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Abstract

Purpose: This study examines how applying innovative I4.0 technologies at the design stage can help reduce construction waste and improve the recovery, reuse, and recycling of construction materials.

Approach: The study adopts a qualitative methods approach, involving a thorough review of current literature, interviews with six experts in digital construction.

Findings: The study identifies and discusses how ten specific digital technologies can improve design stage processes leading to improved circularity in construction, namely: 1. additive and robotic manufacturing; 2. artificial intelligence; 3. big data analytics; 4. blockchain technology; 5. BIM; 6. digital platforms; 7. digital twins; 8. geographic information systems; 9. material passports and databases; and 10. internet of things. It demonstrates that by using these technologies to support circular design concepts within the sector, material recycling rates can be improved and unnecessary construction waste reduced.

Originality: Little consideration has been given to how digital technology can support design stage measures to reduce construction waste. This study fills a gap in knowledge of a fast-moving topic.

Practical implications: This research provides researchers and practitioners with improved understanding of the potential of digital technology to recycle construction waste at the design stage, and may be used to create an implementation roadmap to assist designers in finding tools and identifying.

1. Introduction

In the UK, the construction sector consumes over 60% of total materials used and produces almost a third of the national waste output, (Blundell, 2019). Global figures are similar. Reducing these figures is crucial, firstly to reduce reliance on raw materials and imported products, secondly to reduce waste and quantities for landfill, and thirdly to reduce the pollution associated with disposal, (Rijdt, 2021). Advocates of a circular economy (CE) propose substituting the linear produce-use-dispose model of material usage, with circular material use loops which involve reuse, sharing, leasing, repairing, refurbishing, upcycling, and recycling.

Although a popular component of civil society discourse on waste, the CE concept is only beginning to be applied to the construction sector. Here it would include waste reduction through improved design of materials, products, systems, and business models, (Okorie et al. 2018), as well as extending the life and reusability of structures or materials through advanced design concepts, (Charleston, 2021). Construction stakeholders have always considered waste as an unavoidable by-product, (Guerra & Leite, 2021). However, 33% of all material waste is said to be due to the architects' inability to design-out waste. Architects and designers are unused to considering waste reduction during design, waste is seen as unavoidable, responsibilities are unclear, and training is lacking, (Osmani, 2012). There is therefore an opportunity to minimise waste through better design.

Advanced digital tools and approaches are beginning to have an impact on the construction industry, (Maskuriy et al., 2019). Big data and analytics (BDA), autonomous robots and vehicles, additive manufacturing, simulation, augmented and virtual reality (AR/VR), horizontal/vertical system integration, the Internet of Things (IoT), cloud computing (CC), fog, and edge technologies, and blockchain and cyber-security are among the nine technologies identified by the Boston Consulting Group as building blocks of Industry 4.0 (I4.0) in the context of the built environment, (Rüßmann et al. 2015). Many see these tools as having the potential to support a transition to circularity within the sector, by supporting more effective consideration of construction waste at the design stage, (Reffel, 2021). Akanbi et al., (2017) sees streamlining design, production and consumption leading to improvements in reuse, repair, remanufacture and recycle, and paving the way towards embracing end-of-life decision making and recycling. Thelen, Zijlstra and Zandbergen, (2021) consider that digitalisation has much promise for speeding up the transition to sustainability in the construction industry, (Hedberg, Šipka and Bjerkem, 2019). Ciliberto., et al. (2021) argue that if properly managed, digitally enabled solutions can aid in improving connection and information exchange, as well as making products, processes, and services more circular, and suggest that technology can help recovery of new materials in the waste flow, and obtain secondary raw materials to compete with original materials.

Gorrisen et al., (2016) however, highlight the distance between theory and practice, and note that efforts to transition from a linear supply chain to a circular supply chain have been hampered by gaps and data inconsistencies. More examination of the potential and the reason for slow progress is therefore needed, (Rajput & Singh, 2019).

Aims of the study

The paper examines how the application of I4.0 technologies and approaches at the design stage, can aid in reducing construction waste and in improving the efficiency of its recovery, reuse, and recycling. It also seeks to understand the limitations to delivering advances in circular construction using I4.0 and identify how to address these.

2.0 Conceptual basis for introducing circularity into construction

The circular economy in construction

Advancing a circular approach within the construction industry involves applying techniques at all stages of a building's life cycle, to retain materials in a closed-loop as long as feasible, and to limit the use of new natural resources in a construction project, (Benachio et al., 2020). Practically, this is done by increasing the reusing, sharing, leasing, repairing, refurbishing, upcycling, or recycling of materials, and involves strategies to prolong the life and reusability of entire buildings or materials from the very beginning of the design process, (Charleston, 2021).

Scholars have examined a number of angles to reduce waste, ranging from material reuse to urban planning, with end-of-life activities such as waste management featuring prominently in most studies, (Hossain et al., 2020; Munaro et al., 2020). Comprehensive framing of circular techniques has been offered for building components, prefabricated buildings, and industrialised house construction, (Kedir & Hall, 2021; Minunno et al., 2018). CE initiatives include new building design and construction, sustainable building construction, material and product flows in buildings, and CE in the real estate industry, (Eberhardt et al., 2020).

But Law, (2014) proposes that to progressively shift to renewable resources, designers must ‘design for deconstruction’, to make disassembly and material recovery easier. Consequently, when a building reaches the end of its life, a key aspect of CE thinking is to give a new lease of life to the structure's materials, components, and systems.

Many authors have considered the ways in which designing for circularity should follow a comprehensive approach to enable reusability, flexibility, and adaptability, see (Rahla et al., 2021), (Bocken et al., 2016; Kirchherr et al., 2017; Leising et al., 2018; Sarc et al., 2019). Cetin et al., (2021) has proposed five approaches to reduce resource inputs, waste, emissions, and energy leakage in materials over time. These are:

1. Limiting the loop - essentially using fewer resources by improving the efficiency of manufacturing and design. Several techniques can be used, including *off-site construction*, (Ellen MacArthur Foundation, 2017), prolonging the operational life of buildings and building commodities, (Bocken et al., 2016; Rajput & Singh, 2019), and *smarter usage of space* to boost the value of pre-existing land or buildings by incorporating new functions. This also includes reusing materials in the system without requiring extensive change or resource consumption, (De Wolf et al., 2020). Lowering primary resource inputs, designing for reversibility, and urban mining are all approaches to encouraging reuse.

2. Slowing the loop: This means using less material through extending product life and minimising needless consumption. Techniques within this category include *designing for deconstruction*, where a building's disassembly gains more attention as designers attempt to create a closed-loop resource flow, (Crowther, 2005), and Ciarimboli and Guy, (2005), *designing for reversibility,* where a range of design techniques allows for several resource lifespans until the materials are no longer usable, (Durmisevic, 2019), and *designing for longevity,* which reduces waste and helps ensure assets are used optimally throughout their lifecycles.

