Build Digital

Sustainability & Circular Economy

Sustainability & Circular Economy Horizon Scan and Needs Analysis

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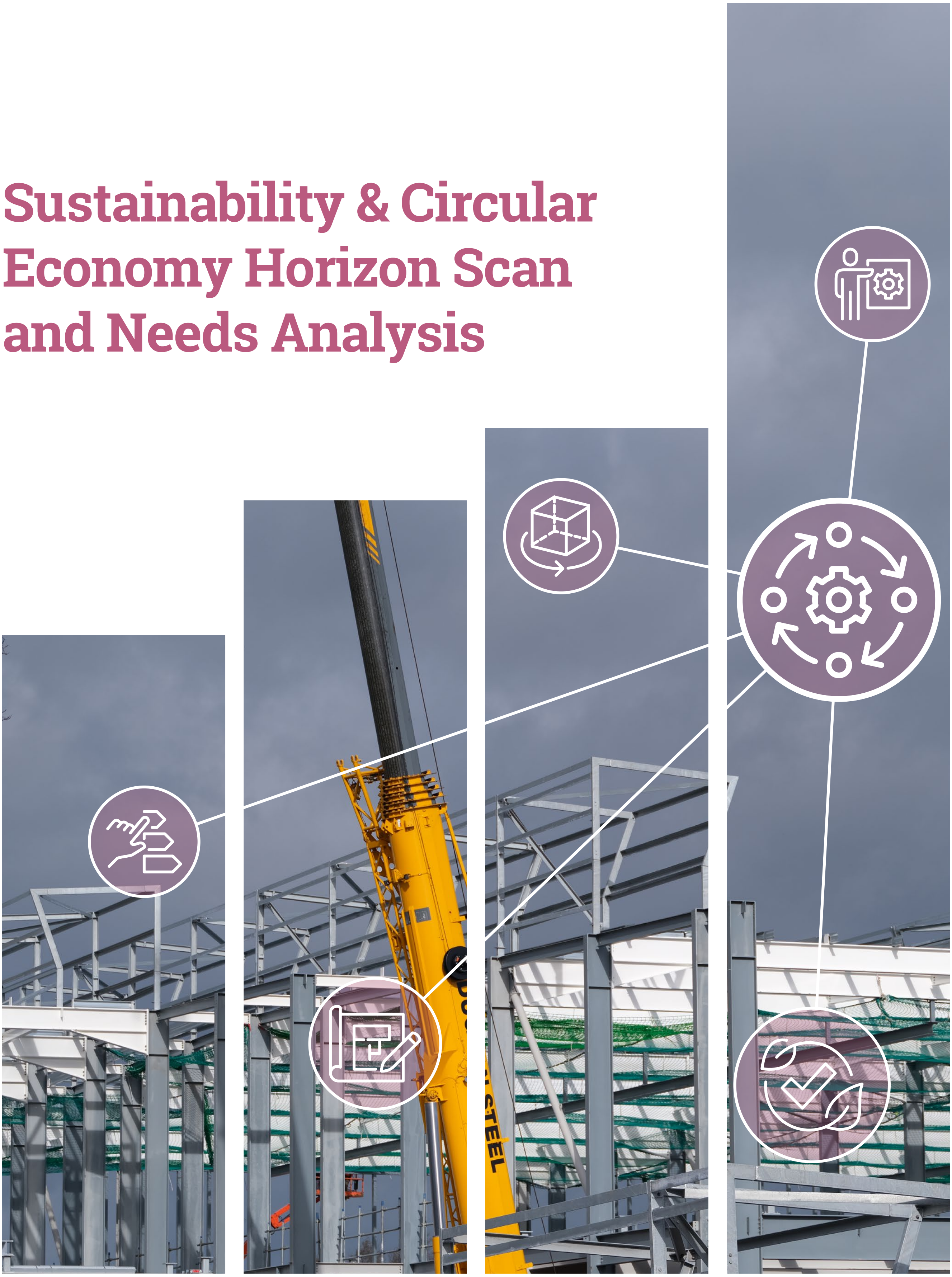

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Preface

Build Digital intends to support the digital transformation of the Irish construction and built environment sectors. They will enable stakeholders, particularly SMEs, clients, and suppliers, to develop, maintain, and continuously improve their capabilities as digitally enabled, standards-based, agile, collaborative, and sustainable participants in the delivery of Project Ireland 2040.

Build Digital, co-funded by the Department of Public Expenditure, NDP Delivery and Reform (PENDR), is one of the seven priority actions implemented by the Construction Sector Group Innovation and Digital Adoption Sub-Group.

A vital tenet of Build Digital is the adoption of a bottom-up approach where the voice of the customer is heard and acted upon. Build Digital has embedded over 50 industry members from across the construction supply chain within its five pillars.

Digital Leadership and Cultural Change, Pillar 1, will drive the cultural change required to realise the digital transformation of the Irish construction industry in support of innovative, effective, and sustainable evolution in mindset and practice. To achieve this, Pillar 1 will provide evidence and develop tools to assist the industry in its digital adoption journey.

Digital Standards, Pillar 2, will champion the benefits of common rules, guidelines, and workflows that facilitate the improvement of information flow and information management across full asset life cycles. Digital standards provide a common language that can be translated to technical specifications enabling clients, designers, contractors, and facilities managers, irrespective of their preferred tools, to communicate efficiently and reduce cost, rework, and disputes. To achieve this, Pillar 2 will develop tools with the assistance of the Digital Procurement pillar for the industry to better understand and work to standards

Digital Education and Training, Pillar 3, are key to the digital transformation of the Irish construction sector. Clients, managers, professionals, and all workers need to have relevant knowledge and abilities to collectively advance the design, construction, and life cycle management of the built environment. To achieve this, Pillar 3 will develop a comprehensive inventory of upskilling courses available for high-quality, consistent delivery across Ireland, supported by a wide range of professional bodies, representative groups, and public and private educational organisations.

Digital Procurement, Pillar 4, will bring national and international expertise on best practice in sustainable digital procurement and digital product supply chain practices to the forefront of the Irish sector. This pillar will drive greater efficiency, sustainability, and productivity in delivering successful construction project outcomes by enabling an integrated green, lean, and digital thread of information across the project life cycle. To achieve this, Pillar 4 will develop tools that will make it easier for SMEs across the entire construction supply chain to learn how to adapt to more agile, digitally-enabled procurement practices.

Sustainability and Circular Economy, Pillar 5, will encourage the industry to move towards a more circular economy with a built environment sector that prioritises designing out waste while viewing products, components, and assets as valuable resources that should retain utility for as long as possible. To achieve this, Pillar 5 will develop a number of tools for SMEs and clients that enable a reduction of consumption by designing out waste and enabling a more circular approach in Irish construction.

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Abbreviations

AI	Artificial Intelligence
BAMB	Buildings As Material Banks
BD	Big Data
BER	Building Energy Rating
BIM	Building Information Modelling
BMS	Building Management Systems
BRPs	Building renovation plans/passports
CDE	Common Data Environment
CDW	Construction and Demolition Waste
CE	Circular Economy
CIBSE	Chartered Institute of Building Services Engineers
CPSs	Cyber-physical Systems
DASBE	Digital Academy for the Sustainable Built Environment
DfP	Design for Performance
DSM	Dynamic Simulation Modelling
DSY	Design Summer Year
EEA	European Economic Area
EPA	Environmental Protection Agency of Ireland
EPDs	Environmental Product Declarations
EU	European Union
GDPR	General Data Protection Regulation
GIS	Geographic Information System
IFC	Industry Foundation Classes
IGBC	Irish Green Building Council
IoT	Internet of Things
LCA	Life Cycle Assessment/Analysis
NABERS	National Australian Built Environment Rating System
NEAP	Non domestic Energy Assessment Procedure
OECD	Organisation for Economic Co-operation and Development
OPW	Office of Public Works
PDT	Product Data Template
POE	Post Occupancy Evaluation
REFIT	Revision of the Construction Products Regulation
SEAI	Sustainable Energy Authority of Ireland
SoS	System of Systems
TRY	Test Reference Year
VOS	Visualisation of Similarities
WEF	World Economic Forum
WGBC	World Green Building Council
WLC	Whole Life Carbon
WoS	Web of Science
ZEB	Zero-Emission Buildings

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Aidan Bermingham, OPW

Lorraine Fitzgerald, Glenveagh

Executive Summary

The construction industry plays a crucial role in addressing the climate crisis as it is the largest global consumer of raw materials and contributes significantly to global energy consumption and emissions. Considering the world's continuous population growth and the imperative to address infrastructure and housing demands, the construction sector needs to adopt further sustainable strategies in its activities to reduce the pressure on natural resources. In addition, the Architecture, Engineering, and Construction (AEC) sector is responsible for generating a substantial amount of waste known as Construction and Demolition Waste (CDW), which is projected to increase due to future construction developments.

Increasing circularity in construction projects could reduce the need for the extraction of raw materials and minimise waste generation by creating closed-loop systems and keeping materials, components, and products in use for as long as possible. The circular economy (CE) is a sustainable development model offering an alternative to the traditional linear 'take-make-waste' model where resources are re-used or recycled as much as possible, and the generation of waste is minimised. In this model, materials and assets are kept in circulation through processes such as reuse, repair, refurbishment, remanufacture, and recycling by restorative and regenerative design.

Thus, the transition to a circular built environment is a viable solution for addressing the negative environmental impacts of the construction industry. Enabling this transition also requires the digitalisation of the AEC sector. Digitalisation can facilitate the transformation towards the adoption of a circular economy in the built environment by closing the material loops by providing accurate information on the availability, location and condition of products, and integrating the stakeholders. In this regard, this report provides a systematic literature review on digitalisation for adoption of circular economy principles in the built environment to identify the current gaps, applicable technologies for facilitating the adoption of CE in the built environment, circular economy frameworks, and circular economy projects and case studies across the EU.

PART 1

Introduction

1.1. Context

The built environment sector has a vital role to play in responding to the climate emergency. The engineering and construction industry is the world's largest consumer of raw materials (Arup, 2016; Guerra & Leite, 2021; Dixit et al., 2022; Nodehi & Taghvaee, 2022). According to the Organisation for Economic Co-operation and Development (OECD) (2019a), the construction industry is responsible for almost 50% of the worldwide annual resource consumption (World Green Building Council, 2019a; OECD, 2022). Buildings are also responsible for 30% of global final energy consumption and 27% of total energy sector emissions (8% being direct emissions in buildings and 19% being indirect emissions from the production of electricity and heat used in buildings)(IEA, 2022). It is notable that both energy consumption and emissions rebounded to above 2019 values, following a drop in 2020 due to Covid-19 restrictions (IEA, 2022). According to the Organisation for Economic Co-operation and Development (OECD) (2019a), the construction industry is responsible for almost 50% of the worldwide annual resource consumption (World Green Building Council, 2019a; OECD, 2022). Buildings are also responsible for 30% of global final energy consumption and 27% of total energy sector emissions (8% being direct emissions in buildings and 19% being indirect emissions from the production of electricity and heat used in buildings) (IEA, 2022). It is notable that both energy consumption and emissions have rebounded to above 2019 values, following a drop in 2020 due to Covid-19 restrictions (IEA, 2022).

Buildings are also responsible for 40% of global energy-related CO2 emissions (World Green Building Council, 2019a; OECD, 2022). Twenty-eight percent of these carbon emissions are from operational emissions, including the energy needed to heat, cool and power them, and the remaining 11% are carbon emissions released during the manufacturing, transportation, construction, and end-of-life phases of all built assets, including buildings and infrastructure. These emissions are referred to as embodied carbon and include emissions from the processing of raw materials, manufacturing of products both on and off-site, as well as the emissions associated with the maintenance and end of life of the materials and products used in the built environment which have largely been overlooked historically (World Green Building Council, 2019a; O'Hegarty et al., 2022). Carbon emissions released before the building or infrastructure begins to be used, also called upfront carbon, will be responsible for half of the entire carbon footprint of new construction between now and 2050 (World Green Building Council, 2019a). It is notable that as operational carbon is reduced, embodied carbon will continue to grow in importance as a proportion of total emissions. Considering that more than half of total carbon emissions from new construction between 2020 and 2050 will be due to upfront emissions (World Green Building Council, 2022), and while it is necessary to continue to focus on addressing operational carbon, the efforts to tackle embodied carbon emissions at the global scale needs to be rapidly increased as well (World Green Building Council, 2019a).

As a result, according to the World Green Building Council (WGBC) (2019a), by 2030, all new buildings, infrastructure, and renovations must be net zero operational carbon and will have at least 40% less embodied carbon with significant upfront carbon reduction. In addition, new buildings, infrastructure, and renovations will have net zero embodied carbon, and all buildings, including existing buildings, must be net zero operational carbon by 2050.

While the world's population is predicted to reach 10 billion by 2060 (OECD, 2019b), the global building stock is expected to double by 2060 (World Green Building Council, 2019a; 2019b; OECD, 2022). It is also predicted that the global construction market is set to grow by US$8 trillion by 2030, reaching a total size of $US17.5 trillion, up by 85% and growing by an average annual rate of 3.9% to 2030 (CIOB, 2015). Considering that by 2050, roughly two-thirds of the world's population will be living in cities and three billion people will need new housing by 2030 (Çetin, Wolf & Bocken, 2021), with improved living standards, the need for construction and energy consumption will increase (International Energy Agency, 2013). Thus, unprecedented growth due to population pressures and urbanisation will put even more pressure on natural resources by 2050 (Iyer-Raniga, 2019).

Currently, the construction sector is responsible for about 23% of air pollution, 50% of climate change gases, 40% of drinking water pollution, and 50% of landfill waste. Also, 50% of ozone depletion is caused by buildings, in addition to the consumption of about 40% of raw stone, gravel, and sand as well as 50% of water each year (Dalirazar & Sabzi, 2020).

Building elements such as foundations, frames, and other forms of superstructure often represent the largest contribution to embodied carbon because of the large volumes of material they use. In addition, these elements often contain carbon-intensive and load-bearing structural materials such as steel, concrete, and masonry (World Green Building Council, 2019a). In this regard, according to the World Green Building Council (2022), cement manufacturing is responsible for 7% of global carbon emissions, with steel contributing a further 7–9%. Approximately half of these emissions are attributed to buildings and construction (World Green Building Council, 2019a).

Furthermore, both cement and steel require very high temperatures during production, making them energy and carbon-intensive (World Green Building Council, 2019a). According to the IEA (2022), the final energy use associated with cement, steel, and aluminium production accounts for 34% of the final energy consumption in buildings in 2021. Other common construction materials, including aluminium and glass, require high temperatures during manufacturing (World Green Building Council, 2019a).

