietzko et al. (2019) put forward three essential functions that online platforms deliver for narrowing, slowing, and closing resource loops: first, digital platforms perform as virtual *market*s, allowing access to and exchange of goods; second, they facilitate the *operation* of product-service systems, enabling data collection for maintenance and repair; third, they empower people to *co-create* circular products and services. For a circular BE, the following roles are defined for digital platforms:

- By connecting the supply and demand side, digital platforms facilitate the creation of circular market ecosystems in the BE in two forms: sharing platforms and digital marketplaces. Sharing platforms operate online, giving temporary access to the idle capacity of resources without transferring the ownership (Ranjbari et al., 2018), as in the case of Airbnb giving temporary accommodation to travellers. For the BE, there are several examples of sharing platforms; for example, the pilot project called "Vacant Space Finding" (City of Amsterdam, n.d.) allows users to book available spaces in the city of Amsterdam (Acharya et al., 2020); EquipmentShare (EquipmentShare, n.d.) allows peer-to-peer construction equipment rental; Workfrom (workfrom, n.d.) lists cafés and coworking spaces for remote workers. On the other hand, digital or virtual marketplaces allow exchanging resources between various actors to regain residual value from discarded materials and products. Such platforms might perform as business-to-business (B2B), business-to-consumer (B2C) or both, depending on the context they operate. An example from practice for the B2B marketplace is the Excess Materials Exchange (Excess Materials Exchange, n.d.), a cross-industry matching platform for the high-value reuse of materials and waste. Another example of a B2C platform is Enviromate (Enviromate, n.d.), a closed-loop marketplace connecting consumers with leftover building materials.

- Furthermore, digital platforms are used to manage information flows in circular building processes. For instance, Xing et al. (2020) designed a cloud-based data exchange platform which connects physical building components with their virtual counterparts through RFID tags, allowing designers to explore reusable products from existing building sites. This platform also serves as a marketplace. Oberti-Paoletti (2020) proposed a web-based platform to track raw materials from pre-consumer agricultural waste to be used in private civil construction projects. Madaster is a platform that registers data on buildings, products and materials and calculates the circularity index of building projects (Madaster, n.d.). See Heisel & Rau-Oberhuber (2020) for the implementation of Madaster in a case study.

- Digital platforms also facilitate communication and collaboration between supply chain actors. Yu et al. (2021) developed a GIS-based collaboration platform to enable industrial symbiosis between recycled concrete supply chain actors. This platform allows stakeholders to monitor material flows and perform negotiations with each other. With the aim of engaging all supply chain actors in the decision-making process of public works, the DECORUM project has developed a multi-user platform (Luciano et al., 2020). This platform supports green public procurement by allowing users to assess the circularity and environmental impact of projects and develop a marketplace for recycled materials. Finally, other researchers proposed an interfirm digital platform concept for allowing various stakeholders to exchange data throughout the life cycle of a building (Kovacic et al., 2020).

3.5.7 Digital twins

Digital twins give a virtual replica of the physical world and are already commonly used in the automotive, aerospace, and process industries to simulate performance. In the BE sector, digital twins can be used for autonomous decision-making, feedback and control, predictive maintenance and so on (ARUP, 2019b). While BIM is a platform for keeping a record of building information, a digital twin works specifically with real-time data fed by sensors analysing the physical asset (Khajavi et al., 2019). Digital twins require data components from BIM or a custom 3D model of the building, but also Wireless Sensor Network integration and data analytics (Tao et al., 2017). The key contribution of a digital twin is its machine learning capabilities (ARUP, 2019b), data-driven by the data collected over the lifetime of the building not only by the sensors but also by the simulations run on the model.

- Connecting digital twins to material passports has the potential to extend the service life of building elements through the predictive maintenance (Kedir et al., 2021a) (see also Section 3.5.9). Moreover, using digital twins and material passports could also enable reuse during the building's demolition phase. Landahl et al. (2018) propose a digital twin platform concept for remanufacturing of construction waste or to support design reuse.

- As mentioned previously, digital twins could also help manage space to turn buildings into flexible spaces. An example is the EDGE Olympic office building located in Amsterdam (Edge Olympic, n.d.). The building has a digital twin that operates on a cloud platform, allowing users to personalise their working environment and use the space flexibly (Edge Olympic, n.d.).

3.5.8 Geographical Information System (GIS)

"Geographic Information Systems (GIS) are computer-based systems for storing and processing geographic information about sets of locations… and can be used as a container of maps in digitised form." (Longley et al., 2018, p. 252). At a basic level, GIS represents macro-scale external environments by linking attribute data with a location reference (Wang et al., 2019). Some examples of its applications include cadastral management, disaster monitoring, infrastructure maintenance, and regional planning (Wang et al., 2019). GIS is also used with BIM for urban data management, energy-efficient building and urban design, optimising climate requirements of buildings, and tracking supply chain and material flows (Wang et al., 2019). In line with the capabilities of GIS, our literature findings suggest two enabling roles for GIS:

- An essential opportunity that GIS offers for a CE is the identification, mapping, and management of resources embedded in building stocks for future reuse or recycling. For example, Wuyts et al. (2020) used GIS analysis to identify vacant houses and their material stock in the city of Kitakyushu in Japan to make informed decisions on the future use of resources. Depending on the quality of vacant housing, authors considered several reuse strategies that include maintenance, intensive use of space, repurposing and urban mining (Wuyts et al., 2020).

- GIS is also used for supporting urban mining and industrial symbiosis in the BE. For the former, scholars employed GIS data sets from municipal or governmental authorities to identify, calculate, and map material stocks in cities (Kleemann et al., 2016; Oezdemir et al., 2017; Verhagen et al., 2021; Wuyts et al., 2020). For example, Kleeman et al. (2016) conducted a GIS-based material stock analysis in Vienna; Oezdemir et al. (2017) used GIS as an integral tool to develop a resource cadaster of secondary materials in a district of Germany to facilitate urban mining at a regional level, and, Verhagen et al. (2021) analysed the building stocks and flows based on GIS datasets to present the potential of urban mining in the Dutch construction sector. For the latter, Yu et al. (2021) developed a GIS-based supply chain model for industrial symbiosis based on recycled concrete aggregate. They used GIS to demonstrate material flows in a virtual environment where actors share information and monitor traffic information together with vehicle movements (Yu et al., 2021).

3.5.9 Material passports and databanks

One of the biggest obstacles to reusing and recycling resources in buildings is the lack of sufficient information about materials and substances at the end-of-use phase (Cai & Waldmann, 2019; Honic, Kovacic, Sibenik, et al., 2019; Munaro, 2019). Some scholars proposed creating and storing material content of assets in a digital environment in the early design stage so that the necessary information becomes available throughout the entire lifespan of buildings to recover residual value back in the economy (Honic, Kovacic, & Rechberger, 2019; Honic, Kovacic, Sibenik, et al., 2019; Munaro, 2019). One such system is Material Passports. Material passport (also known as resource passport and object passport) is a term used to refer to digitally registered data sets of an object describing its characteristics, location, history, and ownership status, in a varying level of detail based on the scope of material passport is used. Material passports are developed at urban, building, product and material levels and operated on BIM or a platform environment.

At the urban scale, a "resource cadastre" concept was proposed by Oezdemir et al. (2017) to map material quantities in a residential area in Germany. Honic et al. (2019) developed a BIM-based LCA integrated material passport that can assess the environmental impact of different building design options. EU-funded project BAMB introduced a digital platform whereby more than 300 material passports are demonstrated at three detail levels, namely, product, building and instance (Luscuere et al., 2019). An example from practice is Madaster (Madaster, n.d.). Madaster is an online platform that offers services for creating and archiving material passports and calculating the circularity level of buildings (Madaster, n.d.).

In addition, the concept of material databanks is introduced as an alternative solution to store, manage and share building information for closing resource loops. Cai and Waldmann (2019) proposed a new actor in the construction supply chain called "material and component bank", which organises the transfer of materials from a demolition site to a new construction site. This independent contractor runs a database supported by BIM data whereby material information is kept up-to-date throughout the lifetime of a building (Cai & Waldmann, 2019). Building on the work of Cai & Waldmann (2019), Jayasinghe and Waldman (2020) developed a web-based centralised databank that collects information from BIM models of existing and new buildings and allows users to analyse stored data for recyclability and reusability potential of building components. Similarly, Bertin et al. (2020) proposed a materials bank in the form of a database to stimulate the reuse of load-bearing structural elements.

3.5.10 The Internet of Things

The Internet of Things (IoT) is considered to be one of the core Industry 4.0 technologies (Lopes de Sousa Jabbour et al., 2018) that *"enables information gathering, storing and transmitting be available for things equipped with the tags or sensors"* (Li et al., 2014, p. 253). In an IoT environment, things such as smartphones, electronic devices and machines communicate with each other and with users, forming an interoperable network (Lopes de Sousa Jabbour et al., 2018) through several other technologies such as Radio Frequency Identification System (RFID), wireless sensor networks and cloud computing (Li et al., 2014). This communication produces a large amount of data which is then analysed with BDA to generate valuable insights for companies (Lopes de Sousa Jabbour et al., 2018) (see Section 3.5.2).

The application of IoT in a CE is dispersed across various fields covering topics from smart cities to sustainable product lifecycle management (Nobre & Tavares, 2017). Bressanelli, Adrodegar, et al. (2018), for example, presented how IoT and BDA support usage-focused business models in a case of a household retailer. Their study identified enabling functionalities for design improvement, product monitoring and lifetime extension, and improvement of end-of-life activities. Furthermore, Ingemarsdotter et al. (2019) designed a framework to categorise IoT-enabled CE strategies and mapped 40 cases from practice on this framework. Authors highlighted that the majority of the cases employed IoT for efficiency in use (e.g., energy and water preservation) and product lifetime extension (e.g., maintenance and repair) (Ingemarsdotter et al., 2019). Building on CE strategies defined by Ingemarsdotter et al. (2019), we introduce five enabling IoT functionalities:

- As discussed in previous sections, the lack of mechanisms to trace the material properties of the existing building stock is a major barrier to reuse. Many scholars proposed to use RFID and IoT sensors for digital and physical traceability of building elements in various building lifecycle stages (Bertin et al., 2020; Copeland & Bilec, 2020; Li et al., 2021; Turner et al., 2021; Xing et al., 2020). For instance, Turner et al. (2021) presented a distributed manufacturing of modular homes where information flow is achieved throughout the whole life stages thanks to the sensors embedded in concrete elements. Another application of resource tracking and monitoring through IoT can be seen in smart building environments, as explained in the next paragraph.

- One of the prominent application areas of IoT in the BE is performance optimisation for preserving resources. Connected devices in buildings can sense, monitor, optimise and control indoor environments with BDA. For example, Interact (Interact, n.d.), an IoT-based lighting system, collects data from the indoor environment through sensors embedded in the lighting system and provides insights into sustainable building operations. Another example from practice is Polder Roof® (Metro Polder, n.d.). Polder Roof® is a green roof system that measures and regulates the rainwater collected on the rooftop with the help of sensing systems and delivers operational insights to the user (Metro Polder, n.d.).

- As discussed in Section 3.5.2, together with BDA, sensor systems help to track, monitor, and control failures (Bressanelli, Adrodegar, et al., 2018); predict maintenance needs of installations (Panfilov & Katona, 2018); and, enable remote maintenance, repair, and upgrades (Ingemarsdotter et al., 2019).

- IoT technology allows real-time monitoring of available space in a given building through smart sensing systems. The Edge, a smart office building, is equipped with around 28.000 sensors allowing employees to book meeting rooms or workplaces through a user-friendly platform (Deloitte, n.d.; MAPIQ, n.d.). With such a flexible workplace organisation, it was possible to dramatically reduce the number of workspaces, i.e., 1080 desks allocated for 2850 employees (MAPIQ, n.d.).

- IoT capabilities offer a healthier and more comfortable indoor environment by controlling heating, ventilation and space conditioning systems. For example, in The Edge smart office building, users are provided with a mobile application that enables them to adjust space lighting and indoor temperature (Deloitte, n.d.; MAPIQ, n.d.).

- Several studies addressed the role of IoT in adopting sustainable business models (Bressanelli, Adrodegar, et al., 2018; Ellen MacArthur Foundation, 2016a; Lamptey et al., 2020; Nobre & Tavares, 2017; Xing et al., 2020). Nombre and Tavares (2017) referred to the partnership between SEAT and Signify Philips Lighting for a “light as a service” business model and argued that IoT empowered both partners to monitor and control installations, leading to cost savings. Other studies highlighted the role of IoT in service business models (Ellen MacArthur Foundation, 2016a); buy-and-sell and lease with reuse models (Xing et al., 2020); and, green business models (Lamptey et al., 2020).

3.6 Mapping enabling digital technologies onto the CDB Framework

As shown in FIG.3.6, this section maps the ten potential enabling DTs onto the CDB Framework based on findings from the expert workshops as well as the literature and practice review. The linkages between circular building strategies and DTs were constructed based on two criteria: a DT or its enabling functions (1) must be studied in the literature or implemented in real-life, (2) if it is not found in literature or practice, they must be either assigned to the same spot at least two times in different expert workshops or explicitly mentioned by the experts. Thus, we prioritised the literature findings when mapping potential enabling DTs and displayed additional expert inputs with dashed frames on the framework. It should be noted that the majority of the points that the experts raised were in agreement with the literature and practice review findings (see Section 3.4 and Section 3.5). Therefore, the influence of the expert workshops on mapping DTs onto the framework was limited. The corresponding literature and practice references can be seen in TABLE S2 Supplementary Materials.

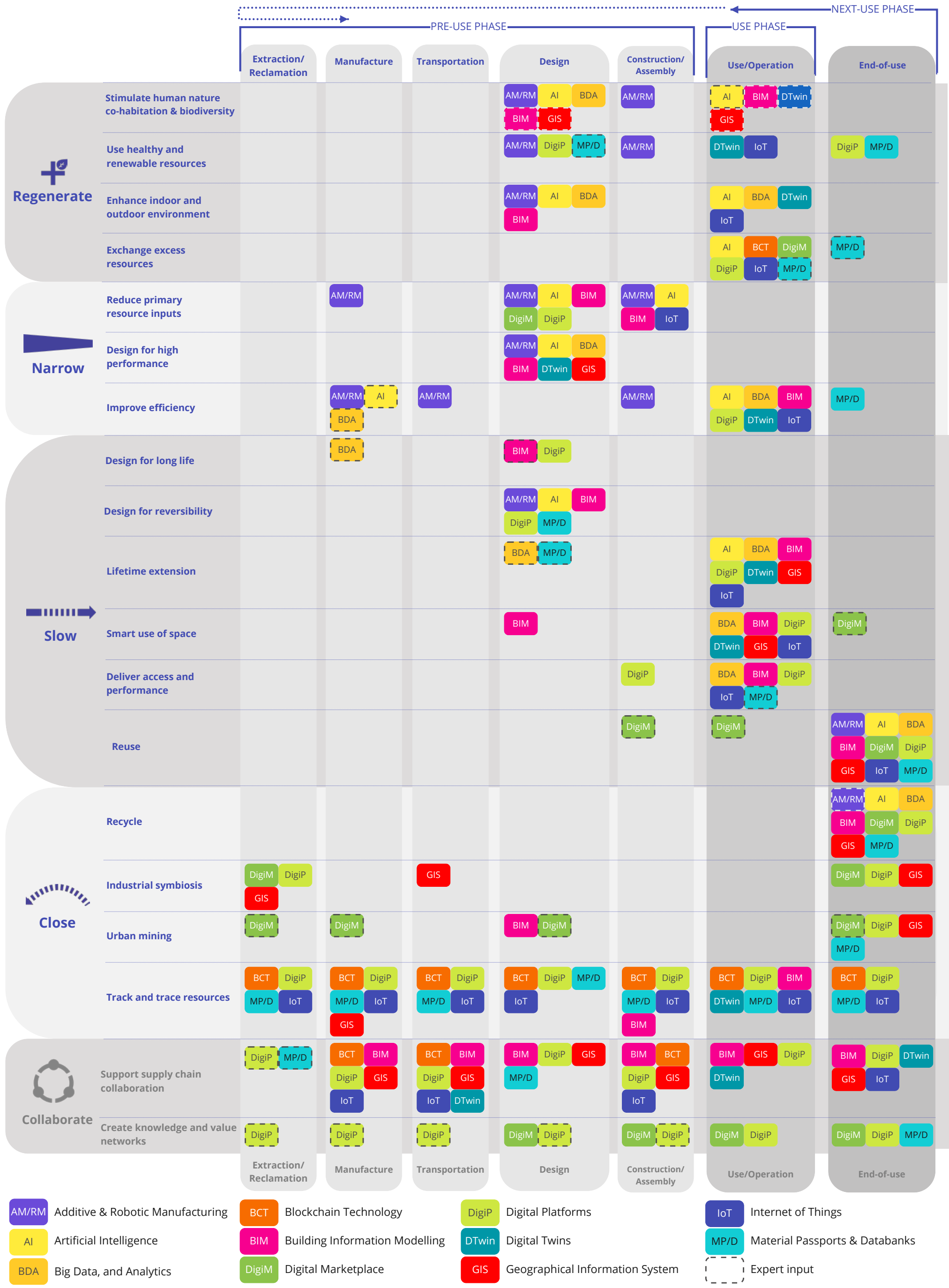

FIG. 3.6 Final mapping of ten potential enabling DTs onto the CDB framework.

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Our findings suggest that AM/RM technologies are prominent among regeneration strategies because they are used to design bio-based materials and ease manufacturing with renewable construction materials (e.g., timber). In addition, AI is employed for advanced data-driven regenerative building design, maintaining green facades, and easing surplus resource exchange along with BCT in positive buildings and neighbourhoods.

As for the narrow strategies, AM/RM, BIM and digital marketplaces appear to be crucial for pre-use phase activities. BIM, add-ins and simulation tools are employed for the optimisation of construction and operational performance in later stages, whereas AM/RM is believed to be beneficial for the reduction of primary resource consumption when manufacturing building components. On the other hand, digital platforms and marketplaces are essential for substituting secondary materials and products in the building design stage for value recovery and allowing multiple life cycles. Finally, narrowing resource flows in the operational phase is made possible through smart building technologies. These DTs are able to sense the indoor and outdoor environment (IoT), analyse sensed data (BDA) and operate with or without human intervention (AI) in order to reduce the operational resource use (e.g. energy and water).

The most prominent slow strategy is thought to be “design for reversibility” and is mainly addressed by academic researchers by proposing new methods and tools. These tools usually work on a BIM platform or are developed as a material passport system, and they target the end-of-use phase reusability of buildings and building parts. Our results show that many possibilities exist for reuse: nine out of ten identified enabling DTs are believed to support reuse activities to some extent. In order to prolong the lifetime of buildings and systems through preventive and predictive interventions, a wide range of applications of digital twins, AI, BDA, BIM, and IoT have been proposed. These technologies are also used for the smart use of space and to enable access and performance business models.

For the closing of resource loops, four DTs stand out: material passports, GIS, digital platforms and digital marketplaces. Material passports were mentioned several times as an enabler of the recovery of residual value from existing building stock; GIS was used to enable industrial symbiosis and urban mining concepts at the urban scale; and digital platforms and marketplaces are seen essential for the creation of a market ecosystem for secondary building materials. As for tracking and tracing resources, BCT, material passports, IoT and digital platforms are thought to play an important role. Finally, for supply chain collaboration, various BIM, GIS and BCT applications have been demonstrated, whereas for creating knowledge and value networks, digital platforms are employed.

Finally, during the workshops, the experts conveyed that most of the DTs interact with or depend on each other in the course of carrying out a certain task and that the CDB framework was limited in its demonstration of these interdependencies. In order to address this issue, we illustrated the linkages between potential DTs, where we observed them when reviewing articles and real-life examples. FIG.3.7 gives an overview of the interdependencies among the potential enabling DTs, with references. It is important to note that interactions between DTs demonstrate leveraged capabilities towards achieving CE goals. For example, as in the paper of Xing et al. (2020) (highlighted in black dashed lines in FIG.3.7), material tracking through a BIM-based cloud platform that uses IoT technology enables different stakeholders to exchange information when reusing building components. Their platform has a web interface, connecting potential clients with product owners, which leads to the creation of new business opportunities.