3. Closing the loop refers to reusing materials and recycling post-consumer usage. It includes techniques such as *careful selection of materials,* (Pomponi & Moncaster, 2017), and *recycling* where raw materials are not removed from use but instead used efficiently and intelligently, therefore staying in the system for longer time, and slowing down the flow of materials, (Bakker et al., 2010). It also can include *urban mining,* which is the resurrection of materials collected in metropolitan areas not explicitly planned for use or recycling, Heisel and Oberhuber., (2020). Intervention during the manufacture or design phases of a project can have significant influence on the recover capability of materials.

Digital reliance is also useful, i.e. the development of a digital product rather than a physical one, (Ellen MacArthur Foundation, 2017). BIM for example, helps stakeholders collaborate more effectively on the design, construction, and operation of buildings. This enables more efficient design methods and aids in building performance and upkeep. By incorporating information on materials, BIM can help explain negative externalities as well as the possibility for recycling and remanufacture, (Arup, 2015).

4. Regenerating the loop emphasises the need to leave the environment (and society) in a better position than previously. It includes returning products to the economy through restorative operations like repair and remanufacturing, (Bocken et al., 2016). Regenerative design is perhaps the highest level of sustainability in architectural design, generating continuous flows of resources in a self-sufficient manner (Mang & Reed, 2012), and is one of the key concepts of circularity in construction, (Çetin et al., 2021). It also includes the *exchange of excess resources,* i.e. capturing economic benefit from regenerative building operations, (Craft et al., 2017). In the case of energy, tremendous advances in smart grid technology have allowed prosumers (consumers who also generate and sell energy) to trade surplus energy within their neighbourhoods in recent years (Mengelkamp et al., 2018).

5. Collaboration and standardization is about encouraging the professionals and processes involved in a project to communicate and collaborate to achieve circularity. This can include *support for supply chain collaboration*, (Brown et al., 2019), and also *creating knowledge and value networks* to offer fresh experience, and help to create a new circular ecology, (Leising et al., 2018). *Designing for optimal procurement* involves using some or all the following approaches to decrease waste: design (for example, designing architectural parts that can be erected quickly); specification (for example, stricter specifications of work operations to reduce waste and allow offcuts); and contracts (e.g., encourage early contractor involvement). The transition will take time and will only be accomplished through collaboration and partnerships (Charef & Emmitt, 2021).

Challenges and opportunities to improve circular design strategies

The literature has identified several challenges to improving circularity in the construction industry. One is the gap between research and practice, with both research and industry developing circular strategies independently of one another, (Eberhardt et al., 2020). CE100, (2016) presents several case studies which highlight common challenges such as: 1. Coordination and on-site training; 2. Matching supply and demand; 3. Facilitating community reuse; 4. Organizing collections of assets; and 5. Reporting and measuring recycling extent of materials. Authors such as (Guerra & Leite, 2021) and Debacker et al., (2021) also highlight difficulties in budgeting and planning, capacity, awareness and regulation. Essentially, the lack of a well-planned design acts as a hurdle to the effective implementation of circular strategies, (Rahla et al., 2019).

The literature also suggests several recommendations to improve consideration of circularity in the design stage. A key one is the incorporation of Material Passports into Building Information Management to allow building stakeholders to monitor materials, identify their origins, and assess their quality (Rahla et al., 2021). Involving stakeholders in all critical decisions from design conceptualization through reuse of building components is also suggested by Debacker et al., (2021). Initiating agreements to coordinate the dimensions of building components and standardize connecting systems, will provide more quality reassurance of reclaimed/ recycled materials by matching supply with demand.

The same author suggests that building and material information management should be centralized - storing building information in a centralised, digital manner, and building trust within the value network by providing transparent and traceable information. This will allow digital information to be used to learn and/or augment intelligence, (Debacker et al., 2021).

The creation of a competitive secondary materials market would also increase circularity by raising demand for both quantity and quality of waste material, as would developing technologies for fast removal of hazardous substance and eliminating the use of hazardous materials in new construction, (European Environment Agency 2021).

Finally, the Ellen MacArthur Foundation (2020) suggests adopting digital infrastructure such as tracking technologies and digital modelling progressively into rehabilitation projects. Here, design teams may use precise 1:1 base models of existing structures to make their jobs easier and allow for more targeted recycling. The Foundation has collaborated with McKinsey to develop the ReSOLVE framework which identifies high-level actions, or principles, that companies may use to cut waste (Regenerate, Share, Virtualize, Optimize, Loop, Exchange).

To contribute to the building of knowledge on this matter, it is necessary to address what the circular economy means in construction, and to analyse how I4.0 tools and techniques can aid in recycling construction waste.

3. Methodological Approach

A two-stage qualitative approach was adopted. A review of literature using such search terms as 'circular economy,' 'circular construction,' 'digital circular economy,' 'digital recycling,' 'construction waste recycling,' and 'use of construction waste' was used to identify the themes, gaps in knowledge and to establish focus areas for the subsequent research. Access to a large number of journals, databases and academic search engines was made available via the Queen's University Belfast library. Searches were made in peer-reviewed academic journal articles as well as recently published books and recent articles in current professional and trade journals and magazines, particularly targeting articles published in 2020 and 2021. 165 separate literature sources were referenced in the full study, with 75 specifically in the literature review.

As well as providing current information to present in the study, the review of literature was used to identify the key issues to be further examined with the interview participants. The opinions of six well-established professionals with demonstrated competence in the field of CE and I4.0 were explored using a semi-structured interview approach, as outlined by Bryman (2008). The six participants were chosen for their involvement in using I4.0 technologies in design and waste management, and for their diversity in representing a range of contexts in the construction industry. It is recognised that six is a relatively low number for such a study, but a quality over quantity approach was adopted with some potential participants excluded due to their lack of relevant expertise. Since digital tools are evolving quickly, it was felt that the in-depth, current and hands-on experience of these six participants makes up for their lack of longevity in the industry. Details of the interviewees are summarised below.

Interviewee	Designation	Location	Experience	Gender
A	Project Manager, Head of Digital Transformation for an organisation.	London	3 years	Male
B	Architect, Circular Economy Specialist	London	2 years	Female
C	BIM Architect	Leeds	3 years	Female
D	Academic Researcher	Sheffield	3 years	Male
E	Project Manager, I4.0 and CE Consultant in the Built Environment	London	5 years	Male
F	Academic Researcher in I4.0 and Digital Supply Chains	Edinburgh	2 years	Female

INSERT-TABLE-1

Table 1. Interview participants

The interviews focus on four aspects: 1. Relevant expertise of the interviewee; 2. Current uses of digital technology in the UK construction industry and relevance to reduction and recycling of waste; 3. Current and potential blockages to circularising construction processes; and 4. Emerging tools and techniques for acceleration of a circular approach.

