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Completing the Circle – How Digitalization will Unlock Circular Construction

Authors: Seyed Hamidreza Ghaffar[1], Paul Mullett[2]

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1 Department of Civil and Environmental Engineering, Brunel University London, Uxbridge, Middlesex, UB8 3PH, United Kingdom

2 Robert Bird Group, Dubai, United Arab Emirates

1. Introduction

The built environment is an ideal sector to exploit circular economy due to its important and substantial resource intensity. However, the circularity culture has historically been limited due to its unique characteristics and the complex nature of circular economy.

A circular economy is theoretically defined as an economic system which is based on strategies that change the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. The aim of circular economy is to accomplish sustainable development, via the realization of environmental quality, economic prosperity, and social equity to the benefit of current and future generations[1]. To effectively overcome the circularity challenges, digitalization and breakthrough technology implementation are crucial.

This includes use of information and communication technologies (ICT), the creation and leverage of digital assets, the development of digital collaboration platforms as well as the application of artificial intelligence, machine learning, internet of things and robotic technologies. These are all recognised as promising solutions since they provide potential support to circular economy oriented decision-making and create opportunities for innovation in the built environment sector. The built environment sector will significantly be affected by the potential of transformative technologies. Although, the application of breakthrough technologies presents both significant opportunities and challenges.

The principles of circularity concept can be summarised in the following major categories[2]:

01

Constructing and developing in harmony with nature, considering the climate emergency;

02

Using waste as a resource where construction materials and products should flow in a closed loop;

03

Resilience through diversitywhere infrastructure development with multi-components are more resilient;

04

Use energy from renewable resources such as solar, wind, hydro and tidal power; and

05

System approach and system implementation is key, e.g., considering multi-factors, multi-actors and multi-stakeholders.

1 https://doi.org/10.1016/j.resconrec.2017.09.005

2 https://doi.org/10.1007/978-3-030-95798-8_4

The theory of circular economy is applicable across all sectors, as it relates to a more efficient use of resources and energy; leading to waste minimisation and reduction of the environmental impacts of product life cycles. Furthermore, circularity strategies can enable potential for new economic openings. Surging demand for zero-carbon technologies and materials provides companies with opportunities to build new green businesses. A recent McKinsey report states that reaching net zero by 2050 could lead to a 60% increase in capital spending on physical assets, compared to the current levels. The necessary investments amount to $9.2 trillion per year until 2050, of which $6.5 trillion per annum would go into low-emissions physical assets and enabling infrastructure. The analysis also showed that rising demand for net-zero solutions could generate more than $12 trillion of annual sales by 2030 across transport, power, and hydrogen. Such a global transformation of the economy can generate significant development potential for climate technologies and solutions[3].

> "circularity strategies can enable potential for new economic openings."

The circular economy challenges in the built environment sector are multidimensional. The largest challenges to successful execution are:

01

Design and construction strategies;

02

Supply chain management;

03

Policy strategies for breakthrough technologies implementation;

04

End-of-Life (EoL) principles,

05

Construction demolition waste management strategies, and

06

Good information exchanges for circularity.

These challenges are closely related to the distinctive characteristics of the built environment sector.

The material consumption pattern in this sector does not provide a suitable starting point to tackle circular economy challenges. This is due to the fact that the life cycle properties of different materials fluctuate significantly[4], and the extensive lifespan of construction products can bring several operational uncertainties at the EoL phase. The fragmented structure of the built environment sector has been a key factor in its low efficiency for decades. Built environment projects happen in highly heterogeneous environments, with critical information and organisational needs, and crossing a relatively large business network in which different stakeholders only speak their own languages. Hence, a huge quantity of waste is generated in the built environment due to the poor organisation among multiple stakeholders across a supply chain that spans considerable geographic and time frames[5].

3 https://www.mckinsey.com/capabilities/sustainability/our-insights/accelerating-toward-net-zero-the-green-business-building-opportunity

4 https://doi.org/10.1016/j.jclepro.2016.12.055

5 https://doi.org/10.1016/j.jclepro.2022.131335

The European Commission (2020)[6] in their action plan for circular economy, summarised critical areas where information communication technology-based decision support tools can in theory assist the implementation of circular economy. These areas of focus include:

01

Promoting circular production by tracking, tracing, and mapping of resource flows;

02

Improving the durability and adaptability of assets in line with circular economy principles based on robust material information management;

03

Innovating data space and providing the governance system for smart circular applications.

ICT has the potential to optimise the product efficiently through its entire life cycle via a collaborative and transparent method based on digitised information. This efficiency also increases the value of these products in relation to circular economy.

6 https://ec.europa.eu/environment/pdf/circular-economy/new_circular_economy_action_plan.pdf

2. Digitalization to combat global climate emergency

To minimise the impacts of the climate emergency there is an urgent need to unleash the power of digitalization. Digitalization in simple terms, usually refers to the integration of digital technologies into everyday life and the widespread introduction of ICT. Recent estimates from the World Economic Forum and Accenture suggest that digital technologies could deliver up to one-fifth of all the reductions needed to achieve the 2050 net-zero goals in energy, materials and mobility[7]. Data transparency, digital talent and collaboration are essential to help deliver the scale needed to achieve digital's decarbonization potential. This potential is realised through the sharing of relevant data that is autonomous, connected, and enables transparency across the value chain. Moreover, it is paramount to ensure that current and future workforces have access to new technologies and skills required to scale digital and transform business processes. Technological innovation can reduce capital costs for net-zero technologies faster than expected. McKinsey research suggests that there is a line of sight to the technologies needed to limit warming to 1.5⁰C above preindustrial levels, although continued innovation is still needed[8]. The research on decarbonization in Europe revealed that more than 85% of emissions in Europe can be decreased with already established technologies, including 28% that are mature and 32% that are in the early-adoption phase[8].