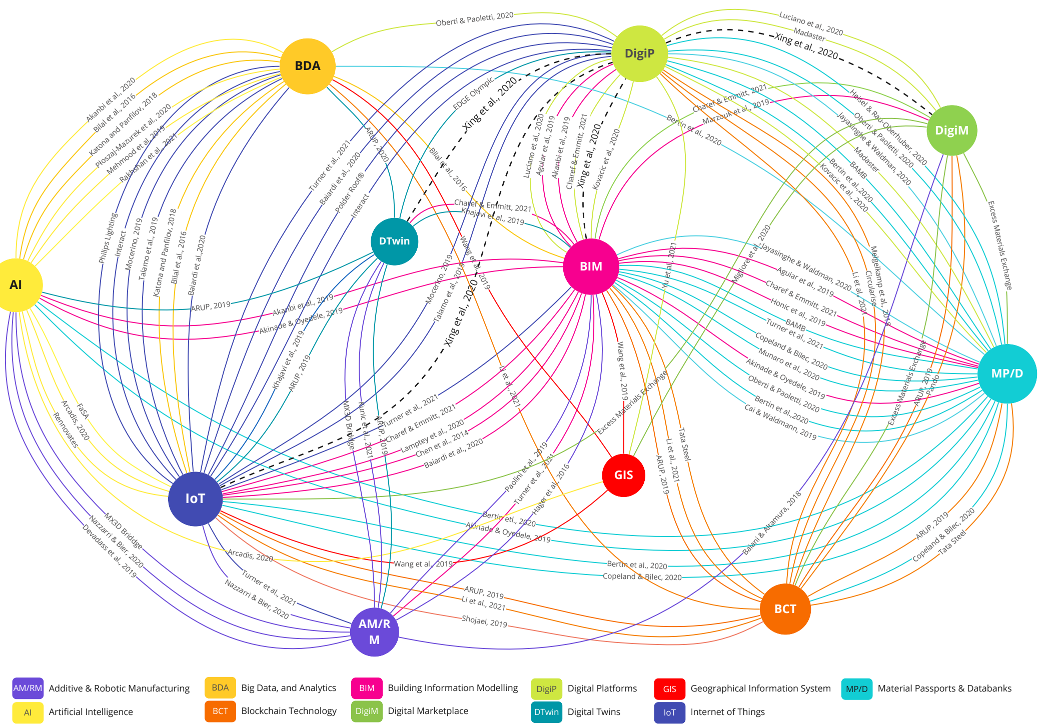

FIG. 3.7 Interdependencies among enabling DTs. The connections between the technologies were mapped based on the literature and practice review.

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3.7 Conclusions

3.7.1 Discussion of contributions

In this study, we have identified ten enabling DTs (AM/RM, AI, BDA, BCT, BIM, digital platforms, digital twins, GIS, material passports and databanks, and the IoT) and explored their potential role in a circular BE across the life cycle stages of buildings. We adopted an iterative four-step method comprising framework development, expert workshops, a literature and practice review, and the final mapping of enabling DTs. Our work contributes to the sparse literature on digital CE for long-lived artefacts (e.g., buildings) and can be considered the first comprehensive framing of the circular digital built environment, as far as we are aware. This (article) chapter makes several significant contributions to the digital CE and circular BE research fields and practice.

First, the CDB framework offers a novel way to categorise the current CE strategies and provides a broad perspective on the understanding of CE in BE research by integrating four core CE principles of regenerating, narrowing, slowing, and closing (Nancy Bocken et al., 2021; Bocken et al., 2016; Konietzko et al., 2020) with the stages of the buildings' whole life cycle. Our framework extends and complements the previous contributions (Eberhardt et al., 2020; Geldermans, 2016; Hossain et al., 2020; Minunno et al., 2018; A. van Stijn & V. Gruis, 2019) in a number of ways. For example, our consideration of "resource" covers not only materials but also water, land, and energy, which is unique, in a way, as there is a tendency to address merely material loops in the circular BE literature. Moreover, we present rarely discussed circular principles such as regeneration in the framework. According to Benachio et al. (2020), the most cited CE definition by the BE scholars, was the one by the EMF, which defines CE as *"… restorative and regenerative by design…"* (Ellen MacArthur Foundation, 2015, p. 2). However, interestingly, regeneration as a circular building strategy has been predominantly overlooked (Kyrö, 2020).

Second, the CDB framework provides a comprehensive overview of the potential enabling DTs and explores linkages between novel DTs and circular building strategies. According to our findings from both the expert sessions and the literature review, the prevalent technologies in the current situation seem to be BIM and material passports. The innovations in the other DTs applied to the BE sector have also been explored as potential enablers, which led to the creation of a thorough overview, extending the current practice and research on digital CE from other industries to the BE industry. For example, on top of the abovementioned two DTs and frequently mentioned Industry 4.0 technologies (AM, BDA, and the IoT) (Bressanelli, Adrodegar, et al., 2018; Lopes de Sousa Jabbour et al., 2018; Pagoropoulos et al., 2017; Rosa et al., 2019), we uncovered AI, BCT, digital platforms, digital twins, and GIS, and discussed how they could support various circular building strategies. We also explored how experts interpret these technologies and demonstrated practical examples from real-life implementation.

Third, our work also contributes to the growing body of literature on the enabling capabilities of DTs for a CE. To this end, mapping ten DTs onto the CDB framework aided not only in expanding our understanding of the varying functionalities of these ten technologies but also in obtaining a synopsis of which stages in a building's lifetime these DTs could be employed in. The CDB framework, in that sense, provides a valuable starting point for researchers who might be interested in a specific DT or a life cycle stage.

Finally, this paper analyses the intersection of three fields—CE, BE and DTs—by offering an integrative review of these domains. This formulation conceptualises an emerging research field.

3.7.2 Implications for practice

This research provides practitioners with clear insights into the capabilities of enabling DTs for the realisation of a circular BE in practice. Using the CDB framework, practitioners may create roadmaps for CE implementation by choosing their circular building strategies and identifying the set of DTs that best support the selected strategies. Furthermore, the framework could be adjusted for a different purpose, e.g., outlining value networks, and could be developed into a tool to further explore circular strategies and DTs by the practitioners.

3.7.3 Limitations and further research

A fundamental limitation of this work was the limited number of keywords used when reviewing the literature, as we concentrated on the papers that explicitly mention "Circular Economy" in title, keywords and abstract. Further circular strategies and DTs might be discussed in other papers, e.g., because they referred to "reuse" or "resource-efficiency" and interactions with digital technology without specifically mentioning CE. Although our search focussed on the BE (comprising buildings and infrastructure), we noticed that the majority of the reviewed articles were conducted at the building scale application, as there have been very few examples from other fields, such as infrastructure.

The second limitation of our investigation was the number and configuration of the expert workshops, as most participants came from Europe, representing a small percentage of the BE industry. Thus, further research is needed to include other perspectives, e.g., from the Global South.

Moreover, our study primarily focused on the enabling functionalities of the listed DTs rather than the implementation barriers in real-life practices. Furthermore, as most of these technologies are still in the early development phases, the implementation or economic viability is out of the scope of today's practice, as this will evolve throughout the development of the DTs. Especially for the technologies with lower levels of readiness, different forms or combinations can enable the transition to a circular BE. Further research should also cover the actual net benefits for environmental, economic and social sustainability, potential trade-offs, and the rebound effects of implementing such technologies.

The outcomes of this study will be used in further research to map and analyse the value chain network, circular strategies and business models, and associated enabling DTs for different stakeholder groups, e.g., social housing organisations, in the BE research.

Supplementary Materials

The following are available online at https://www.mdpi.com/article/10.3390/su13116348/s1. Table S1: Literature overview at the intersection of DTs, CE and the BE. Table S2: References on the CDB framework. Figure S1: Workshop findings in full-size.

Author contributions

Conceptualization, S.Ç., C.D.W., N.B.; methodology, S.Ç., C.D.W., N.B.; investigation, S.Ç.; workshops: S.Ç., C.D.W.; data curation, S.Ç.; literature review: S.Ç., C.D.W.; writing—original draft preparation, S.Ç.; writing—text preparation: S.Ç., C.D.W.; writing—review and editing, S.Ç., C.D.W., N.B.; visualisation, S.Ç.; project administration, S.Ç. All of the authors have read and agreed to the published version of the manuscript.

Funding

S.Ç. received funding from the CHARM Project (Circular Housing Asset Renovation and Management—No More Downcycling) under INTERREG NWE grant number 760. N.B. was funded through the European Union's Horizon 2020's European Research Council (ERC) funding scheme under grant agreement No 850159, project Circular X (www.circularx.eu) (accessed on 2 June 2021).

Institutional review board statement

The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Human Research Ethics Committee of the Delft University of Technology.

Informed consent statement

Informed consent was obtained from all of the subjects involved in the study.

Acknowledgments

We would like to thank all of the experts who participated in the workshops for their valuable contribution to our study.

Conflicts of interest

The authors declare no conflict of interest.

4 Digitalisation for circular social housing practices

An analysis

The preceding chapter delineated ten digital technologies, ranging from artificial intelligence to blockchain, with the potential to assist industry players in implementing circular building principles—specifically, those of narrow, slow, close, and regenerate—across various life cycle stages. This chapter contributes to academic discourse by illustrating real-life applications of these enabling technologies in social housing practice through a comprehensive multiple-case study analysis. It offers empirical evidence from pioneering social housing organisations, shedding light on how these technologies are embraced in circular projects encompassing new builds, renovations, maintenance, and demolitions, and whether they pose challenges. The insights gained from the analysis of real-world cases inform the next chapter, which focuses on material passports as a critical enabling tool and addresses its data-related challenges.

Recap key research question 3: How are digital technologies deployed in the circular projects of forerunner social housing organisations, and what challenges emerge in their broader adoption?

Publication*: **Çetin, S.**[1], Gruis, V.[1], & Straub, A.[1] (2022). Digitalization for a circular economy in the building industry: Multiple-case study of Dutch social housing organizations. Resources, Conservation & Recycling Advances, 15, 200110.

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

* This article received ***the Best Paper Award 2022*** from Elsevier journal **Resources, Conservation & Recycling Advances**.

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 organisations 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 technological, cultural, market, and regulatory factors.

KEYWORDS Digitalisation; circular economy; building; case study; challenge; built environment

4.1 Introduction

The building industry is one of the largest, most resource- and energy-intensive industries in the European Union (EU) (European Commission, 2020e; Márton Herczeg et al., 2014), which creates around 36% of the EU's waste (Eurostat, 2018b). In the past decade, many governments, organisations, 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 & 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 minimising 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, De Wolf, et al., 2021; Konietzko et al., 2020), narrowing resource loops in buildings aims to curtail primary resource inputs by dematerialisation in design, substituting with secondary materials, and operational optimisation; 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 & Rau-Oberhuber, 2020) and can serve as a "material bank" in the future for new buildings (Honic et al., 2021). Extracting valuable materials from anthropogenic stock and reintroducing them into economic processes through reuse and recycling is called “urban mining” (Heisel & 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, Kovacic, & Rechberger, 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 & 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 (Matthias Heinrich & Werner Lang, 2019), which have become an essential instrument in realising circular buildings. Furthermore, it gave an impetus to digitalisation for a CE in the industry as an emerging research field.

Digitalisation 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, De Wolf, 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, De Wolf, et al. (2021) identified several DTs that could potentially support implementing circular strategies across the lifecycle stages of buildings, including building information modelling (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 & Tavares, 2021). Early examples of MPs include the prototype developed by the European project BAMB (Matthias Heinrich & Werner Lang, 2019), the work of Honic, Kovacic and Rechberger (2019), and commercialised MPs like Madaster (Madaster, n.d.) and Cirdax (Cirdax, n.d.). The method proposed by Honic, Kovacic and Rechberger (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, n.d.) operates on an online platform providing industry actors with the registry of building materials and calculating the level of circularity of the buildings (Heisel & 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. (2022a) 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, n.d.), 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.

Digitalisation has also become an important topic in the European policy landscape, particularly for the EU's green transition (European Commission, 2022c). 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, 2021b).

4.1.1 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, De Wolf, 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 & 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, De Wolf, et al. (2021); Çetin, Straub, et al. (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 prioritises designers, architects, or engineers for decision support in the design stage (Çetin, Straub, 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) chapter aims to address these gaps by examining how large-scale social housing organisations (SHOs) deploy DTs in their circular 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 not-for-profit organisations 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 lifecycle 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 4.3 presents the findings, and Section 4.4 discusses the findings and concludes the (study) chapter.

4.2 Methodology

4.2.1 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).

4.2.2 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 the CE implementation (Marino & Pariso, 2020) and research (Khadim et al., 2022; Munaro & 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 organisations are more likely to adopt DTs than smaller ones (see Çetin, Straub, 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 organisations 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 4.1 presents the main characteristics of the selected cases.

4.2.3 Data collection

TABLE 4.1 Main characteristics of the selected cases. Numbers are extracted from organisations' 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

We collected data from multiple sources from October 2021 to February 2022. First, we examined secondary data sources such as case organisations' yearly reports. Then, building on the preliminary findings, we formulated a semi-structured interview protocol with open-ended questions (see APPENDIX). We invited key informants who were directly involved in circular projects, policymaking, or digitalisation processes. The selection of interviewees was purposive and considered different organisational levels (TABLE 4.1). 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 typically lasted between 40 to 60 minutes and were recorded, transcribed verbatim, and anonymised (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).

4.2.4 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, De Wolf, et al., 2021) (see also previous chapter) gives a comprehensive overview of circular building strategies and enabling DTs, built on prior CE conceptualisations (Nancy Bocken et al., 2021; Bocken et al., 2016; Konietzko et al., 2020). It helped us categorise 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 categorise 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 organising, 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 for determining and categorising 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 conceptualisation of four main categories to DT implementation. FIG.4.1 displays the key elements of the frameworks that are used for the case analysis.

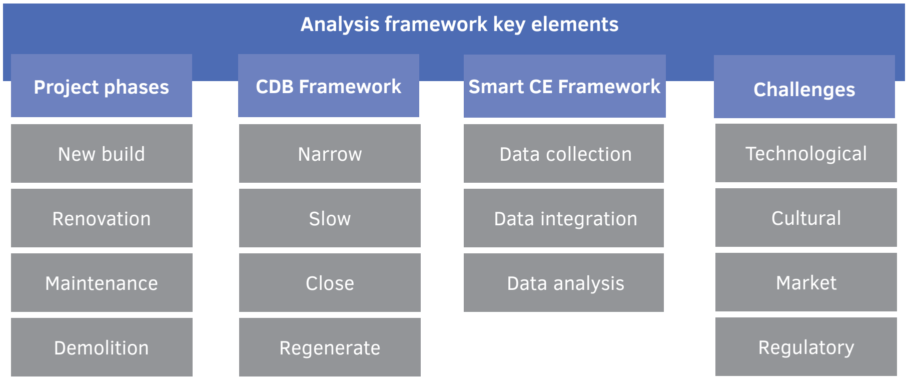

FIG. 4.1 Key elements of the frameworks used analysing cases (Based on previous reseaech of Bocken et al. (2021); Bocken et al. (2016); Çetin, De Wolf, et al. (2021); Kirchherr et al. (2018); Kristoffersen et al. (2020)).

4.3 Findings

4.3.1 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 organisation 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, n.d.). 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 building (BCI, n.d.; Khadim et al., 2022; Zhai, 2020).

The case organisations 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 emphasise different aspects of their circular strategies, as can also be seen in TABLE 4.2.

The digitalisation of 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 organise and make accessible real-estate data that will be expanded towards circularity.

TABLE 4.2 Circularity and digitalisation targets/projects of the cases.

Case	Long- and mid-term circularity ambitions	Circular pilot projects	Digitalisation 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 organisation strategy 2019 -Real-estate information program (digital twin of the housing stock) -Data lake

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 organisation 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 4.2). 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, n.d.).

Case Beta mainly uses an enterprise resource planning system and connected applications for handling real estate data. It has recently introduced a digitalisation package for creating a digital twin of its building stock. Case Beta collaborates with a start-up 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 organisation 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 organisation is also preparing a roadmap building on learnings from pilot projects. Among pilots, urban mining has been the focal point as the organisation 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 organisation 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 digitising architectural drawings. The main goal of generating a digital twin was to improve work processes, data access and sharing, and maintenance operations.

4.3.2 Identified digital technologies

This section presents the findings from the cross-case analysis. A synopsis of the results is given in FIG.4.2, 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 realise 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.4.2). TABLE 4.A.2 in the appendix supplements FIG.4.2 with a selection of interviewee quotes and secondary data.

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 that has 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 emphasised 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).

Slow

Maintenance is the core slowing intervention in case organisations. 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 on 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 realised 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 organisations 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 start-up to remotely inspect their housing stock for condition measurement and ease maintenance processes. This start-up helped both organisations 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 analysed by the start-up'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 recognise 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.

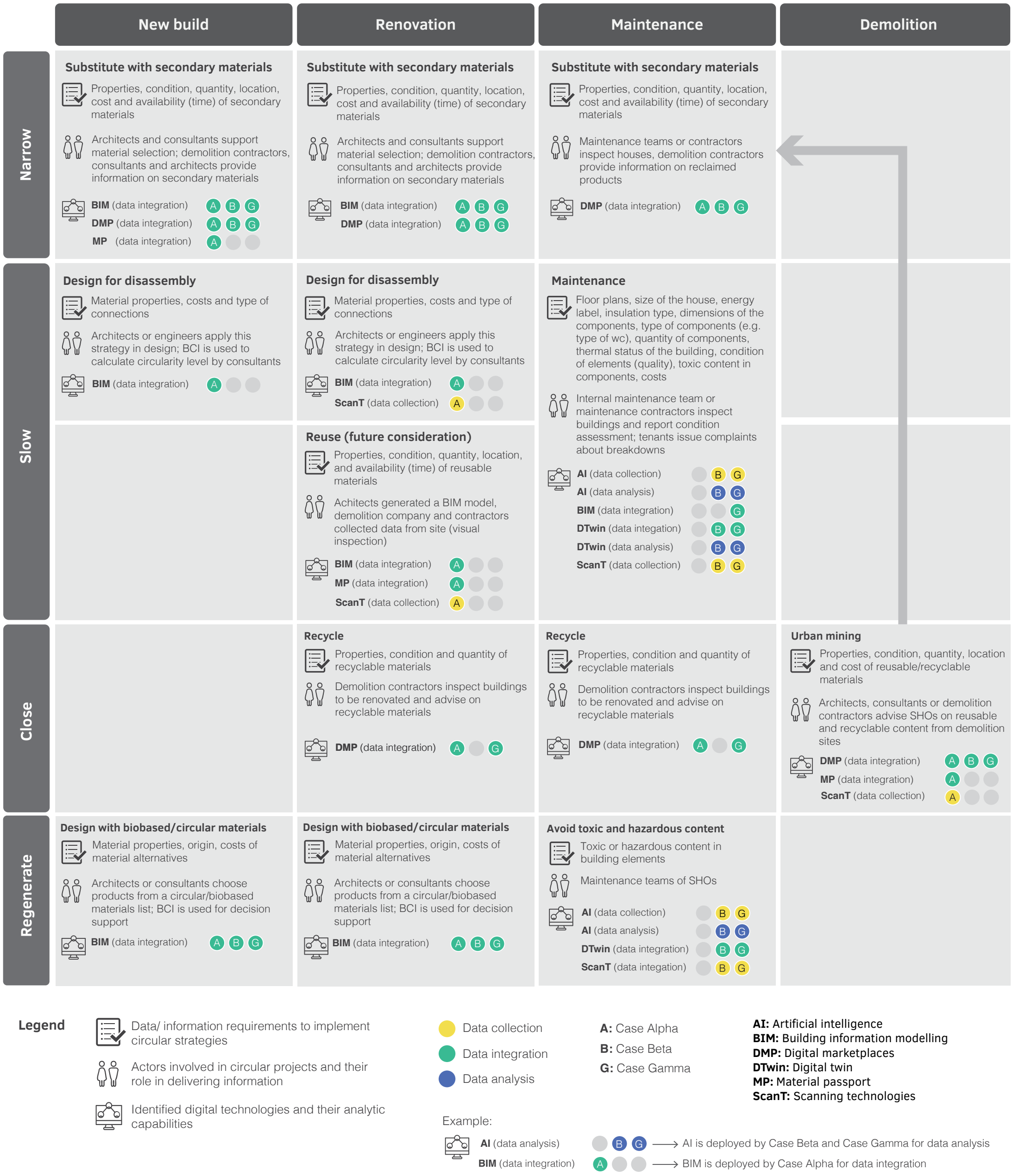

FIG. 4.2 Summary of the cross-case analysis of identified DTs mapped according to CE principles (y-axis) and project types (x-axis).

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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 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.

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.

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, n.d.) 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, n.d.) 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, n.d.) 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.

4.3.3 Challenges

Previous sections explained how SHOs deployed several DTs in circular projects. As shown in FIG.4.3, this section presents the challenges that emerged from the interview data, hindering the implementation of certain DTs and their broader adoption in the sector. We also display a selection of interviewee quotes in TABLE 4.A.2 in the appendix.