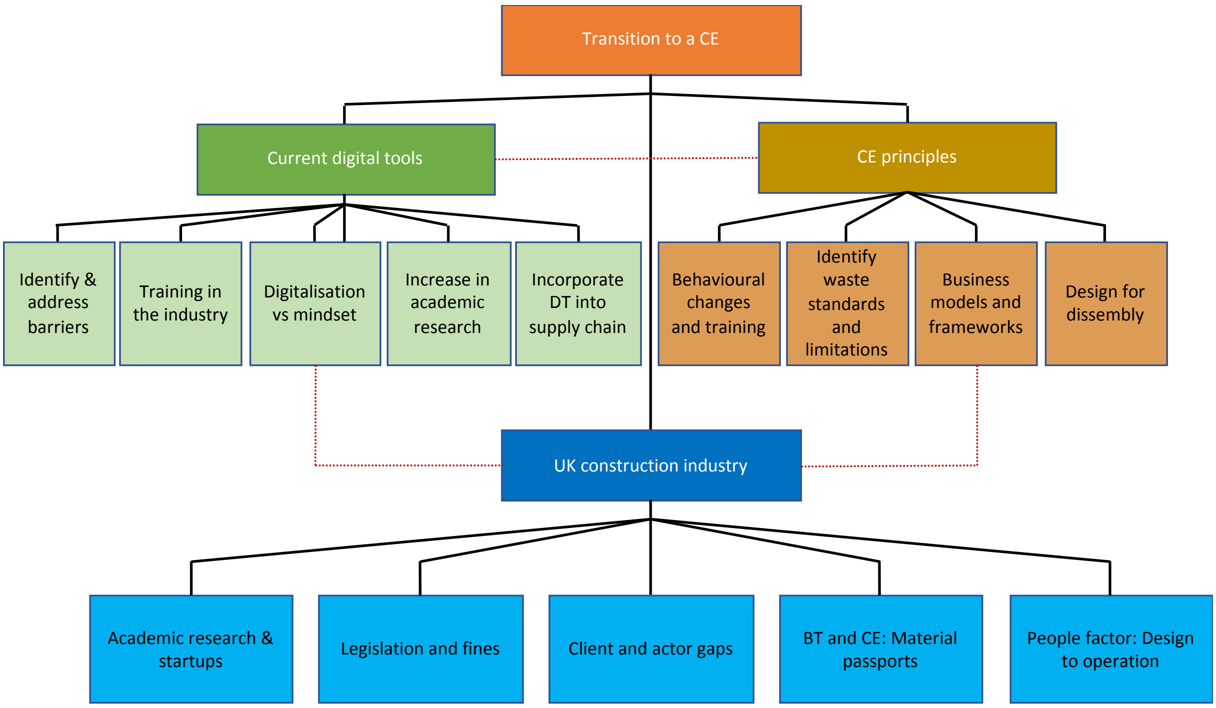
The interviews were recorded, transcribed and coded using NVivo software to match the nodes identified during the literature research, as advised by Miles, Huberman, and Saldaa (2014). The aim of the interviews was to use the information gained, in combination with the information obtained from the academic and trade literature, to develop and ensure a real-time understanding of CE and digital technologies that can accelerate construction waste recycling, in addition to recognising shortcomings in the same.

The qualitative data collection was carried out in compliance with good practice ethics requirements including informed consent; anonymity; and data privacy. Derivation and mapping of the themes outcoming from the discussions is presented below.

4. Results and discussion

4.1. Thematic mapping of interview discussions

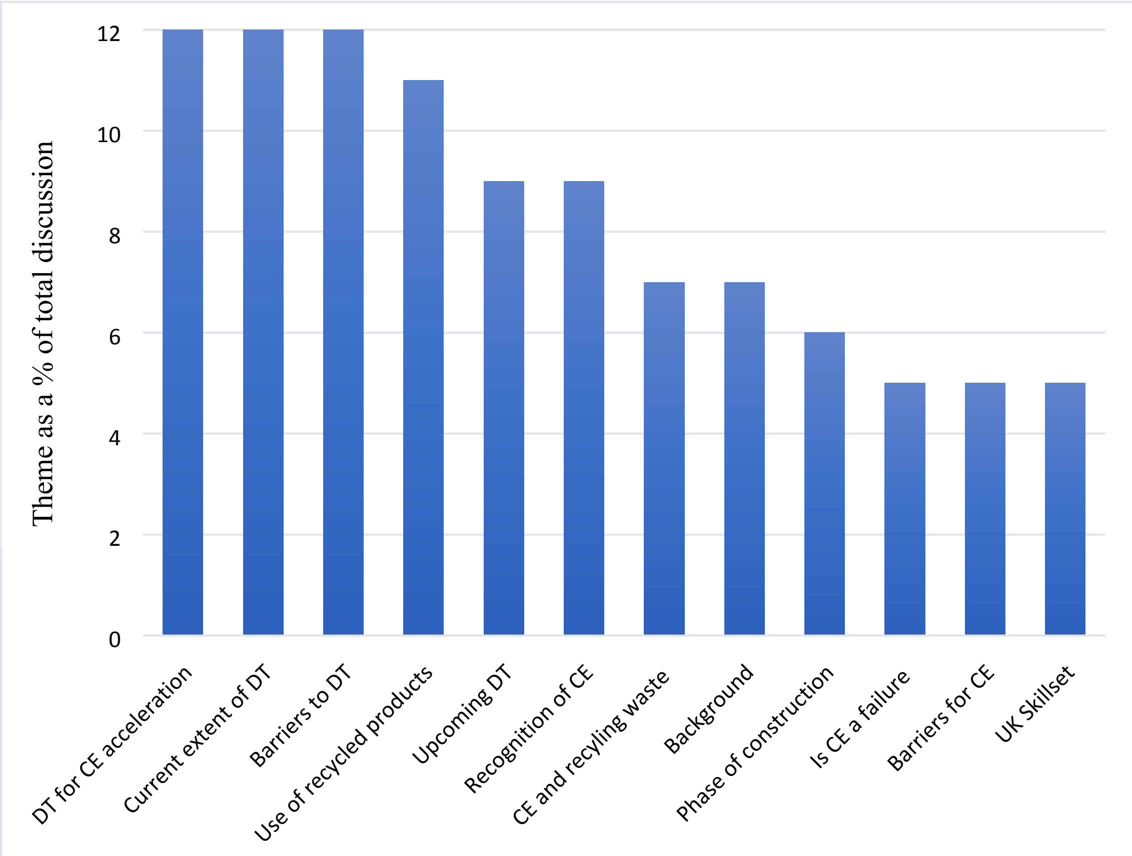
Figure 1 is a mind map derived from the six interviews, which displays the interconnections between three grouped themes: (1) Digital tools, (2) CE principles, and (3) the context of the UK Industry, in the context of construction waste recycling. The function of digital technology in accelerating circularity, and the link between the concept of a circular economy and the practical recycling of building waste were two significant themes that were similarly coded in all six interviews. This suggests that the topic is of current interest, and that the link between digital tools and achieving circularity is important.



INSERT-FIGURE-1

Figure 1. Summary mind map created from interview discussions

Figure 2 shows the codes created by NVivo, and illustrates the variety of topics discussed in the six interviews.