Global cement consumption is also estimated to increase by 12–23% by 2050, while global steel production is projected to grow by 30% over the same period, with recycled secondary steel growing faster than primary production. These materials therefore have an important role to play in radical decarbonisation (World Green Building Council, 2019a). Furthermore, the global demand for steel, aluminium, cement, and plastics is expected to increase, making up two-thirds of the industry's total emissions, with the remaining one-third comprising non-material sources (Iyer-Raniga, 2019).

It is also important to note that the construction sector is the most resource-intensive sector in industrialised countries, using 50% of all materials consumed in Europe. The sector creates 36% of the total waste in the European Union (EU) while emitting 39% of the global energy-related greenhouse gas emissions due to its linear model of extracting, producing, using, and disposing of building materials and resources (Çetin, Wolf & Bocken, 2021).

Without rapid changes in the way that the construction sector operates, this growth will consume vast amounts of natural resources, contributing to an expected doubling of the total global consumption of raw materials towards the middle of the century, and significantly increasing the sector's emissions and climate impact (World Green Building Council, 2019a).

As a result, this sector needs to use the principles of saving in its activities and should apply changes in how its activities are carried out. Transforming the existing linear process to a circular process that increases the use of recycled and renewable resources while reducing energy consumption and the usage of natural resources is essential (Akanbi et al., 2019). Even when carbon emissions are reduced through good design and specification, utilising the best available approaches, technologies, and materials, there remains a significant residual carbon impact that can only currently be addressed through offsetting. A transition to a fully decarbonised building and construction sector requires a complete shift from fossil fuels in building operations (both new and existing), supply chains, and construction processes, as well as maximising opportunities for circularity in materials and buildings (Burrows & Watson, 2021).

1.1.1. Embodied Carbon, Energy, and Materials Consumption: Europe

The building sector is crucial for achieving the EU's energy and environmental goals. In addition, better and more energy-efficient buildings will improve the quality of life for citizens and reduce energy poverty while bringing additional benefits such as improved health, better indoor comfort levels, and green jobs for the economy and society (European Commission, 2018a).

In Europe, buildings are responsible for approximately 40% of EU energy consumption and 36% of energy-related greenhouse gas emissions (European Commission, 2018a; Cardellini & Mijnendonckx, 2022).

In order to reduce energy consumption and carbon emissions by the building sector and to boost the energy performance of buildings, the EU established a legislative framework that includes the Energy Performance of Buildings Directive 2010/31/EU and the Energy Efficiency Directive 2012/27/EU (European Commission, 2018a). According to the 'Energy Performance of Buildings Directive' (OJ L 153 18.6.2010, p. 13) (EUR-Lex, 2021), it is proposed to move from the current nearly Zero-Emission Buildings (nZEB) to zero-emission buildings by 2030. Furthermore, according to this directive (EUR- Lex, 2021), the ZEB requirement should be applied as of January 1st, 2030 to all new buildings and as of January 1st, 2027 to all new buildings occupied or owned by public authorities (European Commission, 2018b).

It is notable that, according to the proposal of the directive (EUR-Lex, 2021), a nearly zero-energy building is defined as "a building that has a very high energy performance, while the nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby", while a ZEB is defined as "a building with a very high energy performance, with the very low amount of energy still required fully covered by energy from renewable sources and without on-site carbon emissions from fossil fuels".

The construction and use of buildings in the EU also account for approximately half of all extracted materials (EUR-Lex, 2014). Additionally, Construction and Demolition Waste (CDW) is the largest waste stream by volume in the EU (Bilsen et al., 2018), accounting for over 800 million tonnes per year, comprising approximately 32% of the total waste generated (Commission, 2018). The EU construction sector also generates approximately one-third of the total waste generated in the EU (Bilsen et al., 2018). This sector is associated with environmental pressures that arise at different stages of a building's life cycle, including the manufacturing of construction products, building construction, use, renovation, and the management of building waste (EUR-Lex, 2014). It is notable that a large majority of CDW is recyclable. However, with the exception of a few EU Member States recycling up to 90%, the average recovery for the 27 European Union countries is just below 50% (EUR-Lex, 2014).

Recycling CDW can lead to significant resource and environmental benefits. For example, metals would have an overall reduction of impacts of more than 90% for aluminium and copper and approximately 15% for low-alloyed steel. Recycling concrete, the most used material in buildings, reduces natural resource depletion and landfilling of waste. Concrete can often be recycled at demolition or construction sites close to urban areas where it will be reused, resulting in reducing transport demand with savings in cost and related emissions (EUR-Lex, 2014). Recycling also enables savings for other materials. For flat glass (used for windows etc.), one tonne of recycled material results in savings of 1200 kg of virgin material, 25% of energy, and 300 kg of

CO_2 emissions, which is directly linked to the melting process (EUR-Lex, 2014).

In addition to the environmental benefits, manufacturers would find economic opportunities when using recycled material. For instance, the flat glass industry in the EU sees a market price for recycled glass of about €60–80 per tonne, sufficiently below the €90 per tonne necessary to compete with virgin material. In the case of glass, there is therefore often an economic benefit for manufacturers to use recycled material. However, the market demand for recycled material remains low (EUR-Lex, 2014).

Furthermore, recycling materials can result in job growth in the deconstruction, sorting, and recycling of construction materials which is typically local work and would create job opportunities throughout Europe (EUR-Lex, 2014).

Despite the potential for significant economic and environmental benefits when recycling CDW, large parts are still landfilled or backfilled, with metals currently the main materials to be recycled due to their high value and existing markets (EUR-Lex, 2014).

In order to promote a more efficient use of resources consumed by new and renovated commercial, residential, and public buildings, and to reduce their overall environmental impacts throughout the full life cycle, the European Commission published a communication titled 'Resource efficiency opportunities in the building sector (COM(2014) 445 final)', which is part of its circular economy package (EUR-Lex, 2014).

Furthermore, in order to transition to a Circular Economy (CE) approach, the European Commission has introduced a new Circular Economy Action Plan (COM(2020) 98 final) (European Commission, 2020b) and a European framework for sustainable buildings named Level(s) (European Commission, 2022b). Also, in response to the Paris Agreement's demand that the building and construction sector be decarbonised by 2050, Level(s) supports the essential assessment over the full life cycle, including design, construction, use, and end-of-life phase. In addition, to build upon the objectives of both the EU Green Deal and the EU Circular Economy Action Plan, Level(s) supports the efforts of the building sector in improving energy and material efficiency, resulting in the reducing of overall carbon emissions (European Commission, 2022b).

1.1.2. Embodied Carbon, Energy, and Materials Consumption: Ireland

According to the Irish Green Building Council (IGBC) report, launched by IGBC on May 6th, 2022 (Irish Green Building Council, 2022), construction and the built environment are directly responsible for 37% of Ireland's emissions. This is made up of about 23% operational emissions associated with the energy used to heat, cool, and light the buildings, while a further 14% are embodied carbon emissions from the mining, quarrying, and production of construction materials, as well as the transport of materials, construction process, maintenance, repair, and disposal of buildings and infrastructure (O'Hegarty et al., 2022).

In addition, according to a report by EPA (2022), the construction and demolition sector in Ireland generated an estimated 8.2 million tonnes of waste in 2020 (based on data reported by authorised waste collectors and local authorities), representing a decrease of nearly 0.6 million tonnes on the 8.8 million tonnes of CDW generated in 2019. However, this decrease is considered a result of the Covid 19 restrictions on the building industry. According to Figure 1, the annual quantity of CDW generated in Ireland displays an increasing trend, and has increased considerably from 2014 to 2019. This corresponds with a steady increase in the level of construction activity nationally (Environmental Protection Agency, 2022).

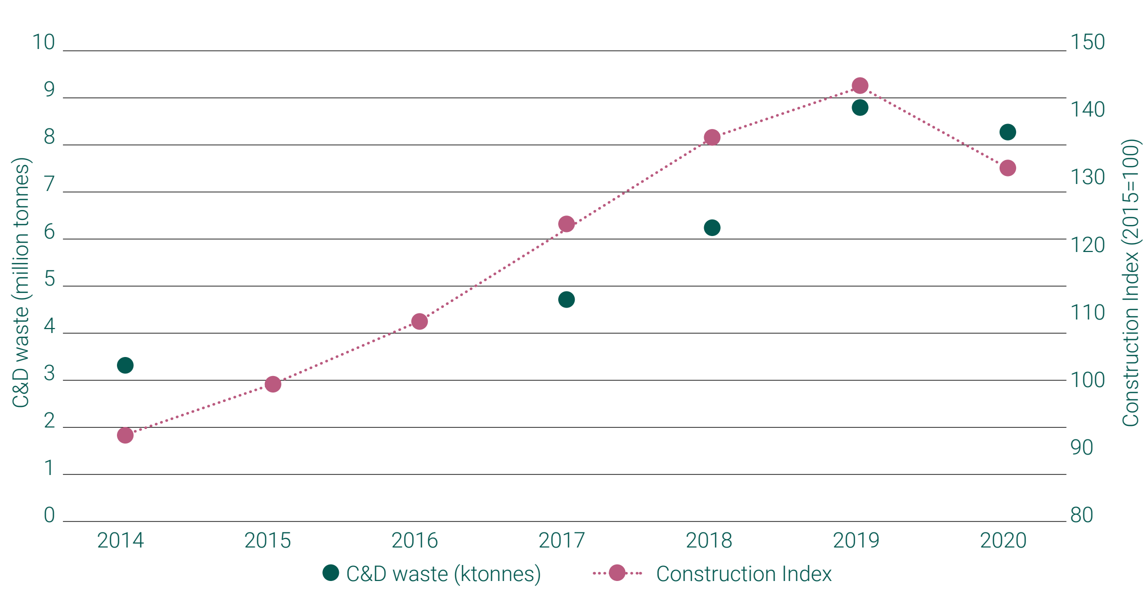


Figure 1
Quantity of Construction Waste Managed in Ireland, Compared With CSO Construction Index (Environmental Protection Agency, 2022).

In the baseline year, 2018, operational-related emissions accounted for 62% of all built environment emissions and 23% of national emissions. In the same year, capital or embodied-related emissions accounted for 38% of all built environment emissions and 14% of national emissions. Furthermore, operational carbon from the residential sector continues to dominate built environment emissions, accounting for 43% of the built environment-related emissions and 16% of national emissions in 2018. Hence, this is a key target area of national climate policy. It is also notable that emissions related to the operation of residential, commercial, and public buildings account for the most significant share of built environment emissions. The residential sector accounts for more than half of all building operational emissions. This is due to the scale of the sector (more than 2,000,000 units), the magnitude of the energy requirement of the sector (35 GWh/year), and its reliance on fossil fuels (75%), particularly for heating (O'Hegarty et al., 2022).

According to the IGBC report (2022), since 2011, embodied carbon has steadily increased in Ireland, as shown in Figure 2. Operational carbon emissions will decrease in line with a reduction in the carbon intensity of electricity, thus resulting in a proportional increase in embodied carbon-related emissions.

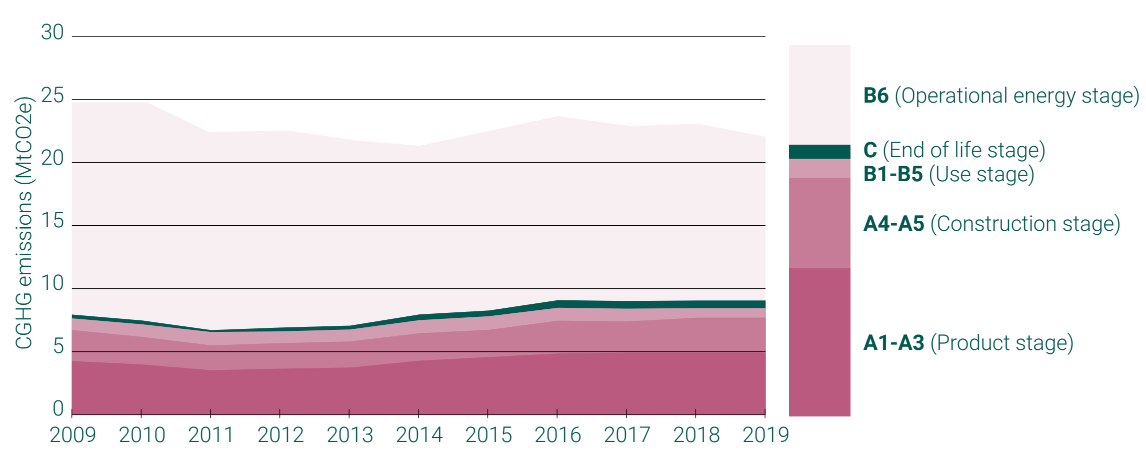


Figure 2
Embodied Carbon of the Built Environment Divided into Life Cycle Analysis States Defined in EN 15978 (O'Hegarty et al., 2022)

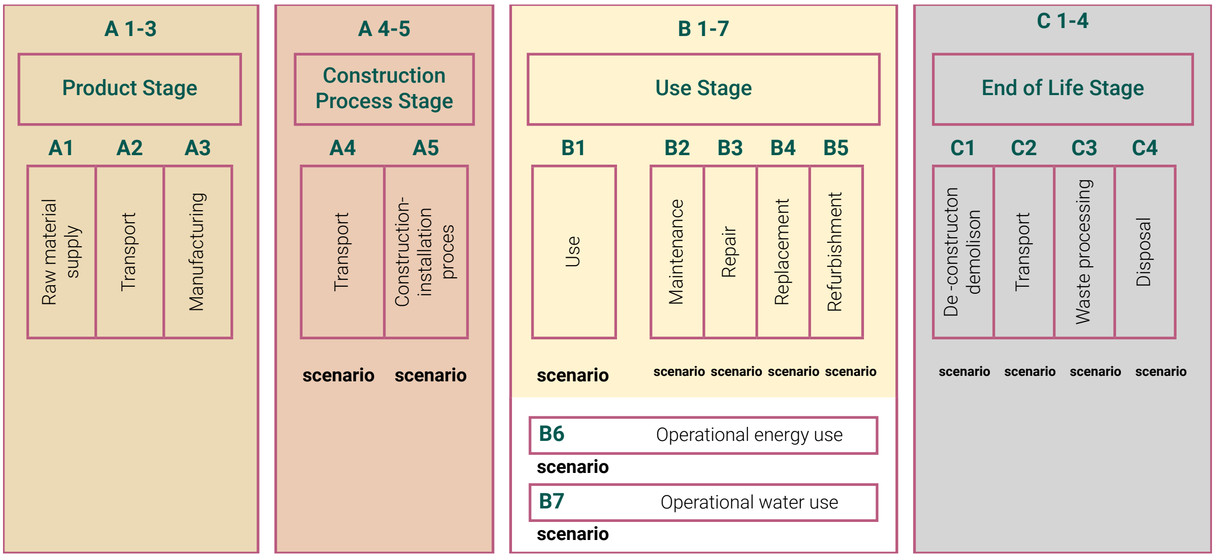


Figure 3
Extract From EN 15978 Sustainability of Construction Works – Assessment of Environmental Performance of Buildings – Calculation Method (O'Hegarty et al., 2022)

Another point highlighted by this report (O'Hegarty et al., 2022) is that during the product stage, production boundaries account for the largest share of embodied carbon-related greenhouse gas emissions, including 21% of built environment greenhouse gas emissions and 54% of embodied built environment greenhouse gas emissions.