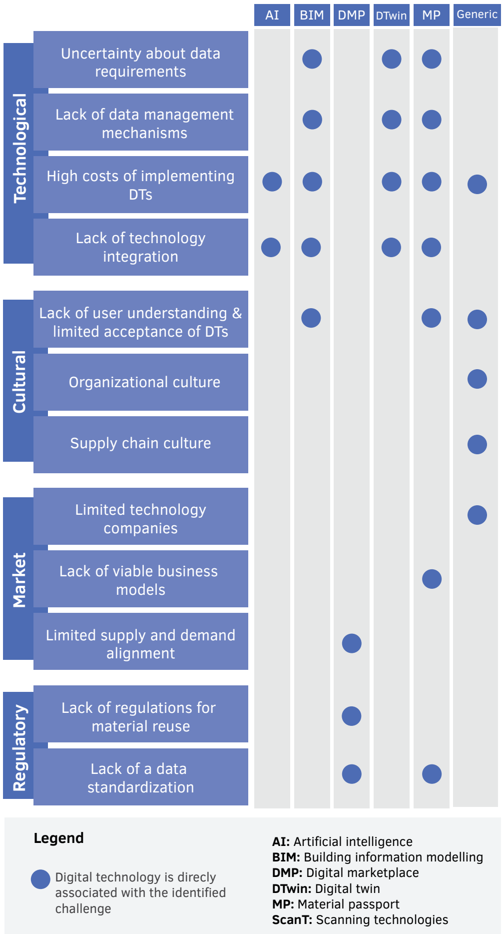

FIG. 4.3 Challenges emerged from the interview data.

Technological challenges

Incorporating DTs in circular processes creates new technology-related challenges for SHOs. One of the major issues that all case organisations 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 organise 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.

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 organisations, 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 organisations. A systemic change is needed that goes beyond SHOs. However, such a systemic change is difficult to achieve in an industry characterised by slow technology adoption and a fragmented supply chain. Interviewees expressed that running pilot projects is helpful for learning in organisations. 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 organisational culture. Both CE and digitalisation 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 organisation to make investment decisions.

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 digitalise 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 organisations emphasised 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.

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 standardisation 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 standardisation could address these challenges in data management and sharing.

4.4 Discussion and conclusions

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 digitalisation, CE and the building industry and is one of the few studies displaying practice-based evidence.

Our findings show that even though the case organisations are at the forefront of circularity implementation in the sector, they have only taken initial steps towards digitalisation, particularly for circularity. Some of the enabling technologies identified in previous research (Çetin, De Wolf, et al., 2021; Heisel & Rau-Oberhuber, 2020; Honic, Kovacic, & Rechberger, 2019; Munaro & 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 organisations value through their capabilities in resource optimisation and data-driven maintenance operations.

4.4.1 Discussion of findings

In addressing the first research question, FIG.4.4 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, Straub, 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).

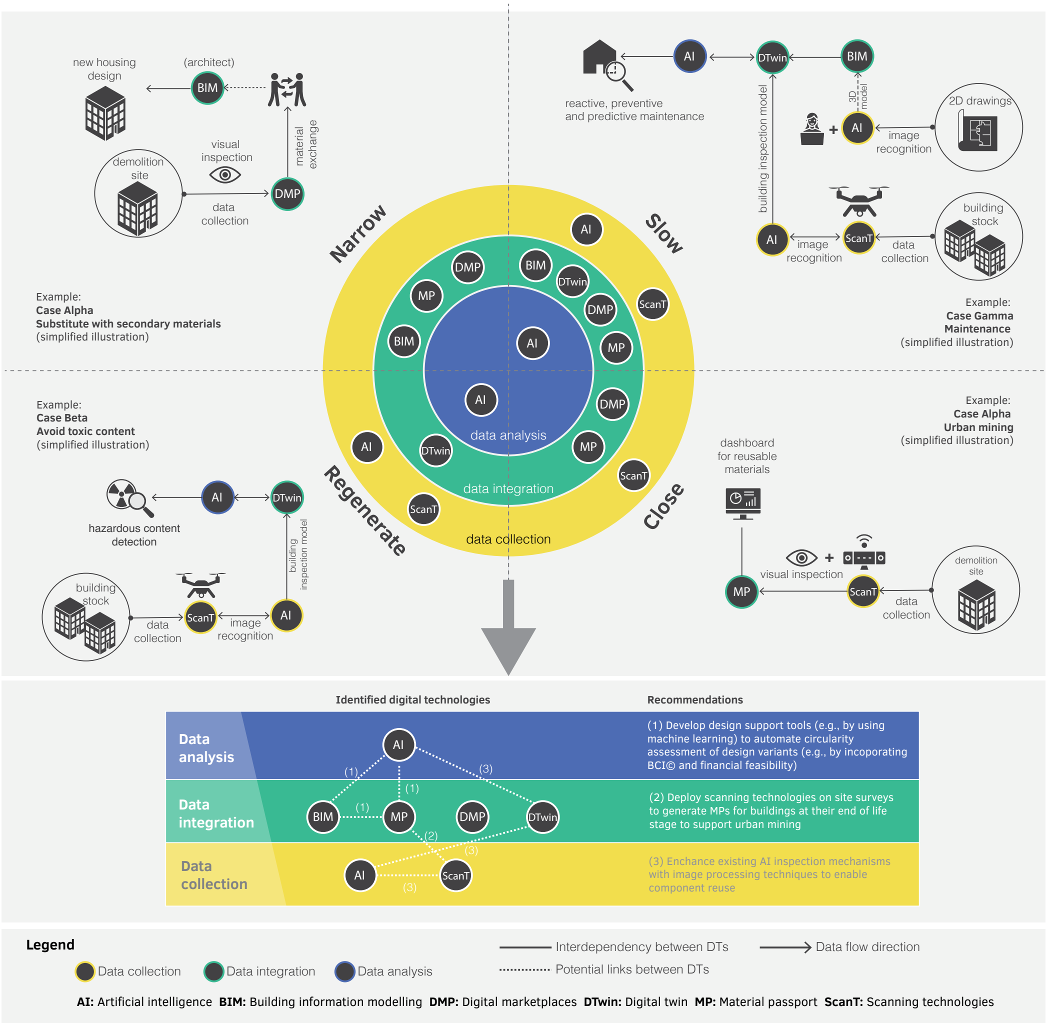

FIG. 4.4 DTs supporting circular building strategies in SHOs are illustrated with examples and interlinks between each other.

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A combination of DTs was used to develop a data-driven maintenance system linked to a digital twin (see example Case Gamma in FIG.4.4). AI seems to be a promising technology for data collection and analysis through computer vision techniques. A novel way of digitisation 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. (2022a), 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 organisations 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 organisations 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, Kovacic, & Rechberger, 2019; Munaro & Tavares, 2021). A possible explanation for this might be that SHOs prioritise 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, n.d.) from a consultancy company is used by all case organisations. This indicator is not only complementary to the design process but can also inform real estate owners about the 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 & 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 organisations 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 commercialised 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 & 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 standardisation 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.

4.4.2 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 organisational 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 digitalisation and circularity.

4.4.3 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 organisations. Lastly, we recommend policymakers and branch organisations stimulate standardisation 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.

Author contributions

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

Data availability statement

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

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, and Sebastian Lawrenz for his support in formulating the digitalisation part of the case analysis framework, and the reviewers for their constructive feedback.

Appendix A

TABLE 4.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 digitalisation? – What is the level of maturity of digitalisation in your organization? – How far is your organization's housing stock digitalised? – 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 4.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)

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TABLE 4.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
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)

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TABLE 4.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
	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)

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TABLE 4.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
	New build and renovation/ (BCI)	n/a	*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)

5 Material passports for social housing stock

A tool

As highlighted in the preceding chapter, social housing organisations encounter significant challenges when incorporating digital technologies into their circular processes. In particular, issues surrounding the creation and implementation of Material Passports—a vital enabling tool—prompt the exploration of new research avenues. This chapter, therefore, addresses the identified challenges, such as *uncertainty regarding the data requirements* and *the lack of a data management mechanism.* Employing a mixed-methods research design, this chapter identifies the key users of Material Passports for existing social housing stock, delineates their data needs, and assesses the availability of required data. In response to identified data gaps, it proposes a digitally-enabled Material Passports framework designed to enhance the adoption of narrowing, slowing, closing, and regenerating strategies in the existing social housing stock.

Recap key research question 4: What are the data requirements of users from material passports for the existing housing stock? Are these data available? If not, how can digital technologies support fulfilling the data gaps?

Publication: **Çetin, S.**[1], Raghu, D.[2], Honic, M.[2], Straub, A.[1] & Gruis, V.[1], (2023). 5. Data requirements and availabilities for material passports: A digitally enabled framework for improving the circularity of existing buildings. Sustainable Production and Consumption, 40, 422-437.

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ABSTRACT

Passports for circularity, e.g., digital product passports and material passports (MPs), have gained recognition as essential policy instruments for the Circular Economy goals of the European Union. Despite the growing number of approaches, there is a lack of knowledge about the data requirements and availabilities to create MPs for existing buildings. By deploying a mixed-method research design, this study identified the potential users and their data needs within the context of European social housing organisations. Three rounds of validation interviews with a total of 38 participants were conducted to create a data template for an MP covering maintenance, renovation, and demolition stages. This data template was then tested in a case study from the Netherlands to determine critical data gaps in creating MPs, including, but not limited to the composition of materials, presence of toxic or hazardous contents, condition assessment, and reuse and recycling potential of a product. Finally, an MP framework is proposed to address these data gaps by utilising the capabilities of enabling digital technologies (e.g., artificial intelligence and scanning systems) and supportive knowledge of human actors. This framework supports further research and innovation in data provision in creating MPs to narrow, slow, close, and regenerate the loops.

KEYWORDS Circular Economy, digitalisation, material passports, building industry, stakeholder identification, data requirements

5.1 Introduction

The building industry is one of the largest resource-intensive, carbon-emitting, and waste-creating industries in the European Union (EU) (European Commission, 2022a; European Construction Sector Observatory, 2018; Eurostat, 2020). Increasing demand for new housing, coupled with the requirements for energy-efficient building stock, puts tremendous pressure on countries to respond to the housing crisis while simultaneously respecting the natural environment. In recent years, as part of the EU's Green Deal (European Commission, 2019), the Circular Economy (CE) has gained attention as an alternative approach to address resource scarcity and climate change-related challenges by decoupling economic activity from the consumption of finite resources (Ellen MacArthur Foundation, 2013b). A CE can be defined as a system that minimises resource inputs, waste, and emissions by maximising the value of products and materials over time (Geissdoerfer et al., 2017) by applying four resource principles: *narrow* (use less), *slow* (use longer), *close* (use again), and *regenerate* (make clean) (Bocken et al., 2016; Konietzko et al., 2020).

Applying these CE principles to buildings, particularly closing the loops, is reflected in the buildings-as-material-banks concept (Matthias Heinrich & Werner Lang, 2019; Heisel & Rau-Oberhuber, 2020). Scholars argue that the current building stock can become a source of materials to construct new buildings or renovate existing ones in the future (Benachio et al., 2020; Matthias Heinrich & Werner Lang, 2019; Heisel & Rau-Oberhuber, 2020; Honic et al., 2021). This can be achieved by disassembling building products and materials that reach their end-of-life in one building and reusing or recycling them in another. Realising reuse or recycling in construction practices is a challenging process partly due to the lack of information regarding materials located in buildings (e.g., their quality, quantity, and properties) which is a result of insufficient documentation (Honic, Kovacic, & Rechberger, 2019; Iacovidou et al., 2018; Koutamanis et al., 2018). To address this information gap, the concept of material passports (MPs) was proposed by researchers and practitioners (e.g., Honic, Kovacic and Rechberger (2019); Platform CB'23 (2020)).

An MP is an instrument providing digitised qualitative and quantitative life cycle information on the characteristics of a product to enable circular principles of narrow, slow, close, and regenerate. MPs can be created at various scales (e.g., material, product, or building) (Platform CB'23, 2020) for supporting different circular building strategies such as design optimisation for increased recyclability (Honic, Kovacic, & Rechberger, 2019) as well as reusing building products at the end of life (Matthias Heinrich & Werner Lang, 2019). To date, several MP solutions have been proposed (Çetin, De Wolf, et al., 2021; Munaro & Tavares, 2021); however, their resulting frameworks remain mainly conceptual and tend to neglect the perspectives and needs of industry actors who are implementing circular strategies in designing, constructing and managing buildings. Identifying the users of MPs and their requirements is an overlooked research area. Also, the lack of understanding regarding MPs by the potential users can be a significant barrier to their adoption. For example, a multiple-case study from the Netherlands *(previous chapter)* showed that practitioners experienced considerable challenges in adopting MPs in their circular housing projects, including uncertainty around data requirements, lack of a data management mechanism, and high costs of creating and managing MPs (Çetin et al., 2022). Another issue with the current MP approaches is that they are primarily created for new buildings during the design stage to manage the whole life cycle data of buildings (Munaro & Tavares, 2021). Yet, very little attention has been paid to existing building stock which is poorly documented (Honic et al., 2021). Considering that the majority of the current building stock can be used in future as a resource for steadily growing new building construction in the EU (Göswein et al., 2022; Honic et al., 2021), it is critical to explore the ways in which MPs are created for existing buildings.

The aim of this research, therefore, is to develop an MP framework for existing buildings based on an empirical investigation of European social housing organisations. This study specifically focuses on the existing social housing stock due to several reasons. First, social housing organisations in Europe typically own a large portfolio of buildings. In some countries, such as the Netherlands, Austria, and Denmark, the social housing stock makes up around respectively 29%, 24%, and 21% of the total housing stock (Housing Europe, 2021). Second, these organisations manage their building portfolio professionally and are involved in all life cycle phases, from housing development until demolition, by closely collaborating with other building industry actors such as architects, construction companies, and material suppliers. They hold a powerful position in the market and can influence the circular practices of the industry. Third, social housing organisations are social entrepreneurs, and they are expected to use their resources in line with collective social interests (Nieboer & Gruis, 2014; Roders & Straub, 2015). Besides implementing carbon reduction measures, implementing circular building strategies, following the EU's CE targets, is becoming a part of their sustainability goals (see, e.g., Interreg North-West project CHARM (CHARM, 2023)). Particularly in some EU countries like the Netherlands, social housing organisations are leading the way towards achieving a circular building industry (Çetin, Gruis, et al., 2021) by not only implementing circular strategies but also experimenting with digital technologies, including the MPs, to enhance their circular operations (Çetin et al., 2022). Also, due to their large building stock and professional management, they typically operate in a data-rich environment.

Given the importance of social housing organisations in the circular transition of the existing housing stock, further research is needed to identify the data needs of key actors involved in circular housing projects. Although some research has been carried out on the data requirements and availabilities for passports in other industries (e.g., Berger et al. (2023); Jensen et al. (2023)), no studies have been found that investigate these matters in the building industry, particularly for existing buildings. This study is, therefore, an initial attempt to explore key MP users and their data needs and to what extent the required data are available in the digital systems of social housing organisations. Focusing on European social housing organisations, this study presents empirical insights and addresses the following research questions:

RQ1: **Who are the potential users of MPs for the existing housing stock, and what kind of data do MPs need to provide to support them in implementing circular principles?**

RQ2: **Which data requirements of an MP can be fulfilled with available data and digital systems of a social housing organisation?**

A mixed-methods research design is deployed to answer the research questions, consisting of a literature and practice review and three rounds of validation interviews with a total of 38 participants, including researchers, social housing professionals, and key stakeholders such as architects, consultants, and reuse companies. The developed data template is then applied in a case study from the Netherlands to demonstrate which data points can be fulfilled by available data and digital systems of social housing organisations. By providing empirical evidence from industry actors, this research contributes to the emerging literature on the intersection of digitalisation and the circular building industry from the standpoint of MPs.

The structure of the paper is as follows. Section 5.2 gives an overview of the research background, explaining current passport approaches in the building industry. Section 5.3 introduces the research design and methods for data collection and analysis. Section 5.4 presents and discusses the findings, and Section 5.5 concludes the study.

5.2 Current Material Passport approaches

5.2.1 European Union policy

To enable a transition from a linear economy to a CE, the EU initiated several strategies in the intersection of circularity and digitalisation in recent years. These strategies include the CE Action Plan (European Commission, 2020b), the European Green Deal (European Commission, 2019) and “A Europe fit for the digital age” (European Commission, 2023). Their common aim is to achieve climate neutrality by 2050 and establish a CE with the support of digitalisation. The EU has also introduced several passport instruments in response to the resource-intensive and waste-generating building construction that follow the targets of the above-mentioned EU strategies. Some examples are the MPs (BAMB, 2019), Digital Product Passports (European Commission, 2022b), and Digital Building Logbooks (European Commission, 2020c). They differ based on which industries they are applied in, their scope and the backbone on which they are based. However, they are developed with the common goal of enabling circularity.

In previous years, several MPs emerged in research and practice (van Capelleveen et al., 2023) (see also Section 5.2.2). Although MPs play a crucial role in transitioning from a linear to a circular building industry, a regulatory framework that enables standardisation and sets common bases does not exist for buildings. Alternatively, Digital Product Passports were proposed by the European Commission as a regulatory framework “for setting eco-design requirements for sustainable products” (European Commission, 2022b). Digital Product Passports ‘‘provide information on a product's origin, durability, composition, reuse, repair and dismantling possibilities, and end-of-life handling'' and shall apply to any physical good placed on the market or put into service. Digital Product Passports is a cross-sectoral concept that does not exclude the built environment (European Commission, 2022b). A concept proposed by the EU only for buildings is Digital Building Logbooks. It is defined as "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" (European Commission, 2020c). This extensive concept covers several sustainability aspects, such as energy efficiency and is not limited to circularity.

Although several attempts exist to introduce new passport instruments at the EU level, a regulatory framework for buildings is missing. It is unclear if the Digital Product Passports framework will be adopted for MPs or if a new regulation for the built environment will be established. The alignment of MPs and Digital Building Logbooks is possible; however, their scope is significantly broader than those of MPs for a CE. Even if not adopted in existing MP concepts, the EU-driven regulations and frameworks concerning Digital Product Passports and Digital Building Logbooks might influence the future evolution of MPs. FIG 5.1 summarises the similarities and differences between these three passport initiatives.

	Digital Product Passports	Material Passports	Digital Building Logbooks
Scale	Product	Area, Complex, Building, Element, Product, Material, Raw material	Building
Industry	Cross-industry	(Mainly) Built environment	Built environment
Regulation	EU Ecodesign Directive	–	EU-wide Framework for a Digital Building Logbook

FIG. 5.1 Differences and similarities between digital product passports, material passports, and digital building logbooks.

5.2.2 Material Passport landscape in the building industry

Since CE became a popular concept in Europe, many sector-specific and cross-sector passport approaches have emerged (Jansen et al., 2022). There is no widely agreed terminology, definition, or standardisation of current approaches (van Capelleveen et al., 2023). Several terms are used for passports, including Data Templates (Mêda et al., 2021), Product Circularity Data Sheets (Mulhall et al., 2022), Material Passports (Matthias Heinrich & Werner Lang, 2019), Digital Product Passports (Jansen et al., 2022), Digital Battery Passports (Berger et al., 2022), and Circular Material Passports (Göswein et al., 2022). Some of these passport initiatives, e.g., Product Circularity Sheet (Mulhall et al., 2022), intend to cater towards several industries, while others have a specific focus, such as Digital Battery Passports (Berger et al., 2022) for the automotive industry.

The passport landscape for the building industry is also diverse. Current approaches lack a unifying scheme and vary in terminology, content, aggregation level, technology use, and maturity level. Although several terms exist, Material Passports (MPs) is the most frequently used term (van Capelleveen et al., 2023). One of the early conceptualisations of the MP is “Nutrition Certificates” by Hansen et al. (2013). Nutrition Certificates are proposed as a tool to enhance the value of building products by describing the characteristics of materials so they can be recovered or reused in continuous loops instead of becoming waste (Hansen et al., 2013). Building on this concept, the EU project BAMB developed an MP prototype tracking the residual value of building products along the supply chain (Luscuere, 2017). The BAMB project demonstrated the MP application on an interactive exhibition building whereby around 70 circular products were connected to data carriers (QR codes), and the visitors could access MPs via their phones (BAMB, 2019). Perhaps the first commercial MP for the building industry is developed by a not-for-profit entity Madaster Foundation in the Netherlands. Madaster is an online platform providing insights into the materials and products used in buildings, their prospective carbon emissions, and economic value (Madaster, 2023).

As outlined in TABLE 5.1, MPs can be used for different purposes. Recovering value from products through reuse and recycling is one of the functions frequently mentioned in the literature (see, e.g., Göswein et al. (2022); Matthias Heinrich and Werner Lang (2019); Heisel and Rau-Oberhuber (2020); Luscuere (2017); Munaro and Tavares (2021)). Some commercial MPs, such as Madaster, also determine the circularity level of a building for construction, use, and end-of-life phases based on material-specific parameters (Heisel & Rau-Oberhuber, 2020). The BIM (Building Information Modelling)-based MP tool developed by Honic, Kovacic and Rechberger (2019) combines LCA (life cycle analysis) method with design optimisation to support designers in making informed decisions on material selection during the early design stage, increasing the recyclability performance at the end-of-life. Similarly, Atta et al. (2021)'s BIM-based MP framework allows architects and engineers to select various building alternatives based on disassembly, recovery, and environmental scores. MPs are also seen as a life cycle data management tool, supporting use phase interventions such as maintenance, renovation, and repair, tracking the changes made in physical objects (Luscuere, 2017; Munaro & Tavares, 2021).