INSERT-FIGURE-2

Figure 2. Themes identified in the interviews

From an analysis of the interviews, all six participants agreed on a number of positive aspects. They agreed that the future is digital, and that improved use of DT will transform the sector and will accelerate circularisation of construction materials and recycling of waste. They agreed that enhancements in the design phase will have a major impact on circularisation and recycling of building materials. They all reckoned that digital technology has the potential to transform all phases of construction, and confirmed that the use of recycled items as construction materials has significant potential.

On the negative side, they all noted that one key barrier to circularisation is the convoluted process a product must go through to be labelled as 'recycled.' They agreed that the initial cost of digitalisation, and a difficult learning curve with slow adoption of DTs are some of the key roadblocks. They highlighted that gaps in digital competence often arose among the parties involved in a project (architects, designers, contractors, engineers, etc.). which often led to difficulties. Even though circularisation has a large appeal, all participants agreed improving recycling rates is difficult to execute.

One consistent theme also agreed by all is that digital tools and the supply chain are interlinked. The use of digital tools, according to the interviewees, may speed up the recycling of building waste, but only if supply chain solutions are improved in order to make it easier to transfer resources (i.e. recycled waste materials) in a manner that is compliant with the various regulations and guidelines.

4.2. Mapping digital technologies for construction waste recycling

From a synthesis of the literature and the analysis of the interviews, this study has identified ten digital technologies which can improve design stage processes in the area of improving circularity in construction. These are discussed in turn below.

Additive and Robotic Manufacturing

Additive manufacturing (AM) or 3D printing is a production technique that involves layering elements together to produce complicated three-dimensional structures, (Gibson, Rosen and Stucker, 2015), while robotic manufacturing (RM) is a production method that enables machines to undertake monotonous, risky, or repetitive tasks such as constructing, moving, or metalwork, (Devadass, 2019). Using AM and RM to optimise the design process and allow 3D printing of concrete (for example) can reduce resource usage and waste, (Rippmann et al., 2018) and also emphasised by Participant F. A 3D printed steel bridge designed using software to produce a highly material-efficient form will significantly reduce steel waste, and lightweight PET material fibre can also be used in 3D printing, which allows for both lightweight construction and the use of recycled resources, (Wang, 2020).

Using AM and RM, designers can also customise connecting components, e.g. for structures, (Brütting, Senatore and Fivet, 2021). The modular nature of printed structures allows construction elements to be reused at the end of their useful lives; for example, reversible wood beams, may be robotically made and dismantled, (Wang, 2020). These principles are gaining traction, (Kuzmenko et al., 2021). Participant E noted the need to industrialise construction further using modular methods while Participant A emphasised the importance of refining the manufacturing steps to allow for this.

Artificial Intelligence (AI)

AI refers to the capacity of a computer or machine to replicate capabilities of the human mind, and it is divided into several subbranches. *Machine learning*, e.g, teaches algorithms to learn from data and find patterns for decision-making with minimal human intervention, while *deep learning* can educate itself for specific tasks, (Kavlakoglu, 2020). AI skills can help with design, infrastructure optimization, and the operation of circular business models, all of which can help with the transition to a CE. Participants A and E emphasised the potential for AI in design, particularly in the arena of using intelligent material databases to track material data through design and beyond, while Participant D emphasised the importance of tracking material flows and material information ‘through all product life cycle phases’.

Using AI in design includes using optimisation techniques to discover the best solution for given performance requirements, e.g. using data-driven techniques, such as neural networks to offer sophisticated solutions for generating multiple design choices which can be compared and the optimal one selected, (Gan et al., 2020). For example, researchers created and tested a machine learning model that can forecast the overall carbon footprint of regenerative building design alternatives to assist architects during the early design process, (Gan et al., 2020).

When AI approaches and algorithms are coupled with other technologies such as Big Data and IoT, they enable the prediction of system faults and the detection of resource requirements in buildings. Machine vision recognition systems supplemented with deep learning techniques, e.g, are used to assess the state of an asset, learn from existing records, and forecast future malfunctions, (Knorr, 2020). Researchers emphasise the possibilities of machine learning algorithms for predicting the energy consumption of buildings, (Mehmood et al., 2019). The FaSA project (Façade Service Application) is a practical example, where with the aid of AI, drones, and sensor technologies, the FaSA programme maps the present status of buildings and anticipates the maintenance requirements of the façade parts, (Akanbi et al., 2020).

AI methods can be beneficial for activities in the end-use phase of a building. Akanbi et al. (2020) developed current neural networks based on national demolition data to estimate the quantity of recycling, repurpose, and waste products obtained throughout deconstructing and demolition activities. Rakhshan et al., (2021) developed a prediction model for estimating and evaluating the reusability of structural components using machine learning techniques. Additionally, Davis et al., (2021) created an on-site waste grading system based on digital images gathered from worksite containers that can classify various types of rubbish to use a classification algorithm.

Big Data Analytics (BDA)

As the internet and digital technology have advanced, data production by people, machines, and their interactions increased dramatically. The phrase ‘big data’ refers to huge data volumes that are too vast for traditional computing solutions to manage, (Gandomi and Haider, 2015). These data are available in a variety of formats, including text, audio, video, and social media. Although the phrase ‘big data’ conjures up images of ‘large,’ other aspects have lately been highlighted, (Akanbi et al., 2020).

BDA can be used in buildings. However, despite the vast quantity of data potentially available during the lifetime of a building through BIM, embedded devices, and sensors, the construction industry has been sluggish to adopt BDA. Smart buildings, resources and waste optimization, dynamic software, efficiency prediction, customized services, energy conservation, BIM and IoT applications are some of the technologies that might be examined in the framework of the CE, (Bilal et al., 2016).

Machine learning algorithms can be trained using big data to develop low-carbon, regenerative structures, (Mehmood et al., 2019), aiding decision-making in design processes and supporting generative design tools, (Bressanelli et al., 2018). Furthermore, data mining techniques are used to enhance building energy performance during the operational phase, affecting the design process and resulting in less resource consumption, (Fan and Xiao, 2017).

BDA, together with IoT, is considered critical to the realisation of smart buildings and cities. Participant E saw the potential for improved data management using a combination of BIM, material passports and big data analytics, while Participant A emphasised the need for intelligent databases and cloud computing to handle the large amounts of data potentially available.

Blockchain Technology (BCT)

Blockchain Technology (BCT) is a decentralised, cryptographically secure peer-to-peer system that allows for transparent value transactions without the use of central authority or intermediates like banks and government organisations. It has five disruptive components, (Mengelkamp et al., 2018): 1. Transparency (visible transactions); 2. immutability (records cannot be changed or deleted); 3. security (blockchain is secured using cryptographic techniques, making it extremely difficult to hack); 4. consensus (network participants must agree to validate transactions); and 5. smart contracts.

BCT has potential uses in building design. BCT can be an enabling technology for circularisation, notably for the administration of complex information networks in supply chain management, (Böckel et al., 2021). In an industry marked by low productivity and a disjointed supply chain, (Hunhevicz & Hall, 2020), BCT may provide possibilities to increase resource value by using efficiency and transparency throughout their lifespan. The construction industry uses contracts to computerise transfers between project parties, monitor procurement logistics, adequate capability changes in BIM models, recording capital assets, preserving resource passports, and streamlining building maintenance based on IoT interactions (Hunhevicz & Hall, 2020). Based on IoT and blockchain technology, a concept for a smart product-service system for prefabricated housing production was developed, where cash flow was controlled autonomously using smart contracts, and data interchange between key parties was performed using a blockchain technology that served as a shared database, (Li et al., 2021).

