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# Disruptive technologies for a circular building industry

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A B S T R A C T

This paper focuses on the circular economy (CE), the building industry, and on the disruptive technological innovations that intersect in these arenas. It outlines how disruptive, often digital, technologies can potentially enable a CE in the building industry, primarily within the two most wasteful phases of the building cycle, the construction and demolition phases. This is achieved through an analysis of the potential of each technology type to enable a CE, using existing literature and desktop research on applied examples of the technological solutions in question. The paper aims to clarify the implementation scenarios of digital technologies for the circular building industry and are organised according to technology type, CE principle, building phase, material family, estimated TRL, and type of application.

## 1. Introduction

The construction industry is one of the largest producers of $CO_2$, and one of the largest consumers of energy and resources in the world [1]. This is not only due to the nature of construction products, which are large and heavy, but also due to the relatively low efficiency of resources [2]. In 2018, the waste from the construction and demolition activities in Europe was approx. 838.9 million tonnes which represented 35.9% of its total waste generation [3], and 38% of the total $CO_2$ emissions worldwide [4]. One third of this substantial amount of $CO_2$ is the result of mining and production of abiotic building materials, and represents 12% of the total global $CO_2$ produced annually [5]. This waste results in a significant loss of valuable materials, such as minerals, metals, and organic materials. Therefore, it is important to devise new concepts, tools, and technologies in the building industry that create closed material loops in a circular economy (CE). In this manner, the more efficient use and recycling of raw materials, may offer tremendous environmental benefits and open new possibilities for the development of innovative solutions, business models, and services in the building sector. Hence, progress made in this direction is beneficial not only for the economy but also for the environment.

Realising a circular economy implies radical technological innovations, and a change in lifestyle, culture, organisation, and production structures. Three knowledge systems play a part in this matter: scientific explanations, socio-scientific explanations and personal values. These are summarized by Vergragt and Groenewegen Jansen, van Heel [6], as 'technology', 'culture' (behaviour and needs) and 'structure' (institutions, economics, etc.). When a system is under pressure, participants often form alliances and search for solutions to the problems that have arisen, making (new) networks, that sometimes can surpass the boundaries of the system (or the domain), and in doing so actually create a new system [7]. Worldwide many waste-processing companies are currently considering their strategic options: expansion, chain integration and/or technological innovation. Their approaches emphasise chain integration and adjustments to internal organizational structure (culture, systems, etc.). Diversification is also being emphasized, in which chain integration takes two lines of approach:

Forward chain integration: In which end processors concentrate on activities earlier in the chain, e.g., collection and recycling;

Backward chain integration: In which waste collection companies concentrate on recycling, dumping and/or incineration of waste flows.

This paper focuses on the circular economy, the building industry, and the disruptive technological innovations which intersect in this arena. The EU "Eco-Innovation Action Plan" of 2011 [8] aims to trigger eco-innovation while reducing environmental depletion. According to the EC definition, "Eco-Innovation is any form of innovation resulting in or aiming at significant and demonstrable progress towards the goal of sustainable development, through reducing impacts on the environment, enhancing resilience to environmental pressures, or achieving a more efficient and responsible use of natural resources" (from Decision N° 1639/2006/EC establishing a Competitiveness and Innovation Framework Programme).

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## 2. Disruptive technologies, circular economy & the building industry

In the EU, many countries show high rates in the re-use of materials recovered from the construction and demolition phases of buildings. Though the current high recovery rates of construction and demolition waste is based, to a large extent, on backfilling, on low-grade recovery or non-re-recyclable applications [9]. Therefore, the inherent value of the materials is declining as the qualitative aspects of recycling are not systematically addressed and recycling is not performed in closed loops.

Beyond the CE, the EU has prioritized digital transformation as recently announced in 'Europe's Digital Decade'. The documentation shows a clear vision for a digital transition in the EU by 2030, which includes the digital empowerment of businesses, contributing to a sustainable, climate-neutral, and resource-efficient economy [10]. This suggests a clear link between digitisation and CE [11]. Digital technologies are considered not only the main driver for the digital transition of various industries [12] but also essential for their transition to a CE [11].

Digital technologies offer numerous opportunities for the digitisation of the construction industry throughout the entire construction life cycle and significant benefits such as reductions in cost, increases in production efficiency, improved quality, and speed. Furthermore, the increased deployment of technologies in our homes offers new data on the interaction between technology, the built environment, and information feedback loops that could lead to human centred solutions for sustainable living. The way we describe and understand our living environments is being radically transformed, as are the tools we use to design, plan, and manage them. A new field of research and development in applied technology is emerging at the crossroads of the physical and digital sides of the built domain [13].

Deloitte identified seventeen digital technologies that are implemented during the full construction lifecycle: Autonomous vehicles, modular construction, robotics, generative design, drones, marketing technology, energy management, digital reality (virtual, augmented, mixed), inventory and supply management, wireless charging, blockchain, IoT and sensing, 3D scanning, additive manufacturing and 3D printing, AI and big data, BIM (Building Information Modelling), and InsurTech for construction [14].

Compared to many other industries, the construction industry is conservative in adopting new technologies, materials, and tools [15]. Nevertheless, the principle of 'technological external economies' provides points of departure for a more direct connection of environment and economy (and thus CE). As a result, innovations from this cluster of developments could promote on-going improvements to the sustainability of spatial planning. In particular, function innovation (the replacement of products by other products or product-service combinations) and system innovation, require cultural and social changes to occur simultaneously with technological changes. Product and function innovation are often parts of system innovation [16]. Function innovation may contribute to dematerialization. Function innovation (by means of the replacement of products by services) does not necessarily imply that the environmental load decreases as a consequence [17].