TABLE 5.1 Overview of material passport approaches in the building industry.

Category	Aspect	Illustrative references
Purpose	Recovering value through reuse or recycling Measuring the circularity level of a building Calculating the economic value of products Design optimisation Life cycle data management	(Matthias Heinrich & Werner Lang, 2019) (Heisel & Rau-Oberhuber, 2020) (Madaster, 2023) (Honic, Kovacic, & Rechberger, 2019) (Munaro & Tavares, 2021)
Technology use	Data template/datasheet Platform-based MP tools BIM-based MP tools Blockchain-based MP tools	(Platform CB'23, 2020) (Madaster, 2023) (Honic, Kovacic, & Rechberger, 2019) (Circularise, 2023b)
Maturity	Conceptual tools (TRL 1 to 3)* Prototypes (TRL 4 to 6)* Commercial tools (TRL 7 to 9)*	(Atta et al., 2021) (BAMB, 2019) (Cirdax, n.d.)
Aggregation level	Area Complex Building Element Product Material Raw material	(Orms, 2023; Platform CB'23, 2020)
Life cycle phase	Production Design/construction Use/operation End-of-life All life cycle phases	(Mulhall et al., 2022) (Honic, Kovacic, & Rechberger, 2019) - (Honic et al., 2021) (Platform CB'23, 2020)

**TRL: Technology Readiness Level. The given TRL scales are indicative of maturity level.*

Another different form of current MP approaches is the level of digitalisation and technological integration. MPs can be created simply as a data template using a spreadsheet tool or as complex as a supply chain infrastructure based on advanced digital technologies. For example, the Dutch public-private initiative Platform CB' 23 formed a large workgroup of stakeholders (e.g., architects, construction companies, and demolishers) and established an extensive list of data points to generate MPs (Platform CB'23, 2020). A similar attempt was made by the Ministry of the Economy of Luxembourg, which launched the Circularity Dataset Initiative in 2018 (PCDS, 2023). This initiative has also concluded a yes/no answer-based list of product circularity data sheets for various industries, including the building industry, to provide standardised information for circularity evaluations (Mulhall et al., 2022; PCDS, 2023). These simple data templates could be considered the first step in creating MP tools.

On the other hand, commercial MPs are typically operated on an online platform (e.g., Madaster, Cirdax, Concular, etc.), where data from BIM or product data spreadsheets are fed into the system to create material-related circularity indices (see, e.g., Heisel and Rau-Oberhuber (2020)). If available, BIM is the main source of data to create MPs for building products (Çetin, De Wolf, et al., 2021). Tools resulting from academic research are usually built with BIM and remain largely conceptual (e.g., Atta et al. (2021); Honic, Kovacic and Rechberger (2019); Honic, Kovacic, Sibenik, et al. (2019)). Regarding the digitalisation level, the passport tool of a Dutch start-up called Circularise is exceptional. This start-up uses traceability software based on blockchain technology and tracks products along the supply chain through physical data carriers, such as RFID tags or QR codes, while protecting the confidential information of supply chain actors (Circularise, 2023b). Circularise collaborates with the Municipality of Amsterdam to increase the traceability and transparency of procurement environmental impact insights from the upstream supply chain (Circularise, 2023a).

Depending on the users' needs and goals, MPs can be created at different aggregation levels and life cycle stages (Çetin, De Wolf, et al., 2021). As listed in TABLE 5.1, Platform CB'23 (2020) proposes a structure for MPs consisting of nested levels of raw material, material, product, element, building, complex (collection of buildings), and area. These scales can be composed of varying degrees of information, and smaller scales can be embedded under larger scales. For example, a British architecture firm developed a BIM-based MP solution generating passports for building products nested under a building passport (Orms, 2023). In addition, MPs can be created for one or multiple life cycle stages. Although the majority of current approaches are developed in the design stage to track products throughout the life cycle stages, very few MPs are created at other life cycle stages, partly due to a lack of information about the existing building stock.

A unique example is the study of Honic et al. (2021), which demonstrated a novel data collection method for creating MPs for buildings at their end-of-life. The authors built a BIM model using laser scanning technology and applied a combination of simplified demolition acquisition and invasive methods, such as drilling and cutting. The resulting MP tool provides an overview of the masses of materials, their environmental impact and the recycling potential (Honic et al., 2021).

From this brief overview, it is clear that there is a lack of standardisation and unity in creating, managing, and exchanging data in current MP approaches. Most academic studies attempt to propose conceptual models and overlook stakeholders' data needs. Although a few public and private initiatives, such as the Dutch Platform CB'23 (Platform CB'23, 2023), provide an extensive list of data requirements, there is no transparency regarding their methodology and whether these could be implemented in existing buildings. Considering the data collection and MP creation challenges identified in the practice (Çetin, Straub, et al., 2021; Göswein et al., 2022; Mulhall et al., 2022), this study will expand current knowledge by identifying key users of MPs and their data requirements.

5.3 Research design

The MP framework for existing buildings proposed in this paper was developed following a mixed-methods research design based on iterative data collection steps. A multiphase mixed-method design allows researchers to combine sequential qualitative and quantitative data collection and analysis methods over a period of time (Creswell & Clark, 2011). This approach leads to more complete, robust, and comprehensive research findings. As presented in FIG 5.2, the study consists of two parts. In the first part, a data and stakeholder identification method was deployed, and in the second part, building on the results from the subsequent steps, the developed data template for MPs was implemented in a case study to assess data gaps and inconsistencies. Finally, building on the findings, a vision for an MP framework is proposed.

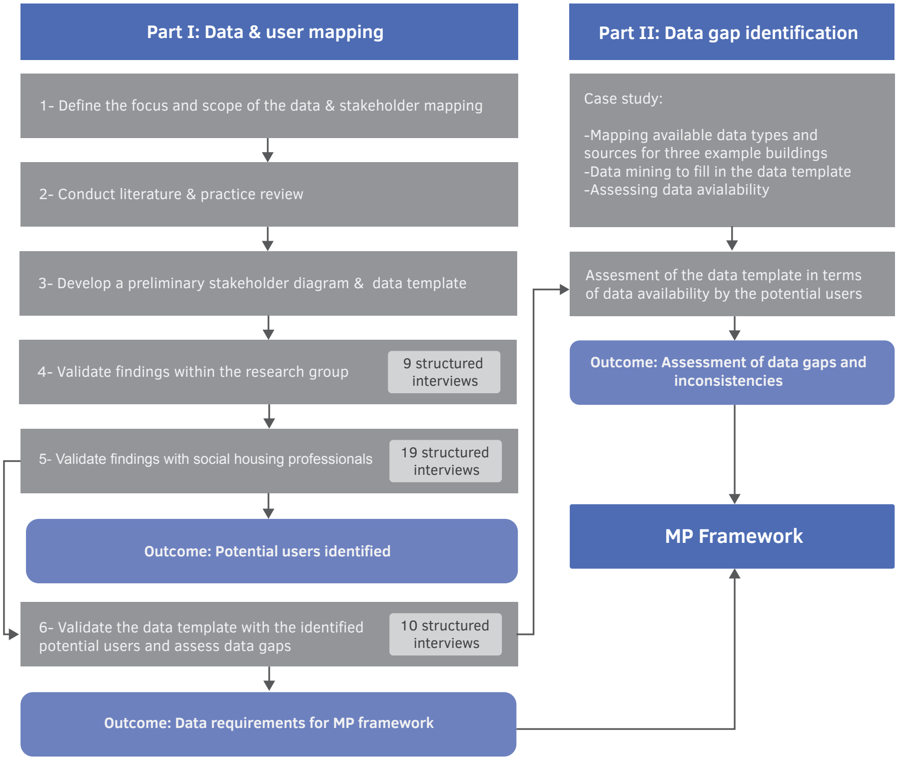

FIG. 5.2 Research design.

5.3.1 Part I – Data and user mapping

We applied the SCOPIS (supply chain-oriented process to identify stakeholders) method introduced by Fritz et al. (2018) to identify key stakeholders and their data needs. SCOPIS is an iterative multi-step method focusing on a service or a good during the identification process rather than concentrating on a single organisation as in the traditional methods (Fritz et al., 2018). Taking a supply-chain perspective is believed to minimise bias and acquire a mixed overview from various stakeholders on multiple issues (Fritz et al., 2018). This method was also used by Berger et al. (2022) to map users of digital battery passports for electric vehicle batteries in the context of CE. We followed six steps, as explained in detail in the following subsections and illustrated in FIG 5.2

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Step 1- Defining scope and focus

As a first step, the focus and scope of the stakeholder data requirements identification analysis were determined based on background literature (Section 5.1). The scope of this research is limited to the housing stock and stakeholders involved in circular projects operating with and within social housing organisations across Europe. Since the main focus is the existing building stock, we considered the use and end-use phases of buildings. The primary activities of social housing organisations during these phases are maintenance (responsive, preventive, and predictive maintenance), renovation, and demolition projects (Çetin et al., 2022). These three project stages were included in the user mapping diagram.

Step 2- Literature and practice review

We conducted a literature and practice review between September and November 2022 to create the preliminary lists of stakeholders (i.e., potential users) and a baseline data template. This step helped us to set a master data template demonstrating all possible data points considered in the previous MP approaches. As presented in FIG 5.3, the review included publications in peer-reviewed and grey literature and was complemented with an additional search of commercial MP tools available in the market. For the literature review, a Scopus search was done by using "circular* AND passport*" as keywords in peer-reviewed articles, conference papers and book chapters. The Scopus database was selected for the review based on its broad coverage of journals relevant to both MPs and built environment research. The initial search yielded 58 results, where 29 papers were eliminated after reading titles, abstracts, and keywords based on the selection criteria. Following a snowballing procedure (Wohlin, 2014), eight additional papers were added. After reading the remaining articles in detail, 16 papers were selected for further in-depth analysis.

Acknowledging that practice is ahead of academic studies regarding MP applications, we also conducted a practice review using the same keywords. Web research in three languages (English, Dutch and German), coupled with the snowballing procedure, resulted in 17 practitioner reports and 20 commercial MP tools. Applying the same selection criteria, in total, 15 practice reports and MP tools were selected for in-depth analysis. We applied three selection criteria: (1) the MP approach should be proposed for CE strategies; (2) the MP approach should have applications in the building industry; and/or (3) stakeholders/users should be mentioned in relation to the use of MPs. The full list of selected sources with data categories and data points can be found in the Supplementary Material.

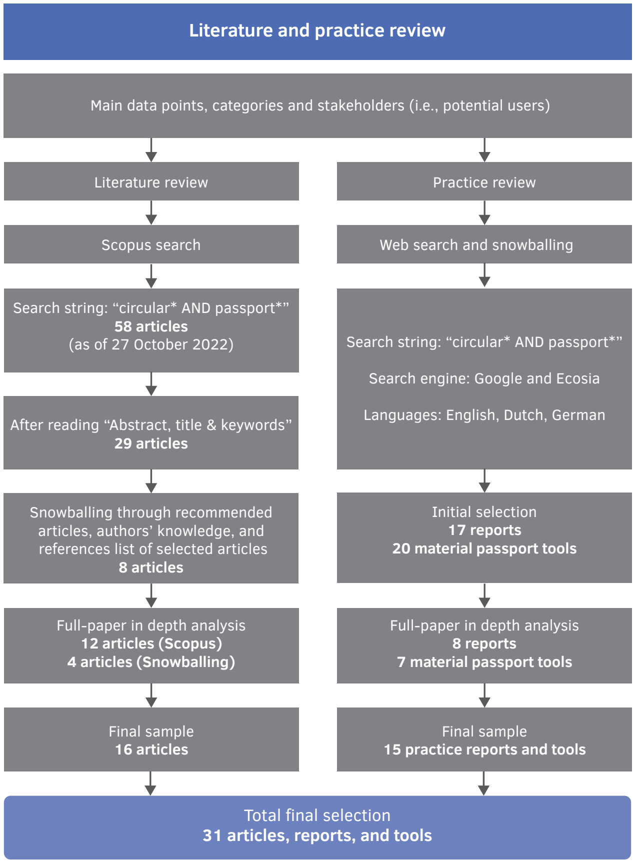

FIG. 5.3 . Practice and literature review process.

Step 3- Preliminary stakeholder mapping and data template

In the third step, we developed a diagram for stakeholder mapping by adapting the rainbow diagram developed by Chevalier and Buckles (2008) that allows allocating stakeholders in line with the degree to which they influence or get influenced by a matter (Reed et al., 2009). In the context of this study, stakeholders are the "potential users of the MPs for existing buildings". Instead of "affected" and "affecting", as proposed in the original method (Chevalier & Buckles, 2008), we classified stakeholders as "data requesters" and "data providers". Since the scope was limited to the use and end-of-use phases of buildings, the diagram included three project stages: maintenance, renovation, and demolition (Çetin et al., 2022). Based on the literature and practice findings, we listed potential users next to the

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diagram and created an online whiteboard template (see Supplementary Material). This online whiteboard template was used during interviews, allowing interviewees to drag and drop potential pre-identified stakeholders according to the degree of their need or provision of data across the project types. Interviewees were allowed to propose new users according to their experience with circular projects. Grouping users who request/provide data "slightly" and "significantly" helped us pinpoint the key users.

To create the preliminary data template, we first compiled a master data template by categorising data points mentioned in the 31 sources selected in the previous review step. The master data template was extensive, consisting of 96 different data points (see Supplementary Materials). Since the selected sources varied in terms of intended life cycle stage and scale of focus, we decided to simplify the list by (1) selecting the most frequently mentioned data points, (2) eliminating data fields that are challenging to collect from existing buildings (e.g., social life cycle assessment), and (3) brainstorming with the research team. The resulting baseline data template, comprising 55 data points, was used for the first validation round with the researchers.

Steps 4,5 and 6 – Validation rounds through structured interviews

The first round of interviews was done with the research community in which the authors are involved. A total of nine researchers were consulted through video calls (n=7) and emails (n=2) in December 2022. TABLE 5.2 gives an overview of the interviewees, and Appendix A presents the interview questions for all interview rounds. We invited our colleagues who do research in the fields of circularity, digitalisation, or housing. Researchers were asked about the main users, functions, and scales of the MPs for existing buildings and to assess relevant data categories and data points that should be included in the data template. This step helped us to reorganise the baseline data template by scaling down data points to 49 points grouped under six main categories. The output generated by the researchers on the user diagram was then compiled and formed the initial set of stakeholder mapping for the following round.

TABLE 5.2 Overview of interviewees of three validation rounds.

Validation round	No	Role	Professional affiliation	Expertise	Years of experience	Country
First round with the research group	1	Assistant professor	University	Digitalisation for circular construction	10	Switzerland
	2	Associate professor	University	Asset management, circular procurement	32	Netherlands
	3	PhD Candidate	University	Circular building components	7	Netherlands
	4	Professor	University	Housing management, circular economy	26	Netherlands
	5	Senior researcher	Research institution	Design, construction and assessment in the built environment	18	Belgium
	6	Professor	University	BIM, digital design, circular construction	20	Austria
	7	PhD Candidate	University	Civil engineering	5	Switzerland
	8	Scientific assistant	University	Reality capture, scan-to-BIM	6	Switzerland
	9	Scientific assistant	University	Digitalisation for circular construction	4	Switzerland
Second round with social housing professionals	1	Project manager	Social housing	Project management new build, renovation, demolition	15	France
	2	Project manager	Social housing	Project management renovation	5	France
	3	EU Project manager	Social housing	Project management, civil engineering, city planning	10	France
	4	EU Project manager	Social housing	Project management	4	France
	5	Project manager sustainability	Social housing	New build, renovation projects	8	Belgium
	6	Program manager sustainability	Social housing	Circular renovation	20	Netherlands
	7	Director sustainability	Social housing	Internal advice on circularity	25	Netherlands

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TABLE 5.2 Overview of interviewees of three validation rounds.

Validation round	No	Role	Professional affiliation	Expertise	Years of experience	Country
Second round with social housing professionals	8	Real estate manager	Social housing	Maintenance, real estate management	20	Netherlands
	9	Design manager/ architect	Social housing	Sustainable housing projects	16	France
	10	Project manager	Social housing	New build, renovation projects	7	France
	11	Project manager	Social housing	Sustainability, circular housing projects	12	Belgium
	12	Project manager/ developer	Social housing	Circular demolition, new build, renovation projects	16	Netherlands
	13	Project manager	Social housing	Circular demolition, new build, biobased buildings	18	Netherlands
	14	Sustainability advisor	Social housing	Circular demolition, new build projects	22	Netherlands
	15	Project leader	Social housing	New build, renovation projects	10	Belgium
	16	Technical advisor	Social housing	Data management	12	Netherlands
	17	Technical policy advisor	Social housing	Data and sustainability	19	Netherlands
	18	Project manager real estate development	Social housing	Renovation, new build projects	8	Netherlands
	19	Senior project developer	Social housing	Renovation and maintenance projects	14	Netherlands

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TABLE 5.2 Overview of interviewees of three validation rounds.

Validation round	No	Role	Professional affiliation	Expertise	Years of experience	Country
Third round with the identified users	1	Project lead	Reuse company (harvester)	Data and innovation management	6	Netherlands
	2	Partner	MP Platform	Material reuse and data	33	Netherlands
	3	CEO	Reuse consultants	Circular renovation and dismantling	25	Austria
	4	Senior advisor	Circularity consultants	Circular new build and renovation projects	18	Netherlands
	5	Project manager	Reuse company (harvester)	Material and product reuse	13	Belgium
	6	Associate architect	Architecture firm	Circular design and data	30	Netherlands
	7	Senior advisor	Social housing	Real-estate portfolio data	15	Netherlands
	8	Architect	Architecture firm	Circular design projects	7	Netherlands
	9	Managing partner	Consultancy firm	Circular engineering	25	Austria
	10	Consultant	Consultancy firm	Circular buildings and MPs	29	Netherlands

A second iteration round was performed with the professionals who work in social housing organisations, such as project managers, architects, and internal advisors. In total, 19 online structured interviews were conducted in January 2023. Two selection criteria were defined: (1) the interviewee must work in a European social housing organisation, and (2) the interviewee must be engaged with circular housing projects, MPs, or real-estate data management. We used our networks to reach potential candidates and, once recruited, encouraged them to nominate further potential interviewees from their respective networks. For identifying the potential users, the diagram with the initial user mapping from the previous round was presented to the interviewees on an online interactive whiteboard application, and they were asked to place potential users according to data requesters/providers in line with their experiences with the circular projects. Housing professionals were further asked to evaluate each data point in terms of relevance to them on a three-point Likert scale: (1) not necessary, (2) nice-to-have, and (3) must-have. Structured interviews, in that sense, were useful for quantifying their answers while collecting their comments on certain data points.

Potential MP users were determined after the second validation round by analysing the outputs of the user diagrams (see Section 5.4.1). In the final round, ten interviews were conducted with the identified users, such as architects and consultants, in February 2023. The focus of the final round was finalising the data template and identifying the data gaps to compare with the case study results (Section 5.3.2). Therefore, next to data relevance, the interviewees were also asked to assess data points in terms of the availability of data from their perspectives on a three-point Likert scale: (1) no availability, (2) low availability, and (3) high availability. Similarly, we used our networks and an online professional networking platform to recruit professionals for the last round. The selection criteria were: (1) the interviewee must be one of the professionals identified as a user of the MPs, (2) the interviewee must have experience with housing projects, and (3) the interviewee must have experience with circular strategies. All interviews were held online and typically lasted between 40 to 60 minutes.

5.3.2 Part II – Data gap identification

The effectiveness of MPs is dependent on the quality and availability of the data used to create them. To gain insights into the complex issues surrounding data availability and accessibility for MPs in social housing organisations, a case study was conducted. A mid-size Dutch social housing organisation that owns around 15,000 homes was chosen as a case. Within the building portfolio, three random building examples were selected for analysis. The process involved the collection and analysis of data from internal company sources, public datasets, and additional data repositories. The repositories were sourced from a partner company which delivers digital services for data retrieval through artificial intelligence (AI)-based computer vision techniques. By leveraging computer vision, the data provider partner identifies and extracts detailed information on the materials and components used in buildings, including their dimensions, from street-level, satellite, and aerial imagery. The collected data was then fitted into the MP template to review the number of data points that were available. Through this process, coupled with the last round of interviews with the potential MP users, gaps and inconsistencies in the data template were identified, providing valuable insights into the challenges and opportunities for social housing organisations in the context of MPs.