The construction stage emissions derive predominantly from the transport of materials. The embodied carbon associated with transport also has the largest individual uncertainty associated with it due to the paucity of granular data related to this sub-section (O'Hegarty et al., 2022). The use stage, predominantly associated with refrigerant leaks, is a sector expected to increase in the future with the rollout of heat pump technology (O'Hegarty et al., 2022). Regarding the end-of-use stage, these are the emissions associated with the disposal of the materials at their end of life (O'Hegarty et al., 2022).

The carbon intensity of the built environment refers to the greenhouse gas emissions emitted for a unit of energy averaged across the mix of fuels used to heat and power the buildings. Key factors affecting the carbon intensity of the built environment include both the proportional usage and carbon intensity of electricity as well as the mix of fossil fuels used in the different sectors of the built environment. These impact the greenhouse gas emissions of buildings in operation as well as the construction of buildings and infrastructure. The decarbonisation of grid-supplied electricity has been significant between 2005 and 2018, with a 40% reduction in carbon intensity achieved primarily due to the significant expansion of the wind power sector. The latest data nonetheless shows that the CO2 emissions intensity of Ireland's energy supply is 20% higher than the European average (O'Hegarty et al., 2022).

Regarding the residential sector, greenhouse gas emissions related to residential operational energy account for 45% of all built environment-related emissions. Furthermore, 75% of the housing stock is C-rated or below, with operational energy of more than 50 kgCO2/m2/year. In addition, 71% of the average home's energy demand is from fossil fuels. Non-residential construction is also increasing in Ireland, and non-residential operation emissions account for approximately 20% of all built environment-rated greenhouse gas emissions. Greenhouse gas emissions from non-residential construction are about 2.7 MtCO2e, with approximately 1.4 MtCO2e due to commercial building. Emissions due to the operation of the non-residential sector in 2018 were 30% of overall operation-related emissions. Moreover, the share of operational carbon attributed to non-residential buildings, including commercial and public buildings, was 29% of all operational emissions in 2018 and represented approximately 20% of all built environment-related greenhouse gas emissions, with a total of 2.1 MtCO2 operational emissions related to the commercial sector and 2.2 MtCO2 related to the public sector (O'Hegarty et al., 2022).

The total and share of embodied emissions are increasing due to the increase of construction in Ireland across all building sectors. The embodied carbon attributed to residential buildings (2.4 MtCO2) outweighed that of non-residential buildings (1.5 MtCO2) in 2018, and all are proposed to increase considerably in the coming years. According to the IGBC (2022), the National Development Plan proposes an addition of 400,000 newly built homes by 2030, which will also increase operational and embodied emissions associated with the residential sector.

In response, the Irish Climate Action and Low Carbon Development (Amendment) Act (2021) (The Climate Act) set a new legally-binding target of a 51% reduction in national carbon dioxide equivalent (CO2eq) emissions by 2030 and an overall target of a climate neutral economy by 2050 (Irish Green Building Council, 2022). Also, the Climate Action Plan proposes all new build to be A-rated. Additionally, a considerable upgrade of the housing stock is planned, and 500,000 homes are to be retrofitted to a B-rating or better (O'Hegarty et al., 2022). This legislation introduced a raft of new measures, including a new Climate Action Plan and a National Long-term Climate Action strategy. The strategy comprises five-year-long local authority mitigation plans and economy-wide five-year-long sectoral carbon budgets to reduce emissions by an average of 7% per year, with further reductions required up to 2050 (Irish Green Building Council, 2022). This roadmap (Irish Green Building Council, 2022) also provides recommendations to address embodied emissions and decarbonise Ireland's built environment across its whole life cycle and has four key aims, including:

1. Outlining key recommendations on integrating Whole Life Carbon (WLC) impacts/issues into national policy and legislation.
2. Developing, in collaboration with key stakeholders, a comprehensive set of actions, timelines, roles, and recommendations to ensure that the building and construction sector has the knowledge and capacity to deliver on these policy ambitions.
3. Securing a cross-sectoral WLC commitment and action on identified areas to rapidly increase progress on this agenda.
4. Providing a blueprint that the government and the construction sector may use to progress the integration of WLC in national policy and building practices in line with the direction of EU policy.

This roadmap targets Irish policymakers and the construction industry, as well as parallel representative groups, product manufacturers, the education sector, financial institutions and investors, and civil society. It also aims to provide stakeholders with a set of steps that will allow them to contribute to the decarbonisation of the built environment and to deliver on Ireland's climate targets. At the EU level, the Irish roadmap, alongside the national roadmaps developed by other Green Building Councils, will support the work of officials in the Commission, Parliament, and Council (Irish Green Building Council, 2022).

This roadmap (Irish Green Building Council, 2022) suggests a totally decarbonised, circular, resource-efficient built environment for 2050. It means that by 2050, in the context of 'decarbonisation', new developments, infrastructure, and renovations will have net zero embodied carbon, and all buildings, including existing buildings, will be required to have net zero operational carbon. Furthermore, 'resources and circularity' in this vision is defined as a built environment that supports the restoration of resources and natural systems within a thriving circular economy. It is notable that the goal of the proposed net zero WLC roadmap for the built environment in Ireland is aligned with the WGBC target of net zero operational and embodied carbon emissions across the whole building life, which requires taking a WLC approach from the outset for new developments, alteration, and renovation projects, with the aim of reaching net zero operational and embodied carbon emissions across the whole building life (Irish Green Building Council, 2022).

Regarding the circularity and the construction, the following recommendations are made by the Irish Green Building Council (2022):

- Establishing a legal framework for a Digital Building Logbook to capture better quality data on buildings and building materials, alongside Building Materials Passports, to facilitate reuse and the transition to a circular economy by 2025.
- Taking actions to immediately facilitate and incentivise the reuse of construction materials.
- Facilitating decisions on certain construction and demolition waste classes, pre-qualifying them for immediate recognition of the products without having to carry out an ISO 14040-44 (International Organization for Standardization, 2006) or Revision of the Construction Products Regulation (REFIT) (European Parliament, 2022) application process for every item on every site.
- Ensuring the Environmental Protection Agency of Ireland (EPA) have sufficient resources to process ISO 14040-44 (International Organization for Standardization, 2006) or REFIT (European Parliament, 2022) applications quickly, smoothly, and cost efficiently.
- Recognising and regulating a new type of waste or demolition contractor role (e.g., urban miner), authorised to collect, segregate, transport, and temporarily store by-products and end-of-waste products without affecting the non-waste status of those products even if they are collected alongside waste materials for recycling, landfill, or incineration.
- Where design, construction, and demolition processes have been modified to support 'deconstruction' or 'disassembly', as opposed to demolition (for example, in line with EU Level(s) or ISO 20887 (International Organization for Standardization, 2020b)), then waste regulation will have to be updated to allow products to be considered as non-waste and reusable rather than considered 'production residue' (waste).
- Supporting the development of recertification and remanufacturing schemes for reuse.
- Encouraging manufacturers to recertify products for reuse and place them back on the market.
- Supporting the use of online materials exchange platforms to determine the potential market value and reuse destinations of construction products post-demolition.
- Introducing a minimum requirement for reused or recycled products in new build and major renovation, and increase this percentage over time by 2030.

In addition to the recommended actions for leading the decarbonisation of Ireland and enabling a circular economy in the construction sector, the following actions have been taken by IGBC (2021):

- Launched the Carbon Designer for Ireland, an early stage whole life cycle carbon assessment tool that can be used to inform the brief development and initial design stages of a project.
- Developing national generic construction data for Ireland to be used in early-stage building-level Life Cycle Assessments/Analyses (LCA).
- Piloting a scheme to demonstrate a user-friendly system for the reuse of construction materials that would otherwise enter the waste stream.
- Supporting Dublin City Council and UCD in gathering better quality data on the effectiveness of green roofs in reducing stormwater runoff from developments and the extent of flooding.
- Organised circularity workshops to introduce people to the general concepts of circular design principles, such as design for adaptability and deconstruction, and circular material and resource use.

1.2. Aims and Objectives

The aim of this report is to conduct a horizon scan and needs analysis for the synergies between built environment digitalisation and circular economy. To that end, a systematic literature review on the current frameworks for digitalisation for the adoption of circular economy in the built environment was conducted. In addition, current gaps, relevant technologies, and EU circular economy case studies and projects in the construction sector were identified.

1.3. Methodology

In this report, a systematic review approach was adopted to identify relevant documents in the field of circular economy and digitalisation in the built environment. In order to conduct the systematic review, two of the most dominant databases including Web of Science (WoS) and Scopus were used as the main search engines. After identification of the keywords and search terms available in Tables 1 and 4, to analyse the current research efforts and gaps, the map of the co-occurrence of the keywords was created using the VOS viewer software.

1.4. Report Structure

In this report, section 1 provides an introduction and overview of carbon emissions, energy, and materials consumption of the construction sector in Europe and Ireland, followed by the necessity of transition to a circular economy and current efforts in this area. Section 2 is dedicated to the horizon scan and systematic literature review about digitalisation and circular economy in the built environment. In detail, a bibliometric analysis of the domain using a systematic review methodology is provided in section 2.2. In section 2.3, the definition of the circular economy, the circular economy principles for the construction industry and a review of the current circular economy projects in the EU, followed by a review of the current applicable technologies for facilitating the adoption of a circular economy in the built environment are presented. Section 2.4 provides a summary of the gaps and current efforts on the development of frameworks for the adoption of a circular economy and digitalisation in the built environment.

PART 2

Literature Review/ Horizon Scan

2.1. Introduction

This chapter provides an overview of digitalisation for the adoption of circular economy principles in the built environment, with a focus on the following subjects:

- A bibliometric analysis of the domain using a systematic review methodology (section 2.2).
- A definition of the circular economy and the circular economy principles for the construction industry and a review of the current circular economy projects in the EU, followed by a review of the current applicable technologies for facilitating the adoption of a circular economy in the built environment (section 2.3).
- A summary of the gaps and current efforts on the development of frameworks for the adoption of a circular economy and digitalisation in the built environment(section 2.4).
- Future work (section 2.5).

2.2. Bibliometric Analysis

Systematic review is the best-known type of review that seeks to systematically search for, appraise, and synthesise research evidence and draw together all known knowledge on a topic area (Grant & Booth, 2009). This type of review aims for exhaustive, comprehensive searching and analyses based on what is known, including practice recommendations, and what remains unknown, including uncertainty around findings and recommendations for future research. It is also transparent in the reporting of its methods to facilitate others to replicate the process (Grant & Booth, 2009).

Systematic reviews can provide syntheses of the state of knowledge in a field, such as identifying future research priorities, addressing questions that otherwise could not be answered by individual studies, and identifying problems in primary research that should be rectified in future studies (Page et al., 2021).

This study therefore adopted a systematic review approach to identify relevant documents in the field of the circular economy and digitalisation in the built environment.

In order to conduct the systematic review of existing studies on the circular economy and digitalisation in the built environment, two of the most influential databases, including Web of Science (WoS) and Scopus, were used as the main search engines based on the functionalities and capabilities of their databases (Norouzi et al., 2021; Ganiyu et al., 2020). Furthermore, according to Echchakoui (Echchakoui, 2020), WoS and Scopus are complementary, and it is best to use both databases. Using such a large dataset improves the analysis by having a more global perspective of bibliometric analysis and eliminating any dependency on the results of the database used (Norouzi et al., 2021).

This study collects documents from both WoS and Scopus databases, and the results were analysed accordingly. In order to visualise the research efforts that address the circular economy and digitalisation in the built environment, plotting the co-occurrence of these terms (i.e. circular economy and built environment, circular economy and digitalisation, built environment and digitalisation, etc.) in graphs was done using the Visualisation of Similarities (VOS) Viewer software (van Eck & Waltman, 2010).

The graph was created based on the WoS and Scopus databases results to capture a general insight. Figure 4 shows the co-occurrence map generated using the VOSViewer, and provides an indication of how related the research efforts are among the circular economy, digitalisation, and the built environment. The source data for the co-occurrence map shown in Figure 4 were the 48,114 articles, proceedings papers, review articles, reports, and early access articles (in English) listed on the Web of Science and Scopus that included the primary keyword combinations (Table 1) in their titles, abstracts and keywords, since the year 1978.

Keywords		
Circular Economy	Built Environment	Digitalisation
	Buildings	BIM
	Construction	Industry 4.0
		Digital twin
		AI
		IoT
		Material Passport
		Blockchain
		Digital Logbook

Table 1
Main Keywords Used for Conducting Bibliometric Analysis

In Figure 4, the terms are located based on the co-occurrences in titles, abstracts, and keywords using the VOS-mapping technique (van Eck & Waltman, 2010). The higher the number of co-occurrences, the closest they are located on the map. The size of the circle indicates the number of occurrences of each term in the title, abstract, and keywords of the documents. The terms are grouped into clusters of closely related terms using a clustering technique presented by Waltman et al. (2010). Six main clusters of similar terms were identified in Figure 4, including 'circular economy and sustainability', 'construction projects and related technologies' (Industry 4.0, Digital Twin, BIM), 'digital data management' (Blockchain, IoT, etc.), 'digitalization', 'energy efficiency', and 'entire life cycle'. The most prominent clusters are the circular economy, Industry 4.0, Blockchain, and the construction industry, but these clusters are significantly distant from each other. Notably, the circular economy is separated from the other clusters. This demonstrates the gap in studies in the fields of the circular economy and the construction industry, and of the circular economy and digitalisation in the construction industry.

As a result, there are gaps in the current literature in the context of the circular economy and digitalisation in the construction industry. Thus, further studies are required to investigate the adoption of circular economy principles in the construction industry and digital technologies required for the adoption of circular economy principles in the built environment.