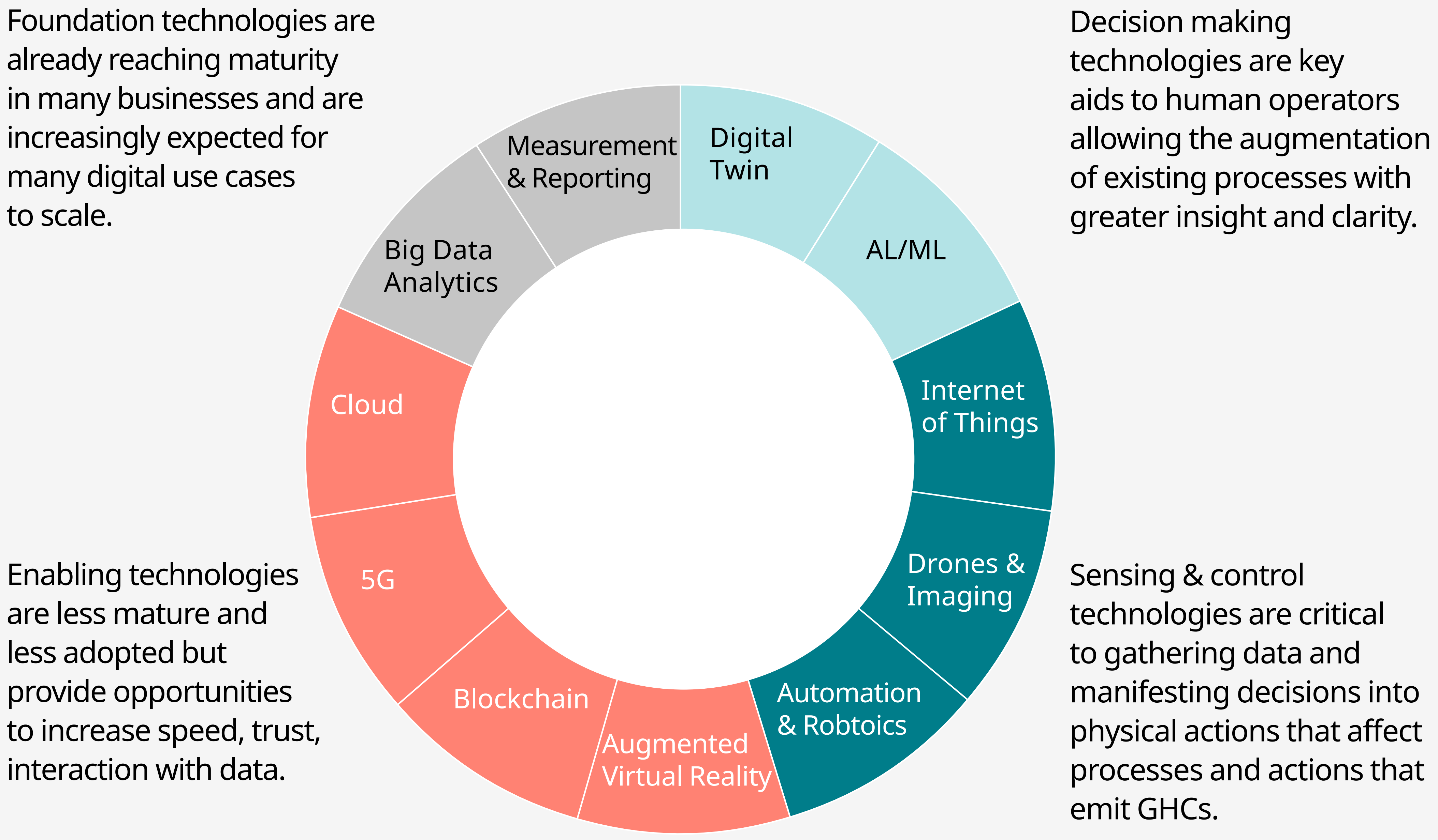
To deliver decarbonization, four clusters of digital technologies can be applied together as shown in figure 1. These innovative technologies offer powerful new way of reaching the vital net zero goal in the built environment.

7 https://initiatives.weforum.org/digital-transformation/climate-scenarios

8 https://www.mckinsey.com/capabilities/sustainability/our-insights/how-the-european-union-could-achieve-net-zero-emissions-at-net-zero-cost

9 https://initiatives.weforum.org/digital-transformation/climate-scenarios

Figure 1 – Innovative technologies which can be utilised for combating global climate emergency (taken from[9])



Digitally-driven methods that will help the built environment to build smarter, safer and more sustainably are at the forefront of the sector's effort. However, information management is a common unresolved challenge across the built environment. Building Information Modelling (BIM) is a game-changer transforming the sector. The ISO 19650 series are international standards for managing information over the whole life cycle of an asset using BIM. To date, information management has focused predominantly on organization activities and contractual processes, but hasn't yet given the same level of attention to products and materials. That being said, work such as ISO 23386 (data dictionaries) and ISO 23387 (product data templates) do a lot to support information management of products and materials. There is a huge volume of information in the built environment, yet much of it is inconsistent in its classification.

A national classification system, Uniclass[10], is available to identify and manage huge amounts of information involved with the whole life cycle of the built environment. However, it is being only partially adopted in the sector and issues with its adoption are due to a lack of openly available and specific class definitions.

