Circular Economy and Sustainability

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A Circular Built Environment in the Digital Age

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Circular Economy and Sustainability

This book series aims at exploring the rising field of Circular Economy (CE) which is rapidly gaining interest and merit from scholars, decision-makers and practitioners as the global economic model to decouple economic growth and development from the consumption of finite natural resources. This field suggests that global sustainability can be achieved by adopting a set of CE principles and strategies such as design out waste, systems thinking, adoption of nature-based approaches, shift to renewable energy and materials, reclaim, retain, and restore the health of ecosystems, return recovered biological resources to the biosphere, remanufacture products or components, among others.

However, the increasing complexity of sustainability challenges has made traditional engineering, business models, economics and existing social approaches unable to successfully adopt such principles and strategies. In fact, the CE field is often viewed as a simple evolution of the concept of sustainability or as a revisiting of an old discussion on recycling and reuse of waste materials. However, a modern perception of CE at different levels (micro, meso, and macro) indicates that CE is rather a systemic tool to achieve sustainability and a new eco-effective approach of returning and maintaining waste in the production processes by closing the loop of materials. In this frame, CE and sustainability can be seen as a multidimensional concept based on a variety of scientific disciplines (e.g., engineering, economics, environmental sciences, social sciences). Nevertheless, the interconnections and synergies among the scientific disciplines have been rarely investigated in depth.

One significant goal of the book series is to study and highlight the growing theoretical links of CE and sustainability at different scales and levels, to investigate the synergies between the two concepts and to analyze and present its realisation through strategies, policies, business models, entrepreneurship, financial instruments and technologies. Thus, the book series provides a new platform for CE and sustainability research and case studies and relevant scientific discussion towards new system-wide solutions.

Specific topics that fall within the scope of the series include, but are not limited to, studies that investigate the systemic, integrated approach of CE and sustainability across different levels and its expression and realisation in different disciplines and fields such as business models, economics, consumer services and behaviour, the Internet of Things, product design, sustainable consumption & production, bio-economy, environmental accounting, industrial ecology, industrial symbiosis, resource recovery, ecosystem services, circular water economy, circular cities, nature-based solutions, waste management, renewable energy, circular materials, life cycle assessment, strong sustainability, and environmental education, among others.

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This work has been supported by Maastricht University, ETH Zurich, and Delft University of Technology.

ISSN 2731-5509 ISSN 2731-5517 (electronic)
Circular Economy and Sustainability
ISBN 978-3-031-39674-8 ISBN 978-3-031-39675-5 (eBook)
https://doi.org/10.1007/978-3-031-39675-5

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

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Foreword

We need an economic system based on the insight that the Earth is a closed system. In a closed system with defined boundaries, materials, just like space, must be considered as limited and treated as such. They should be used accordingly in such a manner that their availability is not limited to one single, temporary application but allows them to circulate in our systems indefinitely.

This insight is of particular relevance for the architecture, engineering, and construction sectors, which, according to the UNEP Global Status Report for Building and Construction, account for 40–50% of material consumption of our global economy and 37% of greenhouse gas emissions. Without decisive action, the severe pressure on resources caused by the construction industry will only aggravate. According to the International Institute for Sustainable Development, roughly half of the building stock needed by 2060 has yet to be built while several critical boundaries of our planetary system have already been surpassed.

For all these reasons, we need a new circular building culture in which we design, develop, build, and rebuild in such a way that "limited-edition" materials are available indefinitely and resources are used responsibly. Buildings need to be conceived as documented and deconstructible material depots, from which, after their useful life, all materials can be recovered for future (building) projects. In addition, we need to reduce our consumption by applying strategies to use fewer materials and resources, and use materials longer. In short, we need to narrow, slow, close, and regenerate our material loops, as the authors of this book articulate.

Yet the complexity of the building process, the fragmentation of the construction value chain, the variety of actors involved, and the long-time horizon of building projects are factors that make the realisation of circularity in the built environment particularly challenging. We therefore urgently need new knowledge and tools that allow us to navigate and, more importantly, shape this highly complex environment in new ways. Data and digitalisation can provide us with exactly these new tools and bring transparency into the building process by bridging the information and knowledge gaps that exist between disciplines, processes and time.

This publication, for the first time, connects and describes the many digital innovations which can drive circularity in the built environment. Its authors come from a global community of scientists and entrepreneurs who are at the forefront of shaping a new building paradigm.

In this book, a groundbreaking vision for the future of the built environment emerges, fueled by cutting-edge technologies that offer new possibilities for circular and regenerative design and construction. This book evokes a vision for a new era of the built environment in which geographical data will enable us to place our building structures and activities more responsibly in the wider context of a place or city; a vision where AI-informed computational design tools will support architects in creating fully circular structures that require less material for construction, can be maintained and adapted during their useful life, and can be easily deconstructed once they reached their expiration date. Additive manufacturing and robotics will bring new possibilities for realising and decomposing these circular structures, while maintenance and material management will be supported by blockchain-enhanced digital twins and material passports. All these new tools will need to converge into one integrated digital ecosystem whereby, as Alexander Koutamanis formulates in this book, "information should be treated not as a product of integration but as the integrator of all activities."