2.3. Circular Economy

The Circular Economy (CE) is a sustainable development model that offers an alternative to the traditional, linear, 'take-make-waste' model. CE is defined as an economic system that replaces the 'end-of-life' concept with reducing, or alternatively reusing, recycling ,and recovering, materials in the production, distribution, and consumption processes. CE operates at the micro level (products, companies, consumers), meso level (eco-industrial parks), and macro level (city, region, nation, and beyond), with the aim of accomplishing sustainable development, thus simultaneously creating environmental quality, economic prosperity, and social equity, all to the benefit of current and future

Research themes

- Circular Economy and Sustainability
- Construction projects and related technologies (Industry 4.0, Digital Twin, BIM)
- Digital data management (Blockchain, IoT, etc.)
- Digitalization
- Energy efficiency

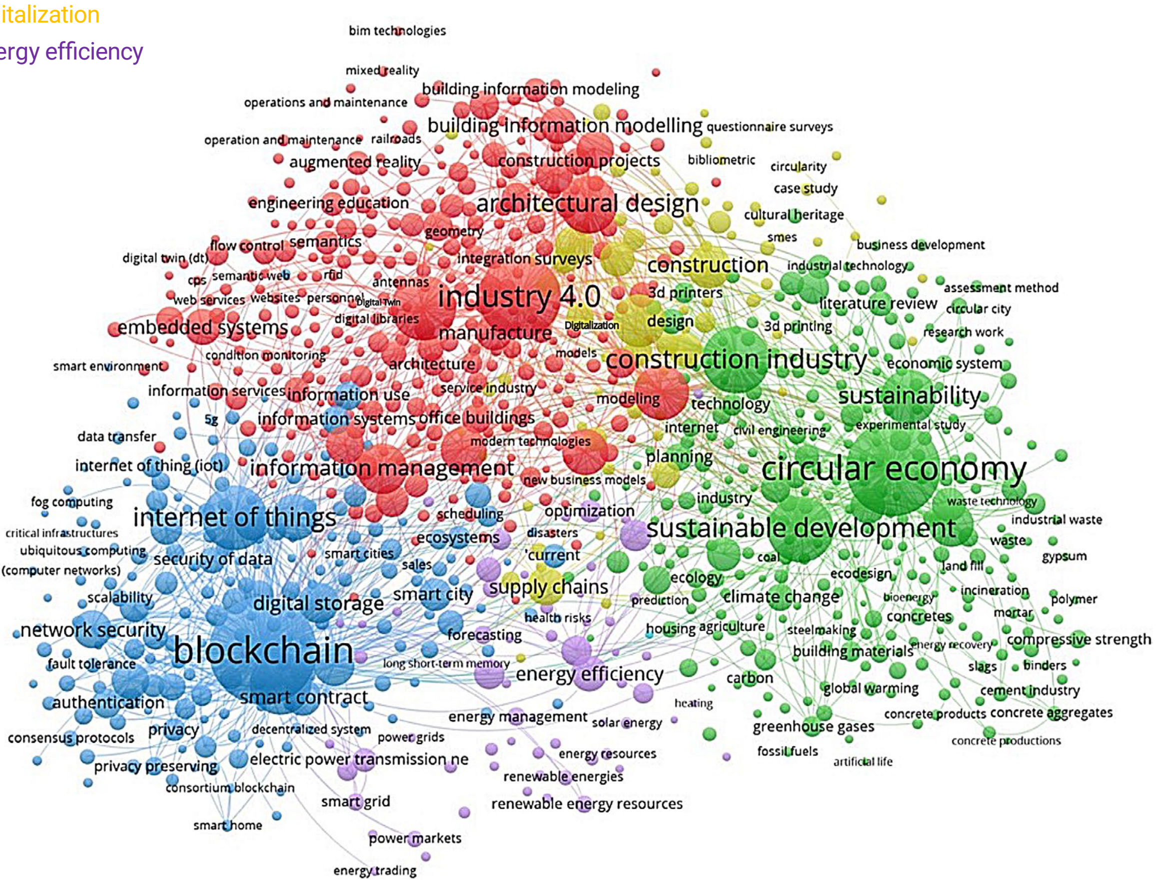


Figure 4

Map of Co-occurrence of the Primary Keyword Combinations in Table 1

generations (Kirchherr et al., 2017; Norouzi et al., 2021; World Economic Forum, 2018).

CE is considered to be a "regenerative system in which resource input and waste, emission and energy leakage are minimised by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, re-manufacturing, refurbishing, and recycling" (Iyer-Raniga, 2019). CE may be achieved through four distinct resource strategies:

- **Narrowing the loop:** Using fewer resources through efficiencies in the production and design process.
- **Slowing the loop:** Using and consuming less through long product life, product life extension, and avoiding unnecessary consumption.
- **Closing the loop:** Reusing materials or post-consumer recycling.
- **Regenerating the loop:** Focusing on leaving the environment (and society) in a better state than before, e.g., by improving biodiversity (Çetin, Wolf & Bocken, 2021).

Thus, circularity is characterised by closed-loop approaches, resource efficiency/productivity, resource efficiency vs. resource effectiveness, and the optimisation of goods/assets. Circularity supports the building or increase in value of asset/stock management, thereby supporting longevity and durability which, in turn, requires that design for longevity and adaptability is supported; thus end-of-life value is retained. From an emissions perspective, a reduction in demand reduces embodied resources such as energy and water, in turn reducing emissions associated with greenhouse gases and related emissions (Iyer-Raniga, 2019).

A circular economy could reduce global CO2 emissions from building materials by 38% in 2050 by reducing the demand for steel, aluminium, cement, and plastic. It could also make the sector more resilient to supply chain disruptions and price volatility in raw materials (Foundation, 2022).

Initially, the 'Three Rs' principles (reduce, reuse, and recycle) were introduced for a CE framework. Wherein 'reduce' refers to the action of minimising inputs and outputs such as raw materials and waste, 'reuse' is the operation of using a product again for the same purpose when it reaches its end-of-life, while 'recycle' is the process of recovering waste to manufacture a new product (Rahla et al., 2021).

In 2018, the World Economic Forum (2018) expanded the basic 'Three Rs' principles of the circular economy to a 'Ten Rs' framework to encompass more actions and achieve a transition towards CE more effectively (Sosnovska & Shtepa, 2020). The R-list includes three key strategies to increase circularity and innovation in product design.

The first strategy emphasises the need for wiser product manufacturing and comprises of following three actions:

- **Refuse:** Depreciate a product with dire impacts and propose an alternative with identical or better functions and fewer impacts.
- **Rethink:** Intensify the product use and adopt smarter strategies such as sharing economy or products with multiple functions.
- **Reduce:** Decrease virgin materials and energy consumption while enhancing efficiency.

The second strategy encourages product lifespan extension and consists of:

- **Reuse:** Reuse a discarded product that keeps the same functions by another user.
- **Repair:** Fix a damaged product to regain its initial performance.
- **Refurbish:** Renovate an outdated product to make it as good as a new one.
- **Re-manufacture:** Make a product using parts from a damaged product that had the same functions;
- **Re-purpose:** Make a product using parts from a damaged product that had different functions.

The last strategy includes:

- **Recycle:** In the manufacturing process of a product, include materials that reached their end-of-life use to make materials with the same, higher (up-cycle), or lower (down-cycle) qualities.
- **Recover:** A process of retrieving heat, electricity, or fuel from non-recyclable materials by incineration (Rahla et al., 2021).

2.3.1. Circular Economy and the Built Environment

The built environment comprises the man-made elements of our surroundings, such as buildings and infrastructure, including transportation, telecommunications, energy, water, and waste systems. Design, planning, and construction contribute to the quality of the built environment, which has a significant impact on human health, well-being, and productivity (Arup, 2016).

The challenge for all of the stakeholders of the built environment is to respond to global housing needs while reducing environmental impacts. However, this is not an easy task considering that the construction industry forms about 9% of the European gross domestic product and that the construction industry has one of the most linear value chains among all economic activities. As a result, the paradigm shift from a linear to a circular built environment and the adoption of more circular practices is urgently needed for the construction sector in order to address emissions, resource depletion, and waste caused by this industry (Mêda et al., 2021).

Minimising negative externalities is a core aim of the circular economy. In the built environment, these include climate change, water, soil, noise, and air pollution. They also include less tangible impacts on human and animal welfare, health, employment, and social equality.

These externalities can apply to both the operation of assets and the sourcing, manufacture, transportation, installation of materials and components, and disassembly. Preventing or minimising these impacts is critical to enhancing natural capital and maximising the use and value of resources (Arup, 2016).

Increasing the service life of assets reduces the need to use virgin materials and, therefore, reduces or eliminates resource consumption. The pooling of materials brings about a shared society such that the sharing of material banks, for instance, reduces the overall use of resources. Waste management may be expanded to focus on the prevention or elimination of waste or the maintaining of the waste's value so that it may be used elsewhere and, subsequently, that new or virgin materials are no longer used. If building-related waste were to be captured, it is estimated that 40% may be reabsorbed back into the system (Iyer-Raniga, 2019).

The history of circularity in the built environment has strong roots in industrial ecology. Industrial ecology and urban metabolism, involving the study of the interdependence of human activity and economic systems on natural systems, form the underpinning foundations of circularity in the built environment. While circularity refers to principles, frameworks, or approaches, the circular economy refers to the economic and business imperatives required to make circularity approaches a reality. Circularity can only work when shared models are successful (Iyer-Raniga, 2019).

According to Ness and Xing (2017), circular economy approaches are most efficient and effective in the built environment specifically in the construction and real estate sectors. Circularity may be achieved at city, neighbourhood, and building scales. At the city scale, governments need to drive policy and regulatory frameworks so that top-down approaches are able to support granular innovation at the building scale (Iyer-Raniga, 2019).

At a city, neighbourhood, or building scale, a compact circular economy is supported by the exercising efficiency in resources, including reusing and recycling, so that environmental pressures are decreased. In addition, productive, efficient urban forms that support symbiotic relationships between environmental, economic, and social forms are desired. Economic activity supports the better use of existing capital within the built environment, and the adoption of circular resource flows assists in reducing footprints and impact on the biosphere (Iyer-Raniga, 2019).

According to Arup (2016), in a circular economy, buildings will be designed for a whole life cycle and not simply an end use. Stakeholders will collaborate on cloud-based building information models with analytical software that clearly visualises a proposal's externalities. Policy and incentives will encourage clients to issue full life cycle contracts from design to operation and disassembly, as well as pushing their ambitions in achieving holistic life cycle certification and awards. Components and structures will often be leased rather than purchased. Performance-based contracts will see tenants and landowners pay for a service such as lighting rather than individual fittings or materials. Circularity will be embedded in all parts of an ecosystem. This will ensure that individual assets are flexible, interchangeable, and highly customisable, and thus will enhance the user experience of the environment. Design decisions such as optimising disassembly and reuse from the beginning of the programme have implications for the operation, renewal, and re-purposing of the building and its components. In the circular model, the construction of a building will be integrated with the resource and reuse cycles of other industries. In operation, the building will use renewable sources and, where possible, locally-available used material streams, in order to enhance resiliency and lower risks to investors (Arup, 2016)

The key steps in transitioning to a circular economy in the built environment at the building level, according to Arup (2016), are where the design, construction, operation, renewal, and re-purposing of buildings are such that:

- Ecosystems remain at the front and centre, where buildings are designed for a whole life cycle and not just for a point in time. Life cycle thinking will ensure the construction, operation and disassembly phases maximise the principles of circularity, such as the use of appropriate materials, renewal energy, adaptable designs, shared resources, lease of assets, and other circularity approaches.
- Design will ensure that buildings may be future proofed, providing opportunities for adaptability and disassembly. Designs will be open source allowing the design community to build further on each other's work, while components will be reused and retrofitted where possible. Design is not purely aesthetic or delightful; it will support the comfort of space and, at the same time, be energy efficient and support wellness.
- Sourcing of materials adaptability and modularity. Materials are flexible, durable, and can be reused. It will also contain components that support reusability.
- Construction is dominated by increased flexibility, prefabrication, digitalisation, and where appropriate and possible, the use of 3D printing.
- Operation is dominated by high efficiencies in energy use, water, and strategies eliminating the waste of materials and resources. It will be dominated by leasing arrangements in tenancies as well as in the servicing of equipment and maintenance.

- Renewal will also be dominated by flexibility and adaptability, where designs will support the reconfiguration of building components such as facades. Buildings can be easily retrofitted and upgraded, eliminating the time and cost of renewal. Virgin resources are either not used or are not necessary.
- Disassembly is minimised, resulting in buildings that may be mobile, flexible, adaptable, and resilient, thus expanding building life spans.
- Re-purposing buildings makes maximum use of components and materials, ensuring that their performance and value are either maintained or enhanced in the built environment sector (Arup, 2016; Iyer-Raniga, 2019).

2.3.2. EU Circular Economy Projects

Level(s)

Level(s) is a free, open-source framework developed by the European Commission for sustainable buildings. This framework provides a common language for assessing and reporting on the sustainability performance of buildings throughout their life cycles. Level(s) also helps building professionals in improving building performance and helps policymakers and certification professionals in aligning legislation and environmental objectives. In general, this framework is a simple entry point for applying circular economy principles in the built environment (European Commission, 2022b; Directorate-General for Environment, 2021).

More specifically, Level(s) provides a set of common indicators and metrics for measuring the environmental performance of office and residential buildings, which can be applied at each stage of a building's life cycle, including Level 1: Conceptual Design, Level 2:Detailed Design and Construction, and Level 3: As-Built and In-Use Stage. It is also notable that the whole life cycle approach in Level(s) covers all stages, from the extraction of raw materials to the deconstruction of the building and the associated management of secondary raw materials and waste. This framework is currently in its test phase, and its ambition is to create a "common European language" for sustainable buildings that can help galvanise debate and direct action to include life cycle thinking and circularity, ultimately improving the energy performance of buildings (European Commission, 2022b; European Commission, Directorate-General for Environment, 2021a; 2021c).

The Level(s) common framework is based on six macro-objectives that address key sustainability aspects over the building life cycle, including greenhouse gas emissions, resource efficiency, water use, health and comfort, resilience and adaptation, and cost and value. This framework will ensure that action taken at an individual building level makes a measurable impact on critical issues for all nations, such as climate change, circular economy, climate adaptation, and health (European Commission, 2022b; 2022a).

In April 2018, the European Commission officially opened the two-year testing phase for Level(s) to organisations seeking to be part of Europe's shift towards circular and life cycle thinking. The projects involved in the testing of Level(s) included 74 residential and 62 non-residential building projects in 21 EU countries, providing balance in terms of the community shaping Level(s). The aim of the testing phase was to support stakeholders across the construction and real estate value chain, from investors to developers, designers, and manufacturers, in testing the Level(s) indicators on their building projects (Directorate-General for Environment, 2018). According to the European Commission (2021b), the final framework is now available and is already influencing stakeholders across the EU.