5.4 Findings and discussion

5.4.1 Material Passport users

The analysis of the interviews showed that at least 15 different types of actors are involved in the use and end-of-use phases of social housing stock when executing circular maintenance, renovation, and demolition projects. The way in which these stakeholders engage with circular processes varies across organisations due to differences in organisational structure, collaboration with external companies, and the size of the building portfolio. For example, some organisations have in-house maintenance teams and sustainability consultants, while others work solely with external contractors and consultants. One interesting finding is that the majority of identified stakeholders take an interchangeable role in both providing and requiring data from the MPs in all project phases, depending on the decision-making along the project life cycle. Furthermore, some stakeholders play a crucial role in delivering data (e.g., architects), while others have little influence on the data flows (e.g., users). To pinpoint the difference in actor influence on data flows, FIG 5.4 divides identified users into two groups: data requesters/ data providers “slightly” and “significantly”. According to interviewees, in the present situation, tenants, municipalities, and the government have a minor role in data exchange as they are typically only informed about circular interventions. We summarise the identified users in the following sub-sections by grouping them as external and internal users in the context of social housing organisations.

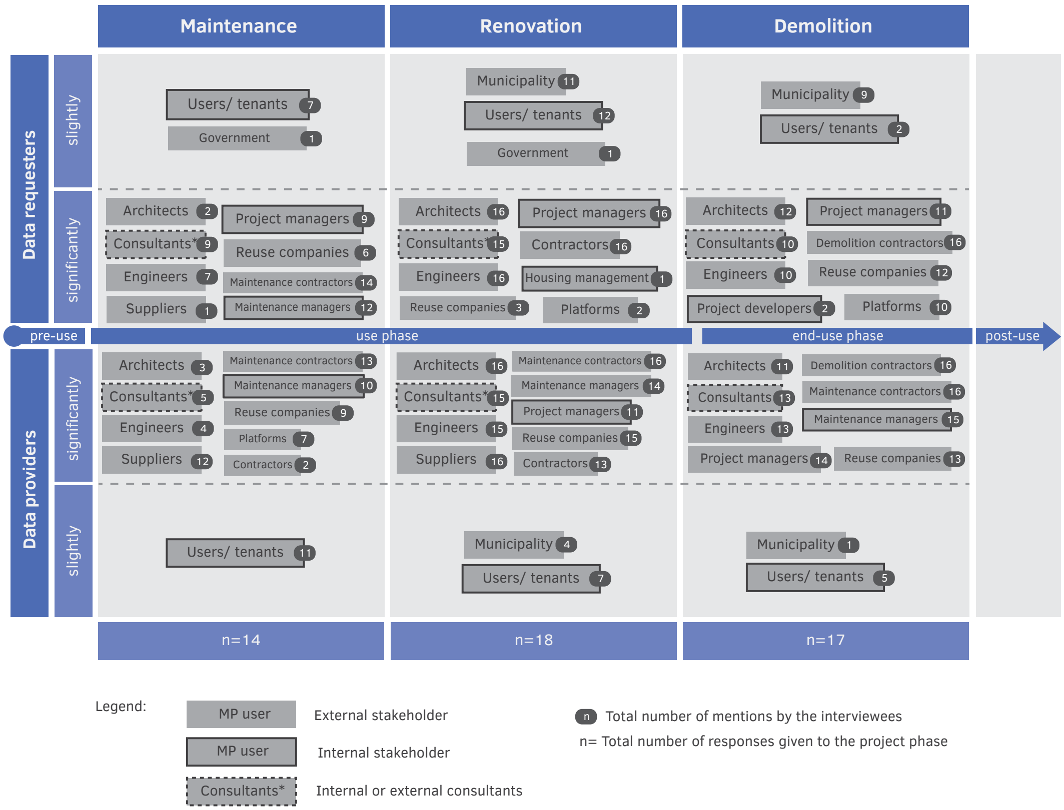


FIG. 5.4 Identified users of the MPs for existing housing stock mapped onto the user identification diagram.

External users

As presented in FIG 5.4, architects, engineers, and consultants are frequently mentioned as external stakeholders who influence the decision-making process in circular projects. In renovation projects, architects make decisions on circular interventions, reusable elements, and new material selection based on the present conditions of a building, thus requiring data from the MPs. They can also feed data to the MPs on renovation design (e.g., architectural drawings or 3D models) and new material selection. Material data from the newly added products are typically provided by the suppliers through architects or project managers. In demolition projects, according to our interviewees, architects have a dual role acting as consultants inspecting the buildings to be demolished (also called donor buildings), making an inventory of reusable elements, thus can provide data as well as require data on the elements to be reused in another new build or a renovation project. Consultants advise on the circularity level of a building and thus require data from the MPs to perform calculations. They mainly hold a high-level position in projects, providing recommendations based on the present situation of the existing stock or building. Compared to architects and engineers, their influence in data generation and provision is low because they are not decision-makers. Similar to architects, engineers are also active across project types. Engineers need life cycle data on an element to assess its physical properties properly (e.g., the age of a timber beam and whether it has been treated before). As some interviewees noted, engineers play an important role in providing data on the functional state of building equipment (e.g., boilers) and assessing the structural condition of donor buildings before demolition.

Social housing organisations work with a diverse set of contractors across circular projects. Maintenance is one of their core tasks and involves responsive (i.e., repair), preventive and predictive (i.e., planned regular maintenance) maintenance processes. Some organisations deliver these services through in-house maintenance teams, whilst others work with external maintenance contractors. Maintenance management software or data platforms support operations where maintenance contractors or managers keep a log of repair works, contracts, and invoices and plan and schedule routines. This system is believed to be fundamental in creating life cycle data for elements and products in buildings. However, in their current workflows, interviewees noted that their organisations lack the ability to integrate MPs into their maintenance systems; thus, this important link is missing.

During the renovation process, contractors deliver the construction works and require data on design and execution. They cooperate with project managers of housing organisations and provide data on the finished works and further coordinate data received from subcontractors and suppliers. In some cases, subcontractors who scan the existing building with laser-point scanners engage with the data collection process. Such scanning data is a valuable source for creating MPs at the building and element levels. Reuse companies that collect, clean, and sell secondary construction materials have an important role, especially if they also supply reclaimed products by using take-back contracts. They provide data on the incoming reclaimed products to the renovation interventions.

Demolition and reuse companies are key actors in the end-of-life phases of buildings. Demolition contractors inspect donor buildings and make inventories of reusable and recyclable parts. This valuable information can then be fed into the MPs and support architects in designing with reusable elements in other new build and renovation projects. Especially in the Netherlands, as interviewees noted, there is a shift in the business models of some demolition companies from being simply demolishers to harvesters. Therefore, it was challenging to distinguish demolition contractors from reuse companies during the data collection process. In addition, next to demolition and reuse companies, consultancy firms specialised in reuse also play a crucial role in identifying and listing reusable elements from the donor buildings. Finally, our interviews confirmed that only a few social housing organisations used MP platforms in pilot projects.

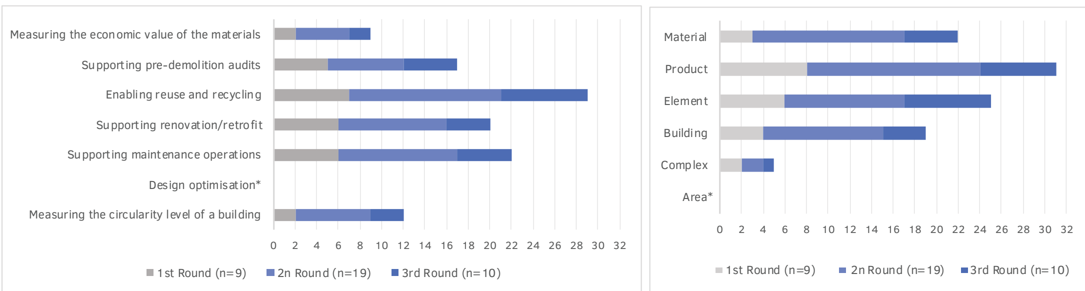
Internal users

Project managers and developers, maintenance managers, and consultants are the key internal actors in circular projects. Project managers are at the centre of data flow, coordinating projects and bridging their organisations with external actors. Thus, their role is dual regarding data delivery and request from the MPs. Similar to external consultants and maintenance contractors, in-house company consultants inform project stakeholders about circular intervention options, thereby also providing data, while maintenance managers are thought to be important in updating the life cycle data of products across the life cycle phases.

Overall, the potential users identified and their engagement with the MPs slightly differ from the previous research due to the focus of this study being the existing building stock. Other research, e.g., particularly the ones on the BIM-based MPs (e,g., Atta et al. (2021); Atta et al., (2021); Honic, Kovacic and Rechberger (2019)), use material data in decision-making for designers (i.e., architects, consultants, and engineers), while our findings indicate that these actors need data on the reclaimed material identification and selection in the use and end-use phase of buildings. Some researchers identify data managers or BIM managers as crucial actors in maintaining life cycle data in the MPs (Aguiar et al., 2019; Honic, Kovacic, Sibenik, et al., 2019). However, such actors were not mentioned by the interviewees. A possible explanation for this could be that the real estate and maintenance data in social housing organisations are not integrated into MP tools yet, although these actors exist in some organisations (e.g., we interviewed one data manager). Instead, maintenance managers or contractors seem to link this gap in creating and updating product information across the life cycle phases.

5.4.2 Data template

Data points that form an MP are directly related to its function and the scale at which it is created. As explained in Section 5.2.2, MPs can be used for various purposes at different aggregation scales. Of 38 interviewees across three interview rounds, 29 indicated that "enabling reuse and recycling" must be a crucial function of the MPs for the existing building stock (FIG 5.5 (a)). This finding aligns with the emergence of the MP concept, which was built on recovering materials from the existing stock to close the loops (BAMB, 2019; Hansen et al., 2013; Heisel & Rau-Oberhuber, 2020). Furthermore, other supportive objectives for narrowing and slowing the loops, such as maintenance (n=22) and renovation (n=20), were also thought to be an essential function of MPs. An interesting finding is that "design optimisation" was not considered a relevant feature by the respondents for the existing housing stock, as it was mainly considered at the design stage in the previous research (Atta et al., 2021; Honic, Kovacic, & Rechberger, 2019). MPs as a measurement tool of the economic value of products and the circularity level of buildings are thought to be less relevant.



(a) Functions of MPs for existing buildings

(b) Scales of MPs for existing buildings

FIG. 5.5 Functions (a) and scales (b) of MPs for existing housing stock according to respondents. Each bar color presents an interview round. n= number of interviewees. The total number of interviewees in all rounds is 38. *None of the interviewees chose "Design optimisation" as a main function and "Area" as a scale of MPs for existing buildings in the first and second rounds. Therefore, it was left out on the last round.

Regarding the scales considered, the majority of the interviewees (n=31) emphasised that the "product level" is the most appropriate scale to consider. However, as some interviewees mentioned, there is ambiguity between scales, and sometimes the "element" and "material" scales could be relevant depending on the situation. The "building" is usually considered an overarching scale consisting of nested MPs for elements, products, and materials. This tendency is also present in the MP approaches developed in the practice (Orms, 2023; Platform CB'23, 2020) and research (e.g., Kedir et al. (2021b)).

The data template developed in this study comprises 50 data points derived from existing MP approaches following three validation rounds through structured interviews. FIG 5.6 presents the data points grouped under six categories— the first one gives generic information at the building scale, and the other five, embedded under the building, give information at the product or element level. Based on the output from FIG 5.5 (b), an MP could be created at the material (e.g., glass), product level (e.g., window) or element (e.g., façade component) levels depending on the potential for re-use at those scales.

Data requirements

FIG 5.6 (a) and (b) illustrate the perspectives of housing professionals (n=19) and potential users (n=10), respectively, where the dark grey, light blue, and blue coloured bars present the total number of responses given on the data requirement degrees of "not necessary", "nice-to-have", and "must have", respectively. Some data points on the building level, such as "Building location" (A.0), "Building year" (A.1), and on the product level, such as "Product name" (B.11), "Location in building" (B.14), "Dimensions" (C.21), "Quantity" (C.24), "Composition of materials" (C.25), "Toxicity/hazardous substances" (D.28), and "Condition and quality assessment" (E.44) were classified as must-have data by the majority of interviewees (both second and third round interviewees). These data points are directly related and imperative to the assessment of a product's condition and suitability for reuse (Addis, 2006) and also were included in the many reviewed MP approaches (see Supplementary Materials). Therefore, our findings confirm the previous approaches that included these data points (e.g., BAMB (2019); Göswein et al. (2022); Munaro and Tavares (2021)).

Among the five product data categories (B to F), "C- Product Properties" and "F-Product End-of-Life Aspects" seem to be critical to meet users' data requirements, while many of the data points included under "E-Product Operational Aspects" are assigned to be "nice-to-have". There could be several reasons for this trend. First, categories C and F support reuse and recycle strategies, thus, closing the material loops, while category E is, to a large extent, related to expanding the life cycle of products, so slowing the material loops. MPs, therefore, are seen as tools for circularity at the end-of-life by the practitioners rather than a whole life cycle data solution as proposed by researchers (Aguiar et al., 2019; Göswein et al., 2022; Munaro & Tavares, 2021). Another reason could be that maintenance activities, although maintenance itself is a circular strategy, are not yet fully operationalised through circular material flows by social housing organisations. Therefore, the link between the use and end-of-use phases of products is not explicitly made in terms of data management. The empirical findings of Çetin et al. (2022) support this, as their multiple-case study with three social housing organisations also showed that practitioners tend to see MPs as an end-of-life tool due to the difficulties in managing life cycle data for a long time. However, though, as some interviewees mentioned, the maintenance log of a product could be a fruitful source of data when deciding on end-of-life treatment options.

There are modest differences between the data requirements of housing professionals (FIG 5.6 (a)) and identified potential users (FIG 5.6 (b)). Three data points, namely, “Building energy label” (A.06), “Drawings and BIM model” (B.18), and “Cleaning instructions” (F.35), seem to be insignificant for the potential external users while many interviewed housing professionals perceive them as nice-to-have. A possible explanation for this could be that the majority of the third-round interviewees (nine out of ten) have expertise in reuse practices (e.g., harvesting, design, and consultancy), and these three data points do not directly impact their decisions in reusing products. For example, one interviewee from a reuse company noted that they need to inspect the donor building for the identification of reclaimable products, whether they have drawings and maintenance or cleaning instructions or not. Building products are subject to changes throughout their lifetime, and condition assessment needs to be performed on the location even though the building is fully documented.

Compared to extant studies that are listed in Supplementary Materials, which delineate a dispersed range of data requirements, this study concentrated on the existing housing stock and developed a data template in a systematic way by building on previous MP approaches and validation interviews with practitioners. Thus, in a way, the data points presented in FIG 5.6 are the first empirical attempt to illustrate the data requirements and their necessity from the practitioners’ perspective. Our findings reveal that the MPs for existing buildings should prioritise data points that explicitly support the reuse and recycling interventions (i.e., Data categories C and F) during maintenance, renovation, and demolition operations. Data categories that are not critical for closing the loops but beneficial for slowing the loops (i.e., Data category E) are also related to the end-of-recovery of building products and must be kept in MPs where possible. Another important aspect of creating MPs is the availability of data, whether these data points are readily available or need an afford to obtain, is explained in the following section.

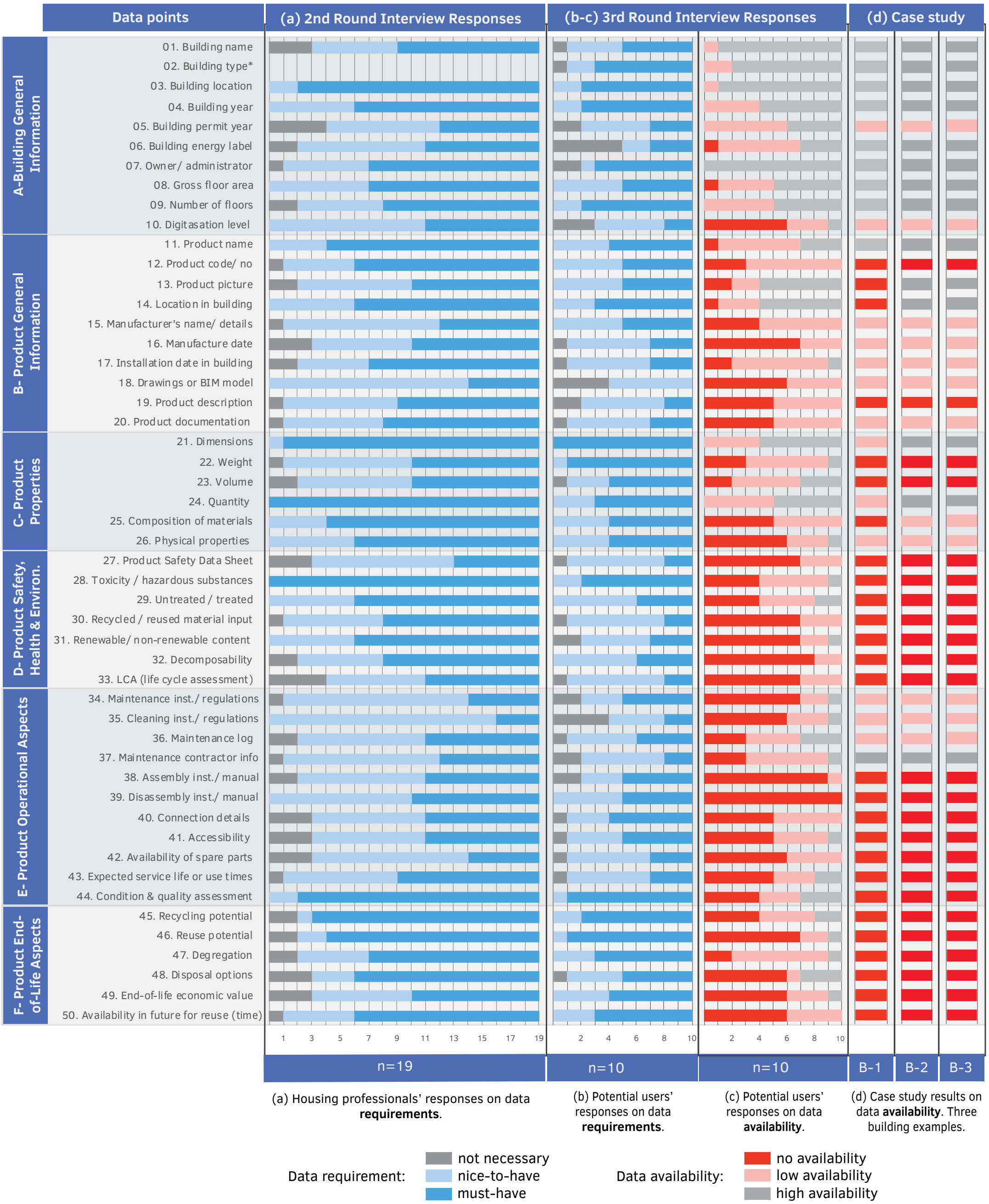


FIG. 5.6 Interviewee responses in the second and third interview rounds and case analysis were mapped as bar charts onto the data template. *Building type is added to the template as a data point on the third round upon interviewee suggestions.

Data availability

Our findings provide crucial insights into the availability and accessibility of data required to create MPs in social housing organisations. FIG 5.6 (c) presents the responses of ten interviewees (i.e., potential users) on the data availability based on their experience with circular projects, and FIG 5.6 (d) illustrates the analysis of three sample buildings from the case study. In Building 1 (B-1), data were obtained for the roof at the element scale, and in Building 2 (B-2) and Building 3 (B-3), data were retrieved for the gutters at the product level (see Supplementary Materials for details).

In general, most general building information, such as “Building name (A.01)”, “Building type (A.02)”, “Building location (A.03)”, “Building year (A.04)”, “Gross floor area (A.08)”, and “Number of floors (A.09)” can be easily accessed through internal databases and shared with the project stakeholders, so these data are typically highly available. However, “Building permit year (A.05)” and “Digitalisation level (A.11)” are generally not available in the main system but may be present in ancillary system databases.

Regarding products and elements within the building, the analysis of exemplar buildings showed that there is limited information available on their composition, installation dates, and manufacturing details. There is often only high-level information on the existence of roofs and facades, but element pictures or codes are usually non-existent. While the dimensions and quantity of certain elements, such as that of windows, could be retrieved if the BIM model of the building is accessible, other physical properties of the element or product, including their weight, volume, and composition, are generally unavailable. These data can also be generated through site inspections by external stakeholders (e.g., reuse companies and architects) or maintenance contractors.