The implementation of digital technologies, however, is expected to benefit the building sector in terms of productivity, quality, and safety. Besides utilising technologies to make construction more efficient and higher quality, an opportunity exists to address waste and develop innovative CE solutions with new technologies. Circular strategies require a systematic perspective. Increases in scale in the construction sector and an increased focus on customization on the other, has resulted in increased complexity and interdisciplinarity across the industry, making the problem even more critical. There is great potential to make the building industry truly circular, especially when combined with new technologies. Despite emerging opportunities, examples of CE and the use of digital technologies in the building industry are still limited.

This paper identifies applied examples where disruptive (often digital) technologies are employed for the development of CE principles in the building industry (Fig. 1). These examples have potentially large environmental impacts when scaled up. It outlines how digital technologies can potentially enable a CE in the building industry, while focusing on the two most wasteful phases of the building cycle, which are construction and demolition. The potential of each technology is analysed based on available literature and desktop research. The examples are used to support implementation scenarios of digital technologies for the circular building industry and are organised per technology type, CE principle, building phase, material family, estimated TRL and type of application. Methodologically, this research was organised in 4 stages:

(1) identifying the disruptive technologies that may benefit the circular economy in the context of the building industry;
(2) filtering those technologies based on the number of currently available validation studies;
(3) analysing the potential CE benefits of each technology through a review of the literature and of applied examples; and
(4) reflecting on how those technologies may impact the CE in general.

## 3. Technological overview & CE

The construction industry is experiencing technological innovations that enable its digital transition throughout building lifecycles, with emerging digital technologies playing an important role in this shift. Even though a lot is written about these digital technologies and their contribution to the digitisation of the building industry, there is no consensus on a definitive list of these technologies in the literature (Rosa 2020). Table 1 shows the number of results retrieved in google and google scholar, respectively, when searching with the keywords of "circular economy", "building industry", "digital technologies", and each of the digital technologies of the construction industry, as suggested by Deloitte. The relatively low number of results per search implies that the searched fields are emerging. Therefore the research (at the intersection of CE, digital technologies, and the building industry) appears to be currently unexplored.

In this article the digital technologies will be discussed from the perspective of CE and the building industry through literature review and applied examples.

While the implementation of these technologies in the building industry is still preliminary, this paper identifies built examples (examples with a TRL of 4 and higher) and clarifies their potential. Technology in the building industry can improve and optimise data management from design, to fabrication, to demolition. However, it can also contribute to the development of new circular concepts for the building industry related to material re-use, to the maintenance of the value of materials through applications, and to strategies that enable high quality recycling. Such strategies may reduce waste generation. This paper will analyse the digital technologies of BIM, robotics, AI, additive manufacturing and 3D printing, blockchain, drones, and digital reality. The contribution of the selected disruptive technologies to the CE in studied during the design & engineering, construction, and demolition phases (Fig. 2). Among the four phases of the lifecycle of a building (namely design & engineering, construction, operations & maintenance, demolition) these three phases generate more than 30% of the total solid waste in Europe [8]. For this reason, the maintenance phase is excluded in this study. There are numerous robust examples of disruptive technologies applied in the maintenance phase, for example, applying blockchain technology in building energy performance measurement, reporting, and verification (MRV) [18], and workplace occupant comfort monitoring with a multi-sensory and portable autonomous robot [19].

The selection of examples in these three phases is based on the level of maturity and their application in the field. Further selection criteria for the reviewed examples are:

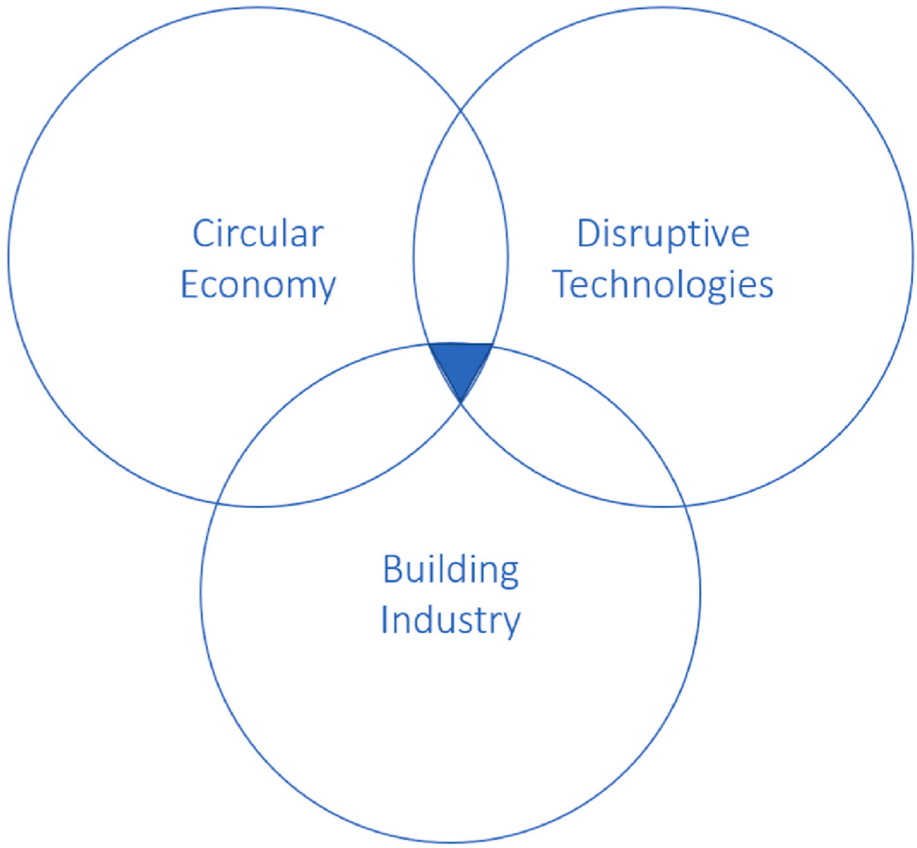


**Fig. 1.** This paper examines the intersection of CE, disruptive technologies, and the building industry.

- The demonstrated technological solution is applied and suggests a new circular solution during the design & engineering, construction and/or demolition phase of a building.
- The demonstrated technological solution is mature, though its implementation in the building industry might still be experimental.
- The demonstrated technological solution has been tested at least in laboratory settings, with estimated TRL generally above 4. The estimation of TRL is suggested by the authors and is based on information available in project publications.
- The demonstrated technological solution implements at least one of the CE dimensions: prioritizing renewable inputs, maximising products and materials in use, and recovering by-products and waste, as defined by the Ellen McArthur Foundation. In the construction industry literature, these principles are often phrased as: optimised material usage, design for disassembly, or design to recycle.
- The demonstrated technological solution has potentially impactful environmental benefits when scaled, for example by addressing a large waste stream or contributing to bulk material savings.
- The demonstrated technological solution is contributing to the digital transition of the building and construction industry.

### *3.1. The technologies (see Table 2)*

#### *3.1.1. Internet of things (IoT)*

Benefits in the context of the building industry and from a CE perspective: Energy savings; Increased asset utilisation through sharing; Optimised material, maintenance, and waste management.

The Internet of Things (IoT) is a term that refers to the networked connection of physical objects, which provides new insights by capturing large amounts of data in real-time [20]. In this technology, electronics, software, sensors, actuators, and network connectivity are embedded in physical objects such as components, appliances, equipment, buildings, and vehicles, enabling them to collect and exchange data over the internet and in a network [20]. The benefits of IoT span across the entire lifecycle of buildings and infrastructure, and promote highly increased efficiencies, such as the optimisation of energy usage, increased asset utilisation through sharing [21] or the optimal management of waste and resources [20].

*3.1.1.1. a Example 1: Oris [22].* ORIS is a digital materials platform for sustainable road solutions. The service promises to reduce the carbon emissions of projects while increasing road durability and usage lifespans using artificial intelligence, connected sensors, and data analytics. This solution has already been deployed in pilot projects in Azerbaijan, France, Mexico, and the UK. One of the key CE benefits of Oris is optimised material usage. This solution is useful during the design and construction phase, providing insights into local conditions, sourcing options, technical specifications, and sustainability optimisation. The environmental gains of this application are promising, taking into consideration that in average 700,000 km of new roads are being built globally every year and 60,000 tons of resources are needed to build 1 km of highway [22].

#### *3.1.2. BIM*

Benefits in the context of the building industry and from a CE perspective: Construction process efficiency; Optimised design from a material and waste management perspective; Support of new CE concepts.

Building Information Modelling (BIM) is the digital representation of a built asset [23], containing relevant information such as the asset's geometry, material properties, and quantities of elements. Today, BIM has become the most widely used technology in the construction industry, from design through project completion and operation [20]. BIM

**Table 1**
The number of results retrieved in google and google scholar, respectively, when searching with the keywords of "circular economy", "building industry", "digital technologies".

| technology | n. results in google | n. results in google scholar | search terms |
|---|---|---|---|
| IoT and Sensing | 5050 | 96 | "circular economy" "building industry" "digital technologies" "Internet of Things" |
| BIM | 4820 | 85 | "circular economy" "building industry" "digital technologies" "BIM" |
| Robotics | 5420 | 80 | "circular economy" "building industry" "digital technologies" "robotics" |
| AI | 7150 | 65 | "circular economy" "building industry" "digital technologies" "AI" |
| 3D printing | 4230 | 63 | "circular economy" "building industry" "digital technologies" "3D printing" |
| Blockchain | 4690 | 51 | "circular economy" "building industry" "digital technologies" "blockchain" |
| Drones | 3180 | 42 | "circular economy" "building industry" "digital technologies" "drones" |
| Digital Reality (Virtual, augmented, mixed) | 4810 | 37 | "circular economy" "building industry" "digital technologies" "digital reality" |
| Modular construction | 1310 | 28 | "circular economy" "building industry" "digital technologies" "modular construction" |
| Energy Management | 3130 | 27 | "circular economy" "building industry" "digital technologies" "energy management" |
| Inventory and supply management | 1260 | 26 | "circular economy" "building industry" "digital technologies" "inventory and supply management" |
| Autonomous vehicle | 1220 | 4 | "circular economy" "building industry" "digital technologies" "autonomous vehicle" |
| 3D scanning | 435 | 7 | "circular economy" "building industry" "digital technologies" "3D scanning" |
| wireless charging | 88 | 0 | "circular economy" "building industry" "digital technologies" "wireless charging" |
| InsurTech for construction | 981 | 0 | "circular economy" "building industry" "digital technologies" "Insurtech" |

3D models can be enhanced with additional dimensions, including schedule (4D), cost estimating (5D), sustainability (6D) and operations maintenance (7D) [20]. An emerging discussion suggests a new dimension should be used dedicated to CE, end-of-life, and disassembly information modelling (8D) [24,25]. Even though BIM's dimensionality is questioned as it might narrow down the discussion on sustainability, practitioners are actively using it [24]. Current use of BIM results in construction process efficiencies that translate to cost and time savings, gains in accuracy, and reductions in errors. Furthermore, it leads to new approaches to minimising waste, such as the support which digital models provide to sustainable end-of-life plans, material passport development, project databases, data checking, circularity assessments, material recovery processes and material banks [23].