The issue is made more difficult by the intricate and sometimes disjointed built environment supply chain. For increased product clarity via written brochures, websites, or the packaging itself, initiatives like the Code for Construction Product Information (CCPI)[11] offer a step in the right direction. However, it doesn't deal with the problem of providing a consistent, dependable and digitally enabled approach to accessing this important information including recognising already-installed materials and products. Each of these issues in the sector can be solved by data identifier technology. With the help of a Universal Persistent Identification Number (UPIN)[12], the traceability system gives contractors, installers, and inspectors' instant access to reliable, accurate product data from any location at any time. BSI Identify issues manufacturers with a unique, persistent and traceable identifier called a BSI UPIN to every product that's specified and incorporated in a building structure. The manufacturer can then mark or tag their products with the UPIN; forming a digital link. The UPIN can be included on the physical product via labels, within QR codes, as well as in any digital records of a building. The BSI UPIN is then able to signpost users to a product landing page where they can quickly find all the most up-to-date information on a product.

10 https://uniclass.thenbs.com/

11 https://www.cpicode.org.uk/

12 https://identify.bsigroup.com/our-service/

Therefore, if the asset's components contain an identifiable UPIN, their make, model, and installation details are easy to hand to confirm that what is specified is being installed. The persistent problem of inadequate data, which in 2020 was determined to be responsible for 14% of worldwide refurbishment work at a cost of $88 billion, can be addressed with data identification technology[13].

Laws, regulations, and legislation dictate much of the built environment. Governing bodies are constantly looking for improvements in the way the built environment sector operates by developing new ways of working. From capturing a golden thread of information digitally to managing change across an entire sector, implementing new ways of working with breakthrough technologies can be challenging.

Construction, heating, cooling, and demolition account for over 40% of worldwide CO_2 emissions[14]. Innovation and the implementation of breakthrough technologies in the built environment can significantly contribute to lowering its carbon footprint. Innovation doesn't mean using breakthrough technologies that have not yet been invented, rather, it is about transforming the practices that have been carried out for centuries by adopting new ways of thinking and employing technologies from elsewhere to address current issues.

Some innovative companies are already creating the materials, goods, and services that are transforming the built environment.

To achieve a sustainable and circular built environment, several strategies should be implemented that exploit the potential for increasing material efficiency and reducing climate impacts. These strategies should ensure coherence across the relevant policy areas such as climate, energy and resource efficiency, management of construction and demolition waste, digitalization and upskilling[15]. It is essential to promote circularity principles throughout the life cycle of assets by addressing the sustainability performance of products, including for example, the possible introduction of recycled content requirements for products, considering their safety and functionality. Furthermore, another essential point of action is the promotion of strategies to improve the durability and adaptability of assets in line with the circular economy principles for buildings design[16] and developing digital logbooks[17]. Durability improvements includes encouraging a long term focus on the design life of major building elements, as well as their maintenance and replacement cycles. Moreover, in line with the circularity principle, adaptability is essential to extend the service life of the building as a whole, either by helping the extension of the intended use or through potential future changes in use.

Since 1990, the productivity of the construction industry has not seen an improvement, compared to the growth in the efficiency of the manufacturing industry[18]. As a labour-driven trade with constraints of conventional/traditional technology that make breakthrough and innovative technologies difficult to intervene in, innovation has become a bottleneck. In the near future, throughout the construction industry, robots could play a significant role, particularly in prefabricated construction. Prefabricated construction has begun to attract considerable attention in the built environment as demands for productivity and sustainable, circular developments increase. With the component-oriented, assembly-based construction features of on-site assembly for prefabricated construction and its primary tasks being the transport, positioning, and connection of components, robots are more than capable to perform a large number of repetitive tasks with high precision, making prefabrication extremely suitable for robotic construction.

13 https://identify.bsigroup.com/blog/product-ID-revolution/

14 https://www.worldgbc.org/news-media/2019-global-status-report-buildings-and-construction

15 https://ec.europa.eu/environment/pdf/circular-economy/new_circular_economy_action_plan.pdf

16 https://ec.europa.eu/docsroom/documents/39984

17 https://doi.org/10.3390/en15061994

18 https://doi.org/10.1016/j.autcon.2015.07.022

Figure 2 – an example of 3D printed building block using low-carbon concrete by AMTC research group