In exemplar buildings B-2 and B-3 (FIG 5.6 (d)), additional data points were available through the case organisation’s maintenance data provider partner. The additional data retrieved include street view, aerial, and satellite imagery of the building assets. Through the use of computer vision algorithms, various elements and features on building roofs and facades were identified, such as windows, doors, shutters, rain pipes, and masonry finishes. The algorithms also allowed for the dimensions and area of these elements to be determined. While the data provider typically utilises their algorithms for condition assessments of buildings, no information on this aspect was available for the selected buildings. Although promising, these data points still do not include element codes for identification and long-term documentation.

Furthermore, data points under Category D, related to product safety, toxicity, decomposability, and life cycle assessment, are not readily available in the social housing organisation's databases, as these were not considered necessary data points in previous projects and are challenging to obtain for existing buildings. Nevertheless, a sustainability metric is typically provided by the maintenance inspectors, which gives a sustainability label to the building. In addition, the risk of asbestos presence in existing buildings is a critical issue in renovation and demolition projects, and an inventory needs to be made by inspectors. As some interviewees noted, sometimes it is possible to estimate the asbestos risk based on the building type and year. Operational aspects (Category E), such as maintenance instructions, logs, and contractor information, may be retrieved from internal maintenance software or secondary external repositories but are not saved in the main central database.

Additionally, assembly and disassembly instructions, as well as the availability of spare parts or condition assessment, are not typically documented. Data points considered in the category "F- Product End-of-Life Aspects", including the reuse and recycling potential, economic value, and availability for reclamation, have also not been a priority for documentation, and hence, no data exists on these aspects. These data points are time-dependent, meaning that they could be produced at the demolition stage if a reuse company, consultant, or architect inspects the building and assesses the condition of recyclable and reusable products. Data point F.50 on the future availability of products could ideally be estimated by using the social housing organisation's demolition planning documentation. However, in the case study's digital systems, this is not considered.

5.4.3 A Material Passport framework to address the data gaps

Overall, the study identified several data gaps and inconsistencies that hinder the collection and access of the required data for creating MPs. The lack of available data points highlights the need for an integrated data management system that can maintain life cycle data in a standardised manner. As shown in FIG 5.7, we propose a framework to address data gaps by combining the capabilities of digital technologies alongside the support of stakeholders. The capabilities of digital technologies, namely, *data collection* (generation and collection of data), *data integration* (organising, storing, sharing and maintaining data) and *data analysis* (interpreting data and obtaining actionable decisions), were drawn from the previous studies (Çetin et al., 2022; Kristoffersen et al., 2020; Siow et al., 2018). For each data category, the framework suggests improvements in technology integration with enabling digital technologies (Çetin, De Wolf, et al., 2021; Yu et al., 2022). The critical data gaps are based on the results presented in FIG 5.6 and are highlighted in red for each data category in FIG 5.7. These data gaps are thought to be "must-haves" in an MP by more than half of the interviewees, and correspondingly their availability is found to be at the scales of either "low" or "no" (FIG 5.6).

Data category	Digital technologies and human actors			Life cycle phase
	Data collection	Data integration	Data analysis	
A-Building General Information	Automated data retrieval from public records Employees of SHOs	Data harmonisation in the central data system, BIM, data lake or alternatively in an MP Platform Employees of SHOs and external stakeholderss	Big data analytics; machine learning	All life cycle phases *(ideally data should be collected in the design stage)*
B- Product General Information [Critical data gaps: B.12, B.14, B.17]	Automated data retrieval from third-party websites Project managers or maintenance managers of SHOs	Data harmonisation in the central data system, BIM, data lake or alternatively in an MP Platform Employees of SHOs and external stakeholderss	Web scraping; machine learning	All life cycle phases *(ideally data should be collected in the design stage)*
C- Product Properties [Critical data gaps: C.22, C.23, C.25, C.26]	Sensing and scanning technologies (e.g., Lidar systems) Site inspectors (e.g., pre-demolition auditors)	Data harmonisation in the central data system, BIM, data lake or alternatively in an MP Platform	Computer vision; machine learning Site inspectors and reuse experts (e.g., consultants)	Use and end-of-use phases *(ideally data should be collected in the design stage)*
D- Product Safety, Health & Env. Aspects [Critical data gaps: D.28, D.29, D.31, D.32]	Drones to capture building images; data retrieval from waste repositories, building registers, satellite images, etc. Safety inspectors and experts	Data harmonisation in the central data system, BIM, data lake or alternatively in an MP Platform	Computer vision; machine learning Safety inspectors and experts	Use and end-of-use phases *(ideally data should be collected in the design stage)*
E- Product Operational Aspects [Critical data gaps: E.44]	Drones to capture building images; data retrieval from satellite images, etc. Maintenance managers or contractors, inspectors or experts	Data harmonisation in the central data system, maintenance system, BIM, data lake or alternatively in an MP Platform Maintenance managers or contractors (to update data)	Computer vision; machine learning; augmented reality, virtual reality Inspectors or experts	Use phase *(ideally data should be collected in the design stage)*
F- Product End-of-Life Aspects [Critical data gaps: F.45, F.46, F.47, F.48, F.49, F.50]	Scanning technologies, drones to capture building images; data retrieval from satellite images, etc. Reuse companies, consultants or architects	Data harmonisation in the central data system, maintenance system, BIM, data lake or alternatively in an MP Platform	MP; computer vision; machine learning; simulations Reuse companies, consultants or architects	End-of-use phase *(data can be obtained during design and use stages)*

Digital technologies
Stakeholders (potential users of MPs)

FIG. 5.7 Proposed MP framework to address identified data gaps.

Overall, data in "A-Building General Information" are highly available and are not critical. A possible improvement for data collection can be made with automated data retrieval from public records, if available online. For example, in the Netherlands, several government agencies and public institutions make their data openly accessible online through open data portals, APIs, and other sources. The Basisregistratie Adressen en Gebouwen is the Dutch national database for addresses and buildings, containing information on all buildings in the Netherlands (BAG, 2023). Big data analytics can then be used to analyse and make sense of the vast amount of data contained in public databases by identifying patterns and trends in the data that may be difficult to discern manually. General data at the building and product level can be harmonised in the central data system (in some cases in the BIM model of the portfolio or data lake (Çetin et al., 2022)) of housing organisations according to the data template presented in FIG 5.6 from an early design stage. If general product data are not available in the main data systems, then the manufacturer's website or third-party websites can be used to retrieve data via web scraping and machine learning (ML) techniques. Web scraping is an efficient technique to gather large amounts of data on buildings that are available online in various informal forms. For example, Yang et al. (2020) created a web crawling algorithm to access building material properties information for energy analysis. ML algorithms can then be trained on the retrieved data to predict future performance (Egwim et al., 2022). These predictions can be added to an MP as new data points, enabling building managers to make more informed decisions about building maintenance and renovation.

The critical data gaps identified in "C-Product Properties", especially "Weight (C.22)" and "Volume (C.24)" of a product, can be calculated or estimated based on dimensions and other physical properties. "Dimensions (C.21)" and "Quantity (C.24)" are typically determined by the inspectors (e.g., reuse companies) before the selective demolition process and can be registered on an external MP platform (see, e.g., the case analyses of Çetin et al. (2022)). In addition, various digital technologies and methods can help with further data acquisition from existing buildings. For example, Gordon et al. (2023) demonstrated a data-capturing technique in a real-world case where authors applied photogrammetry, Scan-to-BIM, and computer vision methods to identify reusable structural steel elements from a demolition site. By using accessible technologies, such as mobile devices as well as Lidar systems, it was possible to collect data to construct a BIM model, which was then used to detect structural elements through computer vision techniques (Gordon et al., 2023). Another interesting image-based material recognition technique tested by researchers is based on laser scanning and ground-penetrating radar technology to identify the geometry and material composition of the building elements (Kovacic & Honic, 2021). Such innovations are promising for completing missing data points during the use or end-of-use phases of buildings.

Identifying toxic and hazardous contents in the building products is of utmost importance in the maintenance, renovation and demolition of the existing building stock. Our findings indicate that there is a critical data gap in this field (FIG 5.7). AI applications can offer solutions. For example, as Wu et al. (2022) showed, ML can be used to anticipate the presence of hazardous materials (i.e., asbestos and polychlorinated biphenyls) in the building stock based on hazardous waste repositories and building register records. The authors used several building-related parameters such as building year, floor area and the number of apartments to train the ML algorithms. Considering the availability and accessibility of general building data, the building stock of social housing organisations can be analysed with such methods to identify hazardous contents. Another AI application, computer vision, can also be used to detect deficiencies and hazardous contents on the building façade by using images created with drones, satellite images or publicly available street views (Çetin et al., 2022). This technology, as discussed in the case analysis, can be used to identify various elements and features on building roofs and facades. Such methods for automated retrieval of material information are becoming increasingly popular due to advancements in both software and hardware sensors. For instance, Raghu et al. (2022b) built a model to detect external façade materials such as brick, stone, wood and stucco, while Kim et al. (2021) explored the generation of algorithms to identify concrete and metal roofs. The algorithms can also be leveraged for condition assessment of buildings, providing insights into the current state of the building and identifying potential maintenance issues, thus, supporting maintenance operations. This is observed in the use of infrared thermal imaging in combination with computer vision to detect facade anomalies (Resende et al., 2022) and in the use of automated inspection systems to detect visually discernible defects in buildings (Munawar et al., 2021).

Furthermore, augmented reality and virtual reality technologies can be used to visualise and simulate buildings' design and maintenance processes. Augmented reality can be used to overlay digital information on the physical building, allowing for more efficient and accurate maintenance and repair. For instance, Wibranek and Tessmann (2023) developed a mobile app with information about reusable building components from nine different MPs. Virtual reality can be used to simulate buildings' performance and energy consumption and predict a building's future maintenance needs (Niu et al., 2016). Additionally, virtual reality can help create a visual representation of materials and parts that can be reutilised in construction projects (O'Grady et al., 2021). A similar application can be carried out to depict MP information across the building life cycle.

Finally, the most critical data gaps were identified in the "F-Product End-of-Life Scenarios" category. Determining the reuse and recycling potential and degradation of a product is typically done by experts (e.g., reuse contractors or consultants) based on condition assessment. Therefore, as mentioned above, computer vision technology can help experts is assessing the quality and quantity of products. In addition, as demonstrated by Honic et al. (2021), an MP approach can alternatively be deployed based on laser scanning and traditional data acquisition methods (i.e., demolition acquisition and urban mining assessment) to evaluate the recycling potential of materials embedded in existing buildings. Some commercial MP platforms, such as Madaster (Madaster, n.d.), provide the economic residual value of materials in buildings. In terms of finding out the availability of a product for reuse in the future various simulation techniques can be deployed based on the demolition planning of social housing organisations.

5.4.4 The emerging role of AI for Material Passports

The use of AI in the building industry can bring about significant advancements, one of which is the implementation of MPs. By leveraging ML and computer vision algorithms, AI can identify and categorise materials, track their origin, assess their environmental impact, and predict their future performance. Following the MP framework introduced in Section 5.4.3, the emerging role of AI can be summarised as follows:

- Data Collection: AI can automate the collection of material-related data from various sources, such as product databases, material suppliers, manufacturers, and construction documents (Bodenbender et al., 2019), as well as crawl and extract relevant data from websites, documents, and other digital sources, minimising the manual effort required (Kovačević & Davidson, 2008).
- Data Integration: AI can help organise material data into structured databases or digital MPs. Automated tagging and categorisation of materials can create a searchable and easily navigable repository of information (Kovačević & Davidson, 2008; Radinger et al., 2013).
- Data Analysis: AI algorithms excel in analysing large and complex datasets. They can process the collected data to identify and categorise materials, including their properties, certifications, and compliance with sustainability standards. ML techniques can be employed to recognise patterns and correlations within the data, enabling insights into material performance, life cycle assessments, and potential environmental impacts (Barros & Ruschel, 2021). Computer vision can be used to analyse images of materials and help identify their types and existing conditions (Munawar et al., 2021).

Thus, the use of AI for MPs can enable architects, designers, and construction professionals to make informed decisions regarding material reuse, recycling, and disposal, leading to reduced waste, and improved resource efficiency.

5.5 Conclusion

This study set out to explore data requirements and availabilities to create MPs for existing buildings in the European social housing context. There are many MP approaches to support circular strategies in the building industry. However, they vary in terminology, content, scale, technology use, and maturity level and largely overlook users' data needs. This paper thus addressed this research gap by deploying an empirical study based on a multi-step data collection method, including a literature and practice review, three rounds of interviews with a total of 38 respondents, and a case study. A data template consisting of 50 data points is developed and tested in a case study.

By confronting data requirements with data availability, this study identified several critical data gaps, including, but not restricted to, the composition of materials, existence of toxic or hazardous contents, condition assessment, and reuse and recycling potential of a product. Considering the identified critical data gaps, an MP framework is proposed that draws on data collection, integration, and analysis capabilities of digital technologies alongside the knowledge support of key stakeholders. This framework sketches an overview of enabling digital technologies such as AI and scanning technologies to address the data gaps in creating MPs to apply narrow, slow, close, and regenerate principles. As such, the framework can be used to give direction to further research and innovation in data provision for enabling the adoption of circular strategies in (social housing) construction, renovation, and maintenance practice.

5.5.1 Limitations and recommendations

The scope of the present work was limited to existing buildings within the context of European social housing organisations and stakeholders involved in circular housing projects. Further research could examine other countries, building typologies (e.g., commercial or public real estate), and life cycle stages (e.g., design stage) to determine the data needs of stakeholders involved in the respective value chains. Since the number of interviewees in the last validation round was limited (n=10), we could not collect data from all identified MP users. A further detailed survey is recommended with a large sample of stakeholders involved in MPs and circular construction projects. Although the developed data template is based on a robust research methodology (i.e., multi-step data collection consisting of literature and practice review and validation interviews), identified data requirements will likely differ among stakeholders based on the purpose of use. Further research could investigate the link between the functionalities of MPs and the data points required to create MPs. This will help to develop tailored MPs for certain functions and/or stakeholder groups.

Although this research took a supply chain perspective to identify the data requirements of actors, data exchange and data confidentiality issues between actors were out of scope. Thus, further research could examine how data can securely be stored, tracked, and shared with relevant stakeholders such that the data is available across project stages (design, construction, operation, maintenance, and end-of-life) and beyond (the second life of a product). Furthermore, blockchain technology's potential in handling MP data across life cycles could be studied by considering confidential data and trust issues.

The effectiveness of AI algorithms in extracting relevant information depends on the quality and consistency of the data inputs. Therefore, efforts should be made to ensure the availability of comprehensive and up-to-date data to maximise the potential of AI in material data collection and analysis. Another challenge lies in the standardisation of data formats, terminologies, and classifications across different sources and stakeholders. Further research and collaboration are needed to develop common standards and protocols for data integration, enabling seamless exchange and interoperability of material data among various systems and platforms. Furthermore, while AI algorithms can make predictions and provide insights into material performance, their accuracy can also rely on the robustness of the algorithms themselves. Thus, it is crucial to validate and refine AI models continuously. Future research should focus on developing methodologies for validating AI-generated insights and integrating user feedback to improve the accuracy and usefulness of the generated MPs.

For professionals working at social housing organisations as well as other professional real estate owners and their supply chain partners, it is recommended that they attune their periodical data collection for maintenance purposes (in particular condition assessments) to data requirements for enabling circular practices. Thus, they can use 'natural' moments for data collection to create MPs and thereby facilitate the adoption of circular strategies in their maintenance, renovation, and end-of-life practices.

Author contributions

Sultan Çetin: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Visualization, Project administration Deepika Raghu: Methodology, Validation, Investigation, Data Curation, Writing - Review & Editing Meliha Honic: Methodology, Investigation, Data Curation, Writing - Review & Editing Ad Straub: Conceptualization, Writing - Review & Editing, Supervision Vincent Gruis: Conceptualization, Writing - Review & Editing, Supervision, Funding acquisition.

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

Sultan Çetin, Vincent Gruis and Ad Straub received funding from INTERREG NWE project CHARM (Circular Housing Asset Renovation & Management—No More Downcycling), project number NWE 760. Meliha Honic is funded through ETH Zurich Postdoctoral Fellowship (21-2 FEL-06). The authors would like to thank Tim van de Kerkhof and Kevin van der Vliet for providing data on the case study, all interviewees for their valuable input and reviewers for their constructive comments.

Appendix A

TABLE 5.A.1. Interview guideline for validation rounds.

No	Interview questions	Validation round
1	What should be the main function of a material passport for existing buildings? a) Measuring the circularity level of a building b) Design optimisation c) Supporting maintenance d) Supporting retrofit/renovation e) Enabling reuse and recycling (i.e., dismantling) f) Supporting the creation of pre-demolition audits (material inventories) g) Measuring the economic value of the materials Other:	1, 2, 3
2	Material passports can be created at varying degrees of detail. Which scale should be the material passports for existing buildings developed for? a) Area b) Complex or building portfolio (collection of buildings) c) Building d) Element (e.g., façade glazing) e) Product (e.g., window) f) Material (e.g., glass) g) Raw material (e.g., sand)	1, 2, 3
3	Please indicate on the (online) stakeholder diagram who needs and feeds data onto material passports.	1, 2
4	Please indicate which of the data points on the data template are “must-have”, “good-to-have”, and “no-needed” for creating material passports for existing buildings in your opinion. *(Interviewees are provided with 50 points data template to answer this question).*	2, 3
5	Please indicate which of the data points on the data template are “highly available”, “low availability”, and “no availability” for creating material passports for existing buildings from your professional experience. (Interviewees are provided with 50 points data template to answer this question).	3
6	Is there any crucial data point missing in the data template? If so, could you please add it.	1, 2, 3

6 Conclusions

This thesis has explored how social housing organisations (SHOs) could transition towards circular housing practices with the support of digital technologies. Being one of the prominent actors in the largest energy- and resource-consumer and waste-creator industry, European SHOs (particularly Dutch ones) were chosen as the focus of this research. SHOs own and professionally manage a large portfolio of buildings. Due to their strong market position, they influence how housing projects are delivered sustainably. Since this PhD project started, there have been considerable developments in implementing circular strategies in social housing projects in Europe, and many pilot projects have been realised, testing not only circular building techniques but also emerging digital tools and instruments such as reversible BIM and material passports. Drawing on findings from the state-of-the-art literature and practice reviews and empirical studies published in four papers, this thesis provides insights into the complementary role of digital technologies in *collecting, integrating, and analysing data* to apply the core Circular Economy (CE) principles of *narrow, slow, close, and regenerate* in circular social housing projects.

6.1 Revisiting key research questions

This research is structured around four key research questions. After revisiting and answering the key research questions, overall conclusions will be drawn in Section 6.2, reflecting on overall research aim.

RQ 1: What are the current state, barriers, and enablers of Circular Economy implementation in Dutch social housing organisations? (Chapter 2)

We conducted a Delphi study with 21 social housing experts from 19 early adopter Dutch SHOs to answer the first key research question. At the time of data collection in 2020, Dutch SHOs were at an experimental phase of CE implementation, generating actionable knowledge through testing new circular construction techniques in new build, renovation, and demolition projects. Compared to business-as-usual practices, SHOs applied more frequently *narrow* strategies, e.g., substituting materials with reclaimed materials and *regenerate* strategies, e.g., using biobased materials in new build and renovation projects. Maintenance (i.e., regular repairs and planned maintenance), as a *slow* strategy, was already present as keeping the housing portfolio in good quality is one of the core responsibilities of SHOs. However, very few SHOs applied circular approaches in maintenance projects[8]. Recycling was the predominant *close* strategy applied in demolition projects, although SHOs sought to find feasible value-capturing methods through urban mining techniques. Finally, our findings showed that many SHOs have started including CE as a long-term environmental sustainability policy (not binding) in company reports, websites, and presentations.

The Delphi study identified the five most pressing barriers that hinder the application of CE principles in housing projects and potential enablers to address these issues, as presented in TABLE 6.1. Findings showed that the top two barriers stem from organisational issues around "putting priority to other sustainability targets", i.e., energy transition of the housing stock and "operating in a linear system". The goals set by the EU and the Dutch government have played an essential role in the energy transition, and a similar approach for CE is believed to be necessary for the uptake of CE in social housing. Since CE is a new topic for SHOs, "lack of awareness, knowledge and experience" is a tremendous barrier which could be addressed by more collaborative actions such as sharing knowledge among SHOs created through best practice case studies. The fourth and fifth barriers listed are associated with financial aspects. Whether new or reclaimed, circular materials have higher costs than that traditional construction materials due to, for example, higher labour costs of reclamation activities. A potential solution proposed by the participants was introducing a CO_2 tax on circular construction materials. Finally, "unclear business case" was mentioned frequently as an important barrier. To innovate new circular business models, experimentation is necessary in pilot projects. For example, some of the SHOs experimented with service business models and demonstrated them in best-practice case studies.