*3.1.2.1. a Example 1: Madaster platform [26].* Madaster is an online platform that generates a materials passport for buildings, construction objects and building portfolios, and calculates their circularity level. Materials, products, and elements that are used in construction objects are registered and documented on the platform. The data can be registered and documented from their Building Information Models (BIM) and with smart connections to various data sources on products and materials (e.g., life cycle assessment and CO2 data), financial sources (the value of materials), and data sources on the health-related aspects of materials (their toxicity for example). This solution is already available in Germany, the Netherlands, Norway, Switzerland, and Belgium. One of the key CE benefits of Madaster is the potential to design buildings to be recyclable: by registering materials they become digitally discoverable for future use. This technology is useful during the design, construction, and demolition phases and the platform promotes the documentation of the built environment according to material identity and location. With the help of the passport, the materials retain their identity and actual value, helping to prevent them from becoming waste during demolition phase.

### 3.1.3. Robots

Benefits in the context of the building industry and from a CE perspective: High precision; Assembly; Automation.

Using physical robots in the construction industry for the manufacturing of building components may lead towards automated workflows on the building site that embrace CE with increased accuracy, precision, and reduced production time.

Furthermore, robots can perform labour intensive, difficult or repetitive tasks such as lifting heavy objects and placing them in exact coordinates or working with non-standard materials from waste sources with high accuracy, resulting to components of high value. Robotic arms can complete a large range of tasks and support custom solutions per project, from laying bricks to performing complex assemblies with high precision. Their capabilities can be combined with sustainability principles such as sorting waste materials or assembling structures from waste sources.

*3.1.3.1. a Example 1: Circular Experience [27].* Studio RAP designed and built an interior wall and balustrade using waste wood and a robotic routine. The wall is permanently installed in the circular pavilion inside the ABN building in Amsterdam (NL). The waste material was sourced from the production process of laminated frames, and was reused in a parametrically controlled, robotic fabrication process. The interior is made up of tens of thousands of unique wooden elements in both pine and larch that were arranged in a robotic assembly routine. One of the key CE benefits of this construction method is optimised material (re) usage during construction.

*3.1.3.2. b Example 2: Rock print pavilion [28].* This project is built with loose aggregate and twine by a mobile robot. The project investigated a method for the design and robotic aggregation of low-grade building material into load-bearing architectural structures that are re-useable and re-configurable with high geometrical flexibility and minimal material waste. As such, it focuses on a principle called "jamming", which refers to aggregate granular materials (like gravel) that is quite literally crammed together in such a way that it holds its form and shape like a solid. This was implemented in an exhibition pavilion. One of the key CE benefits demonstrated is design for disassembly. As there is no glue or coating used, the structure can be easily dismantled to the initial state of the raw materials. Furthermore, this building method allows the reuse of materials multiple times, without extra processing. This technological solution is useful during the construction and demolition phases.

*3.1.3.3. c Example 3: Wood Chip Barn [29].* The 'Wood Chip Barn' is a robotically fabricated arching structure, which is made up of 20 distinct