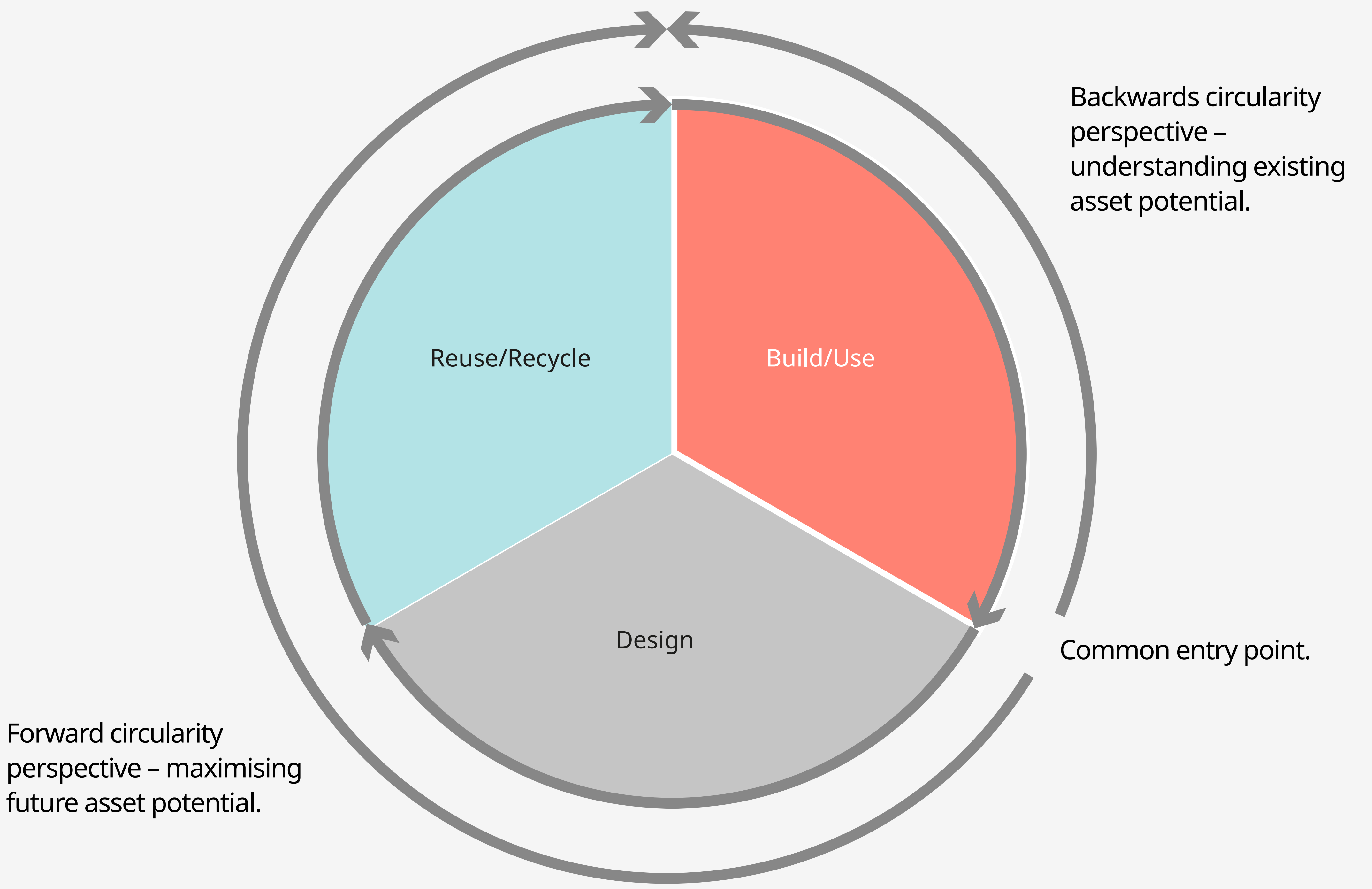
The manufacturing of the prefabricated elements itself can also be done by robots. e.g., robotic 3D printing of various materials to manufacture building blocks (see figure 2[19]). Other innovations in materials used for MMC are also important for the net-zero targets. The use of 3D printing technology in conjunction with innovative printable low-carbon concrete is gaining momentum amongst researchers[20],[21],[22] however, more time and investment is required to reach a feasible cost for this technology.

When looking at the role of digitalization of the wider built environment and how it can be supported by circular economy, it is important to understand not only the general challenges of circularity in relation to the built environment but also the challenges related to the perspective of the given starting point.

When considering circularity, it is done with the concept of a loop (described in Section 1), however the practical application of circularity must start somewhere. This starting point is a key factor in the types of challenges faced and the technologies that may be used to support a solution that supports circularity principles. Depending on the circumstances it may be necessary to look both forwards or backwards (also referred to as downstream or upstream[23]), or both as follows;

- Backwards (Anti-clockwise) – Full or partial use of assets that are already in existence, including strategies for reuse, recycling or repurposing; and
- Forwards (Clockwise) – Considerations of materials, products, design and construction methodologies that support future circular economy principles.

Figure 3 – illustration of the principle of forwards and backwards circularity



19 https://www.brunel.ac.uk/research/Projects/Project?entryid=f5ff758e-9d0f-423e-82c5-bea35152e557

20 https://doi.org/10.1016/j.matdes.2022.111183

21 https://doi.org/10.1016/j.matdes.2021.109574

22 https://doi.org/10.1016/j.conbuildmat.2020.118928

23 https://doi.org/10.56330/LXAH1188

3. Digital applications for backwards circularity

The consideration of backwards circularity applies where it is necessary or beneficial to make use of existing assets for reuse, recycling or repurposing. The vast majority of existing built environment assets have little or no data available for their design, material specification, products and construction, and data that does exist is not readily accessible except by the owners or historical contributors to the design or construction, which is often legally protected through intellectual property law. Data in a digital form has existed only for a few decades, with data rich information models only starting to become common practice (in certain markets and sectors) within the previous decade. This presents a real challenge for determining the quality and potential of any donor asset selected for use, however these challenges are also dependent on the specific scenario.