Because the technology provides openness and dependability of data flows across the supply chain network, the most commonly stated use case of BCT in CE is enabling material passports, from the extraction phase through the end-of-use phase, and in the following use cycles, (Böckel et al., 2021). However, although participants A, D and E all saw the ability to track material flow in the supply chain using digital technology as crucial, Participant A emphasised that AI and intelligent databases can do this without employing blockchain technology. None of the other interview participants emphasised the role of BCT.

Building Information Modelling (BIM)

Building Information Modelling (BIM) is the digital representation of a constructed object, (Charef & Emmitt, 2021). BIM contains pertinent information such as the geometry of the building, material characteristics, and element amounts (Kovacic et al., 2020). Many players in the architectural, engineering, and construction industries have used BIM for a variety of objectives, including design, design visualisation, design optimization, cost estimation, construction planning, and facility management, and all interviewees had experience in BIM. BIM can minimise inefficiencies in traditional building processes by enabling unified delivery of the project through efficient information exchange between all stakeholder groups, as outlined by Participant B; secondly, it may aid in streamlining the building process to reduce resource usage and waste formation, (Wong & Fan, 2013).

In sustainable design and construction, BIM software and extended modules are used to maximise design quality (e.g., indoor climate, energy, daylighting, site), (Habibi, 2017) as well as for incorporating life-cycle analysis (LCA) into the architectural design process, (Xue et al., 2021). Research has expanded BIM's ability to include early design considerations for resource loop slowdown and closure. For example, Akanbi et al. (2021) presented a disassembly and deconstruction statistics model to evaluate the end-of-life performance of the building designs and developed a BIM-based tool to anticipate the recyclability and renewability potential of design alternatives. Additionally, a BIM software add-on that employs machine learning approaches to assess the probable waste materials of design options has been devised.

BIM may also be used as a model of an asset's whole life cycle from design to end-use, (Aguiar et al, 2019), allowing resource flows to be traced and monitored. BIM is also used to manage and maintain assets, as well as to monitor the operational performance of systems during the usage phase, (Gao and Pishdad-Bozorgi, 2019). Emerging sensor technologies included in BIM models give new opportunities for improving system efficiency. BIM can also be adopted in demolition operations if a digital copy of the building does not exist, however, this is an uncommon occurrence, (Xue et al., 2021).

Collaboration is seen to be crucial in building circular supply chain networks in the construction sector to limit, delay, and shut resource loops, as mentioned in the research review, (Leising, Quist and Bocken, 2018). BIM can bring project stakeholders together as a collaboration platform for effective information exchange and transparent project coordination, (Chen et al., 2018; Fang et al., 2016; Xue et al., 2021). By providing crucial information about the performance of structures, BIM can assist in helping material registries and memory banks to be used as a repository of material data or as a working platform, (Maskuriy et al., 2019).

Participant F noted how well-established BIM now is, and saw how it in conjunction with cloud technology and smart tools can ‘make everything simpler’. Participant B explained how using BIM and other DTs had helped her organization eliminate waste and save time on a project, while Participant E notes that the management of digital data is much better if it begins life digitally, i.e. generated in BIM systems or material passports, and that this can expedite material segregation and collection for recycling. On the other hand, Participant C stressed how using BIM requires investment in training and professionalism not just in the software and hardware systems, and Participant A emphasised the additional cost involved in moving to a BIM system.

Digital Platforms (DP)

A DP is an operating system that offers fundamental capabilities about which derivative programmes may be developed from a technical standpoint. From a non-technical perspective, it is an internetwork that connects diverse groups of people to exchange products or services, (Asadullah, 2018).

In the construction industry, DP can be deployed to manage information flows. For example, Xing et al. (2020) built a virtualized data interchange service that brings actual building elements with simulated counterparts using RFID tags, allowing designers to investigate reusable goods from existing work sites. Oberti-Paoletti (2019) suggested using a web-based infrastructure for tracking pre-consumer agricultural waste that would be utilised in private civil building projects.

Digital platforms make it easier for supply chain participants to communicate and collaborate, as outlined by Participant C. Yu et al.,2021 developed a GIS-based collaboration tool to encourage business symbiosis among recycled concrete supply chain members. This technology allows participants to track moving data and interact with each other. The DECORUM project created a multi-user platform with the goal of including all supply chain participants in the design decision-making process of public works, (Luciano et al., 2021). This supports sustainable public procurement by enabling users to evaluate project recycling and impact on the environment while also establishing a community for recycled goods.

Digital Twins

Digital twins provide a virtual representation of the real environment and are already widely used to mimic performance in the automobile, aerospace, and chemical sectors. Digital twins can be used for automated judgement, monitoring and regulation, preventative analysis, or other applications, (Arup, 2019). A digital twin works with real-time data provided by sensors analysing the physical asset, whereas BIM is a platform for preserving a record of building information, (Khajavi et al., 2019).

Digital twins consider data elements from BIM or a custom 3D model of the structure, and a Wireless Sensors link and database management, (Tao et al., 2018).

Digital twins can be used for predictive maintenance, by connecting digital twins to material passports, which has the potential to increase the service life of building materials. The use of digital twins and material passports may allow for reuse throughout the destruction phase of a structure (Arup, 2019). Chen and Huang (2021) and Landahl et al. (2018) suggested digital twin system concepts for construction debris recycle or design reuse.

Buildings may also be transformed into flexible environments with the aid of digital twins. The EDGE Olympic office building in Amsterdam is an example. The building has an electronic version that operates on a cloud service and allows users to personalise their work environment and make dynamic use of the space, (MAPIQ, 2021). And as pointed out by Participant F, the use of digital twins is increasing, and as their adoption increases with time, so will there use in tracking materials and components allowing for future identification for future reuse.

Geographical Information system (GIS)

At a fundamental level, GIS depicts macro-scale external environments by linking attribute values to a geographical referent. Some of the applications include surveying monitoring, disaster prevention, public infrastructure, and spatial planning. GIS is widely used in tandem with BIM to manage metropolitan information, design power facilities and cities, improve structure climate requirements, and track sourcing and material movements, (Wang et al., 2019).

Using GIS for the identification, mapping, and management of materials inherent in building stocks for future reuse or recycling could have an important contribution towards circularity. For example, in the Japanese city of Kitakyushu employed GIS analysis to detect unoccupied dwellings and their material stock to make educated judgments about future resource usage, (Wuyts et al., 2020). The authors evaluated a variety of reuse options, including maintenance, intensive space usage, repurposing, and urban mining, depending on the condition of the abandoned dwelling.

Yu et al. (2021) built a GIS-based supply chain management system for smart manufacturing using recycled concrete aggregate. They used GIS to depict the flow of materials in a virtual environment where participants exchange design knowledge and monitor congestion and automobile movements.