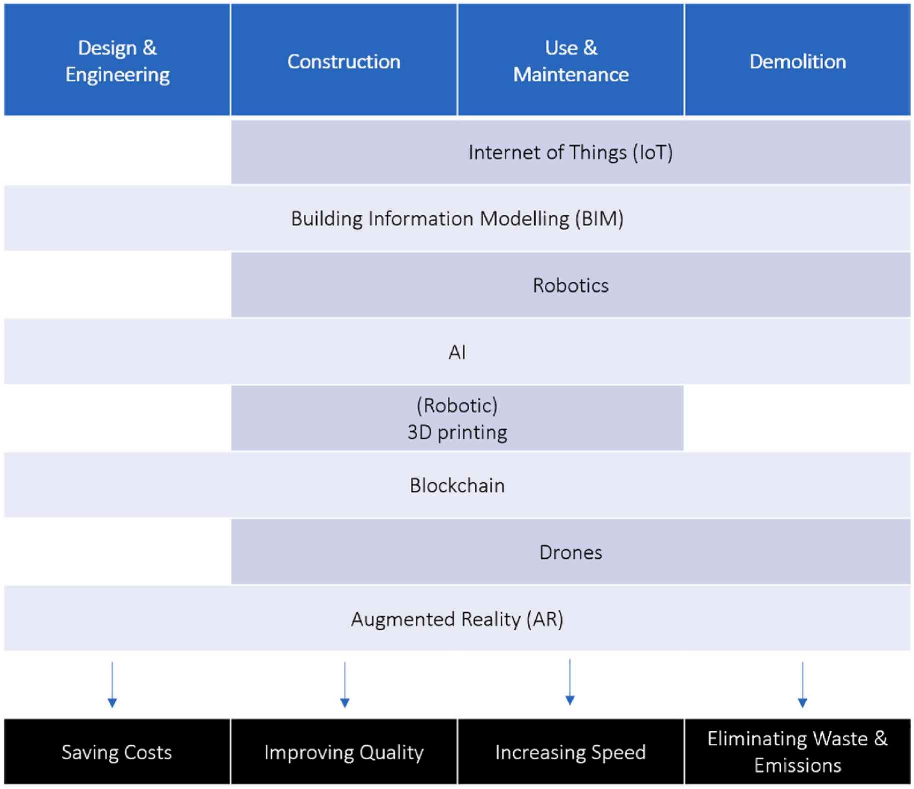


**Fig. 2.** The examined digital technologies throughout the construction lifecycle and the corresponding benefits.

**Table 2**
BE & CE benefits per disruptive technology, based on the literature review.

| Disruptive Technologies | BE & CE Benefits |
|---|---|
| Internet of Things | • Energy savings<br>• Increased asset utilisation through sharing<br>• Optimised material, maintenance, & waste management |
| BIM | • Construction process efficiency<br>• Optimised design from a material and waste management perspective<br>• Support of new CE concepts |
| Robots | • High precision<br>• Assembly<br>• Automation |
| AI | • Increase efficiency throughout the entire value chain<br>• Monitoring and maintenance optimisation |
| (Robotic) 3D Printing | • Optimised material use<br>• Possibility to use recycled or recyclable materials<br>• Locally sourced materials<br>• Potential for zero waste construction |
| Blockchain | • Increased functionality, efficiency, and visibility<br>• Decentralised tracking of information like material and waste flows |
| Drones | • Onsite digital asset tracking, continuous spatial inspection, and progress monitoring<br>• Promotes waste reduction |
| AR | • Optimised construction on-site<br>• Remote repair and construction |

beech forks sourced directly from the surrounding woodland. Through 3D scanning, digital design and fabrication methodologies, the inherent form and structural capacity of the naturally formed tree is transferred and exploited directly within the structure. Each component is 3D scanned to determine the structural arrangement and milled to form interlinking connections with a robotic arm. The workflow and toolkit developed used complex tree branches (disregarded by conventional forestry and wood building practices) to create a pavilion. One of the key CE benefits demonstrated is optimal material usage during the construction phase. Furthermore, this approach demonstrates that the diverse characteristics of onsite material can be exploited directly without wasteful industrial processing.

### *3.1.4. AI*

Benefits in the context of the building industry and from a CE perspective: Increase efficiency throughout the entire value chain; Monitoring and maintenance optimisation.

Artificial Intelligence (AI) is a label given to computing systems that exhibit the ability to perceive information, retain it as knowledge, and apply it to making decisions [20], which is supported by data and learning algorithms that enable the extraction of deeper levels of knowledge [11]. Current AI efforts include project schedule optimisation using historical data, improvements to worker safety through image recognition and the classification of signals and patterns to deploy real-time feedback and solutions. AI based solutions improve the efficiency of the construction process throughout the entire value chain and may contribute to the CE with design improvement, monitoring, and maintenance optimisation.

*3.1.4.1. a Example 1: AMP Cortex [30].* AMP Cortex is powered with AI in order to select materials to be recycled following demolition. It is engineered to recognise, sort, pick and process construction and demolition (C&D) debris, including metal, wood, gypsum, and concrete. This technology is deployed to maximize the ability of recycling facilities to recover tons of material an hour and handle multiple fractions with one robotic station with high accuracy and material purity levels. The technology has been installed in 160 locations globally. One of the key CE benefits is the recovery of by-products and waste, during the demolition phase. Furthermore, the analysis of the collected data contributes not only to improving the operational efficiency of the recycling facilities, but also to the creation of new value streams for recyclables.

*3.1.4.2. b Example 2: Mine the Scrap [31].* Mine the Scrap is a data driven service that designs new structures from existing scrap. Waste is transformed into useable material with computer vision and construction automation. The irregular, non-uniform stocks of construction scrap become the building blocks of new forms, using pattern recognition, scanning and classification to find the unique best use of each piece in a new structure. Key CE benefits include the reuse of by-products, decrease in waste and the optimal use of material. The service is applicable during the demolition and design phases.

#### 3.1.5. (Robotic) 3D printing

Benefits in the context of the building industry and from a CE perspective: Optimised material use; Possibility to use recycled or recyclable materials; Locally sourced materials; Potential for zero waste construction.

3D printing or additive manufacturing is a family of technologies that produces three-dimensional objects, layer-by-layer, directly from a digital file [32]. The technology enables the production of free form shapes that cannot be produced by any other method. There are many opportunities for the introduction of 3D printing into the building industry for the creation of circular components, which remain relatively unexplored. This technology can support the production of buildings using local materials, such as local natural materials (organic material, soil, etc.) or local (inorganic) waste streams. As it is an additive construction technique, it is possible to create construction processes with reduced or zero waste. By combining this technology with computational design workflows such as algorithmic design and optimisation methodologies, it is possible to produce parts with optimised performance and minimal material use. Lastly, it is possible to create parts from one material that can simplify disassembly, can be easily repaired or recycled.

*3.1.5.1. a Example 1: Casa Covida [33].* 'Casa Covida' in Colorado (US) designed by the architecture firm Emerging Objects, explores the concept of on-site and low-cost construction from locally sourced soils. This is achieved with a portable 3D printer, designed to be carried onto a site where local soils can be harvested and used immediately to 3D print large scale structures. This solution has already been tested in a pilot building in Colorado, USA. Key CE benefits include optimised material usage and the use of local resources for reduced logistics. This technological solution is useful during the construction phase. The development of a low-cost, and portable 3D printer, enables construction on-site where local soils can be harvested and used immediately to 3D print large scale structures.

*3.1.5.2. b Example 2: concrete printing bridge [34].* This project used 3D concrete printing to produce optimised structures that carry the same stresses, while reducing material use by up to 60%. The potentials of this technology and material combination are demonstrated with a bridge built in Amersfoort (NL) in collaboration with the University of Ghent and Technion Israel Institute of Technology. One of the key CE benefits was optimal material use during the construction phase via structural optimisation and 3D printing.

*3.1.5.3. c Example 3: ARUP's metal 3D printed knot [35].* This project shows that complex and individually designed steel structural elements can be efficiently produced with metal 3D printing. Even though they are significantly smaller and lighter, they can carry the same structural forces and loads as standard elements due to their irregular shape, whilst reducing the necessary material and minimising the structure's carbon footprint. One of the key CE benefits is optimal material use during the construction phase via structural optimisation and 3D printing.