ReSOLVE

Arup, in collaboration with Ellen MacArthur Foundation, has developed and tested the ReSOLVE framework to outline key principles of the circular economy and to explore practical applications that can benefit all parties working in the built environment sector (Arup, 2016). The ReSOLVE framework is a key output of the Ellen MacArthur Foundation's research. This framework outlines six actions, namely Regenerate, Share, Optimise, Loop, Virtualise, and Exchange, that can be applied to products, buildings, neighbourhoods, cities, regions, or even to entire economies in order to guide the transition towards a circular economy (Arup, 2016).

The definition of these six strategies is as below (Acharya et al., 2018; Ellen McArthur Foundation, 2016):

- **Regenerate:** Regenerating natural capital by safeguarding and increasing the resilience of ecosystems or by returning valuable biological nutrients safely to the biosphere. In the built environment, it includes the use of renewable energy to power buildings (e.g. solar, wind, geothermal, biomass, tidal, wave), the use of buildings as energy generators (e.g. solar panels on roofs), land restoration (e.g. saving virgin land and building on brownfield sites), resource recovery (e.g. regenerate organic waste and compost production), and renewable production systems (e.g. biogas production and electricity production).
- **Share:** Maximising asset utilisation by mutualising the use of assets or by reusing them. Examples include on-demand office space and the reuse of structural steel. In the built environment, sharing also would include residential sharing (e.g. peer-to-peer renting), infrastructure sharing (e.g. parking sharing, shared infrastructure areas, and shared green areas), appliances/tools sharing (e.g. sharing practices and sharing water), co-housing, office-sharing, and shared water consumption (e.g. water treatment facilities).
- **Optimise:** Optimising system performance by prolonging asset use periods, reducing waste during production, or optimising the logistics

system through the implementation of reverse logistics. Examples include sensors for predictive maintenance and industrial eco-parks. In the context of the built environment, 'optimise' includes industrial process, off-site production (e.g. prefabrication), smart urban design (e.g. using inner-city vacant land, promoting compact urban growth and high-quality urban environments, and promoting integrated, sustainable, and participative urban development), energy efficiency (e.g. integration in the environment, building envelope, and equipment), water efficiency (e.g. reducing consumption grids, re-circulation of water, using closed water, and water re-use), material efficiency (e.g. renewable, recycled, recyclable, non-toxic components, and lower energy content), and reduction in transport.

- **Loop:** Keeping assets in cycles by refurbishing, remanufacturing, or recycling. Examples include building refurbishment and recyclable insulation with recycled content. In the built environment, 'loop' includes optimisation of the end-of-life of building and materials (e.g. durability, maintenance, repair, upgrades, removal, deconstruction, and re-use), modularity of the building (e.g. modular building techniques, multi-purpose volumes, and flexibility in buildings), and remanufacturing of materials (e.g. piece-by-piece demolition, material banks, and stock management).
- **Virtualise:** Displacing resource use by delivering virtual services such as replacing physical products with virtual services (e.g. e-books instead of books), replacing physical with virtual locations (e.g. online shopping and video conferencing), and delivering services remotely (e.g. cloud computing and storage). In the built environment, teleworking, virtualisation of products, virtualisation of processes (e.g. BIM, digital mock-up, and automated maintenance), and smart appliances (e.g. smart home systems, connected appliances, and efficiency for lights) can be adopted for this purpose.
- **Exchange:** Selecting resources and technologies wisely by shifting to renewable energy and material sources, using alternative material inputs, replacing traditional with advanced technical solutions, or replacing product-centric delivery models with new service-centric ones. In the built environment, examples include better-performing materials (e.g. advanced materials discovery), better-performing technologies (e.g. 3D-printing, building management systems, and electric engines), and new products and services (e.g. multi-modal transport) (Ellen McArthur Foundation, 2016).

The Circular Economy 100

CE 100 is a pre-competitive innovation programme established by Ellen MacArthur Foundation to enable organisations to develop new opportunities and realise their circular economy ambitions faster (Iyer-Raniga, 2019). CE 100 includes leading companies, universities, and emerging innovators and is developing new approaches and tools to lead the transition to a circular economy. This programme brings various stakeholders together to support, learn, build capacity, network, and collaborate on a circular economy (Iyer- Raniga, 2019).

The goal of creating the global CE 100 platform is to combine the efforts of government, business entities, and research institutions to accelerate the transition to a circular economy. Thus, taking advantage of the development of the information society, CE 100 contributes to the creation of a mechanism for collective management decision-making and provides recommendations on the implementation of global best practices and the possibility of activating circular processes at the level of individual enterprises (Sosnovska & Shtepa, 2020).

In other words, CE 100 is a representative initiative defined as a global platform reuniting global companies, innovators, networks of academics and universities, and regions with a view to accelerating the transition to a circular economy (Bonviu, 2014; Ellen McArthur Foundation, 2016).

Using the advantages of the information society and the internet, CE 100 attempts to facilitate this transition by means of three levels of support: creating a mechanism for collective problem solving, building a library of best practice guidance to help businesses fast track success, and providing a scalable mechanism for building circular economy capabilities within businesses (Bonviu, 2014).

In order to create opportunities for formal collaboration between CE100 members, the Ellen McArthur Foundation introduced Co.Projects that are driven by members, for members, with a focus either on research initiatives or pilots (Ellen McArthur Foundation, 2016).

According to the Ellen McArthur Foundation (2016), Co.Projects leverage the CE100 network with the aim of overcoming challenges and exploring opportunities faced by organisations making the transition to a circular economy; challenges and opportunities that they may otherwise not be able to address in isolation.

In this regard, and in the context of the built environment, the Built Environment Case Studies Co.Project was developed, which is a collaboration between BAM, BRE, cd2e, London Waste & Recycling Board, Ouroboros, Tarkett, and Turntoo. This Co.Project's objective was to provide useful case studies for the CE100 community and to test the ReSOLVE framework to understand what circularity in the built environment looks like while showcasing CE100 member initiatives. Based on a publication by the Ellen McArthur Foundation (2016), the Co.Project team has now produced a pack of built environment case studies sourced from CE100 members, including examples ranging from infrastructure, building projects, material usage, and relevant programmes (Ellen McArthur Foundation, 2016).

Buildings as Material Banks (BAMB)

BAMB is an EU-funded project that brings 15 partners from seven European countries to enable a systemic shift in the building sector by creating circular solutions (BAMB, 2022; Debacker & Manshoven, 2016).

According to Debacker & Manshoven (2016), "BAMB will contribute to the enablement of a systemic shift where buildings designed for change can be incorporated into a circular economy. Through design and circular value chains, materials in buildings maintain their value in a sector producing less waste and using less virgin resources. Instead of being to-be waste, buildings will function as banks of valuable materials, building materials and building systems conserving material value and functionality, so materials and building components can be reused, thus decreasing the need for primary resource mining".

The aim of the BAMB project is to develop and integrate tools, including Materials Passports and Reversible Building Design supported by new business models, policy propositions, management and decision-making models, and circular building assessment tools that will enable the shift to a circular building sector (Capelle, 2019).

During the course of the project, these new approaches were demonstrated and refined with input from six pilots. The BAMB project started in September 2015 for 3.5 years and progressed as an innovation action within the EU-funded Horizon 2020 program (Debacker & Manshoven, 2016).

As part of the project, more than 400 Materials Passports for various products, components, or materials were developed together with a software solution. The software will facilitate the appropriate accessibility of information for different stakeholders at specific stages in the process (Capelle, 2019).

Furthermore, the following inter-disciplinary aspects were investigated within the BAMB project (Debacker & Manshoven, 2016):

- Value chain at the building and product level.
- Availability of information between actors along the value chain, with a specific focus on the applicability of BIM within the current building practice in the EU (i.e. review of BIM standardisation within the EU and review of EU and International BIM related systems and plug-ins related to sustainability).
- Identification of commonly used methods to refurbish and maintain buildings for major construction types.

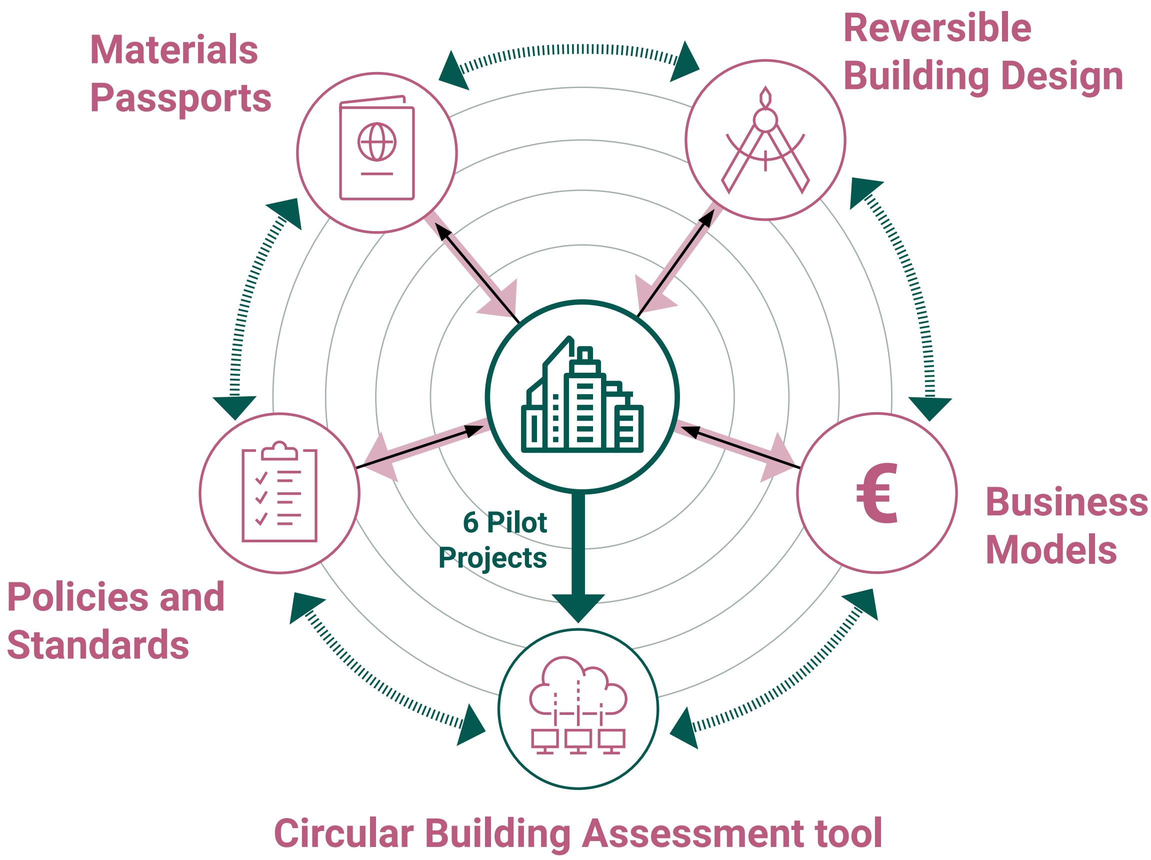


Figure 5
Articulation of the Pilot Projects Around the Buildings as Material Banks Horizon 2020 Innovation Projects Major Topics (Capelle, 2019)

- Elaboration on the cause of demolition of buildings and major maintenance needs of buildings.
- Estimation of the availability, composition, amount, and quality of CDW in the EU.
- Estimation of re-use potential of buildings, components, and materials within the existing building stock.
- Identification of existing (niche) solutions, applications, strategies, key actors, and barriers to accelerate the reuse of residues as material resources and generic components applicable for various buildings trans-functional buildings.
- Identification of existing initiatives and regulations hindering or supporting the reuse of materials, components, and buildings.
- Identification of existing financial and business models preventing or promoting the reuse of resources, materials, components, and buildings (Debacker & Manshoven, 2016).

The BAMB project has also been tested through various case studies in different EU countries as shown in Figure 6.

The Circular EcoBIM

The Circular EcoBIM project is aimed at creating a BIM standard type Product Data Template (PDT). This offers a data structure for BIM objects and a set of applications that allow for the calculation of building and component circularity passports, the integration and development of product Environmental Product Declarations (EPDs), and the calculation of Level(s) system indicators for buildings from building models. Therefore, the project contributes to the implementation of circularity practices in construction (EEA Grants Portugal, 2022b).

More specifically, the purpose of the Circular EcoBIM project is to exploit the potential of BIM to improve the selection of materials and the assembly of constructive elements so that, at the building's end-of-life, the materials can be reclaimed, reused, and recycled, and the environmental impacts reduced in order to promote and facilitate circularity practices in the construction sector. They subsequently proposed a user-friendly BIM platform that provides plugins and the necessary data, given that BIM is a robust and efficient working technology that is becoming increasingly popular in the construction sector (Circular EcoBIM, 2022).

Figure 6
Location of the BAMB Project Case Studies (Capelle, 2019)

In this regard, as shown in Figure 7, Circular EcoBIM proposed to create a set of BIM-based tools to enable a circular construction model. The three tools that are proposed will help architects and project managers improve environmental performance and increase the reusing, recovering, and recycling of construction materials. The first tool is a PDT, which is a database for collecting information about the environmental performance and circularity potential of construction materials. A PDT enables the organising and directing of data collection for the specific applications of the remaining Circular EcoBIM tools. The second tool is software plugins for existing BIM software that allow the calculating of a circularity passport, Level(s) system indicators for sustainable buildings, and EPDs based on the building design. The third tool is a digital twin platform that enables visualisation and interaction with the BIM model and the environmental performance in a digital environment. Information gets synchronised between the Digital Twin, BIM software, and the database, allowing the building manager to access all project data rather than the manager having to browse through multiple data sources (Circular EcoBIM, 2022).