Material Passports and databanks

The absence of knowledge on materials and chemicals at the end-of-use phase is one of the most significant barriers to reusing and recycling resources in buildings, (Ana et al., 2018). Some scholars have argued for capturing and preserving property composition in a digital environment at the early design stage, so that the necessary information is provided for the remainder of the building's life, allowing the economy to grow resale value, (Çetin et al., 2021; Guerra & Leite, 2021; Norouzi et al., 2021). A material passport is a system that refers to digitally recorded data sets of an object that describe its features, location, history, and ownership status in different levels of detail depending on the scope of usage. Material passports are produced at the city, structural, commercial, and material layers and managed via BIM or a portal, (Leising et al., 2018; Massaro et al., 2021). Participant E argues that material passports can expedite material segregation and collection for reintroduction into the supply chain.

In Oezdemir et al., (2017), a resource land surveying model was proposed to map material volumes at the city level in a housing neighbourhood in Germany. BAMB, an EU-funded project, created a software portal that shows over 300 materials passports at three degrees of detail: item, structure, and example (Luscuere et al., 2019). Madaster is another example of an online platform that allows users to create and archive material passports as well as calculate building circularity levels.

Material databanks have been presented as an alternate method for storing, managing, and sharing building data to close resource cycles, e.g. by Participants A and E. A proposal for a "material and component bank," was made that coordinates the movement of resources from a demolition site to a new construction site. An independent contractor who maintains a database based on BIM data that keeps material information up to date throughout the life of a structure, (Cai & Waldmann, 2019). Jayasinghe and Waldman (2020) developed an internet-consolidated databank that collects data from BIM models of current and future buildings and allows the user to analyse data for recovery and recycling and reusability of building components. Bertin et al. (2020) suggested a resources library built on a registry to encourage the recycling of load-bearing building elements. Participant F suggests that this could grow demand for recycled materials.

The Internet of Things (IoT)

The Internet of Items (IoT) is one of the key Industry 4.0 technologies that "allow information to be collected, stored, and sent for things outfitted with tags or sensors", (Ly et al.,2021 p. 253). In an IoT environment, mobile phones, electronic devices, and robots interact with one another and with individuals by making use of technology such as Radio Frequency Identification System (RFID), wireless sensors, and cloud services to create an interoperability ecosystem. This communication generates a significant quantity of data, which is subsequently analysed with BDA to provide organisations with important insights (Lopes de Sousa Jabbour et al., 2018).

Performance optimization for resource conservation is one of the most common IoT applications in the BE. Building-connected devices can use BDA to aid in the detecting, analysing, improving, and controlling the indoor spaces (Construction Tech, 2021) an IoT-based lighting system, e.g gathers data from the indoor environment via monitors put in the lighting system which provides information into long-term built structures. Polder Roof® (2021) is another example of a roof structure that use embedded sensors to monitor and regulate rainwater gathered on the roof and gives the client with operational insights.

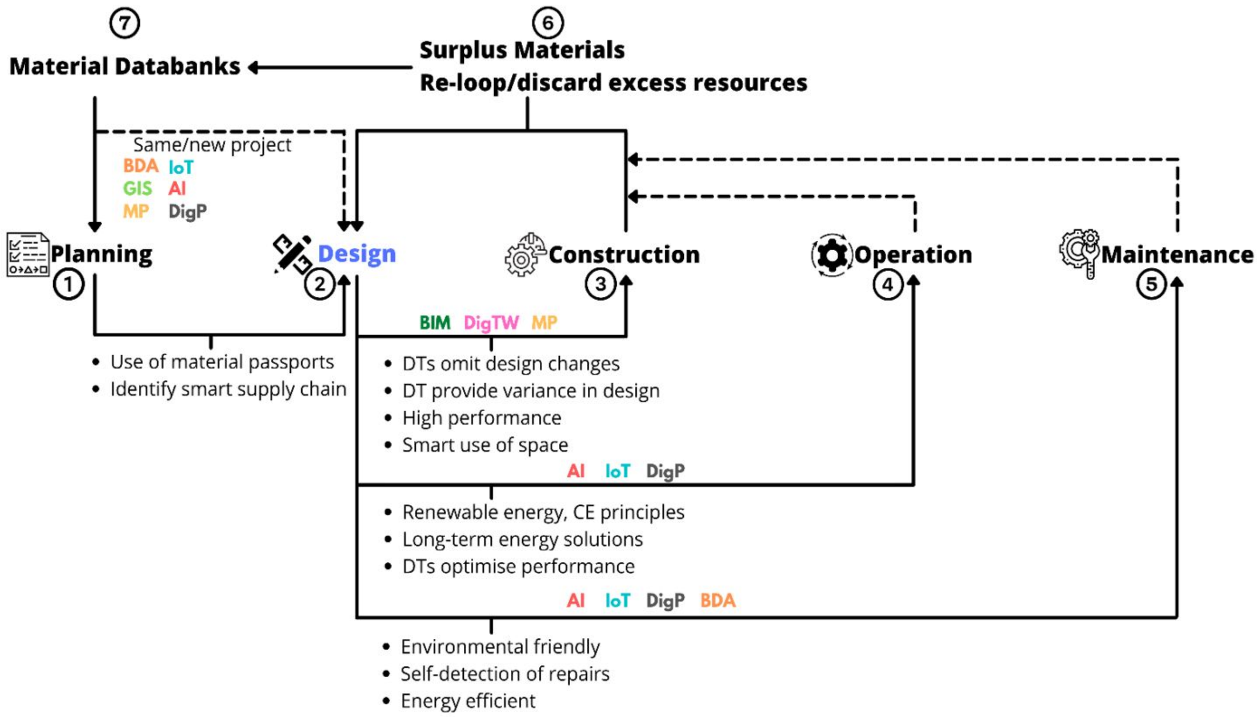
Sensor systems, assist in tracking, monitoring, and controlling failures, predicting installation maintenance needs, and enabling remote maintenance, repair, and upgrades (Panfilov and Katona, 2018). IoT technology enables smart sensing devices to monitor the available space in a building in real-time. Staff may rent meeting rooms or offices using a consumer interface at The Edge, an intelligent office building with over 28,000 detectors, (Deloitte, 2021, MAPIQ 2021). It was possible to decrease the incidence of workspaces, with 1080 workstations given for 2850 people to accommodate workplace flexibility layout, (MAPIQ, 2021).

By managing heating, ventilation, and

space conditioning systems, IoT capabilities provide a healthier and pleasant interior environment, influencing design choices. Participant E argues that using IOT along in conjunction with material passports and AI can help improve the segregation, collection and re-introduction of reused materials into the supply chain.

5. Conclusions and implications for practice

This review has demonstrated that introducing digital innovations in the design process can be a key contributor to circularising construction, and is well within the grasp of the industry. Entry points and opportunities for such contribution are synthesised and summarised in the following diagram.