*3.1.5.4. d Example 4: Print Your City [36].* Print Your City transforms plastic waste from household streams locally into street furniture and building components with robotic 3D printing and citizen participation. Citizens are involved through their donations of material and through the co-creation process. This process is supported via an on-line design platform that enables customization of the furniture of the city. Besides being produced locally from recycled sources, the final components are recyclable again. This solution has already been tested in two pilot projects in the Netherlands and Greece. The key CE benefits demonstrated are the recovery of waste and the optimal use of material. This solution is applicable during the construction phase and facilitates the using of local plastic waste as a material for construction and the production of vibrant public space.

#### 3.1.6. Blockchain

Benefits in the context of the building industry and from a CE perspective: Increased functionality, efficiency, and visibility; Decentralised tracking of information like material and waste flows.

Blockchain, is a distributed and decentralised ledger that efficiently, transparently, and immutably records transactions through secure and encrypted logs (Heiskanen, 2017; Turk and Klinc, 2017; Crosby et al., 2016). Currently, blockchain is used in the building industry to accurately record changes to a BIM model where a group of users have access (Turk and Klinc, 2017). Blockchain can be used to manage and create reliable transaction records in the supply and demand of materials. Information can be stored within a blockchain to track the material's location throughout its lifecycle. Further potential uses of blockchain include (but are not limited to): tracking supply chain logistics, timestamping changes in BIM models, maintaining material passports, and automating building maintenance based on IoT interactions.

*3.1.6.1. a Example 1: Circularise platform [37].* Circularise is a Dutch start-up that digitises and traces materials across complex supply chains on a public blockchain without risking confidentiality. Through a decentralised approach they combine transparency and secured privacy to enable the industry to make valid claims about sustainability. Circularise helps plastic manufacturers, brands, and OEMs to trace raw materials from source, into parts and ultimately to end products. This solution is already tested in the plastics sector. This solution is useful during the design phase and supports the CE benefit of optimal material use.

#### 3.1.7. Drones

Benefits in the context of the building industry and from a CE perspective: Onsite digital asset tracking, continuous spatial inspection, and progress monitoring; Promotes waste reduction.

Drones, also known as unmanned vehicles or remotely piloted aircraft, are rapidly maturing. A key benefit of this technology is that it is extremely versatile depending on the drones' capacity, size, abilities, and functionalities [38]. Hence, their usage and application in the construction industry is spreading for tasks such as supervising and monitoring the construction of a project and real-time data collection such as climatic conditions, dimensions, and positions. From a circularity point of view, this technology may contribute to optimised performance on construction sites, speed up the monitoring process, or could increase precision in construction which may lead to reduced waste generation. Experimental applications include the use of drones on construction sites to diminish labour intensive tasks, to perform work with greater precision, and to achieving real-time data feedback.

*3.1.7.1. a Example 1: Mud Shell [39].* Mud Shell used drones to coat a shelter in clay. This fast construction method demonstrates its potential application in refugee camps and disaster zones. Mud Shell is an affordable and sustainable emergency housing system that could be adopted anywhere in the world. It aims to be a new model of an emergency shelter, using local materials and drones. This solution is already tested in London as an exhibition installation. This technology use locally sourced mud and on-site construction. One of the key CE benefits demonstrated is optimised material usage during the construction phase.

*3.1.7.2. b Example 2: Flight Assembled Architecture [40].* In this project, drones were used to build structures. Flight Assembled Architecture was built from over 1.500 modules which were placed by drones programmed to use digital design data to execute the construction. The resulting mono-material structure is assembled dry (without cement or joining material) and with high precision. Therefore, the structure was designed to be easily taken apart without waste. This solution is already tested as an exhibition installation in France. This technology is able to build complex forms with high precision using of traditional brick building blocks. One of the key CE benefits demonstrated by the project is optimised material usage during the construction phase.

### 3.1.8. Augmented reality (AR)

Benefits in the context of the building industry and from a CE perspective: Optimised construction on-site; Remote repair and construction.

Augmented Reality (AR) in the construction industry typically involves digital information being overlaid on a user's real view. This is often achieved using a device with a camera such as a tablet, smartphone, or headset. The building industry could benefit by employing this technology to produce complex forms on-site with high quality results and with affordable technological means. Further, it can help repair processes that in turn enable products to be used for longer [38]. Non-technical staff can be guided remotely through repairs or the construction of parts that are hard to access.

*3.1.8.1. a Example 1: Kitrvs winery facades [41].* This project used augmented reality to produce a non-standard fabrication facade built at full architectural scale. A complex brick-building facade for a winery in Greece was constructed through augmented manual bricklaying. The façade was made from 13,596 individually placed bricks using a technology named "augmented bricklaying". This technology achieves to build remotely a complex brick facade in high accuracy, supporting the optimised material usage during the construction phase.

*3.1.8.2. b Example 2: Fologram [42].* Fologram is platform for designing and making in mixed reality. It positions digital content accurately in 3D space and automatically compensates for hologram drift over large distances. It enables the use of design models as fabrication instructions and eliminates the need to create complex 2D drawings. This solution is already tested in various case studies, including the Tallinn Architecture Biennale. Two of the key CE benefits demonstrated by this technology is optimised material usage due to efficiency and speed during the construction phase (Table 3).