Barriers related to data or digitalisation, which are the main subjects of this thesis, are also listed within the top ten most pressing barriers. "Lack of standardisation in circularity" hinders the application of material passports as it causes confusion about data requirements to create material passports. Furthermore, due to the "lack of an information exchange system", SHOs struggle to circulate material data among supply chain actors when introducing new circular business models and applying circular building strategies.

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8 It must be noted that in "maintenance" operations, there are a considerable amount of material inflows and outflows. Although maintenance is a circular strategy in itself, more circular approaches can be put in use to reduce primary resource consumption and construction waste in carrying out maintenance as well.

TABLE 6.1 The most pressing barriers to apply CE principles in social housing projects and (selected) potential enablers to address them.

Rank	Barriers	Potential enablers (selected examples)
1	Higher priority in other issues (Organisational)	Binding CE legislation
2	Operating in a linear system (Organisational)	Better collaboration with other sector parties
3	Lack of awareness, knowledge, and experience with the CE (Social & cultural)	Best practice case studies
4	High purchasing costs of circular materials (Financial)	Introducing CO_2 tax on circular construction materials
5	Unclear business case (Financial)	Experimentation for clear business case

RQ 2: What digital technologies can potentially enable a CE in the built environment, and in what ways? (Chapter 3)

The second research question has been addressed by developing a framework for the (potential) application of digital technologies to support CE strategies in the bult environment. The interplay between digitalisation and CE has taken a great interest and has been discussed by many disciples. However, academic discourse lacks perspectives from the built environment. The framework developed in this research, *Circular Digital Built Environment Framework (CDB Framework)*, can be considered the first comprehensive academic work identifying enabling digital technologies that support built environment actors in applying circular strategies across the life cycle stages. The research design consisted of multiple iterative steps for data collection and mapping through literature and practice review and three online expert workshops.

The resulting framework presents ten enabling technologies, including (1) additive and robotic manufacturing, (2) artificial intelligence (AI), (3) big data and analytics, (4) blockchain technology, (5) building information modelling (BIM), (6) digital platforms and marketplaces, (7) digital twins, (8) geographical information system (GIS), (9) material passports and databanks, and (10) the Internet of Things (IoT). The *CDB Framework* links these ten digital technologies with circular building strategies grouped under core CE principles of *narrow, slow, close, and regenerate* and maps them across the whole life cycle stages, as summarised in FIG 6.1. This framework contributes to the emerging research field at the intersection between CE, digitalisation, and the built environment and expands the current academic discourse by providing a thorough overview of enabling functions of digital innovations.

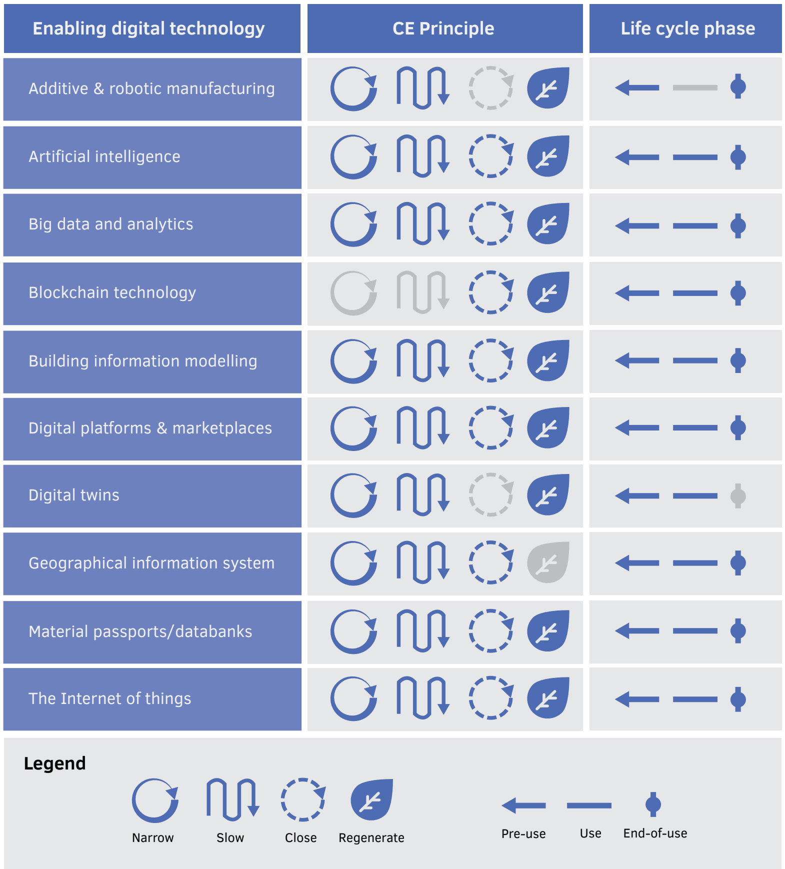

FIG. 6.1 Summary of enabling digital technologies that were mapped onto the CDB Framework.

The enabling digital technologies identified in this study address several CE principles simultaneously and can be applied in various fields and life cycle stages. We can briefly outline their outstanding supporting features for CE as follows (See Chapter 3 for details):

- Additive and robotic manufacturing technologies offer solutions to use bio-based materials (e.g., mycelium) and recycled materials (e.g., PET) in manufacturing building products and minimise transportation distance, thus reducing fuel and energy consumption.

- AI is a powerful technology that impacts every aspect of our lives. For circularity, the subsets of AI, machine learning is used for design optimisation to support architects in low-carbon building design with regenerative design principles and computer vision is used for identifying defects as well as reusable elements on the building façade so the lifetime of building components can be extended.

- Big data and analytics allows for interpreting a large amount of data obtained from buildings or systems and is used to improve maintenance operations by giving insights into sustainability-oriented decision-making. It is especially crucial in detecting and preventing failures in building systems in advance.

- Although generally known as the technology behind cryptocurrencies, blockchain technology is believed to be disruptive in dealing with complex information networks in circular supply chain management. It is used to transfer material data stored in a material passport along the supply chain actors in a transparent and reliable way. Blockchain technology is also used for peer-to-peer trading of renewable energy produced on building rooftops.

- BIM, as being the dominant digital technology of the building industry, has many enabling functionalities for circularity. One prominent use of BIM is early design optimisation to predict the reusability or recyclability of building design alternatives at the end of life. BIM stores a considerable amount of useful material data and is frequently considered the main data source for creating material passports.

- There are various types of digital platforms in the building industry, such as sharing platforms and digital marketplaces. Sharing platforms give temporary access to a product or space without transferring ownership, thus minimising the need for manufacturing new products or constructing new buildings. On the other hand, digital marketplaces are crucial to creating a market ecosystem for reclaimed building materials and products to reduce the dependency on primary resources.

- Digital twins are increasingly used during the operational stage to manage smart buildings. This technology is useful to improve building operations, thus decreasing energy consumption and allowing flexible use of space.

- GIS is typically used at an urban scale to identify, map, and manage resources embedded in the building stock. It allows material stock analysis in cities and facilitates urban mining at a regional scale.

- Material passports are fundamental tools to recover the value from the products or materials that reach their end-of-life to *close* the resource loops. They are designed to store detailed information, usually along the life cycle stages, about the products so the industry actors can make informed decisions when applying circular building strategies.

- IoT applications are used in smart buildings to regulate energy and water systems to reduce resource consumption. In the meantime, sensor systems allow tracking and monitoring of building components as well as enable service business models such as lighting-as-a-service.

RQ 3: How are digital technologies deployed in the circular projects of forerunner Dutch social housing organisations, and what challenges emerge in their broader adoption? (Chapter 4)

As depicted in Chapter 3, digital technologies present numerous promising functionalities for implementing circular building strategies. However, existing literature predominantly remains conceptual and lacks perspectives from industry actors regarding their application in real-life contexts. In Chapter 4, we aimed to address this crucial research gap and expand the current body of knowledge through the lens of SHOs to provide practice-based evidence.

We conducted a multiple-case study to collect empirical data from three large Dutch SHOs that have been actively applying circular building strategies in housing projects as well as including CE principles in their portfolio policy. We analysed these three cases by using the *CDB Framework* and *analytical capabilities* of digital technologies (i.e., data collection, data integration, and data analysis) across the project stages, as outlined in FIG 6.2. We further identified challenges associated with the adoption of these technologies that emerge from the interview data.

The subsets of AI, namely, computer vision and machine learning, are used in two different ways for data collection and analysis. First, an AI application is used to create up-to-date skin models of the housing stock by using satellite and drone images for maintenance purposes. The system can recognise building components and spot defects and hazardous contents, thus helping *slow* and *regenerate* the loops. Second, with the machine learning techniques, one of the cases generate a digital twin of the housing stock. The BIM model is enriched with machine learning through modelling interior spaces from 2D architectural drawings. BIM is mainly used by architects and engineers for design communication during new build and renovation projects. However, its broader adoption during the operational stage is very limited as SHOs find it challenging and costly to store and update BIM models.

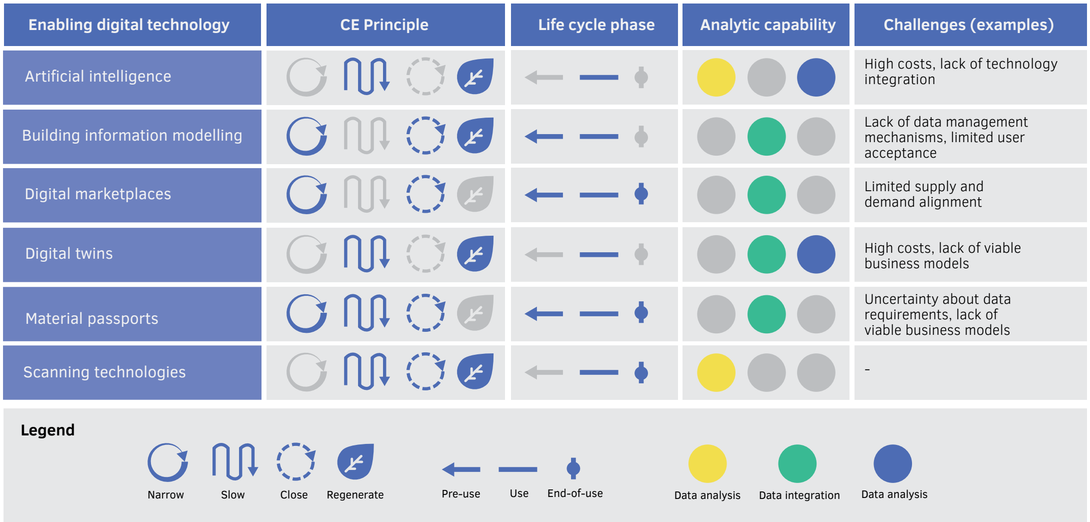

FIG. 6.2 Summary of multiple-case study findings.

Digital marketplaces, typically operated by a third party, such as a demolition contractor, are frequently used in all project stages to find or sell secondary products and materials. These platforms allow SHOs to reduce primary material use in new build, renovation, and maintenance projects and avoid waste and downcycling in demolition projects. A pressing challenge appears to be the lack of supply and demand alignment, as it is usually hard to find a sufficient volume of the same reclaimed products. SHOs acknowledge the importance of material passports for circularity. However, their use is limited to pilot projects, and they are not implemented in business-as-usual operations. The reason is that creating and maintaining material passports is very resource intensive (i.e., time, money, and human resources), and there is a lack of data standardisation and management mechanism and uncertainty about users' data requirements. In general, the lack of standardisation in both circular construction and data management is a considerable challenge, as we also found in the first study, that urgently needs solutions.

RQ 4: What are the data requirements of users from material passports for the existing housing stock? Are these data available? If not, how can digital technologies support fulfilling the data gaps? (Chapter 5)

Material passports have gained a prominent position amongst the policy instruments to achieve the CE goals of the EU in several industries and have been recognised as essential tools for recovering value from building products and materials that reach their end-of-life and for managing life cycle data to support a number of *narrow, slow, close*, and *regenerate* strategies. There are many passport approaches in the building industry, varying in terms of data structure, technology use, maturity level and the intended life cycle stage. The majority of the current passport approaches focus on new buildings and overlook the data needs of users. As we also found in previous studies, there is a lack of data standardisation to resort and exchange reliable information on the material composition in products. Mixed-method research consisting of a literature and practice review and three rounds of validation interviews with a total of 38 participants from Austria, Belgium, France, the Netherlands, and Switzerland was conducted to answer the fourth research question.

Our study identified over 15 potential users and produced a data template suitable for generating material passports for existing buildings, aligning with the data requirements identified for these users. While the primary application of material passports in social housing practice revolves around "enabling reuse and recycling," their role in supporting maintenance and renovation operations is also recognized. In this context, material passports directly support *narrow* and *close* strategies and exhibit potential for implementing *slow* and *regenerate* strategies.

The data template developed in Chapter 5 comprises 50 data points grouped under six main categories as follows: (1) Building general information, (2) Product general information, (3) Product properties, (4) Product safety, health and environmental aspects, (5) Product operational aspects, and (6) Product end-of-life-aspects. FIG 6.3 illustraters these data categories alongside their corresponding life cycle stage when data are collected and CE principles that they support.

We also determined which data points are must-have, nice-to-have, and unnecessary in a material passport through structured interviews with researchers, SHO professionals and their stakeholders. Furthermore, we tested the data template on three example buildings from a case SHO from the Netherlands to determine critical data gaps, and in response, we proposed a material passport framework utilising the *analytical capabilities* of digital technologies and supportive knowledge of human actors (see FIG 6.3).

Data category	Digital technologies and human actors			CE principle	Life cycle phase
	Data collection	Data integation	Data analysis		
A-Building General Information	Automated data retrieval from public records Employees of SHOs	Data harmonisation in the central data system, BIM, data lake or alternatively in an MP Platform Employees of SHOs and external stakeholderss	Big data analytics; machine learning		
B- Product General Information	Automated data retrieval from third-party websites Project managers or maintenance managers of SHOs	Data harmonisation in the central data system, BIM, data lake or alternatively in an MP Platform Employees of SHOs and external stakeholderss	Web scraping; machine learning		
C- Product Properties	Sensing and scanning technologies (e.g., Lidar systems) Site inspectors (e.g., pre-demolition auditors)	Data harmonisation in the central data system, BIM, data lake or alternatively in an MP Platform	Computer vision; machine learning Site inspectors and reuse experts (e.g., consultants)		
D- Product Safety, Health & Env. Aspects	Drones to capture building images; data retrieval from waste repositories, building registers, satellite images, etc. Safety inspectors and experts	Data harmonisation in the central data system, BIM, data lake or alternatively in an MP Platform	Computer vision; machine learning Safety inspectors and experts		
E- Product Operational Aspects	Drones to capture building images; data retrieval from satellite images, etc. Maintenance managers or contractors, inspectors or experts	Data harmonisation in the central data system, maintenance system, BIM, data lake or alternatively in an MP Platform Maintenance managers or contractors (to update data)	Computer vision; machine learning; augmented reality, virtual reality Inspectors or experts		
F- Product End-of-Life Aspects	Scanning technologies, drones to capture building images; data retrieval from satellite images, etc. Reuse companies, consultants or architects	Data harmonisation in the central data system, maintenance system, BIM, data lake or alternatively in an MP Platform	MP; computer vision; machine learning; simulations Reuse companies, consultants or architects		

Legend

Digital technologies
Stakeholders (potential users of MPs)

Narrow · Slow · Close · Regenerate

Pre-use · Use · End-of-use

FIG. 6.3 Material passport framework utilising digital technologies and knowledge of human actors.

By confronting data requirements with data availability, we identified several critical data gaps. Some of the identified critical data gaps are, including, but not restricted to, the composition of materials, existence of toxic or hazardous contents, condition assessment, and reuse and recycling potential of a product.

Digital technologies can support SHOs and their stakeholders to fulfil these data gaps in several ways. Automated data retrieval techniques can be deployed for obtaining general building or product information from publicly accessible repositories and these can be analysed with machine learning techniques to fill the data template. Drones and scanning technologies can be used to construct image or BIM models of the housing stock, so then these models can be used to identify reusable elements through computer vision. In addition, machine learning techniques can also be used to anticipate the presence of hazardous materials, such as asbestos, in building elements based on hazardous waste repositories and building register records. Ideally, all collected and analysed data are integrated in a central data system (or BIM model or data lake) by structuring data according to the data template.

6.2 Overall conclusions

This dissertation explores potentially enabling digital technologies and how they support SHOs in adopting Circular Economy principles of *narrow, slow, close,* and *regenerate* material loops in housing practices. There are at least ten potentially enabling digital technologies, ranging from blockchain technology to GIS, that allow building industry actors to apply circular building strategies. Some of these technologies are already in use by SHOs (e.g., AI-based inspection systems) while others are still in the development stage (e.g., additive manufacturing). Based on empirical findings of this thesis, a graphical summary is given in FIG.6.4 to show how digital innovations are used by SHOs in circular housing projects. Their roles in achieving main CE principles are explained next.

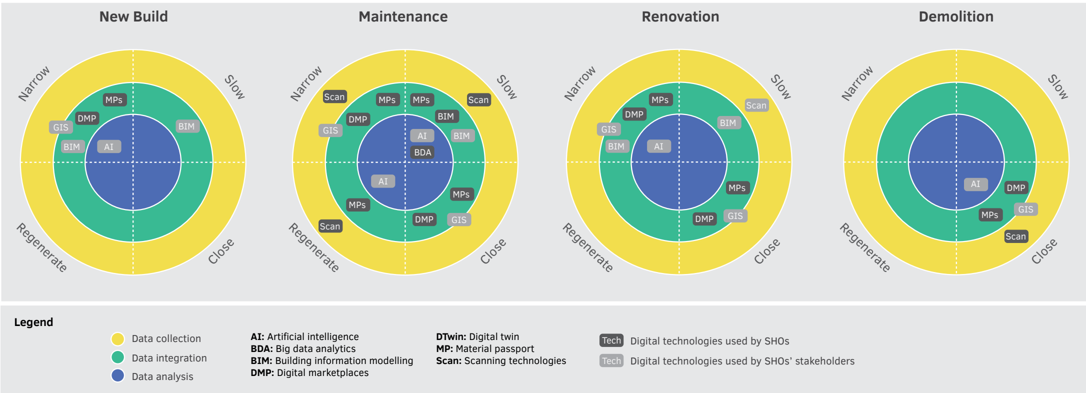

FIG. 6.4 Illustration of which and how digital technologies support narrow, close, slow, and regenerate material loops across social housing project phases.

Narrow

Our empirical findings showed that SHOs substitute new construction materials with reclaimed ones to reduce the primary resource use in new build, renovation, and maintenance projects. Digital marketplaces play a crucial role in searching and listing secondary materials or products. These platforms are typically operated by demolition or reuse companies and are increasingly used by SHOs as most of these companies provide a temporary storage space for the reclaimed products allowing timely supply and demand matching. We see new forms of collaborations between these platforms and SHOs. For example, a Dutch reuse company offers SHOs a tailored business account where reclaimed materials or products of a SHO can be listed and sold to other sector parties. A potential next step to accelerate their use by SHOs and stakeholders, particularly by architects, would be to provide more useful data on the dimensions and physical properties of products in a digitised form (i.e., as a BIM model) alongside with expected time for availability.

Another important digital tool for *narrowing* the loops across the project phases is material passports. Although our findings indicate that the use of material passports is limited, with the developments in policy landscape (i.e., new regulations on digital product passports (European Commission, 2022b)) and increasing number of tools available on the market, we expect the market uptake of this instrument will increase in near future. As we showed in Chapter 5, material passports can be an important data integration tool to provide useful life cycle data on the reusable or recyclable products in new build, renovation, and maintenance projects and thus reduce the demand for new construction materials. But, next to *narrow*, other CE principles can also benefit from material passports. For example, in a product's material passport, material contents are registered, including hazardous or toxic matters. This supports *regeneration* and *close* strategies by avoiding unsafe reuse of reclaimed products. SHOs could implement material passports several ways: (1) purchasing a software licence from a material passport provider, (2) integrating a data template into existing data systems by attuning their periodical data collection for maintenance purposes, (3) generating own material passports based on BIM model or digital twin of their housing portfolio.

In addition, other technologies such as BIM and AI-based algorithms can -indirectly- support SHOs in optimising building design options. These technologies are usually used by architects or engineers to make informed decisions on circular building design options and material selection. Furthermore, GIS could potentially be used to analyse and simulate material flows within social housing stock and help aligning supply and demand of secondary materials.

Slow

Maintenance is an essential lifetime extension strategy for buildings and building products. SHOs deliver various types of maintenance services: responsive (repairs), preventive and predictive maintenance. Maintenance operations are at the core of SHOs' business next to housing provision. While some SHOs make great investments in digital systems, some others deliver maintenance services through handymen and keep records on simple spread sheets. Our findings indicate that some advanced digital innovations are already being used by large SHOs, such as AI-based image recognition systems in combination with scanning technologies. For example, drones are used to collect façade images and Lidar systems are used to acquire data from the interior spaces. These collected images are then analysed with computer vision techniques to identify building elements and assess their condition. BIM or digital twin, although adopted by very few SHOs, could become a central data integration system to manage maintenance operations. Material passports could also be integrated into such central data systems to support maintenance and renovation activities. Furthermore, big data analytics could be used for gaining insights into predictive maintenance.