Such scenarios may include

01

The donor asset is an integral part of the development

02

The donor asset is owned by the same developer

03

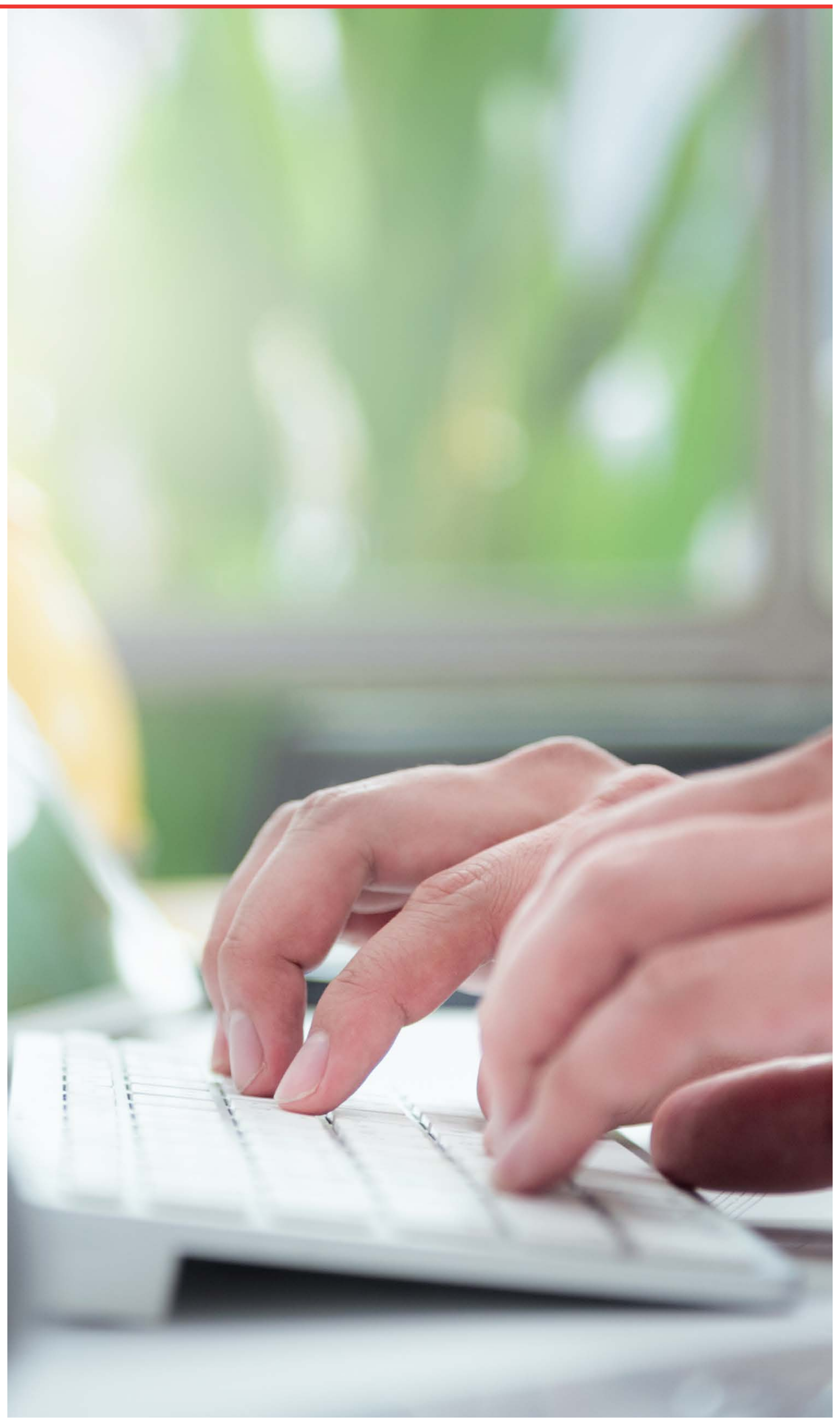
The donor asset is owned by a different party

04

Donor assets have already been incorporated into a recycling process

In the first three cases the primary data challenge is one of understanding inventory. Whether it is repurposing an existing asset or using components from a different site, in all instances the understanding of inventory is critical to the development of an optimum embodied carbon solution.

Where the donor asset is an integral part of a new development (via repurposing), re-use may typically refer to whole buildings, floors, zones or systems. Demounting or demolishing the existing asset may not be required unless repair or reconditioning of the elements is necessary, or re-use is limited to specific components (e.g. retaining columns and beams but replacing the floor system). In this scenario however having a complete understanding of the existing asset is critical to the feasibility and concept design of the wider development. The painstaking, traditional process of survey, inspection and testing may now be significantly enhanced by the use of reality capture, robotics and Artificial Intelligence. Accurate, cost-effective capture of geometry is possible using photogrammetry and laser-scanning techniques, previously only available using prohibitively high-end



360-degree cameras and low-accuracy photogrammetry can be used for inspection and recording purposes via mobile phones and other hand-held devices, the accurate capture of geometry still requires careful planning, appropriate precision and applied technological tools for interpretation. Combinatorial applications of transformative technologies are now starting to become possible whereby drones and robots such as Boston Dynamics Spot[24] can be used to methodically collect site information, and then AI-powered tools[25] can be used to interpret data to produce components within a design model.

If the donor asset is owned by the same developer but is not part of the same development (e.g. part of a broader inventory of building stock) then, assuming the asset is not designed specifically for reuse, the focus is on component reuse rather than building repurposing. The challenges described above may still be relevant in understanding potential for using an asset to add to reusable inventory, whereby a developer can survey its building stock for reuse ahead of any feasibility studies. However, if the donor asset has already been demolished and components identified for reuse have been removed and stored the next step is quantifying and cataloguing the materials and section geometries and making this information readily accessible.

Reused components will have to go through materials sampling testing and also geometric assessment to conform with tolerance requirements to meet standards. Technology can assist with this process, again using laser scanning techniques to determine geometries and imperfections. Traditional scanning techniques may be inefficient and impractical to use in a storage facility or processing yard and as the demand for reuse increases there would be benefits in the sector moving to scanning technologies employed in timber or manufacturing industries[26] to increase throughput and improve the efficiency of geometric assessments, including automated categorization and compliance checks.

At a design level, the process for reuse becomes more challenging with a reversal of traditional design processes. Rather than the output of design being geometry, section sizes and material requirements these revert to inputs to derive an optimum solution based on available inventory.