New tools alone will not be enough to bring the urgently needed transformation of our system. We also need a new consciousness for the consequences of our actions. We seem to be far from Jean-Jacques Rousseau's remark (from his 1754 essay "On the Origin of the Inequality of Mankind") that "the fruits of the earth belong to all, but the earth to none." We need to develop a new building culture that, among other things, will reconcile the health of our planetary system and the interests of future generations with the temporary needs of people, society, and businesses. Digitalisation in the many areas of the built environment as described in this book has the potential not only to see new buildings via augmented reality but to shape a circular built environment through an augmented consciousness.

Co-founder of Turntoo Sabine Oberhuber
The Netherlands

Architect, Founder of RAU, Turntoo, Madaster Thomas Rau
The Netherlands

Sabine Oberhuber is one of the first pioneers of the circular economy and co-founder of Turntoo, the first company in the Netherlands focusing on the transition to a circular economy. She has developed some of the first business models and strategies for circularity and has helped shape the thinking about the transition to a circular economy. Turntoo works with leading companies and public bodies to develop circular business models and processes to reduce or eliminate material waste, realising breakthrough concepts such as Light as a Service, in cooperation with Philips. Turntoo also assists municipalities with circular city strategies and area development.

Thomas Rau is an architect, entrepreneur, innovator and founder of RAU, Turntoo and Madaster. The architectural firm RAU has developed innovative concepts and set the tone in the field of environmentally conscious, climate-neutral and energy-efficient building at an early stage. RAU is now the undisputed authority in the Netherlands on plus-energy building and circular value creation in architecture. Thomas Rau was nominated for the Circular Economy leadership Award of the World Economic Forum and received the Circular Hero Award by the Dutch Ministry of Infrastructure.

In 2016, Thomas Rau and Sabine Oberhuber published the best-selling book *Material Matters*, in which they describe the critical building blocks for achieving a circular economy. In 2016, they initiated Madaster, the cadastre for materials. Madaster is active in eight countries and considered as the leading solution for creating and registering material passports for the built environment. For its potential for systemic change, Madaster won the Digital Top 50 Award for Social Impact which is awarded by Google, McKinsey and Rocket Internet.

Acknowledgements

We would like to extend our heartfelt gratitude to all those who have immensely contributed to the quality of this book. Their valuable insights and expertise have enriched our understanding and presentation of the subject matter. We are grateful to the authors for delivering excellent and thought-provoking chapters and perspectives. We are tremendously grateful to Jennifer Bartmess for her invaluable expertise and dedication while reviewing and copyediting the chapters. We would also like to thank the anonymous reviewers who participated in the blind peer-review process for their careful evaluation and thoughtful comments. Our sincerest appreciation goes to our team members who provided feedback on the technologies discussed in this book. Additionally, we would like to thank our families and friends for their unwavering support. Finally, we express our gratitude to the readers of this book. It is our sincere hope that this work helps them navigate through the emerging field of a circular built environment in the digital age and that this knowledge will contribute to a regenerative future.

Open access of this book was made possible with the financial support from the TU Delft Open Access Fund, the Maastricht University Library's Open Access Book Fund, the Swiss National Science Foundation (SNSF) Project Fund under grant agreement No 200021E_215311, and the European Union's Horizon 2020's European research Council (ERC) funding scheme under grant agreement No 850159 (project Circular X).

Introduction

> "The ability of technological advancement to do more and more with less and less until eventually you can do everything with nothing."
>
> R. Buckminster Fuller in *Nine Chains to the Moon*

By 2050, two-thirds of the world's population will be living in cities, and by 2030, three billion people will need new housing (UN Habitat 2023). As a growing sector, especially due to increasing urbanisation and the need for new housing, the architecture, engineering, and construction (AEC) industry is responsible for depleting resources, generating waste, and emitting greenhouse gases at a tremendous scale and speed. Construction and demolition processes are highly resource-intensive, accounting for more than 40% of the total raw materials extracted worldwide and generating over 35% of total waste – additionally, the building sector is responsible for approximately 39% of global energy-related greenhouse gas emissions (Schrör 2011; Allwood et al. 2011; Yuan et al. 2012; Di Maria et al. 2018; Abergel et al. 2019; Eurostat 2020; and summarised by Çetin et al. 2021). The industry's linear model of production is at the core of the problem: resources are extracted, buildings are used, and then materials are disposed of when a building is no longer needed. If we continue this linear model to meet the unprecedented and growing demand for constructing new buildings, we will deplete the Earth's resources and pave the way for an even greater climate catastrophe.

Industry 5.0 technologies and circular economy principles hold untapped potential for achieving a sustainable built environment. This book aims to address the urgent need for a sustainable built environment by leveraging this potential. Industry 5.0 is focused on creating a sustainable, human-centric, and resilient future using advanced technologies. While many industries have already begun implementing circular economy principles through digitalisation, the AEC industry is lagging behind.