## 4. Discussion

Among the four main phases of a building's lifecycle (design, construction, maintenance, and demolition) the construction and demolition phases are the most wasteful. This implies that developing new

**Table 3**
Overview of technologies and examples discussed.

| | Project name | Technology | Operation | Building Phase | Material Family | TRL | Application | CE value |
|---|---|---|---|---|---|---|---|---|
| 3.1.1. a | Oris | IoT | Optimisation of maintenance | All phases, particularly in construction & maintenance | All materials | 4–5 | Digital materials platform | Maximises product use |
| 3.1.2. a | Madaster | BIM | Optimisation of material flows | All phases, particularly interesting in demolition | All materials | 7–8 | Material passport | Recovery of by-products and waste |
| 3.1.3. a | Circular experience | Robots | Reuse of waste wood | Construction/Demolition | Wood | 7–8 | Interior architecture | Recover oof by-products and waste |
| 3.1.3. b | Rock Print Pavilion | Robots | Dry assembly | Construction/Demolition | Rock, twine | 3–4 | Temporary pavilion | Recover of by-products and waste |
| 3.1.3. c | Wood Chip Barn | Robots | Reduction of waste | Construction | Natural shaped wood | 5–6 | Temporary pavilion | Recover of by-products and waste |
| 3.1.4. a | AMP Cortex | AI | Sorting demolition waste | Demolition | Demolition waste | 7–8 | Sorting facilities | Recover of by-products and waste |
| 3.1.4. b | Mine the Scrap | AI | Reuse of scrap | Design & Construction | Scrap materials | 3–4 | Classifying and reusing scrap materials | Recover of by-products and waste |
| 3.1.5. a | Casa Covida | 3D printing | Local soil | Construction & Demolition | Earth | 5–6 | Small scale architecture | Renewable inputs (resource efficiency) |
| 3.1.5. b | Vertico 3D Concrete Printing Bridge | Robotic 3D printing | Optimisation of material usage | Construction | Concrete | 7–8 | Infrastructure/bridge | Renewable inputs (resource efficiency) |
| 3.1.5. c | ARUP's metal 3D printed knot | 3D printing | Optimisation of material use | Construction | Metal | 5–6 | Building component | Renewable inputs (resource efficiency) |
| 3.1.5. d | Print Your City | Robotic 3D printing | Waste material, locally sourced | Construction & Demolition | Household plastic waste | 7–8 | Street furniture | Recovery of by-products and waste |
| 3.1.6. a | Circularise | Blockchain | Digitises and traces materials | Construction & Demolition | All materials | 7–8 | Online platform | Recovery of by-products and waste |
| 3.1.7. a | Mud Shell | Drones | Local soil | Construction | Clay | 3–4 | Shell | Renewable inputs (circular sourcing) |
| 3.1.7. b | Flight Assembled Architecture | Drones | One material, dry assembly | Construction | Brick | 3–4 | Exhibition | Renewable inputs (circular sourcing) |
| 3.1.8. a | Kitrvs | AR/VR | On-site complex fabrication | Construction | Brick | 7–8 | Facade | Renewable inputs (resource efficiency) |
| 3.1.8. b | Fologram | AR/VR | On-site complex fabrication | Construction | Various materials | 7–8 | Platform | Renewable inputs (resource efficiency) |

circular solutions and building components that minimise waste during construction and demolition have potential to create large positive environmental impacts. Though, these CE strategies are more effective if they are implemented in the design phase. The selected applications show technological solutions that relate to the following core CE principles: (1) disassembly, reuse, and recycling during the design and engineering phase, (2) optimal material use during the construction phase, and (3) prioritizing renewable inputs and recovering by-products and waste during the demolition phase (see Table 2).

This study identified eight disruptive technologies that may benefit the circular building industry and explored their potential role across the life cycle stages of buildings (see Table 3). The CE benefits were clustered per stage of the buildings' life cycle (excluding use & maintenance) (Fig. 3) and in the context of the three core CE principles (Table 4).

The analysis of the selected examples shows that during the design & engineering phase the examined technological solutions assist mainly in disassembly and optimal material use. These solutions take advantages of technologies such as IoT, BIM, AI and Blockchain. The technologies typically offer an online platform or digital tool, that enables global issues to be addressed (for example sustainable roads) at a local level. The environmental gains from this stage are mostly reflected during the construction and demolition phases. During the construction phase, the CE dimension that is most often addressed is optimal material use via IoT, BIM, robotics, (Robotic) 3D printing, drones and AR. The CE scenarios that are supported include local resourcing, zero waste manufacturing, re-use of non-standard material, and the reduction of logistics. During the demolition phase, the CE dimension that is most often addressed is the recovery of by-products and waste via BIM, robotics, AI, and drones. The CE scenarios that are supported are maintaining the value of materials via registering and digitisation, improving the efficiency of sorting in recycling processes and enabling the reuse of materials due to dry assembly.

This research was limited by the number of keywords used when sourcing literature and the number of applied examples that were examined. Additionally, the maintenance phase was excluded in this review. Thus, further research is needed to include more relevant keywords and applied examples in all lifecycle phases of buildings. Although this study focused on implemented case studies, most of the cases were still in the early phases of development.

## 5. Conclusions

The building industry is the most wasteful industry worldwide. At the same time, the building industry is very conservative in adopting new technologies, especially in the construction phase. This paper outlines opportunities and potentials to develop circular construction processes and products using disruptive technologies and to support upcycling previously discarded materials via high-value and long-lasting applications.

It may be argued that within these integrated approaches spatial segregation of (recovered) resources and their use through innovative technologies may pose a problem. Moreover, it is the increasing complexity and lack of transparency that appear to be stumbling blocks in addressing the issue of spatial segregation and which seem to indicate a vicious circle. This can be explained by considering the relation between uncertainties and complexity: To incorporate no uncertainties is hardly complex and does not lead to innovations, whereas to neglect uncertainties can also be too simple. In the latter case, all sorts of measures are tried and implemented without the uncertainties being explicitly considered. Then, the problems are usually passed on to the management phase or the systems managers. The true extent of complexity lies somewhere between and may lead to useful innovations which are put forward as necessary.