An understanding of inventory therefore extends beyond what material is available and whether it conforms to standards, and more so a managed process to connect inventory stocks directly into upstream design processes. This is particularly pertinent as the market for reuse opens up and reusable supply comes on-stream from different parties (i.e. Item 3 above). At the time of writing there is still no standardised way of cataloguing and

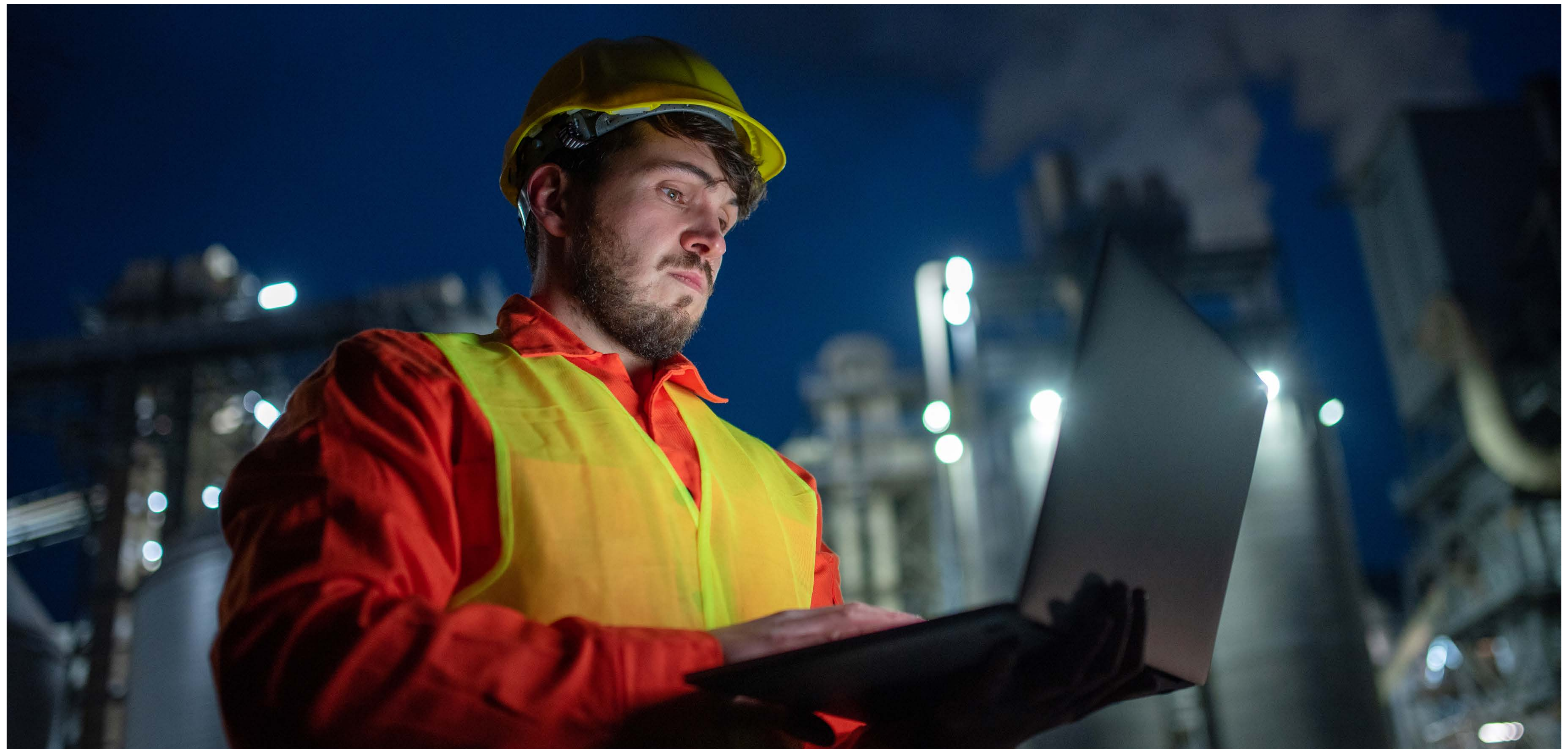
"An understanding of inventory therefore extends beyond what material is available and whether it conforms to standards, and more so a managed process to connect inventory stocks directly into upstream design processes."

24 https://fieldtech.trimble.com/en/product/spot

25 https://www.clearedge3d.com/edgewise/

26 https://lmi3d.com/resource/holzindustrie-broschure/

“The development of digital tools using visual scripting such as Grasshopper, or the use of Python code with modules for AI-based optimization algorithms, has enabled engineers to search for solutions far more effectively than before.”



publicising reuse inventory, however it is a concept of interest to several players in the marketplace. An open, web-accessible database (or even marketplace) for suppliers to catalogue their reuse inventory, geographic locations and quality compliance in a standardised system would be revolutionary in terms of increasing the opportunities for reuse. The technology for this would be straightforward, however it appears that greater market momentum and confidence is needed for the investment to take place.

From a design perspective, there are an increasingly large number of parameters that designers must contend with to make good, holistic choices. These range from the fundamental selection of building shape and form, through to the particulars of material and product specification. Factoring in the potential for reuse from a number of different inventory sources in different geographic locations, makes the challenge of finding an optimum solution even more complex. A solution that may be optimal as a new-build may be poorly matched against available inventory, whereas a ‘sub-optimal’ structural frame design solution may perfectly match what is available nearby. With embodied carbon significantly lower for reused materials (influenced of course by any necessary refurbishment and shipping/ haulage carbon impacts) the choices become much more focused towards inventory visibility, accessibility and an ability to process parameters to arrive at an optimal solution.

Some progress has been made in this area, however mostly by individual players’ intent on finding bespoke solutions to their project needs. The development of digital tools using visual scripting such as Grasshopper, or the use of Python code with modules for AI-based optimization algorithms, has enabled engineers to search for solutions far more effectively than before. The rise of so-called ‘carbon calculators’ has also facilitated the process, the simplest of which exists in spreadsheet format such as that by the Institution of Structural Engineers[27], but much more complex tools have been developed in the marketplace to directly leverage data made available from the application of Building Information Modelling (BIM) to provide both material quantities and carbon- based reporting. The combination of such insights with desktop optimization tools has the potential to revolutionise the way we design for reuse.