INSERT-FIGURE-3

Figure 3. Opportunities for digital innovations in design

The design process may be made faster and more efficient by adopting responsive design techniques and introducing the concept of material passports to track the use of recycled materials. Better use of digital tools can contribute to faster and better design decisions. With digital tools in the picture, design may be better optimised with no information loss between actors, which increases the chances of using recycled content. Better consideration of the design process which takes construction waste into account when selecting from several design alternatives, will reduce the need for last minute design changes during the construction phase, leading to significantly reduced quantities of construction waste.

Also, by employing circular design concepts like disassembly, deconstruction, and reversibility, it is possible to approach circularity. Surplus materials may be detected in advance using digital technology, and re-entered into the material process loop, either reducing the amount of raw material needed in the project or re-entering the material supply chain for other projects.

By incorporating digital technology better into the design process, it is possible to implement circular principles through the building operations phase, for example in the use of renewable energy, long-term design, smart technology, and the reversibility of places. And when it comes to building maintenance, efficient design using digital technology - including AI and IoT - can lead to smarter and more efficient maintenance, also reducing unnecessary waste.

Throughout the building lifespan, the use of material databanks and passports will allow the tracking of materials and their properties around the material loop. This includes following the progress of materials and components through building fabrication, tracking their maintenance and/or replacement, and/or following their progress as unused elements available to re-enter the supply chain, or else as they become waste and enter a recycling loop to be either reused or reprocessed, or in the worst case, towards disposal. The inclusion of this information in the BIM model, in the digital twin, and then into the building management database, allows decisions to be made on its value and usability through the loop.

The construction industry is already innovating and digital innovations are being incorporated into the workstream. But with digitalisation, not all of the actors in a construction project will have the capability to access advanced digital technology at the same rate. Many designers and architects may be well-versed in BIM, IoT, and smart technologies, while project managers, site managers, contractors and others may not be as well-equipped, resulting in capability gaps. Effective collaboration is therefore essential for the successful completion of any project, and the more either regulatory or voluntary incentives can be deployed to further embed I4.0 technologies into both large and small firms in the construction industry, the more effective the industry will be in delivering a truly circular economy.

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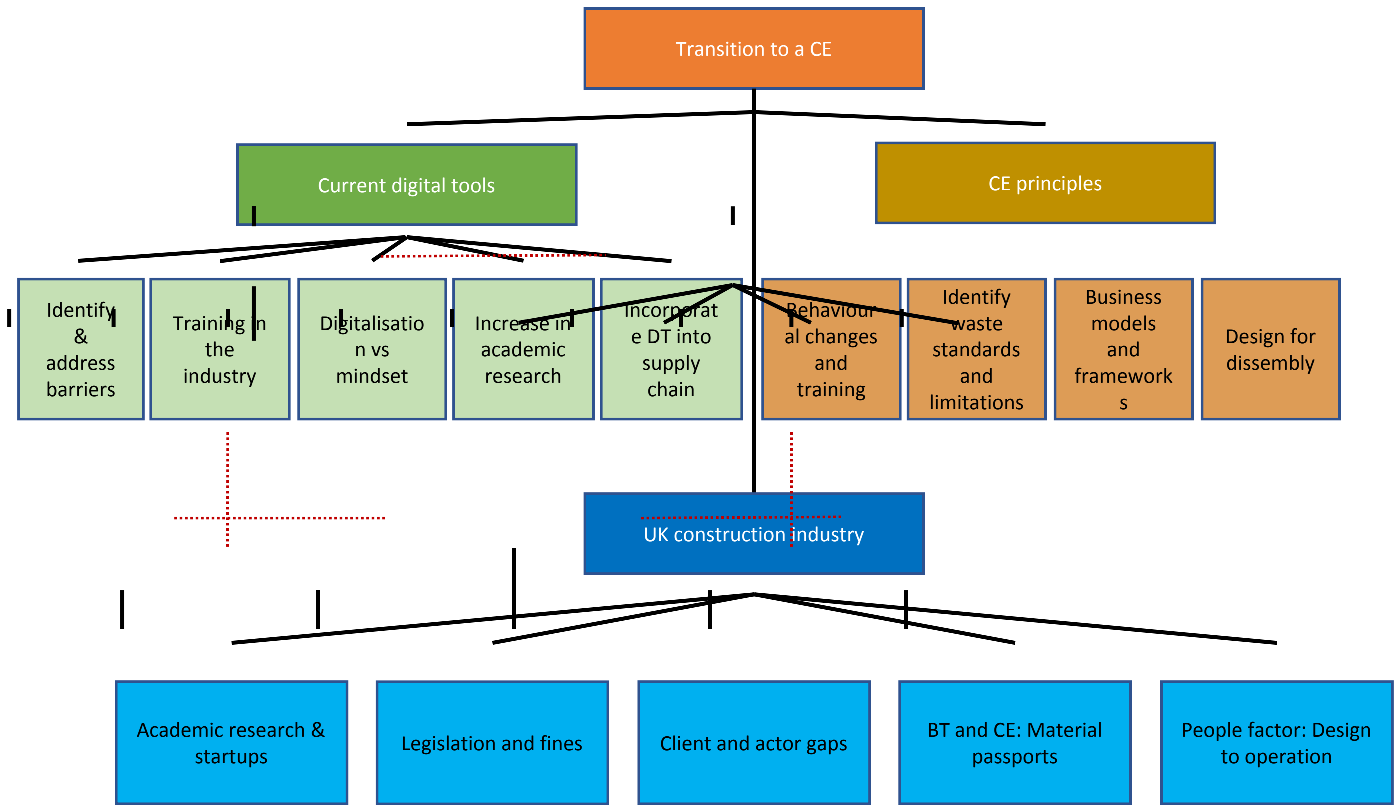
Transition to a CE
Current digital tools
CE principles
Identify & address barriers
Training in the industry
Digitalisation vs mindset
Increase in academic research
Incorporate DT into supply chain
Behavioural changes and training
Identify waste standards and limitations
Business models and frameworks
Design for dissembly
UK construction industry
Academic research & startups
Legislation and fines
Client and actor gaps
BT and CE: Material passports
People factor: Design to operation