To address the challenges the construction industry faces, we can apply circular economy strategies, such as service life enhancement of materials, rehabilitation, dis- and reassembly, design for reuse, and implementation of regenerative design. The goal is to make the built environment part of the solution rather than part of the problem. We must urgently shift from a linear take-make-waste model to a circular one in which we use resources wisely and prevent them from becoming waste. Adopting digital innovation is crucial to achieving this paradigm shift, but currently there is a lack of understanding of the potential synergies between the circular economy and digital transitions. This "twin transition" could be leveraged to tackle the unprecedented challenges facing the industry. This book highlights the importance of these synergies and explores how digital technology can help accelerate the circular transition of the built environment.

But first, what is a circular model? The circular economy has become a popular concept among scholars, NGOs, business professionals, and policymakers to address issues of sustainable development (Geissdoerfer et al. 2017; Kirchherr et al. 2017). The concept has evolved through the work of designers and architects such as McDonough and Braungart (2002), who coined the cradle-to-cradle concept, Benyus (1997), who led the work on Biomimicry and designing according to nature's principles, and Stahel (2010), who advocated new business models focused on performance and services rather than mere product sales. Policies focused on waste reduction, pollution prevention, and resource efficiency have existed in many parts of the world for decades but have only recently culminated in circular economy policies with the opportunity to create a broader more comprehensive framework to address resource issues (Bocken et al. 2017). Yet as several organisations, regions, and countries across the globe are increasingly bringing circular economy explicitly into their visions, goals, and policies, it has become an important concept to help transfer thinking about the future of the society, economy, and sustainable innovation.

In this book, we regard the circular economy as an important lever to support sustainable development and secure the resources to sustain our current and future generations by minimising the resource inputs and waste, emissions, and energy leakage of products over time (Bocken et al. 2021). This may be achieved through four distinct resource strategies (see Çetin et al. 2021; Konietzko et al. 2020):

- Narrowing the loop: using fewer resources through increased efficiency in the production and design process
- Slowing the loop: using and consuming less by extending product lifespans, and avoiding unnecessary consumption
- Closing the loop: reusing materials or resource-efficient post-consumer recycling
- Regenerating the loop: focusing on leaving the environment (and society) in a better state than before

Clarifying the relevance of a circular model brings us to a second question: how is digital technology relevant? There are many opportunities to combine digital with circular principles in existing buildings, new buildings, and even demolition projects (Çetin et al. 2021). Digitalisation can solve practical challenges related to material scarcity and carbon emissions reductions. Digital technologies could also help with de- and re-constructing buildings more quickly, economically, and intelligently. For example, we can use the advances we have seen in recent years in digital fabrication to start a digital *de-fabrication* design approach, augmented by other digital innovations (such as matchmaking algorithms, extended reality, blockchain, etc.). This would disrupt the current construction sector's value chain and reverse the current architectural design approach towards de- and re-fabrication for effectively reusing building materials. Digital transformation holds great potential for helping the transition to a circular economy.

Emergent digital innovations make this a timely topic. Digital technologies – from building information modelling (BIM) software to Internet of Things (IoT) sensors, artificial intelligence (AI) algorithms, blockchain technology, or digital fabrication technologies – can help architects, engineers, and construction professionals optimise design, construction, monitoring, decision-making, maintenance, and performance of building systems to improve efficiency and reuse, reduce waste, and even provide safer working conditions.

This book addresses the pressing need for a comprehensive overview of the technologies that are most relevant to the circular building industry and how they can be used to achieve circularity goals. Each chapter focuses on a particular digital technology and its application for the circular economy, providing at least one practical example and discussing potential future developments. Leading experts in the field of digitalisation and circular economy offer their insights into how emerging digital technologies can be used to address circular economy strategies in the built environment.

The book is divided into three distinct parts, each with a unique focus, for a more in-depth exploration of each technology and its application, as well as a clear framework for understanding how these technologies can work together to drive the circular economy transition.

Part I explores the role of data, with topics including digital representation (BIM and digital twins), geographic information systems (GIS), scanning technologies and reality capture, AI, machine learning, and material passports in enabling digital innovation for circularity. Part II delves into design and fabrication, covering technologies such as computational tools, additive manufacturing and robotic fabrication, and extended reality. Part III examines business, management, and governance, exploring topics such as reverse logistics, blockchain technology, digital logbooks, circular business models, and regeneration.

Finally, the book concludes with a discussion of how these digital tools can be combined to create practical, economic, and policy-driven solutions to drive the twin transition of shifting to a circular economy and digital transformation in the built environment. By presenting a comprehensive exploration of these technologies and their potential applications, this book aims to inspire and accelerate the knowledge needed to drive the circular economy transition.

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Introductory Perspective

For a long time, the built environment was mostly based on natural ‘zero carbon’ materials, such as dimension stone (Roman aqueducts), clay (houses in Saana), backed clay (bricks), plants (trees and bamboo), materials which decay without harm to Nature, or become food for other organisms – bacteria, insects, worms – at the end of their use. The industrial revolution in the UK mass-produced iron, steel, and cement, extending society’s limits beyond natural materials into a high-carbon material domain.