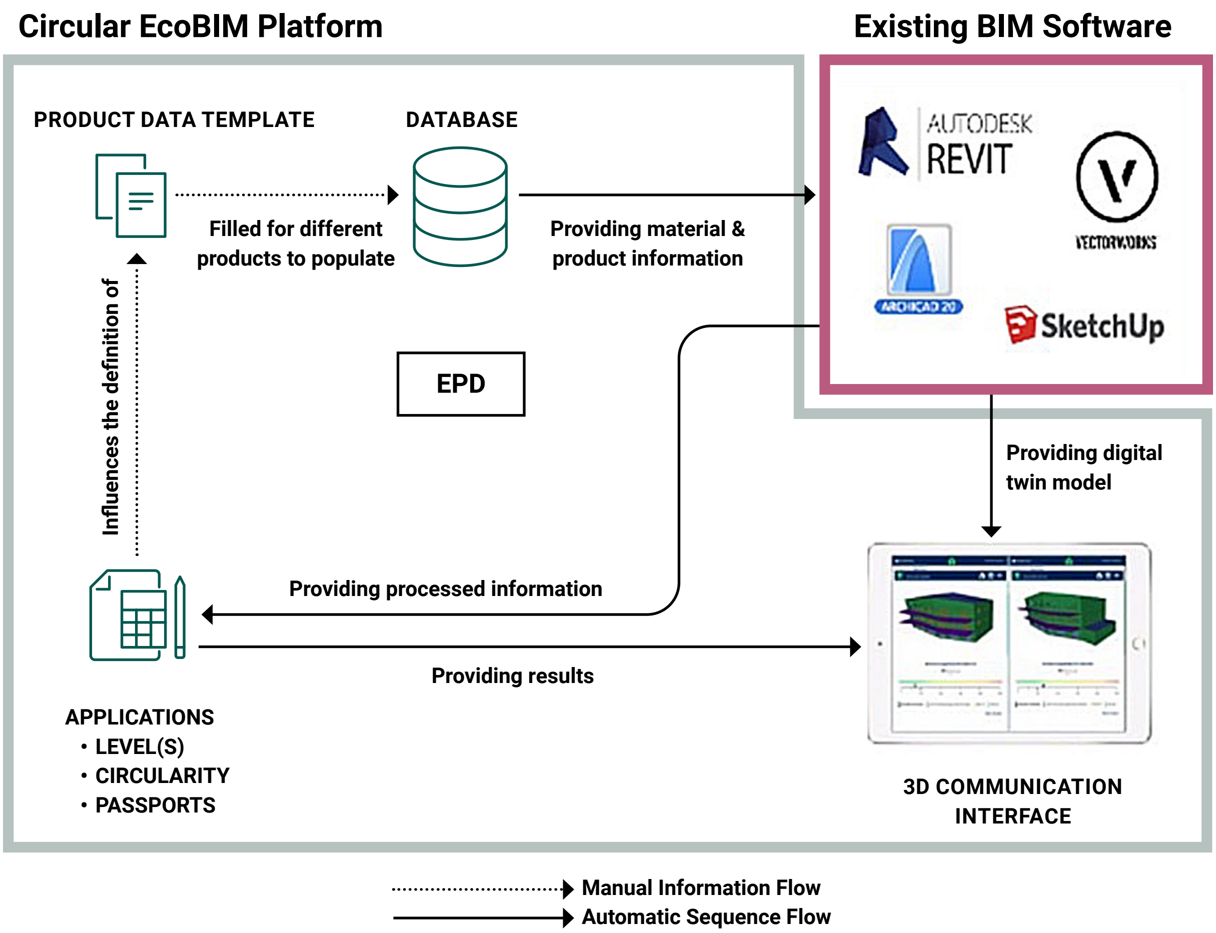
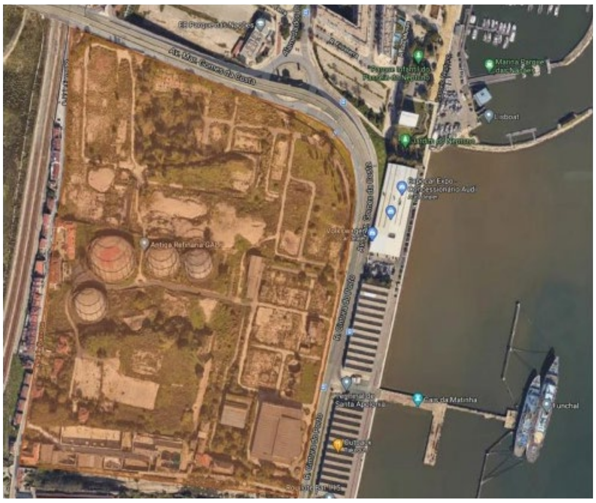


Figure 7
Circular EcoBIM Platform (Circular EcoBIM, 2022)

Furthermore, these tools are planned to be tested and used to improve the environmental and circular performance of two landmark demonstration projects, including the brownfield redevelopment Matinha in Lisbon and the Herdade do Pinheirinho in Grândola, as shown in Figure 8.

Matinha plot, Lisbon



Herdade do Pinheirinho, Grândola

Figure 8
Circular EcoBIM Case Studies (Circular EcoBIM, 2022)

This project will allow for the calculation of aggregated circularity indicators but also for the mapping of opportunities for improved resource management at various stages of the building's life cycle. The project will also promote the prevention of waste and the incorporation of secondary raw materials in the construction sector (Circular EcoBIM, 2022).

The Circular EcoBIM project is supported by the EEA Grants, a close cooperation between Iceland, Liechtenstein, and Norway and the EU through the Agreement on the European Economic Area (EEA) towards a green, competitive, and inclusive Europe (Circular EcoBIM, 2022).

The GrowingCircle

The GrowingCircle project is promoted by IC Instituto da Construção, Portugal, with NTNU Trondheim University, Norway as a partner. It was approved under the EEA Grants 2014-2021 'Environment, Climate Change, and Low Carbon Economy Programme' (GrowingCircle, 2022).

The aim of the GrowingCircle project is to highlight the added value of Data Templates through their implementation in several case studies from design to construction, as well as their inherent impacts for the use phase and eventual building decommissioning (GrowingCircle, 2022).

The lack of construction-related data is a common thread throughout the construction process that causes increased risks for the use phase. Furthermore, it introduces inefficiencies and impacts on the efficiency, sustainability, and implementation of more circular practices (GrowingCircle, 2022).

As a result, the GrowingCircle project planned to raise awareness among agents through training/ dissemination actions for the role of Data Templates and indicated their impact through practical implementation in specific case studies (EEA Grants Portugal, 2022e).

The first case study of the GrowingCircle project was the CH Custóias refurbishment project, including 58 houses, which is the basis for the development of other case studies (GrowingCircle, 2021). The location of this project was Matosinhos, Portugal, and the owner of the project was MatosinhosHabit, EM.

The Circular Buildings

The Circular Buildings project is developed by the Smart Waste Portugal Association in collaboration with three drivers: Engenharia, Inovaçãoe Ambiente, the Faculty of Engineering of the University of Porto (FEUP), and the Portuguese Construction Technology Platform (PTPC). It is financed by the EEA Grants.

This project began in May 2020 with the aim of developing decision support tools to promote increased reuse of materials and reduced waste production in the construction sector (Smart Waste Portugal Association, 2022), including a set of standards for defining building material passports and the calculation of material, water, energy, and component efficiency metrics.
The standards were also created for the purposes of defining circularity indicators in EPDs associated with the circularity of materials and products (Smart Waste Portugal Association, 2022).

According to the Smart Waste Portugal Association, the developed tools can be applied to different types of buildings and will allow for the promotion of sustainable practices and the principles of the circular economy in the construction sector. The tools also allow effective planning of the re-qualification and demolition of buildings and the reduction of associated environmental impacts. Futhermore, it is expected that the results of the project will influence the business models of construction companies which intend to carry out the rehabilitation and urban reconstruction of buildings, and plan the transmission of knowledge related to circular construction within the local and national value chain (Smart Waste Portugal Association, 2022).

It is notable that, according to the Smart Waste Portugal Association, the entire value chain, from suppliers and builders to users, can obtain information through the project tools (e.g. materials passports, energy and material efficiency indicators, circularity indicators in DAP, and tools for calculating environmental and economic benefits) to make decisions that guarantee the sustainability of buildings, allowing the choice of more sustainable products and materials, increasing their period of use and maximising their end-of-life value.

The Circular Buildings project contributes to the enhancement of waste identification, separation at source, logistics, waste processing and treatment options, and process of quality monitoring and control, in line with the objectives of the EU Construction and Demolition Waste Management Protocol and the Government of Portugal's Circular Economy Action Plan (EEA Grants Portugal, 2022a).

The developed tools were also tested through a demonstration project titled ' Renovation and expansion of the basic school Dr. Fl´avio Goncalves' in P´ovoa de Varzim in 2021. The project consisted of the remodelling, re-qualification, modernisation, and expansion of the school buildings and the re-qualification of the outdoor spaces (Smart Waste Portugal Association, 2022).

(De)construct for Circular Economy

The objective of the (De)construct for Circular Economy project is to promote a regional strategy for the reuse of building products and recycling of Construction and Demolition Waste (CDW) in order to reduce the environmental impact of the construction sector and promote circularity in this sector (EEA Grants Portugal, 2022d).

The expected results from this project are as follows:

- Municipal construction regulations;
- Pre-demolition audit guide and a model of materials passport;
- Mathematical model to optimise the location of CDW storage facilities in municipalities and the regional recycling network;
- Involvement of local, regional, and national stakeholders, and the creation of a sustainable network for the processing, distribution, and commercialisation of CDW (Comunidade Intermunicipal do Baixo Alentejo, 2022).

This project is promoted by the Comunidade Intermunicipal do Baixo Alentejo and is financed by the EEA Grants (EEA Grants Portugal, 2022d).

The CircularBuild project

The CircularBuild project is promoted by CONCEXEC and funded by EEA Grants. The project is aimed at investigating alternative materials for panels, replacing those currently used, that enable the complete circularity of the modular panels' production system. Such a process allows for the total reuse of waste generated by the 'deconstruction' of houses as raw material for new panels or new houses without compromising the building's performance in terms of energy efficiency, and consequently contributes directly and widely to the new paradigm of 'Zero Carbon Buildings' (EEA Grants Portugal, 2022c). It is also projected that this project would increase the application of CE principles in the construction sector, increase the efficiency in the use of resources, and accelerate the transition of the construction sector to a circular and efficient economy (CircularBuild, 2022).

The expected results of the project are also as follows:

- Innovative pilot solutions to increase resource efficiency;
- Panels with satisfactory performance not inferior to the traditional base solution under study;
- Replacement of materials by more energy efficient ones as well as with greater circular potential in the construction of the panels;
- Panels built with recycled materials that display industrial viability;
- Reused panels after dismantling a pilot module for the construction of a new module;
- Reduced manufacturing times and costs;
- Increased utilisation of secondary raw materials (resulting from the separation of used materials);
- CE in the construction sector;
- Improved economic performance than the traditional base solution under study;
- Enhanced environmental performance than the traditional base solution under study;
- Construction and demolition waste avoided in pilot construction (CircularBuild, 2022).

Circular Construction In Regenerative Cities (CIRCuIT)

CIRCuIT is a collaborative project funded by the EU's Horizon 2020 programme, bringing together 31 partners across the entire built environment chain in Copenhagen, Hamburg, the Helsinki region, and Greater London. It started in 2019 and will be finished by November 2023 to bridge the implementation gap between theory, practice, and policy, and to showcase how circular construction approaches can be scaled and replicated across Europe to support the creation of regenerative cities (CIRCuIT, 2022).

The objective of this project is to undertake a fully circular and regenerative transition and to create a value chain that will allow the aforementioned countries to become fully smart, eco-friendly, regenerative, and circular economies (European Commission, 2019b).

The EU-funded CIRCuIT project is aimed to present the whole system of elements engaged in the transition process from dismantling buildings for the reuse of materials to Circularity Hubs and the CIRCuIT Academy, promoting the development of further solutions in 36 demonstration projects. In these demonstration projects, the tools of the present and future that will boost regeneration while reducing the use of virgin raw materials are or will be presented (European Commission 2019b). CIRCuIT is planned to demonstrate three innovative solutions in the four cities, including the dismantling buildings to reuse materials, transformation and refurbishment, and design for disassembly and flexible construction. According to the European Commission (2019), this project will develop urban planning instruments to support cities in implementing circular construction solutions and initiate changes at the system level. The project will also implement a Circularity Hub, a data platform to evaluate the progress of circular economy and regenerative capacity, and set up a knowledge sharing structure named the CIRCuIT Academy to promote the upscaling of solutions. The objective of this project is to increase the regenerative capacity of the four cities, reduce the yearly consumption of virgin raw material by 20% in new built environments, and save 15% of costs (European Commission, 2019b).

The results from the CIRCuIT project indicated that:

- Specific data on material stocks and flows is scarce overall, lacks granularity, and generally is uncertain in terms of robustness.
- The building types that are of interest for demolition and transformation vary greatly between the cities. All the cities identified modernist industrial/commercial buildings. In Copenhagen, London, and Hamburg, though not to significant extents in Vantaa, residential buildings were found to be threatened by demolition. London, Hamburg, and Vantaa all observed that low-rise and low-density stock is replaced with higher-rise and higher-density stock.
- The legislative context in urban planning and in building permits does not provide adequate room for setting specific demands in circular economy in planning practices at city level. Current national laws limit the possibility of directly implementing actions and set specific demands on circular economy in city administrations.
- The level of detail and emphasis on the opportunity, assessments of the potential impact of the policy, descriptions of the potential policies, and references for similar policies, do vary. Therefore, a discussion is needed with city policymakers across the four cities to identify the aspects that would be most beneficial to inform their decisions (European Commission, 2019a).

There are also other circular examples at each level of the construction industry (Çetin, Wolf & Bocken, 2021; Iyer-Raniga, 2019; Succar & Poirier, 2020) but the prospect of linking all aspects of the built environment through a fully inclusive and comprehensive circular economy remains a challenge (Arup, 2016).

In addition, smarter product manufacturing and use and the recycling of materials through recovery both bear a higher value in a circularity strategy compared to simply using the material for incineration to generate energy. If a higher level of circularity of materials is used in a product chain, those materials remain in the chain for a longer period. Hence, the use of newer materials to make products is reduced or eliminated. This has a direct impact on the environment. Beyond a strategic approach, the move to increasing circularity requires innovations in core technology, innovations in product design, innovations in revenue models, and social-institutional change (Iyer-Raniga, 2019). Monitoring chains of products and services to evaluate circular economy progression and achievements is a challenge. (Mêda et al., 2021)

Improved information management and tools or technologies to better understand and capture construction product characteristics is a key requirement. Also, information circularity and traceability are critical for more efficient and sustainable practices. In summary, the construction industry's digital transformation is crucial to integrate processes and technologies aimed at overcoming the challenges of adoption of a circular economy in the built environment (Mêda et al., 2021).

2.3.3. Circular Economy and Digitalisation

Digital technologies have a key role to play in supporting the transition to a fully decarbonised built environment (Irish Green Building Council, 2022). Digitalisation can boost the transformation towards a more sustainable circular economy. It can help close the material loops by providing accurate information on the availability, location, and condition of products. Digitalisation also enables more efficient processes in companies, helps minimise waste, promotes longer life for products, and minimises transaction costs. Thus, digitalisation boosts the circular economy business models by helping to close the loop, slow the material loop, and narrow the loop with increased resource efficiency.