Design for disassembly is another *slow* strategy that SHOs increasingly consider in new build and renovation projects. Designing buildings with separable connections allow elements to be reused in the next cycles. This strategy is applied by architects during design stage and BIM seems to be an enabling technology for SHOs' designer stakeholders. In renovation projects, scanning technologies such as point cloud scanners are used to create BIM models of the existing buildings, which then informs the design process.

Close

In SHOs, there is a tendency in linking demolition projects with new build or renovation projects to supply secondary materials from buildings to-be-demolished (i.e., donor buildings). Similar to *narrow*, for recovering reusable or recyclable products and materials, SHOs use digital marketplaces. In some cases, scanning technologies are used for detailed pre-demolition audits. Material passports could play a very crucial enabling role in delivering data on the reusability or recyclability potential of the products in demolition projects. Our findings indicate that SHOs, through reuse companies or consultants, create an inventory of reusable parts, which is similar to material passports. This practice could be enhanced and automated with computer vision technology.

Regenerate

Two *regenerate* strategies seem to be dominant in new build, renovation, and maintenance operations of SHOs. The first one is using bio-based or circular building materials in new build and renovation projects. BIM as a design optimisation tool supports architects and engineers for designing with circular materials. The second one is avoiding toxic and hazardous contents in buildings. The AI-based building inspection system mentioned earlier can spot toxic and hazardous materials on the building façade. However, it still has limitations in identifying certain hazardous contents, such as asbestos. It is possible to improve such systems with machine learning techniques to estimate the presence of asbestos by using hazardous waste repositories.

6.3 Scientific contributions and recommendations

The scientific contributions of each study constituting this thesis has been presented in Chapters 2, 3, 4, and 5. In this section, the overall contribution of the whole thesis is discussed, and recommendations are given for future research.

6.3.1 Bridging CE, digitalisation, and the built environment research fields

This thesis provides the first comprehensive conceptualisation of an emerging research field at the intersection of CE, digitalisation, and the built environment with a specific focus on SHOs. Consequently, it establishes a much-needed and underexplored link between these three domains, adding valuable insights to the expanding body of knowledge in the circular built environment literature and supporting theory building in multiple dimensions. (FIG 6.5).

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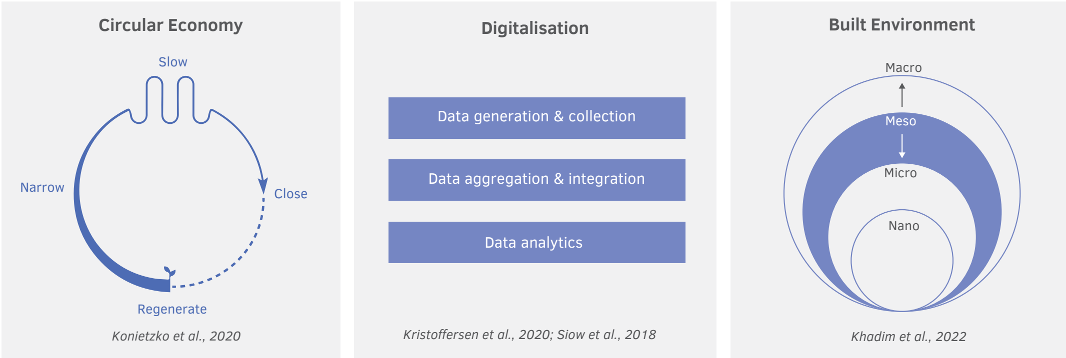

FIG. 6.5 Main frameworks used throughout the thesis to link CE, digitalisation, and the built environment research fields. (Sources: Khadim et al. (2022); Konietzko et al. (2020); Kristoffersen et al. (2020); Siow et al. (2018))

First, early studies of circular built environment research primarily focused on the application of *slow* and *close* strategies (e.g., reuse of materials, design for disassembly, etc.) at the design and end of life stages (Benachio et al., 2020). This thesis adopts a holistic approach, extending the exploration to encompass *narrow* and *regenerate* strategies, while also shedding light on the often-overlooked operational stage of buildings. Through this broadened perspective, the scope of the utilization and potential application of digital technologies is expanded. It is noteworthy that the *regenerate* principle is frequently neglected in academic discourse, despite the fact that the two most frequently cited CE definitions (Ellen MacArthur Foundation (2013b), and Geissdoerfer et al., (2017)) define CE as a "regenerative system" (Kirchherr et al., 2023). This thesis therefore includes all four core principles of CE and considers all life cycle stages (that are relevant for the SHOs), redirecting our attention from predominant to overlooked research areas.

The Circular Digital Built Environment Framework (CDB Framework), developed in Chapter 3, integrates examples from research and practice and maps ten enabling digital technologies for supporting 19 circular building strategies grouped under four core CE principles, spanning the entire life cycle stages. Offering a novel and comprehensive overview, this framework serves as a valuable tool for researchers, facilitating the examination of underexplored connections between digital technologies and CE principles across various fields within the built environment research domain. Further research is recommended to investigate how digital technologies, such as robotic manufacturing, could activate and accelerate the application of the *regenerate* principle. Regeneration is especially vital in augmenting the utilisation of renewable resources in housing production, recognising that the growing housing demand cannot be sufficiently met solely by closing material loops.

It also holds essential implications for concurrently improving natural and built environments by involving people in circular building processes. In this context, the incorporation of digital technologies such as extended reality for designing and managing circular buildings is recommended.

Second, this thesis focuses on the social housing stock, which is placed at the meso scale[9] -another underexplored layer- of the built environment research. SHOs own and professionally manage a large portfolio of buildings in cities, where resources flow between layers of the built environment with the involvement of a wide network of stakeholders along the housing value chain. Very few existing studies examined CE in SHOs, e.g., from a social innovation (Marchesi & Tweed, 2021) and social and ecological (Eikelenboom et al., 2021) perspectives. This thesis contributes to this young research field by exploring how forerunner SHOs implement CE principles (Chapter 2). Moreover, it illustrates how material and data flows occur in circular housing projects from a digitalisation standpoint (Chapter 4 and 5). Additionally, it underscores the significance of SHOs in delivering sustainable housing from a CE perspective, expanding the current scientific discourse beyond the focus on energy transition.

Reflecting upon the findings of this study (i.e., barriers of CE implementation in Chapter 2), further research is recommended to combine concepts around energy transition and circularity from a digitalisation point of view, as these two aspects are frequently dealt with separately and cause considerable challenges in prioritising sustainability targets of SHOs. New digital frameworks at the EU level, such as digital logbooks for buildings, should adopt a holistic approach, encompassing data fields related not only to energy performance but also to the circularity of resources in buildings. Future research could explore the involvement of other stakeholders at the meso level, including the public or real estate owners. Additionally, investigating the use of digital technologies in tenant involvement in circular processes would be a fruitful area for future work, particularly within the context of social innovation.

Third, at the start of this PhD, most theories on digitalisation for a CE stemmed from the fields of smart manufacturing (Kristoffersen et al., 2020; Lopes de Sousa Jabbour et al., 2018) and servitised business models (e.g., Antikainen et al. (2018); Bressanelli, Adrodegari, et al. (2018)), focusing on Industry 4.0 technologies and their enabling roles. On the other side, the built environment research predominantly concentrated on two technologies: BIM and material passports (e.g., Honic, Kovacic, & Rechberger (2019)), lacking an exhaustive overview of other promising

9 The meso level refers to neighborhoods or industrial parks in the broader literature (Khadim et al., 2022) and is overlooked in the circular built environment literature.

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technologies that could potentially support industry actors with CE implementation. Three parts of this thesis (Chapters 3, 4, and 5) considerably contributed to the conceptualisation of digitalisation for a circular building industry field by (1) identifying and showcasing how (at least ten) digital technologies can enable a CE in the built environment, (2) categorising them according to analytic capabilities of data collection, integration, and analysis, (3) exploring their real-life implementation, and (4) investigating whether they offer value to the industry actors.

6.3.2 Insights from empirical studies: "Just because we can does not mean we will…"[10]

This thesis contains one of the few studies that provides empirical evidence regarding the use of -allegedly- enabling digital technologies in circular housing practices of SHOs (Chapter 4). Extant literature presents an optimistic outlook of digital technologies by stressing their "enabling" functionalities for circularity, including our work presented in Chapter 3. This is understandable in a way that "enabling" functions is an important starting point for research to uncover the potential benefits of digital technologies and build a knowledge base. However, it's essential for researchers to move beyond this phase and engage in critical discussions on social and environmental issues, such as, potential risks, ethical considerations, and unintended consequences.

Looking back on findings of Chapter 4, a gap between research and actual world became clear. By collecting empirical data and including perspectives of the industry actors who are at the forefront of CE implementation, this thesis showed that the majority of enabling digital tools proposed by researchers are not adopted in real life or caused considerable challenges if implemented. For example, material passports, perhaps the most promoted digital tool for CE in literature (see e.g., (Atta et al., 2021; BAMB, 2019; Heisel & Rau-Oberhuber, 2020; Honic, Kovacic, & Rechberger, 2019)), introduced several challenges rooted in technical, cultural, regulatory and market factors. Among these, the lack of user acceptance, limited understanding, and high costs around their implementation stand out. These findings, to some extent, resonate with ongoing discussions about barriers stemming from people's motivation to change, as observed in the implementation and use of BIM in organisations within the building industry (See, e.g., Siebelink et al., 2021).

10 "Just because we can does not mean we will…" is a quote from Chan, 2020.

The insights gained from empirical findings, therefore, could help us better understand the missing link between research and practice and develop solutions that have immediate and tangible impacts on urgent societal and environmental challenges. To do so, we need to enlarge our lense when conducting research on digital circular built environment . As Chan (2020) stressed in his critical perspective, technology adoption is not about what technology can do but often about non-technical aspects such as the will of people to embrace the change that digitalisation offers. As we have observed in Chapter 2 and Chapter 4, both transitions, circular and digital, require fundemantal shifts within organisations, encompassing aspects such as, leadership, priority-setting, learning and sharing, and business model innovation. Hence, it is recommended to undertake interdisciplinary empirical research in this emerging field that considers the practical context, regulatory frameworks, and organizational, social, cultural and business aspects. An alternative research direction for exploring potential solutions could involve "circular business model experimentation." Engaging in business model experimentation would enable organizations to swiftly test and comprehend new technologies, exploring the value they generate in real-life scenarios before committing to broader implementation (Bocken & Antikainen, 2019). This framework could be applied to examine not only business related aspects but also organisational and cultural shifts neccassary to realise big scale tansformations within organisations.

6.3.3 Hidden environmental impact of digitalisation

Another important field for future research is environmental impact assessment of using digital technologies for circular purposes to address the rebound effects. Due to optimism around digital technology, we tend to forget about the hidden footprint of digital technologies stemming from abundant resource use (i.e., water, energy, land, materials, etc.) (Obringer et al., 2021) and digital waste creation (i.e., unused or abandoned data stored in a digital system) (Obringer et al., 2021). An interesting research area would be investigating the footprint of governing a digital tool, say a material passport platform, along the whole life cycle stage of a building to assess whether it would be worth to store large amount of data to reuse materials at the end-of-life. It is recommended to conduct critical research on the necessity of using popular innovations like blockchain technology to achieve a circular building industry.

6.3.4 Interplay between data, digital technologies, and key stakeholders

Although this thesis initially focused on digitalisation (Chapter 3), empirical findings presented in Chapter 4, particularly the challenges associated with adopting material passports in circular projects, redirected our attention towards SHO actors and their data requirements. In Chapter 5, we dove into data issues around material passport and developed a framework. Since the start of this PhD research in 2019, material passports has gained enormous interest from policy, practice, and research. Notwithstanding this great attention, critical issues persist regarding the data requirements for their creation. This research contributes to the ongoing academic discourse by identifying the data needs of key material passport users and exploring the feasibility of collecting this data from SHOs' digital systems. The study introduced a data template and proposed a framework to address critical data gaps through the data collection, integration, and analysis capabilities of digital technologies, supported by the knowledge of key stakeholders.

Reflecting on the evolution of the material passports framework, it is recommended that researchers and passport initiatives adopt an ecosystem perspective rather than focusing on a singular actor or product. As our findings indicate, neither digital technology nor human knowledge alone can adequately meet the data requirements of material passports. Therefore, a new collaborative approach should be established, fostering multi-dimensional interactions between digital technology and humans. Furthermore, instead of developing a singular technological solution, the integration of various enabling technologies should be considered.

6.4 Recommendations for practice and policy

This section presents how the findings of this thesis as a whole can support the building industry actors, particularly SHOs, in applying CE principle in housing practices.

6.4.1 Get started with digital innovations that are already in use

First and foremost, *the CDB Framework* presented in Chapter 3 is a useful tool to get started with CE as it covers all CE principles of *narrow, slow, close,* and *regenerate* and lists many circular building strategies along with practical examples. It further supports industry actors in deciding and developing a digitalisation strategy for their circular projects. This framework is made available by the authors for the use of practitioners in an online collaboration platform [11]. Practitioners are recommended to explore circular building strategies that fit their sustainability targets alongside with the digital solutions mapped onto the CDB framework.

Our empirical findings showed that digital marketplaces, AI-based inspection systems, and some forms of material passports (i.e., digitised material inventories of donor buildings) are already adopted in circular pilot projects of forerunner SHOs. New starters are recommended to test these existing tools to gain experience before making big investments. In addition, experienced SHOs could share their learned lesson with the rest of the sector to increase the awareness towards digitalisation for circular buildings.

6.4.2 Data- all what matters

As the fifth chapter showed, some enabling tools like material passports, can be created in a simple spread sheet form and can be integrated into the central data systems of SHOs. They can also be developed (or offered by external software firms) with more complex digital technologies like blockchain technology. When choosing a digital solution, SHOs are recommended to examine first the data requirements of their employees and available data sources in their organisations for the circular

11 https://miro.com/miroverse/digital-circular-economy-framework/

strategies that they want to implement. It is also recommended to attune their periodical data collection moments to create material passports. The data template developed in the fifth chapter can be used to organise and manage data.

Recently, the EU introduced new policy instruments for sustainability of buildings, such as Digital Building Logbooks (European Commission, 2020c). It is expected that data regarding circularity alongside with other sustainability aspects such as energy performance or renovation history of a building would be combined in logbooks. SHOs are recommended to consider EU instruments when organising their real estate data.

Data standardisation is utmost importance for achieving reliable and transparent data management for circularity. Sector initiatives such as Platform CB' 23 have already made good progress in developing data templates for CE for various scales and life cycle stages. These good intentions should be supported by the legislation and standardisation institutions in order to make concrete improvements in the industry. Also, it is very important to consider EU-wide initiatives such as digital logbooks and sector branch organisations like AEDES and public-private initiatives like Bouw Digitaliseringsraad to accelerate the standardisation efforts while avoiding potential overlaps.

In summary, SHOs and all housing value chain partners are recommended to take an inclusive ecosystem perspective to focus on data requirements for implementing critical CE strategies rather than wasting resources in popularised digital technologies. Data must come first!

6.4.3 A vision for regenerative twin transitions

At the time of writing these sentences in July 2023, many countries are dealing with red alerts issued due to fierce heatwaves and unprecedented record-breaking temperatures. Biodiversity loss has reached alarming levels, and changing climatic conditions have disrupted agriculture production, resulting in reduced crop yields and food scarcity in several regions. The profound impact of the climate crisis requires urgent and collective response from individuals, companies, and nations to mitigate its devastating effects.

As demonstrated by this thesis, the CE offers numerous possibilities for improving the built environment's impact on the planet through digitalisation. However, it does not truly address the magnitude of the challenges we face. It is critical for practitioners, academics, and policymakers to embrace a more radical framework: ***regeneration***.

Regeneration, often the least emphasized principle of the CE, holds great potential to restore our planet. It implicates rethinking and redesigning systems and processes in a way that not only minimises harm but actively contributes to restoration of environment. This principle calls for a shift from simply reducing negative impacts to actively enhancing ecosystems, biodiversity, and natural resources.

In the current policy landscape, EU has emphasized the urgency to address the challenges of the climate crisis in Twin Transitions initiative (EU Science Hub, 2022). The Twin Transitions explicitly advocate for the simultaneous green and digital transformation of the European economy. This comprehensive vision will become very important for many industries, including the building industry.

The Twin Transitions could provide a unique opportunity for SHOs to align their digitalisation efforts with the broader sustainability agenda. By developing short-term and long-term strategies, SHOs can embark on a path that embraces environmental sustainability while harnessing the power of digital technologies. In this context, business model experimentation with digital technologies becomes even more crucial, as it enables SHOs to explore innovative approaches, test new tools, and pioneer novel solutions that advance both the circular and digital transitions towards regeneration. It is recommended that SHOs formulate collaboration networks with experienced SHOs, software companies, contractors, consultants, and other relevant stakeholders to plan, develop, and implement experimentation endeavours.

To apply the *regeneration* principle in the built environment for twin transitions, a holistic approach is necessary, considering the entire lifecycle of buildings and infrastructure. This involves incorporating regenerative design and management practices that prioritise regenerative materials, renewable energy systems, and effective resource utilisation. Furthermore, collaboration and knowledge-sharing are important— Practitioners, academics, and policymakers should come together to develop innovative strategies, techniques and digital solutions that foster regenerative practices and governments and institutions should introduce policies providing economic incentives for businesses and individuals to adopt these approaches.

By prioritising the *regeneration* principle in a digital circular built environment, we can not only reduce our negative impact but actively contribute to healing our planet. Embracing this principle, alongside other circular economy strategies, can pave the way for a more sustainable and resilient future, where the built environment plays a vital role in supporting ecological balance and the well-being of both people and the planet.

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About the author

Sultan, born in Ankara, Türkiye, always had a knack for nature and design from her playful childhood. Growing up with her twin brother, they spent endless hours outdoors, inventing toys from garden treasures. This love for creativity led her to study architecture and civil engineering in Eskisehir, where she graduated with honors.

After working several years in international large-scale construction projects as a design manager in Azerbaijan, Russia and the Netherlands, Sultan started her PhD delving into how digital technologies support actors in the building industry, particularly social housing organisations, when implementing circular strategies in housing projects. Her research gained recognition through multiple articles and collaborations with the University of Birmingham, ETH Zurich, Maastricht University, and Aalborg University.

Sultan took the initiative to co-found the pioneering cross-industry networking and knowledge-sharing platform, Digital Circular Economy Lab (DiCE Lab), in collaboration with scholars from ETH Zurich. Additionally, she edited the first comprehensive book on this research field alongside Prof. Catherine De Wolf and Prof. Nancy Bocken which will be published in December 2023 by Springer Nature. Sultan actively seeks to bridge the gap between her academic work and practical applications. For instance, following the devastating earthquakes in Turkiye, she founded the Research & Industry Alliance for Recovery (RIAR) platform. RIAR brings together over 60 volunteers dedicated to finding solutions for the affected regions' recovery. In recognition of her work, Sultan was awarded the Embassy Science Fellowship from NWO and the Ministry of Foreign Affairs, and in 2024, she will conduct research on circular and digital strategies for pre- and post-disaster resource management in earthquake regions in Türkiye.

Living in Amsterdam with her two kids, Vincent Toprak and Tomris Lente, and partner Galip Okan, Sultan finds joy in cooking, sharing meals, playing with her children, and diving into literature and cinema. In her personal life, she embraces the principles of the circular economy, leading a happy and fulfilling existence.

List of Publications

Journal articles

Çetin, S., Raghu, D., Honic, M., Straub, A. & Gruis, V., (2023). Data requirements and availabilities for material passports: A digitally enabled framework for improving the circularity of existing buildings. Sustainable Production and Consumption 40, 422-437. https://doi.org/10.1016/j.spc.2023.07.011

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23#22

Towards a circular building industry through digitalisation

Exploring how digital technologies can help narrow, slow, close, and regenerate the loops in social housing practice

Sultan Çetin

This thesis explores the integration of Circular Economy (CE) principles of narrow, slow, close, and regenerate in the social housing practice through digital technologies. Beginning with the examination of the CE implementation in Dutch social housing organisations, the research extends its focus to the broader built environment, introducing the Circular Digital Built Environment Framework and identifying ten enabling technologies. Subsequent chapters explore real-world applications of these digital technologies in circular new built, renovation, maintenance, and demolition projects of forerunner social housing organisations. The thesis includes a comprehensive study of material passports, addressing challenges around data management and proposing a digitally-enabled framework. The thesis concludes with critical reflections on the findings and their implications and provides further recommendations for research and practical applications in advancing circularity in the building industry through digital technologies.

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