A notable symbol of the beginnings of the industrial revolution is the Iron Bridge, built in 1779. This remarkable monument stands as a testament to where the Industrial Revolution originated and dominates the small town that shares its name. The first known instance of mass steel production is credited to China in the third century AD. They employed techniques similar to what is now known as the Bessemer Process, which later enabled bulk steel production. In 1855, Henry Bessemer obtained British patents for a pneumatic steelmaking process, using blasts of air to remove impurities from molten steel. In 1824, Joseph Aspdin of Leeds, Yorkshire, England, secured a patent for a material produced from a synthetic mixture of limestone and clay, which came to be known as cement.

Today, the construction industry is the biggest consumer of material resources as well as a major polluter. Cement and steel are the backbones of infrastructure and buildings. Cement production creates 2.3 billion tonnes of carbon dioxide per year, while iron and steel production releases some 2.6 billion tonnes – 6.5% and 7.0% of global CO_2 equivalent emissions, respectively (Fennell et al. 2022). Their future will depend on public policies of environmental protection, market supplies of natural resources, and the availability of landfills.

In the twentieth century, steel-reinforced concrete and steel structures were increasingly used, together with technical progress in industrialised building methods and new materials: plastic for pipes and cables, chemicals for joints and insulation.

In the late 1960s, when I studied architecture and urban planning at ETH Zurich, our focus was on design and engineering issues, building regulations and zoning laws. The World population was 2.5 billion people, partly living in big cities of the Northern hemisphere, New York, London, Tokyo, Moscow, and Paris. The Digital Age consisted of computation centres where big machines were fed by punch cards. Neil Alden Armstrong had just set foot on the Moon, using computers with 128-bit chip technology. In 1950, Eduard Stiefel at ETH rented the Zuse Z4, a relay computer developed in Germany by Konrad Zuse, making it the world's first commercial digital computer. The Z4 was the first computer at a continental European university, it remained at ETH Zurich for 4 years.

In the twenty-first century, the Digital Age introduced CAD, digital twins, Internet of Things, and 'speaking' elevators mainly in industrialised regions, which enabled more efficient construction methods but also created digital outcasts in the population.

Today, eight billion people live on our planet. China, India, and Africa are with over one billion people, with Africa having the fastest population growth. Major cities are on both sides of the equator: Tokyo, Jakarta, Chongqing, Delhi, Shanghai, Seoul, Mumbai, Manila, New York City, Sao Paolo, Beijing, and Mexico City. Concrete is the second-most-consumed product on the planet, after clean water: world production of cement is 530 kg per person per year, and of steel, 240 kg (but only part of which goes into the built environment). Changes to building codes and in the education of architects, engineers, and contractors could reduce demand for cement and steel by only 26%, according to the International Energy Agency (IEA 2019).

The objective of the Circular Economy is "doing more with less over longer periods" by maintaining the value, purity, and utility of stocks (of natural, human, cultural, financial, and manufactured objects and materials), with a focus on the sustainable use of these stocks. In other words, the Circular Economy is about the design and construction as well as the use phase, the smart operation, and maintenance of the built environment. A circular economy in construction is also a solution towards the environmental impacts of buildings.

The Digital Age can contribute to increasing the efficiency of building and construction activity and support the standardisation of materials and dimensions to facilitate the efficient reuse of components and material resources (urban mining). But remember that in industrialised regions, the annual volume of new construction is only about 2% of the stock volume!

Therefore, the biggest contribution of the Digital Age will be in improving the sustainable use of the stocks of infrastructure and buildings by extending their service lives and improving their operation and maintenance phase – the heart of the Circular Economy.

Walter R. Stahel

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Walter R. Stahel, a Swiss architect and sustainability advocate, is renowned for co-founding the Product Life Institute in Geneva and pioneering the concept of the circular economy. His book, *The Performance Economy*, introduced selling goods as services to encourage resource efficiency. Stahel collaborates with the Ellen MacArthur Foundation and the European Commission. He received accolades such as a doctorate honoris causa from the Université de Montréal and a senior research fellowship at the Circular Economy Research Centre in Paris. In 1989, Stahel and Orio Giarini published *The Limits to Certainty*, emphasising that finite resources were a limit to the unsustainable linear industrial economy and proposed a circular economy that utilises resources effectively and considers ecological factors.

Contents

About the Editors

Catherine De Wolf is an Assistant Professor of Circular Engineering for Architecture at the Swiss Federal Institute of Technology of Zurich (ETH Zurich), where she conducts research on digital innovation towards a circular built environment. She has a dual background in civil engineering and architecture and completed her PhD at the Massachusetts Institute of Technology (MIT). She is a faculty member in the ETH Centre for Augmented Computational Design in Architecture, Engineering and Construction (Design++), the ETH AI Center, the Swiss Federal Laboratories for Materials Science and Technology (Empa), the Circular Future Cities group of the Future Cities Lab, and the National Centre of Competence in Research on Digital Fabrication (DFAB). She has worked in academia (e.g., University of Cambridge, University of Technology Delft, Nanjing University), in industry (e.g., Arup, Elioth, Ney & Partners), and in governmental institutions (e.g., Joint Research Centre of the European Commission). She also co-founded the circular construction company Anku, the Structural Engineers 2050 Commitment, and the Digital Circular Economy (DiCE) Lab.