The final case of backwards circularity is where donor assets are incorporated into waste management and recycling processes. This is discussed further in Section 5.

27 https://www.istructe.org/resources/guidance/the-structural-carbon-tool/

4. Digital applications for forwards circularity

The consideration of forwards circularity is an activity that aims to maximise opportunity. It involves the application of design and construction methods to ensure that any new assets are built with circularity in mind, considering the facets of circularity mentioned in Section 1.

The extent to which assets may be reused varies greatly, and broadly covers the following range:

01

Use of materials that can be readily recycled or can incorporate circular waste management strategies

02

Structures that incorporate future flexibility through design

03

Demountable building systems

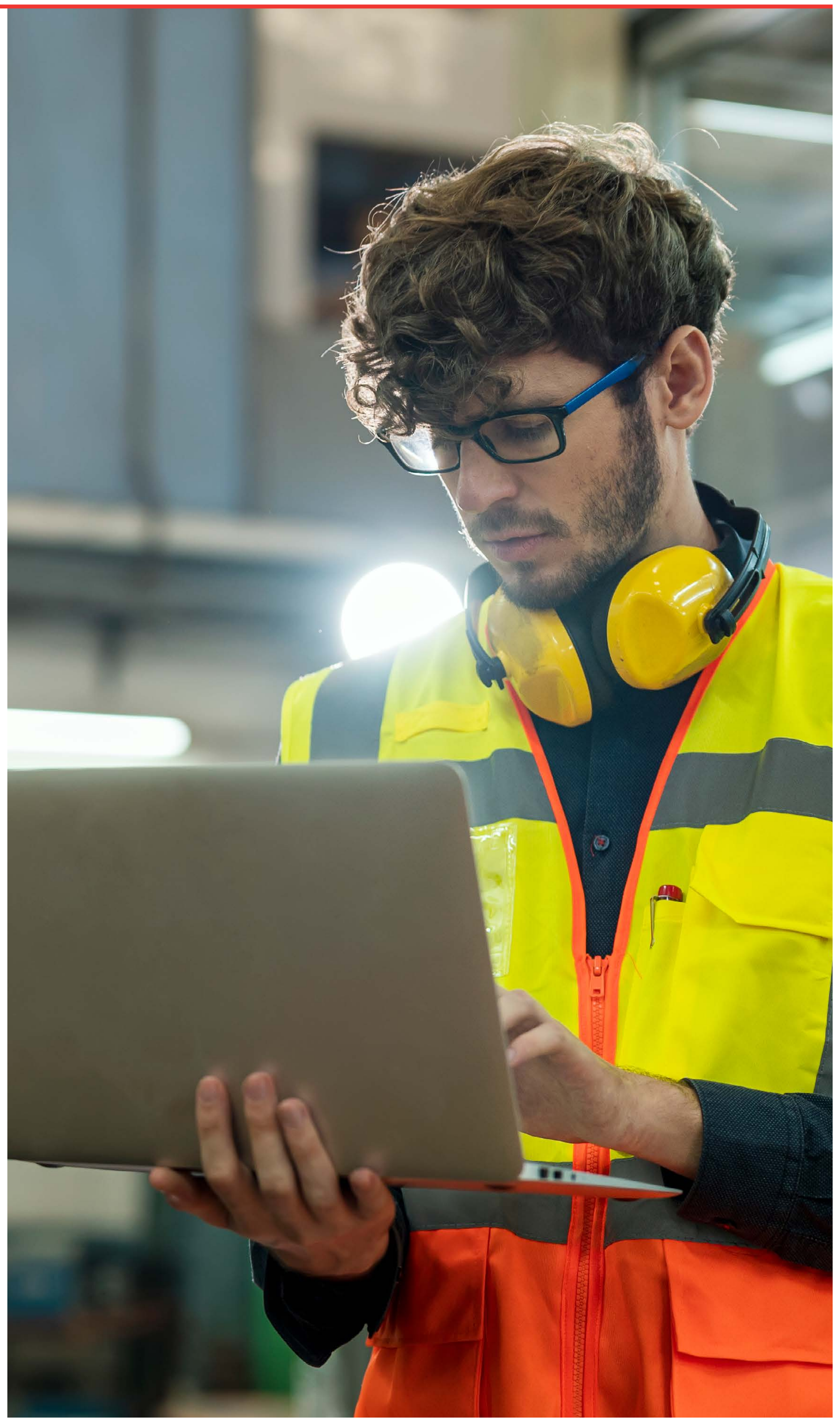
04

Fully reversible, componentised structures

This first and simplest approach is to utilise materials that have an inherent ability to be recyclable.

Some of the major issues acting as bottlenecks to the uptake of recyclable material in buildings are highlighted below:

- Lack of effective communication between key stakeholders
- Cost and lack of consistent supply along with quality issues including unknown performance
- Low consumer demand for products containing recycled materials
- Cost comparison to virgin materials
- Lack of innovative procurement and contractual models that encourage the use of recycled content
- Limited information sharing or pilot projects and examples that can be used to demonstrate successful outcomes



To increase the uptake of recyclable material in buildings, better quality recycled materials are important. This can be achieved through improved collection, sorting and processing via digitalization and robotics technology. Certainly, better-quality recycled materials that are comparable to virgin raw materials, could in turn stimulate the market. Digital tagging, which can help identify the material and its providence, BIM, which contributes to categorising information in an exploitable manner, and BSI.Identify which helps access media resources via a persistent digital link, are amongst the innovations that can help improve the recycling process and recovery of secondary raw materials. Evidently, more research, development and demonstration activities as well as modifications to product specifications and procurement with policy/legislation are paramount.