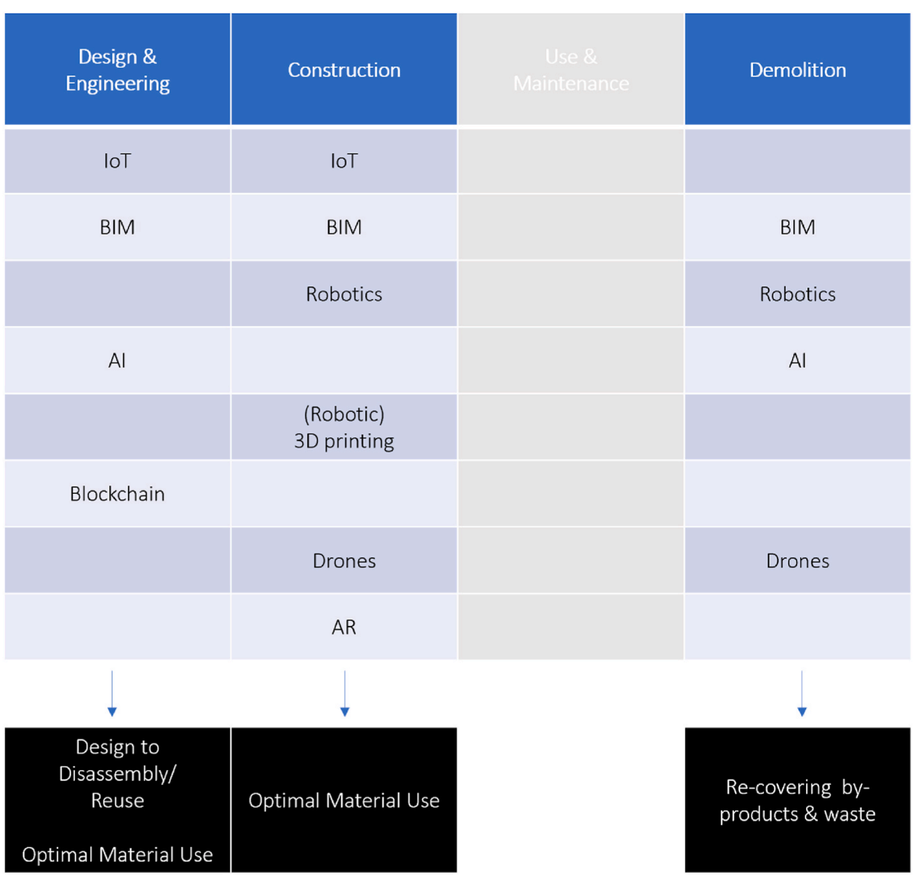


**Fig. 3.** CE benefits per disruptive technologies & building phase-based on the studied examples.

**Table 4**
CE scenarios clustered in the context of the three core CE principles, based on the examples studied.

| | | Design to disassembly, reuse, or recycling | Optimal material use | Re-covering by-products & waste |
|---|---|---|---|---|
| IoT | – | - Insight into local conditions and sourcing options. | | |
| BIM | – | - Calculating the percentage of circularity of a building during the design phase. | | - Maintain material via registration of location and digitalisation: Material Passport |
| Robotics | | | - Re-use of non-standard materials (formerly discarded, non-industrially processed etc) | - Enable re-use of materials due to dry assembly. |
| AI | – | - Generative design methods that automate the use of non-standard materials (former discarded, non-industrially processed etc) | | - Efficient sorting (increased purity levels in reduced time) |
| (Robotic) 3D printing | | | - Zero waste production<br>- Local resourcing<br>- On-site construction and reduced logistics | - Repeatedly recyclable building components |
| Blockchain | – | - Enables transparency and secured privacy to make valid claims about sustainability | | |
| Drones | | | - Use of local materials | - Enables the re-use of materials due to dry assembly. |
| AR | | | - remote construction in optimal workflow and high accuracy<br>- efficiency & speed during construction phase | |

The intersection of new technologies, the CE and construction is relatively unexplored by existing research. Therefore, this paper identified which technologies could or already play a role in the realisation of a CE of the building industry and explored their potential roles in the two most wasteful phases of building lifecycles. The resulting eight digital technologies selected (viz.: IoT; BIM; robots; AI; 3D printing; blockchain; drones; and AR) were discussed, including their TR Levels and potential role in a circular building industry. The technologies were discussed in terms of their CE benefits and opportunities using a literature review, and analyses of concrete examples where the technologies were implemented. The technologies discussed have the potential to produce new pathways to a circular building industry, that support concepts such as local, zero waste production, optimised workflows and material distribution and that enable the use of local resources, such as soil, waste, abundant materials etc. Furthermore, they may be supportive of other circular strategies such as sustainable operations management, resource efficiency, the optimisation of resource flows, and the tracking and tracing of post-use products. This is mainly achieved via the digitalisation of processes, the interconnection of information, and the creation of new workflows.

The implementation of these technologies in building industry is still in a preliminary phase. Therefore, most of the examples are not (or only in a conditioned context) tested at full scale. They are therefore often difficult to assess in terms of their business viability. It should be expected that state of the art circular construction techniques (such as recycling by crushing, mixing, etc.) will stay dominant in the field of circular construction policies and market, at least for the current decade.

## CRediT authorship contribution statement

**Foteini Setaki:** Writing – original draft. **Arjan van Timmeren:** Writing – review & editing, Supervision, Conceptualization, Writing – original draft.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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## Data availability

No data was used for the research described in the article.

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