Sultan Çetin is a PhD candidate at the Delft University of Technology. She received bachelor's degrees in Architecture and Civil Engineering in Turkey and a master's degree from Eindhoven Technology of University. Sultan worked as an Architect on international projects in Russia, Azerbaijan, and the Netherlands for several years. Since 2019, she has been conducting doctoral research on digitalisation for a circular building industry. She founded the Digital Circular Economy (DiCE) Lab with Catherine De Wolf in 2021. After the disastrous earthquakes in Turkey in 2023, she founded a network platform called RIAR (Research Industry Alliance for Recovery) to connect experts to find recovery solutions.

Nancy Bocken is a Professor in Sustainable Business and Circular Economy at Maastricht University, Maastricht Sustainability Institute (MSI) and is a leading researcher on topics such as sustainable business models, business experiments for sustainability, circular economy, and sufficiency. She is also a Fellow at Cambridge

Institute for Sustainability Leadership, advisor to TNO (Dutch association for applied scientific research) and a Board member of the Philips Foundation. Before going into academia, she held positions in the logistics, banking, and consulting sectors. She holds a PhD from the Department of Engineering, University of Cambridge and is a co-founder of her own circular and sustainable business, HOMIE.

Part I
Data

Chapter 1
From Building Information Modelling to Digital Twins: Digital Representation for a Circular Economy

Alexander Koutamanis

Abstract Building information modelling (BIM) has ushered in the era of symbolic building representation: building elements and spaces are described not by graphical elements but by discrete symbols, each with properties and relations that explicitly integrate all information. Digital twinning promises even more: a digital replica in complete sync with the building and its behaviour. Such technologies have obvious appeal for circularity because they accommodate the rich information it requires and link circularity goals to other activities in AECO (architecture, engineering, construction and operation of buildings).

Present implementations of BIM may fall short of the promise, and digital twinning may be hard to achieve, but they remain crucial not only for circularity but for all AECO disciplines. To realise the potential of such representations, information should be treated not as a product of integration but as the integrator of all activities. Similarly, digitalisation should be at the core of business models and deployment plans, not an additional or even optional layer at a high cost. This calls for a coherent approach that includes the full capture of building information, supports the detailed exploration of circular operations, uses the results to constrain decisions and actions and does so throughout the life cycle.

Keywords Information · Digitalisation · Representation · Building information modelling (BIM) · Digital twinning

1.1 Building Information Modelling and Digital Twinning

Rhetoric has three modes of persuasion: pathos, ethos and logos. Circularity is derived from pathos: appeals to emotions and ideals, expressing beliefs about the environment and materiality. It is reinforced by ethos: arguments from authorities and other credible sources, such as scientists and industry leaders. When it comes to

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C. De Wolf et al. (eds.), *A Circular Built Environment in the Digital Age*, Circular Economy and Sustainability, https://doi.org/10.1007/978-3-031-39675-5_1

implementing circularity, however, it is the logos that matters most: the reasoning that underlies business models, material flow calculations, feasibility assessments, implementation requirements, deployment plans, etc. Information is the basic resource for making such analyses and projections reliable and transparent: valid, meaningful data that describe past and future states of the world, providing input to and accommodating output from decision processes.

This chapter focuses on the critical, fundamental role of information in the context of circularity. It explains the two most relevant general-purpose technologies, building information modelling (BIM) and digital twinning, and links them to passports and logbooks proposed specifically for circularity. It then moves on to current and proposed uses of the technologies in AECO (architecture, engineering, construction and operation of buildings), including with respect to circularity, and concludes with guidelines for developing circularity business models and practical applications.

1.1.1 BIM

BIM is a frequently misrepresented and therefore misunderstood technology. Many poor definitions describe not the phenomenon itself but its applications and effects (Sacks et al. 2018), often from the perspective of existing analogue practices. The production of drawings and other conventional documents to incrementally improve efficiency or reduce errors takes up a disproportionate amount of the BIM literature but does not explain how BIM is structured and how its structure helps to achieve certain objectives. Instead, it makes BIM appear as a mere step in AECO computerisation. The truth is more revolutionary: BIM marks the transition to *symbolic representation* (Koutamanis 2022). While earlier technologies like computer-aided design (CAD) focused on the graphic implementation mechanisms of building representations, BIM makes explicit the symbols described by these mechanisms.

Symbolic representation is already the norm in many computer applications. In a digital text, the capital ‘A’ is not a group of three strokes, as in handwriting, but the Unicode symbol U+0041, explicitly entered through a keyboard and stored as such, regardless of how it appears on the screen. Any change to the symbol does not come from changing the three strokes but from changing the properties of the symbol (e.g. a different font or size) or switching to a different symbol (e.g. U+1D434 for the mathematical capital ‘A’). Symbolic representation underlies a lot of machine intelligence. In digital texts, knowing each letter allows computers to recognise words and sentences and subsequently understand grammar and syntax.