However, there are still many challenges to be solved in order to gain the desired benefits and gaps hindering digital technology-aided circular business models implementation (Antikainen et al., 2018). Technology alone is not a silver bullet, but innovations in technology can help deliver decarbonisation in the built environment on many fronts (Irish Green Building Council, 2022).

For instance, virtual building information models, generally used at the design stage, can utilise various software applications and plug-ins to calculate WLC. Increasingly sophisticated energy modelling software, satellites, and weather data can help predict the operational energy demands of buildings, while data on construction materials and transport emissions, particularly in the form of digital EPDs, can be utilised for calculating the embodied impacts (Irish Green Building Council, 2022). Stakeholders can also collaborate on cloud-based BIM models with analytical software that clearly visualises a proposal's externalities (Arup, 2016).

Furthermore, considering that there is often a gap between the energy performance predicted in design and what happens when a building is occupied, digital twins can be used to link real-time data on building user behaviour from wearable technologies (e.g. smartwatch apps), motion detectors, and swipe access cards, with building management systems data from building equipment, as well as from occupied spaces through sensors to track temperature, humidity, light levels, and air quality (e.g. CO2 and carbon monoxide). This can initiate real-time mechanical carbon-saving responses like opening vents or switching off appliances, equipment, lighting, heating, and cooling systems (Irish Green Building Council, 2022).

Digital solutions are spread across the construction industry and focus on automating processes across the whole built environment's life cycle. The digital twin concept integrates many technologies and methodologies, such as Building Information Modelling (BIM). BIM is a methodology that, among other roles, has the capability to define building elements and faciliate an asset's visualisation and preparation for operation. Several systems assist the construction process, during design (e.g. software for structural dimensioning), through execution or construction (e.g. systems for development and monitoring schedules), to information repositories (e.g. Common Data Environment (CDE), databases, and information containers) that should later be utilised in the use phase (e.g facility or asset management) (Mêda et al., 2021).

As mentioned earlier, increased digitalisation also supports the adoption of circular opportunities. Digital transformation, alongside 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, 2021). 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, 2021). Likewise, in the 2020 EU Circular Economy Action Plan (European Commission, 2020a), innovation and digitalisation were seen as drivers for tracking, tracing, and mapping resources and dematerialising the economy for lower dependency on natural resources. Thus, a clear link between digitalisation and CE in the policy environment within the European context can be concluded (Çetin, Wolf & Bocken, 2021).

Compared to other sectors, digital transformation has been slow in the built environment, but there have been considerable developments in the last few decades. This could be due to the fragmented value chain in this sector, which is the reason that digital platforms are increasingly being developed (Çetin, Wolf & Bocken, 2021).

In this regard, digital technologies, which some scholars refer to as Industry 4.0 technologies, are thought to be essential for the transition to a circular economy in the construction industry (Çetin, Wolf & Bocken, 2021).

Industry 4.0

'Digitalisation' generally describes the integration of digital technologies into everyday life. This integration is called 'Industry 4.0' because it embodies the fourth industrial revolution (Sarc et al., 2019). Industry 4.0 has been identified as a major contributor to the era of digitalisation. Its implications for sustainable development have gained widespread attention from the perspectives of the triple bottom line, sustainable business models and circular economy (Khan et al., 2021).

Industry 4.0 incorporates Big Data (BD) Internet of Things (IoT), which is divided into two parts, including 'Industrial Internet of Things' and 'Consumer Internet of Things', and Artificial Intelligence (AI) for leveraging manufacturing operations. The potential of Industry 4.0 is thus remarkable for achieving sustainable industrial value creation across social, economic, and environmental dimensions by improving resource efficiency (Sarc et al., 2019; Khan et al., 2021).

The term 'Industry 4.0' was coined by German researchers Kagerman et al. (Kagermann et al., 2011) to help shape the future of the German economy. Industry 4.0 uses fundamental technologies, such as Cyber-physical Systems (CPSs) and IoT, to connect humans, machines, and other resources as well as products and services in the real world (Khan et al., 2021).

Sustainability is also considered a primary driver of Industry 4.0. Industry 4.0 technologies can be integrated with value chains by collecting and actively sharing data to provide real-time information about machines, productions, operations, and component flows. This helps managers track, monitor, and make sustainable decisions about post-consumption product recoveries. These recovery-based approaches replace the traditional linear 'take, make, use and dispose' philosophy with a circular one that benefits organisations and supply chains socially, economically, and environmentally (Geissdoerfer et al., 2017; Khan et al., 2021).

Digital Twins

A 'digital twin' is defined as a "virtual representation of a physical system (and its associated environment and processes) that is updated through the exchange of information between the physical and virtual systems" (VanDerHorn & Mahadevan, 2021).

The digital twin is a data-focused concept and allows bi-directional data interaction between the physical built and a digital/responsive twin, and it is part of the digital transformation strategy which aims to increase the construction sector's productivity, competitiveness, and efficiency (Mêda et al., 2021).

The digital twin construction is a platform integrating data from different systems. It is the data integrator combining the physical object and the digital mirror (Mêda et al., 2021).

Digital twins aim to interconnect sensors in physical assets to cyberspace, fostering the collection, processing, and analysis of data to simulate and control the assets or built objects. The digital twin concept can still be vague, but for the construction industry's purpose, it is essential to understand that its materialisation starts in the projects' early phases and will support increasing dimensions during the construction process. It gains shape throughout the project's execution, intercommunicating data at all times, and thus the digital twin construction terminology becomes more appropriate or specific for the construction sector (Mêda et al., 2021).

According to Sacks et al. (2020), "digital twin construction is a new mode for managing production in construction that leverages the data streaming from a variety of site monitoring technologies and artificially intelligent functions to provide accurate status information and to proactively analyse and optimise ongoing design, planning, and production. Digital twin construction applies BIM technology and processes, lean construction thinking, the Digital Twin Concept, and AI to formulate a data-centric mode of construction management".

According to Mêda et al. (2021), the conceptualisation of digital twins in the construction industry is scattered. However, it is attached to the concept of Industry 4.0 and mainly concerns IoT devices, big data and artificial intelligence.

In the construction industry, a digital twin is a platform that integrates data and different systems, making it a System of Systems (SoS). It can be visualised into multi-domain ontologies or multi layers (Mêda et al., 2021). However, there are challenges in the adoption of SoS, such as fraud detection, data interoperability, and extra costs in updates and upgrades caused by the SoS geographical distribution (Borth et al., 2019). BIM is a vector of building data, and integrating it with IoT is crucial to many solutions, such as indoor safety management, digitalisation, and visual representations. IoT device incorporation into buildings should target sustainable indicators assessment into a total life cycle management. Much remains to be done and IoT technology implementation in the construction industry should be further explored in both academic and industrial fields (Mêda et al., 2021). According to Mêda et al. (2021), it is evidenced that digital twin construction concepts mainly address the data interaction between the physical and virtual assets, the sensing technologies applied in both construction and in-use phases, and the possible distinguished levels of evolution of a digital twin construction.

A concept of the digital twin evolution was presented at the First Building Digital Twin International Congress on May 27th, 2021 (Mêda et al., 2021). Digital twin is upscaled following five stages regarding the increased information evolution into a physical to virtual maturity, as follows: 0: Traditional, 1: Transitional, 2: Conceptual, 3: Replication and 4: Front running. There is a common understanding of an evolutive path to a fully connected digital twin. The way the data flows (manual or automatic) between the physical and digital objects can indicate a level of evolution of the digital twin construction (Tchana et al., 2019). In this regard, there are three evolutionary steps including:

- Digital model (manual data flow between physical and virtual objects). As an example, there is a designed 3D model of a building that corresponds to the physical element, and when a change is made to the physical building, it is updated in the digital environment (Tchana et al., 2019).
- Digital shadow (with an automatic data flow from physical to virtual and manual data flow

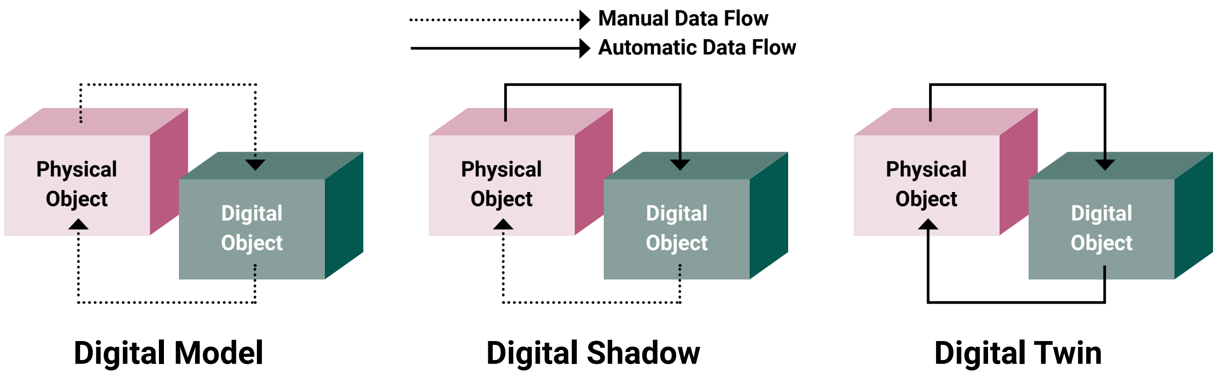


Figure 9
Evolution of the Digital Twin (Tchana et al., 2019)

from digital to physical objects). As an example, a sensored site or building where the data is collected but the system is not able to interact and take action in the physical space (Tchana et al., 2019).

- Digital twin (with bi-directional data flowing between physical and virtual objects). For example, a smart building with IoT technologies collects data from the built environment (e.g. temperature and amount of people in each room) and adjusts the HVAC systems (Tchana et al., 2019).

BIM

The transition to a circular economy requires the integration of information systems, and the dominant information system in the construction industry is Building Information Modelling (BIM) (McGinley, 2018). BIM is an integrated process that involves collaboratively developing and using a computer-generated parametric model of a building to facilitate whole life management of the building from planning to operation (Akanbi et al., 2018).

BIM has the capability of storing different types of information in its digital model. It also allows for the storing and sharing of information with the stakeholders, helping to avoid uncertainties and errors while contributing to building process optimisation (Daniotti et al., 2021). It is justifiably an important tool for the adoption of a circular economy in the built environment (Benachio et al., 2020).

The adoption of BIM will help apply the planned strategy throughout the asset's life cycle (Rahla et al., 2021). The principal objective of BIM is to streamline construction efforts through intensified collaborative planning and a clear definition of goals at the early stages of a project (Ganiyu et al., 2020). BIM justifiably is a paradigm shift from the traditional style of working in silos to a collaborative strategy using a digital representation of the building with the potential to stimulate efficient waste management (Ganiyu et al., 2020). Furthermore, using BIM can enable the selection of sustainable materials and components during the design stage and also help quantify the volume of materials which can potentially be recovered at the end-of-life of the facility (Hossain et al., 2020).

In the context of the circular economy, BIM has the ability to accumulate life cycle information about a building that makes it suitable for the circular economy process (Akanbi et al., 2018). For the effective implementation of a circular economy in the construction industry, the status and quality of the building materials in the economy needs to be known. In this regard, performance evaluation of building materials during and at the end-of-life is required. BIM, therefore, offers three core features that make it suitable for whole-life performance management of buildings. These core features consist of object parametric modelling, bi-directional associativity, and intelligent modelling (Akanbi et al., 2018).

The parametric modelling feature is for capturing design form and functionality using parameters and rules. Parametric representation ensures that the form and functionality of designs are preserved in response to contextual change (Akanbi et al., 2018). Bi-directional associativity provides suitable support for changes that may occur in building models. Intelligent modelling ensures that supplementary data, which are needed for various analytical, simulation and evaluation purposes, including schedules, cost information, energy analysis details, lighting information, waste management plan, etc., are provided in addition to 3D geometric data (Akanbi et al., 2018).

Furthermore, According to Akinade et al. (2018), BIM capabilities could help in achieving a circular economy in construction in key areas, including automatic clash detections, design error reduction, an early collaboration of stakeholders, visualisation, simulation of waste performances, waste management reporting, etc.

As a result, in the context of a circular economy, BIM can be considered an effective tool for minimising waste throughout the building's life cycle (Rahla et al., 2021).

In Ireland, as part of their Future of Construction initiative in 2018, the World Economic Forum (WEF) published an action plan to accelerate BIM adoption. The WEF report highlighted actions that companies, industry organisations, and governments are advised to implement to accelerate the adoption of BIM for delivering better project outcomes. According to the authors of the report, BIM is seen as the centrepiece of the construction industry's digital transformation. However, they acknowledged that the adoption of BIM has remained low both globally and in Ireland (Hore et al., 2021). In order to accelerate the adoption of BIM and drive the digital transition programme in the Irish construction industry, using an adaptation of the 'WEF BIM Adoption Circle' model could be applicable (Hore et al., 2021).

Data Templates

Digital data templates are standardised, interoperable data structures used to describe the characteristics of the construction products, systems, or others based on reliable sources of information, such as standards, regulations, or other references (International Organization for Standardization, 2020c). Data is made machine-readable, acting as an enabler or facilitator for information exchange and data management throughout the construction's life cycle (Mêda et al., 2021).

According to ISO 23387 (International Organization for Standardization, 2020a), "data templates will enable construction project stakeholders to exchange information about construction objects through an asset life cycle, using the same data structure, terminology and globally unique identifiers to enable machine-readability. Data templates should be standardised and made available across the built environment sector through data dictionaries based on ISO 12006-3:2022. Data templates should be used in conjunction with Industry Foundation Classes (IFC) in ISO 16739-1:2018 to enable and support open BIM processes".

Product information management is a challenge as data dealing involves different stakeholders spreading throughout the construction process. Therefore, data templates could mitigate this problem (Mêda et al., 2021) and facilitate the transition to a circular economy in the built environment.

Digital Logbook

The digital building logbook is defined as a framework for all relevant buildings' information storage. It has the capability to receive, store, exchange, trace, and update all data related to buildings and their components (Mêda et al., 2021).

The European Commission (2020) (European Commission, 2020c) defined the digital building logbook 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. A digital building logbook is a dynamic tool that allows a variety of data, information and documents to be recorded, accessed, enriched and organised under specific categories. It represents a record of major events and changes over a building's life cycle, such as change of ownership, tenure or use, maintenance, refurbishment and other interventions".