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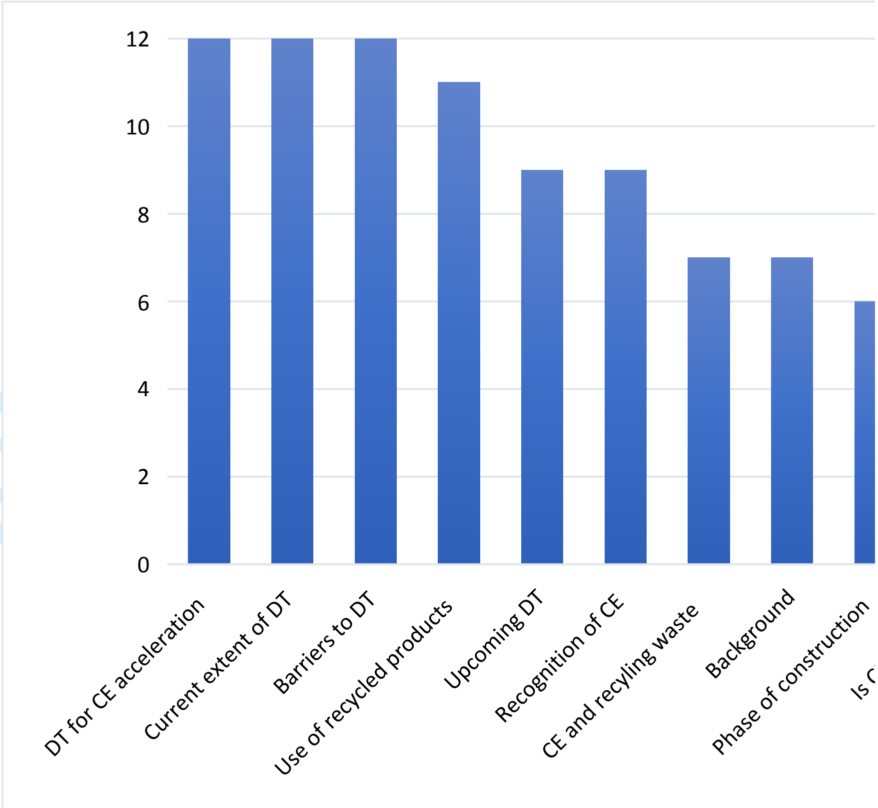
DT for CE acceleration	12
Current extent of DT	12
Barriers to DT	12
Use of recycled products	11
Upcoming DT	9
Recognition of CE	9
CE and recyling waste	7
Background	7
Phase of construction	6
Is CE a failure	5
Barriers for CE	5
UK Skillset	5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Current extent of DT
Barriers to DT
Use of recycled products
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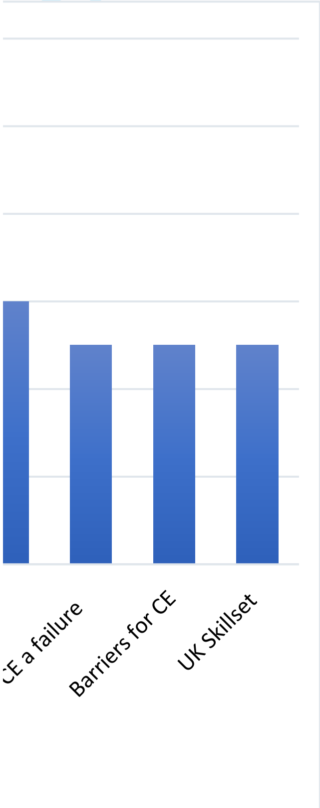
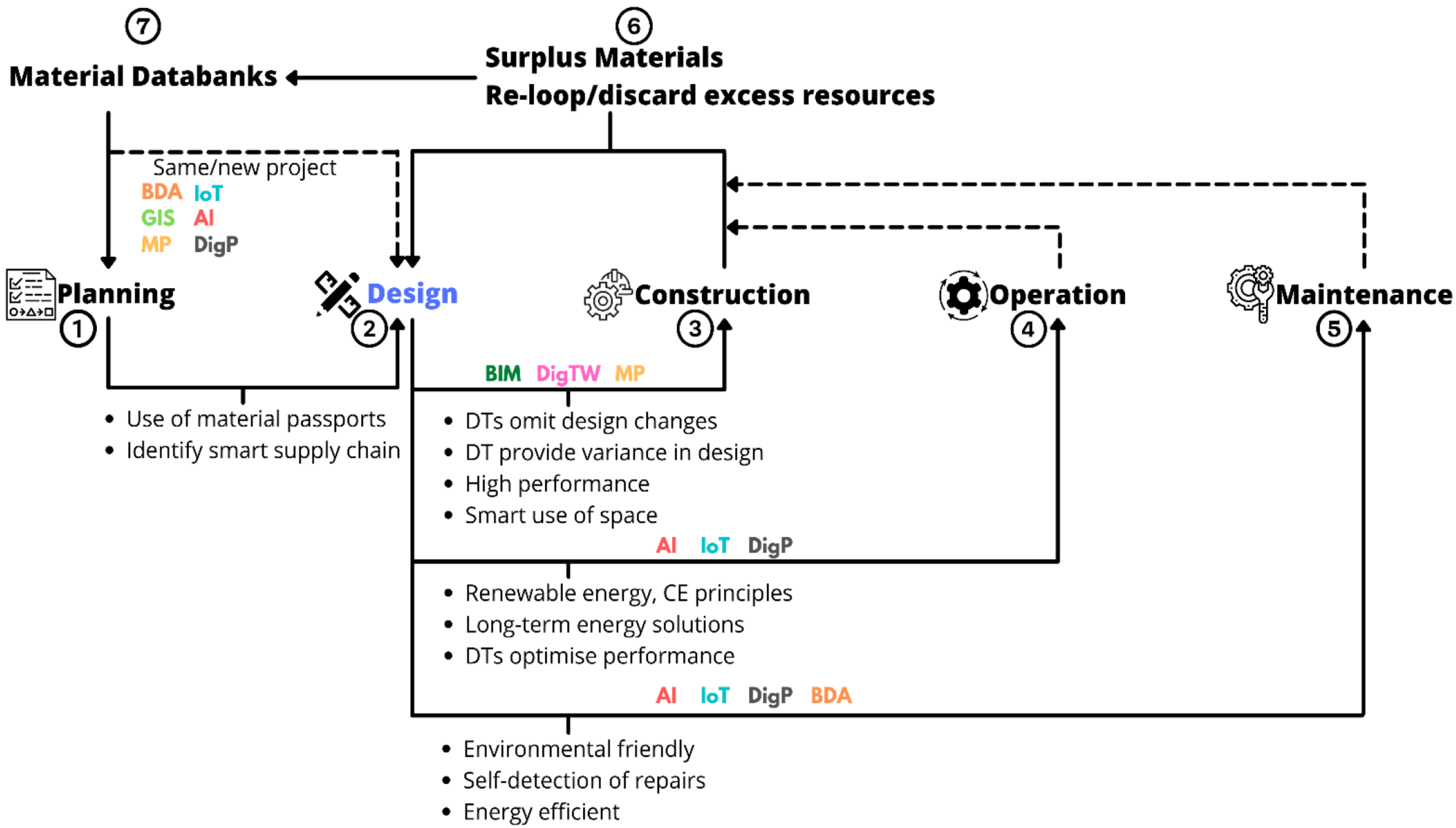
Recognition of CE
CE and recyling waste
Background
Phase of construction


CE a failure
Barriers for CE
UK Skillset


7
Material Databanks
6
Surplus Materials
Re-loop/discard excess resources
Same/new project
BDA IoT
GIS AI
MP DigP
Planning
1
Design
2
Construction
3
Operation
4
Maintenance
5
BIM DigTW MP
Use of material passports
Identify smart supply chain
DTs omit design changes
DT provide variance in design
High performance
Smart use of space
AI IoT DigP
Renewable energy, CE principles
Long-term energy solutions
DTs optimise performance
AI IoT DigP BDA
Environmental friendly
Self-detection of repairs
Energy efficient