Similarly, in BIM, a window is not the group of line segments one sees in a graphic view like a floor plan but a symbol explicitly entered in a specific location of a wall. One can reposition the window in the wall, but changing its type or even its size may require switching to a different symbol. The interfaces of BIM software tend to depart from facsimiles of analogue drawing, which confuse users into

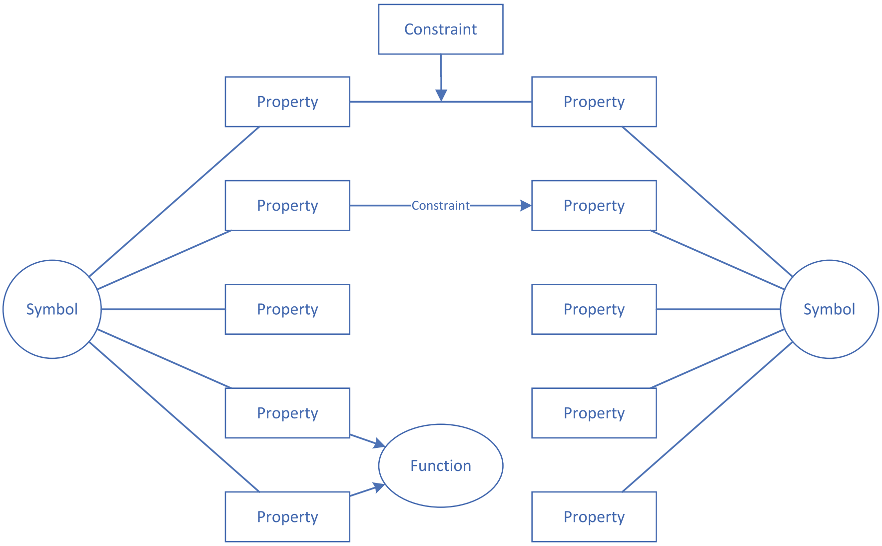

Fig. 1.1 Symbols, properties and connections

thinking that they are drawing and obscure the symbolic structure of the model. We should think of BIM models not as 2D or 3D drawings with additional data but as *graphs* of interconnected symbols. In fact, connections are between specific symbol properties (Fig. 1.1): the co-termination of two walls links the endpoints of their axes, while the orientation of a wall is inherited by the windows it hosts.

External constraints, such as the maximum height of a roof in planning regulations, are also linked to relevant symbol properties, while other constraints affect relations between two symbols, such as when windows are not allowed in certain wall parts. As a result, all primary information resides in the properties and relations of the symbols in a model. This allows for the derivation of further information through functions, e.g. calculations of fire resistance on the basis of the material composition of a building component. It also supports the production of various views of the model, including conventional drawings. As for machine intelligence, the potential is already evident in the *behaviours* of symbols: a window sticks to the hosting wall, and the shape of a room follows the bounding building elements.

Integration, a key selling point of BIM, comes from this symbolic structure. With all information residing in symbols, there are no multiple representations from different disciplines that must be combined to obtain a full description. Instead, all actors have access to different symbols, properties and relations in a model, in adjustable *worksets* that give them specific rights and responsibilities. This integration of information and its dynamic relation to authorship and custodianship also mean that information processing and AECO activities can be accommodated in BIM. The same holds for continuity through phases and stages: a symbolic representation can contain the entire history of a building.

BIM is often called ‘object-oriented’. This is misleading because the term has a different meaning in computer science but also because we should not equate symbols with real things. In English, the letter ‘a’ corresponds to five different sounds (phonemes). Knowing how to pronounce the letter depends on the context (the word). When considering representations in building, the correspondence between symbols and things can be even fuzzier. A window may be considered a discrete component, but a wall is an assemblage with variable composition and indeterminate form. Its material layers often continue into other walls, forming construction networks that are not captured by wall symbols in BIM. A main reason for this is geometric bias: continuous walls are segmented into separate symbols by the geometry of their axes.

Despite such fuzziness and resulting ambiguities, the symbolic representation underlying BIM remains the obvious choice for AECO computerisation, with a potential similar to that of the Latin alphabet or the Hindu-Arabic numerals. The graph of symbols and their relations is a transparent, consistent and efficient foundation for any application. The capacity for integration and continuity means that information efforts can be consolidated into a single representation that caters for all aspects, goals and disciplines.

1.1.2 Digital Twinning

While the use of BIM has yet to reach a satisfactory level or achieve significant efficiencies, AECO has already adopted a new buzzword: digital twinning. In contrast to BIM, digital twinning has yet to consolidate into a recognisable technology. Quite frequently, any virtual model seems to qualify as a digital twin, purely on the basis of intent. However, a digital twin is more than a model: it is a digital replica of something physical. It describes the form, behaviour and performance of the thing, including uses, users and direct context – all that is required for precise and accurate analyses and forecasts of future states of the physical twin.

Information in a digital twin is dynamic and reciprocal: sensors in the physical twin that monitor temperature, light, sound, occupancy, vibration, etc., send their data to the digital twin, where they become attached to relevant properties of the appropriate symbols. The products of the digital twin travel in the reverse direction, guiding actuators in operational adaptations, e.g. the functioning of heating systems, and informing users through displays (Fig. 1.2). In other words, the twins are connected in both directions in near real time and are capable of communication and synchronisation (Chen 2017; Liu et al. 2018). Consequently, we can distinguish between representations (static models, as in BIM), shadows (representations which are updated by data from the physical things) and twins (full two-way synchronisation) (Fuller et al. 2020; Sepasgozar 2021).