Furthermore, according to the European Commission (2020c), the digital building logbook "can include administrative documents, plans, description of the land, the building, and its surrounding, technical systems, traceability, and characteristics of construction materials, performance data such as operational energy use, indoor environmental quality, smart building potential, and life cycle emissions, as well as links to building ratings and certificates. As a result, it also enables circularity in the built environment. Some data types stored in the logbook have a more static nature, while others, such as data coming from smart meters and intelligent devices, are dynamic and need to be automatically and regularly updated. A digital building logbook is a safe instrument giving users control and access to third parties, respecting the fundamental right to the protection of personal data. Data may be stored within the logbook and/or hosted in a different location to which the logbook acts as a gateway". (Mêda et al., 2021).

Furthermore, supporting the development of digital building logbooks and overseeing their implementation is also emphasised by IGBC (Irish Green Building Council, 2022). In Ireland, IGBC (2022) suggested the establishment of a legal framework for a Digital Building Logbook to capture better quality data on buildings and building materials, alongside Building Materials Passports to facilitate reuse and the transition to a circular economy by 2025.

Ireland and Digitalisation for Decarbonisation of the Built Environment

The following recommendations are made by IGBC (2022) for the decarbonisation of Ireland's built environment across its whole life cycle by using digital technologies:

- Establishment of national BIM protocols for mandatory use for all publicly funded projects (e.g. the Gemini Principles in the UK) by the Office of Public Works (OPW), outlining standardised open-source file types and provide BIM files (inclusive of all EPDs information) to support LCA and digital twin requirements.
- Establishing a public sector digital twin pilot programme for different public building types, with priority on office buildings by the OPW.
- Regular tracking of progress towards 2030 and 2050 targets so as to increase transparency within the sector, for example, by launching an online dashboard. For energy renovation, the Build Upon Framework is suggested, and making this data available at the local authority level to support greater citizen engagement.
- Developing and maintaining a central database for embodied carbon to cover both asset and product levels, gathering data across the industry, standardising inputs, and assisting in setting benchmarks and targets per sector.
- Development of the construction product database containing product-specific EPDs, generic EPDs, and defaults for construction products.
- The building level database should focus on LCA data for new buildings. Utilisation of a single methodology, a national WLC assessment methodology aligned with the European Framework for sustainable buildings (Level(s)) and the publicly availability of the information as open data.
- Development of an interactive construction material pyramid such as the Danish Materiale Pyramiden (Centre for Industrialised Architecture, 2022) to enable designers and all key stakeholders to quickly identify construction materials with lower embodied carbon.
- Provision or adoption of free open-source Dynamic Simulation Modelling (DSM) energy modelling software by the industry, in addition to proprietary DSM software packages. This is key as DSM can more accurately model large complex non-domestic buildings and their systems, including part load operation and heat recovery. BIM Level 3 and 4 modelling using iSBEMie, or any of its proprietary front-end packages, is not appropriate for large complex

non-domestic buildings, but iSBEMie is the only level of modelling available in Ireland for Non-domestic Energy Assessment Procedure (NEAP) compliance modelling and non-domestic Building Energy Rating (BER) assessments. Free, open-source DSM software packages such as EnergyPlus, or proprietary DSM software packages for creating performance models that can estimate building energy use with more accuracy than the simplified iSBEMie software used for compliance modelling.

- Provision or adoption of an appropriate energy modelling methodology, reporting framework, and Post Occupancy Evaluation (POE) criteria by the industry. The Technical Memorandum 54 (TM 54:2022) from the Chartered Institute of Building Services Engineers (CIBSE) provides a detailed methodology for evaluating the operational energy performance of buildings at the design stage. The National Australian Built Environment Rating System (NABERS) energy rating scheme, now being adopted in the UK under the Design for Performance (DfP) energy rating scheme, provides a framework for accurately estimating operational energy performance at the design stage and verifying actual operational energy performance post-occupancy. Also, upskilling in the industry is required to ensure these tools and methodologies deliver to their full potential.
- POE of completed projects needs to become standard practice. Therefore, the development of a General Data Protection Regulation (GDPR) compliant national building stock database containing information on actual emissions and energy consumption of buildings by the Sustainable Energy Authority of Ireland (SEAI) by 2025 is required.
- SEAI and Met Eireann should develop free, open-source Test Reference Year (TRY) and Design Summer Year (DSY) weather data sets for multiple locations in Ireland.
- Development of carbon metering protocols and tariffs that adjust carbon tax applied accordingly by Eirgrid. To enable Building Management Systems (BMS) control for load shifting linked to grid CO2 intensity rather than time of day and optimisation of local energy storage for lowest carbon intensity.
- Develop digital building logbooks and capture this information centrally to gather better quality data on buildings and support the aggregation of retrofit projects and the reuse of construction materials.
- Developing digital building renovation plans/ passports (BRPs) that inform retrofit pathways for existing buildings that are held within a central property database.
- Developing an integrated retrofit one-stop-shop aggregation platform to capture data from BRPs to enable more cost-effective renovation at scale, and bulk purchase of materials and products (Irish Green Building Council, 2022).

Furthermore, as new digital technologies are needed to support the better use of existing buildings and the reuse of construction materials, the following suggestions are made in this context (Irish Green Building Council, 2022):

- Development of an office scheduling protocol and portal by the OPW to optimise public sector office space use.
- Promoting the development of technologies supporting the sharing schemes, including for construction products and tools, such as libraries of things.
- Developing building material passports to retain information on performance and ingredients in order to enable building products and materials to be reused in future (to align with the new requirements of the Ecodesign Directive).
- Further developing of physical and virtual marketplaces for the reuse of construction materials.
- Creating a Buildings As Material Banks (BAMB) database of developments, including demolitions and refurbishments, creating a geographical map of resources suitable for reuse.
- Initiating the development of Urban Metabolism (BAMB) mapping for all non-protected buildings by Local Authorities by 2025. Urban Metabolism (describing and analysing material flows using digital technologies such as GIS, BIM, databases of digital logbooks, materials passports, and EPDs) is an important pillar for achieving a decarbonised built environment (Irish Green Building Council, 2022).

Furthermore, other projects and hubs are working towards digitalisation and adoption of circular economy principles in Ireland's built environment.

Digital Academy for the Sustainable Built Environment (DASBE) is a hub for the provision of upskilling, capacity building, and education in the construction sector on green construction, energy efficiency, circular economy, and digital skills (O'Brien, 2021).

The main aim of DASBE is to create National Digital Academy that enables the construction industry, SMEs, manufacturers, and workers to upskill and gain new knowledge in a cost-effective, worker-centric learning environment. The target groups in this project are construction professionals, crafts workers, and new talent such as students (O'Brien, 2021).

According to DASBE 2021, this programme will be a key tool for enabling a circular economy and digital transformation, responding to market needs in the construction sector by facilitating learning and access to information on upskilling opportunities.

2.4. Summary

To summarise, Table 2 is provided to indicate current efforts on the development of frameworks for the adoption of a circular economy and digitalisation in the built environment.

Table 2

Summary of Current Studies on Digitalisation and a Circular Economy in the Built Environment.

Keywords	Projects/ paper	Scope	Technologies	Framework	Life-cycle phase	CE principles incorporated (9R's)	Case study (Testing the framework)	Key contribution of paper
Circular Economy And Digitalisation	Lifecycle information transformation and exchange for delivering and managing digital and physical assets (Succar and Poirier, 2020)	Construction Industry in general	BIM, AI, digital twin	The lifecycle Information Transformation and Exchange (LITE) framework	Whole life-cycle	refurbishment, recycling, and reuse	-	Proposes the UTE framework for investigating. managing, and predicting information flows across an asset lifecycle to respond to the challenges faced by the construction industrydue to the digital transformation
Circular Economy AND Digitalisation AND Built environment	Innovation realisation for digitalisation within Dutch small architectural practises: stateof the art and future needs (Geoghegan et al., 2022)	European construction design SMEs-particularly Dutch small architectural practices.	BIM	-	-	-	-	Highlighted the importance of projects information requirements for SMEs and the multi-faceted digitalisation challenges experienced by small architectural practices and building design SMEs.
Circular Economy And BIM	BIM data model requirements for asset monitoring and the ci,cula, economy (Davila Delgado and Oyedele, 2020)	Buitt assets	BIM	-	operational phase	Reuse, Recycle	-	Investigation of the current capabilities of open standard data models for performance monitoring and circular economy principles for the operational phase of built assets.
Circular Economy and BIM	BIM competencies for delivering waste- efficient building projects in a circular economy (Ganiyu et ol., 2020)	Con.struction firms	BIM	-	Not specifically defined	Not specifically defined	-	Identified and analysed critical BIM competencies for delivering waste-efficient building projects in a circular economy.
Circular Economy and Digitalisation	Circular Digital Built Environment: An Emerging Framework (Çetin, DeWottand Boeken, 2021)	Built Environment (buildings and infrastructure)	(1) Robotic manufacturing, (2) AI, (3) big data, (4) blockchain, (5) BIM, (6) digital platforms/ marketplaces, (7) digital twins, (8) GIS, (9) material passports/ databanks, (IO) IoT.	Circular DigitalBuilt Environment framework	Pre-use phase, Use phase, next· use phase	(1) Regenerate; (2) Narrow; (3) Slow; (4) close	-	Circular Digital Built Environment framework - integrating 4 core CE principles for whole life-cycle of the buildings
Circular Economy And Digitalisation	Incremental Digital Twin Conceptualisations Targeting Data-Driven Circular Construction (Meda et al., 2021)	Architecture. Engineering, Construction, and Owner operator (AECOO) sector	Digital data templates, digital building logbooks. Digital Twin Construction	Ine<emental DTC Framework	Whole life, cycle	-	-	Developed the "Digital data-driven concept'" to structure. store, and trace data. for facilitating digital transformation for a circular built environment
Circular Economy And Digitalisation	Using the ReSOLVE framework for circularity in the building and construction industry in emerging markets (Iyer-Raniga, 2019)	Buildings (office building,modul ar building [House])	SIM, material banks, QR codes used in materials	ReSOLVE framework and The Seven Layers (S7}	3 case studies considered all stages of the building litecycle	Regenerate, Share, Optimize, Loop, Virtualise, Exchange Reuse, remanufactu re.and recycling	(l)Small refurbished office building (France) (2) Mid-size refurbished (Netherlands) office building (3) A demonstration house (Scotland) (4) Judicial Police facility (France)	Proposes the requirements for transition to a Circular built environment in emerging markets

As a result, the following gaps were identified in the context of the adoption of circular economy principles and digitalisation in the built environment, based on the literature review that has been conducted so far.

Gaps

- Lack of life cycle framework for synergising digitalisation and a circular economy in the built environment in order to facilite the transition to a circular economy.
- Lack of common information management framework for facilitating the adoption of circular economy principles in the built environment.
- Lack of common regulations or policies related to the digitalisation and adoption of technologies for reducing conflicts and uncertainties regarding the data and information sharing for implementation of a circular economy in the built environment.
- Limited number of studies in the context of digital logbooks for a circular economy in the built environment.
- Insufficient studies on the adoption of digital twins, AI, and IoT for a circular economy in the built environment.
- There is a gap in addressing the education and skill gaps of the workforce and the whole value chain stakeholders regarding the required technological skills needed for the transition to a circular economy business model in the built environment.
- Limited case studies/demonstration projects and reports on the performance of the current frameworks.

2.5. Future Work

Build Digital should aim to start addressing the gaps identified in Section 2.4 by:

- Developing theoretical or practical frameworks and accompanying implementation guides for the adoption of a circular economy in the built environment in Ireland.
- Developing a common framework and accompanying implementation guide for digitalisation for the adoption of a circular economy principles in the Irish built environment.
- Leverage circular economy demonstration projects or case studies in the building sector (or the construction industry in general) in Ireland.

Additional future work will also consider the gap in the literature. The secondary keyword combinations identified and presented in Table 3 need to be investigated in detail in order to cover the gap in the field of synergies between digitalisation and circular economy in the built environment.

Keyword combinations
• Circular economy AND Built environment AND Digitalisation Circular economy AND Built environment AND BIM • Circular economy AND Built environment AND Industry 4.0 Circular economy AND Built environment AND Digital Twin Circular economy AND Built environment AND AI • Circular economy AND Built environment AND IoT • Circular economy AND Built environment AND Material Passport Circular economy AND Built environment AND Blockchain Circular economy AND Built environment AND Digital logbook
• Circular economy AND Buildings AND Digitalisation Circular economy AND Buildings AND BIM • Circular economy AND Buildings AND Industry 4.0 Circular economy AND Buildings AND Digital Twin Circular economy AND Buildings AND AI • Circular economy AND Buildings AND IoT • Circular economy AND Buildings AND Material Passport Circular economy AND Buildings AND Blockchain Circular economy AND Buildings AND Digital logbook
• Circular economy AND Construction AND Digitalisation Circular economy AND Construction AND BIM • Circular economy AND Construction AND Industry 4.0 Circular economy AND Construction AND Digital Twin Circular economy AND Construction AND AI • Circular economy AND Construction AND IoT • Circular economy AND Construction AND Material Passport Circular economy AND Construction AND Blockchain Circular economy AND Construction AND Digital logbook

Table 3
Secondary Keyword Combinations Based on Main Keywords in Table 2.

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Appendix

Circular Economy	Built Environment	Buildings	Construction
Circular economy AND Built environment	-	-	-
Circular economy AND Buildings	-	-	-
Circular economy AND Construction	-	-	-
Circular economy AND Digitalisation	Built environment AND Digitalisation	Buildings AND Digitalisation	Construction AND Digitalisation
Circular economy AND BIM	Built environment AND BIM	Buildings AND BIM	Construction AND BIM
Circular economy AND Industry 4.0	Built environment AND Industry 4.0	Buildings AND Industry 4.0	Construction AND Industry 4.0
Circular economy AND Digital Twin	Built environment AND Digital Twin	Buildings AND Digital Twin	Construction AND Digital Twin
Circular economy AND AI	Built environment AND AI	Buildings AND AI	Construction AND AI
Circular economy AND IoT	Built environment AND IoT	Buildings AND IoT	Construction AND IoT
Circular economy AND Material Passport	Built environment AND Material Passport	Buildings AND Material Passport	Construction AND Material Passport
Circular economy AND Blockchain	Built environment AND Blockchain	Buildings AND Blockchain	Construction AND Blockchain
Circular economy AND Digital logbook	Built environment AND Digital 74 logbook	Buildings AND Digital logbook	Construction AND Digital logbook

Table 4
Primary Keyword Combinations Used for Conducting Bibliometric Analysis

Build Digital

Rialtas na hÉireann
Government of Ireland

Tionscadal Éireann
Project Ireland
2040