Digital twins of buildings are invariably based on BIM (Boje et al. 2020; Sacks et al. 2020; Begićžand Galićž2021; Mêda et al. 2021; Shahat et al. 2021; Tagliabue et al. 2021; Alibrandi 2022; Shaharuddin et al. 2022). At the same time, it is stressed

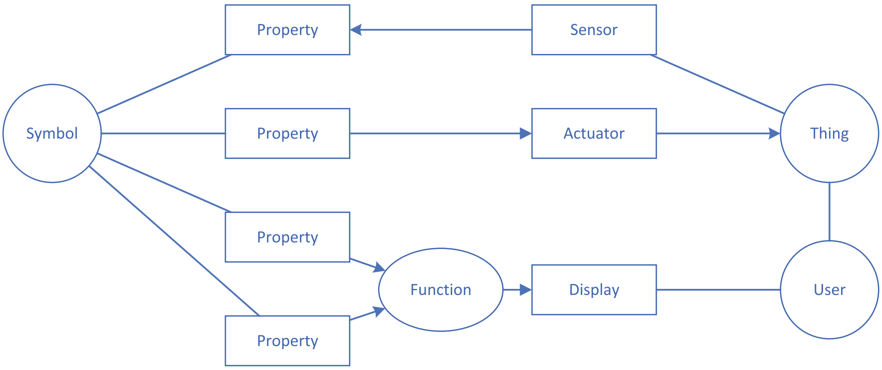

Fig. 1.2 Connections between symbols in a digital twin and things in a physical twin

that digital twinning is more than BIM, as it includes sociotechnical and process aspects, especially in use (Boje et al. 2020; Davila Delgado and Oyedele 2021; Sepasgozar 2021). This makes it significantly more demanding than as-built BIM in terms of reliability, precision and completeness. Furthermore, it is questionable whether BIM can accommodate and process the big data produced by sensors in the built environment. Rather than a foundation, BIM is a predecessor to digital twinning, based on the same symbolic approach to representation (Boje et al. 2020; Koutamanis et al. 2021).

More than on BIM, digital twinning relies on the Internet of Things (IoT): the networks that connect sensors, actuators and displays in a building, making it 'smart', i.e. automating certain operations, such as opening doors and regulating ventilation systems. In addition to such local automation, the IoT also collects data from all sources to capture the history and the overall conditions in a building. This improves local operations by connecting them to global goals and constraints. The IoT is not just an enabler but a necessity because digital twinning presupposes a building heavily populated by IoT for bidirectional communication and synchronisation, including feedback to users and operators (Farsi et al. 2020; Fuller et al. 2020; Lu et al. 2020; Sepasgozar 2021). The collection of data for digital twinning could be much more extensive than in most smart buildings, resulting in a lack of suitable physical twins and possibly rendering digital twinning a pipe dream. Alternatively, one could tolerate low-fidelity solutions as early deployment stages and encourage incremental development (Mêda et al. 2021). However, experience with BIM maturity levels suggests that such tolerance is self-defeating because it provides alibis for not taking the trouble to use the technology properly while continuing processes that actually undermine it. The degree of validation and verification required in digital twinning makes any attempt to pass off static models as twins as misguided as calling 2D drawings BIM.

1.1.3 Passports and Logbooks

BIM and digital twinning are general-purpose technologies. There are also stand-alone information technologies specifically developed for circularity in AECO. These are referred to by terms such as *building* or *material passport* or *logbook*. Chapter 5 by Honic et al. in this book describes the potential of such technologies and relevant life cycle and standardisation challenges in detail. Therefore, from the perspective of this chapter, it suffices to emphasise that BIM, as an integrated information environment, is more than a useful source of data (Durmišević 2018; Bertin et al. 2020). There is a significant overlap between BIM and material or building passports (Charef and Emmitt 2021), even when the latter are based on other sources for product composition breakdown.

The advantage of BIM is that it makes materials situated and connected to life cycle processes (Honic et al. 2019). This supports design for deconstruction and disassembly (Minunno et al. 2018; Xing et al. 2020; Marzouk and Elmaraghy 2021; O'Grady et al. 2021) and other circularity goals. Translating manufacturers' disassembly instructions into simulations in BIM improves legibility and completeness, especially concerning resources that may be available or required. It also verifies the disassembly procedures and validates designs with respect to them. Including the location of a component among its metaproperties in a passport does not offer the same advantages.

In conclusion, passports and logbooks are amenable to the integrating power of BIM and digital twins, which can accommodate product information (Kebede et al. 2022), life cycle energy data (Shah et al. 2023) and other key information in their properties and relations. In BIM, information collections such as material passports can become views of the model, similarly to bills of quantities. Linking their goals and constraints to all activities in design, construction and operation through BIM returns connections to information sources that help make material flow registration and analysis realistic and reliable (Miatto et al. 2022).

1.2 BIM in the Built Environment

There is general agreement that digital uptake in AECO is slow and limited, even though investment in digitisation may not be that low (Turk 2021; Koutamanis 2022). Nevertheless, BIM was received with unprecedented willingness and optimism as a solution to major inefficiencies and malperformances (Sacks et al. 2018; Ernstsen et al. 2021), but rapid adoption was not accompanied by a scope wide and coherent enough to effect fundamental changes. There are persistent complaints about BIM costs, complexity and social and organisational aspects that contrast with its arguably unrealistic promotion (Miettinen and Paavola 2014; Oesterreich and Teuteberg 2019) and put smaller enterprises at a disadvantage (Dainty et al. 2017; Murguia et al. 2023). BIM is commonly deployed in hybrid situations, where it overlaps with other technologies (Davies 2017). This conflicts with the holistic character of BIM and reduces its potential. As AECO remains attached to existing, document-based practices, BIM is generally restricted to office use and the production of such documents. Out of the office, the reliance of AECO on low-cost human labour does little to promote digitalisation.

Even in office use, BIM has not always facilitated innovation. Its emphasis on integration and interoperability is not linked to models of labour division and specialisation (Turk 2020). It is also questionable that complex assemblages such as buildings can be broken down into hierarchical ontologies by merely observing real-world buildings and following pre-existing, paper-based standards (Koutamanis et al. 2021). Unfortunately, such limitations are seldom experienced, as most applications and models tend to remain selective, partial and restricted to specific tasks, such as clash detection between load-bearing structures and building services.

BIM has yet to make its presence felt beyond design and construction, in the costly and resource-intensive use stage (Gao and Pishdad-Bozorgi 2019; Abideen et al. 2022; Benn and Stoy 2022; Durdyev et al. 2022; Matos et al. 2022; Pinti et al. 2022; Tsay et al. 2022). Making and especially maintaining as-is models appears to be beyond the scope or capacities of most organisations, which are already overwhelmed by the amount of existing information and the multiplicity of channels through which they exchange information.

1.3 BIM and Digital Twinning for a Circular Economy

BIM, while not perfect, remains preferable to its predecessors and indicative of the symbolic direction building representations are taking. Implemented properly, it offers information integration and continuity, unambiguous interpretation by both humans and machines and full and reliable support of complex analyses. This supports goals such as circularity and the information-intensive processes they require.

At the same time, present limitations in BIM create interest in technological advances. Digital twinning promises the additional capacity to accommodate and process all states of the physical twin, past and present (Rafael Sacks et al. 2020). This helps transform static evaluations into dynamic life cycle processes, combining, e.g. end-of-life assessment with adaptable planning (Chen et al. 2021). This transition from static to dynamic is demanding but seems justified by feasibility evaluations, which confirm a significant potential for improved life cycle assessment and control (Tagliabue et al. 2021).

Neither BIM nor digital twinning are goals for AECO; they are means towards domain-specific performances. Moreover, circularity may be viewed as an imposed, external societal constraint. As with any such constraint, it may conflict with established practices and be poorly served by existing tools, which are attuned to other priorities. To remove such obstacles, the general capacities of digital twinning, BIM and digitalisation should be taken for granted, and attention should be on specific, critical issues (Çetin et al. 2021). General intentions, such as reducing inefficiencies, improving communication, optimising design performance or just providing visualisations (Wong and Fan 2013; Akinade et al. 2017; Minunno et al. 2018; Charef and Emmitt 2021), can be relevant but do not amount to a specific, coherent approach.

1.3.1 Registration of Relevant Information

The first step in a coherent approach to circularity with BIM or digital twins is to learn to rely on symbolic representation. Any full model or twin can easily cover circularity information needs without additional investment, but in practice representations can be selective or opportunistic and hence incomplete or inconsistent. Deferring the information burden to any particular goal and its stakeholders (as with passports) is not a viable option. Instead, all AECO stakeholders should insist on joint, permanent working environments, not disconnected repositories or documentation for different phases. There can be no half-hearted BIM or digital twin deployment: economising on investment means severely limited potential and low returns.

The first reason why a digital solution cannot be made for circularity solely is *cost:* the value of what it supports can hardly be justified by the returns, certainly in the perception of most AECO stakeholders with different priorities. General-purpose solutions such as BIM are clearly preferable because they support most such priorities. If circular goals can be added to them, then circularity stakeholders can reap the benefits, while others are stimulated to include circularity in their considerations.

The perennial question in AECO is not so much who makes a BIM model but who maintains it, especially in the life cycle of a building. If this does not happen collaboratively by conjoining the core processes of all actors, and preferably automatically, there is little hope for success. Collaborative solutions also lower the participation threshold for smaller enterprises and offer enticing benefits in terms of digital support and room for fruitful specialisation. In return, the enterprises contribute to the completeness and up-to-dateness of information simply by using it.

The second reason for a lack of digital solutions for circularity is *selectivity:* any information solution motivated primarily or exclusively by circularity inevitably remains restricted to circularity factors and aspects. It may even suffer from inattentional blindness, which causes omissions of important data simply because we concentrate on other matters (Chabris and Simons 2010). One can naturally work with conscious concentration towards a full, inclusive solution, but then the results would amount to something akin to BIM or digital twins, i.e. a comprehensive solution that could only justify costs and improve returns by being open to other goals and priorities, too.