The next approach is to design for future flexibility. This can be achieved through a range of different techniques including over-sizing foundations and columns, selection of span lengths, building in ‘soft zones’ for future penetrations and stairs. Such techniques have been used by engineers for centuries to mitigate expansion plans, allow for building repurposing and even accommodate possible overloading. This can be a complex task, very sensitive to the client’s needs and anticipation of future expectations. Multi-disciplinary design is already difficult and the incorporation of further parameters risks burdening designers with an unmanageable number of permutations. More recently, computational design tools can prove very useful in determining optimal solutions for multiple design parameters and configurations, helping to narrow down solutions that meet both current and future demands, whilst minimising embodied carbon demands. This is of course dependent on a clear understanding of holistic optimal performance keeping in mind cost, quality, time and sustainability in a broader sense.

Of course, designing for an uncertain level of future flexibility also incorporates a risk of over-design which could be more onerous in terms of total embodied carbon. Such decisions should therefore be taken with a logical and informed strategy to ensure that future flexibility is both realistic and likely to meet future societal demands. Incorporating embodied carbon measurement and, as mentioned above, employing optimization techniques to ensure designs remain holistically optimal.

History has demonstrated that drawings and documents often get lost and buried in office filing cabinets, destined never to reach the hands and eyes of those who need to see them. This becomes increasingly imperative for the implementation of future flexibility. Designed-in flexibility that is not known about is a lost and wasted opportunity. A key component of successful future flexibility is to therefore ensure that such measures are documented and recorded in building management systems, preferably stored digitally in accessible form.

Demountable building systems are not new, and there have been many cases over the years of buildings being designed to be disassembled and re-assembled. Such buildings usually take the form of temporary structures, or proprietary building systems with limited and specific functions and forms. Many modular and componentised systems have been developed to allow rapid construction (and de-construction) for specific circumstances including medical facilities, emergency shelter, military and security facilities, temporary offices and events accommodation. Whilst usually designed, installed and removed by a proprietary manufacturer/supplier these structures oftentimes remain in place long after their intended life cycle. Examples include post-war accommodation in the UK that has remained in use for decades beyond its initial purpose. The demountable/temporary structures market has moved along considerably from the days of poor quality wooden portacabins and now incorporate full off-site, digitally controlled manufacturing capabilities. Indeed, the limited and ‘closed’ nature of many proprietary systems supports digitisation through the use of well-defined, componentised parts enabling digital design through to manufacture.

It’s important to note that demountability does not necessarily equate to full circularity. Many of the systems are capable of being reused completely or partially reused following refurbishment, however the applicability remains fully enclosed within the realm of application. The proprietary nature of the systems, and the digital systems that support them, are not necessarily able to be integrated into more general applications which limits the extent of possible circularity.

The idea of fully reversible, conventional, structures capable of circularity is relatively new, although history shows examples of where this has been attempted (e.g. Joseph Paxton’s building for The Great Exhibition which was taken down and entirely rebuilt[28]). Modern construction typically relies on inherently irreversible processes to achieve performance; indeed the process of formation and connection is deliberately so as to ensure strength, reliability and durability. Reinforced and prestressed concrete are cast composites, pre-cast concrete is usually secured via cast-in-situ connections and toppings, and whilst steel is theoretically reversible it often comes with composite floors, shear studs and specific bolt configurations which are not easily reversed or re-configured. Whilst it is possible to extract and reuse components from existing assets, for example from steel frame structures, it is often time-consuming and costly.

“Indeed, the limited and ‘closed’ nature of many proprietary systems supports digitisation through the use of well-defined, componentised parts enabling digital design through to manufacture.”

28 https://en.wikipedia.org/wiki/Great_Exhibition

This particular issue cuts right to the heart of industry productivity and is a complex topic encompassing procurement approaches, construction methods and materials, supply chain integration, and digital design and manufacture. The challenges that current construction methods and materials present to the processes of designing and building also flow through to circularity. The issue of forwards circularity is therefore intertwined with those more broadly of industry productivity and delivery reliability.

The generalised concept of modular and componentised construction has advanced considerably in recent decades incorporating volumetric modular, panellised modular and componentised systems. Most of these systems, although intended for permanent structures, and not considered inherently reversible or circular. Where this can be achieved it is, as is common with demountable structures, limited to the application of the particular system.

For a building system to be fully reversible, and indeed broadly circular, the component parts must be generic and share common features than facilitate connection, disconnection and re-connection in an efficient, reliable and durable manner.

As pointed out by the author previously[29], one possible solution to this problem is the development of a digital platform that is fully integrated into the supply chain, facilitating consideration of upfront componentised design and enabling a fully digitised design process through to manufacture and construction. This Lego-type of approach is often mentioned[30] as a solution to construction's over-complexity however it also presents a compelling opportunity for improving circularity in the sector.

The challenge with such solutions is that they must encompass the whole project supply chain, engaging product manufacturers, supplier, builders and designers to develop systems that are compatible, have known properties and performance characteristics, defined interfaces and have, collectively, fully predictable cost and time outcomes. The reason why such systems have yet to be successful is because it requires a large and complex digital platform to facilitate, driven by an industry stakeholder with sufficient leverage and influence over the supply chain.

Fortunately there are market stakeholders starting to consider the potential of such a platform and take the first steps in investing in its development. One such platform is Lendlease's Podium[31]. This platform aims to connect the full project life cycle providing data and insights from project conception through to manufacture, implementation and operation. In particular, the Podium for Development tool is tailored towards generative componentised design that is integrated with a collaborative supply chain. The generative, automated design elements of the platform enable the design team to understand how decisions impact cost, time and carbon early in the design phase.

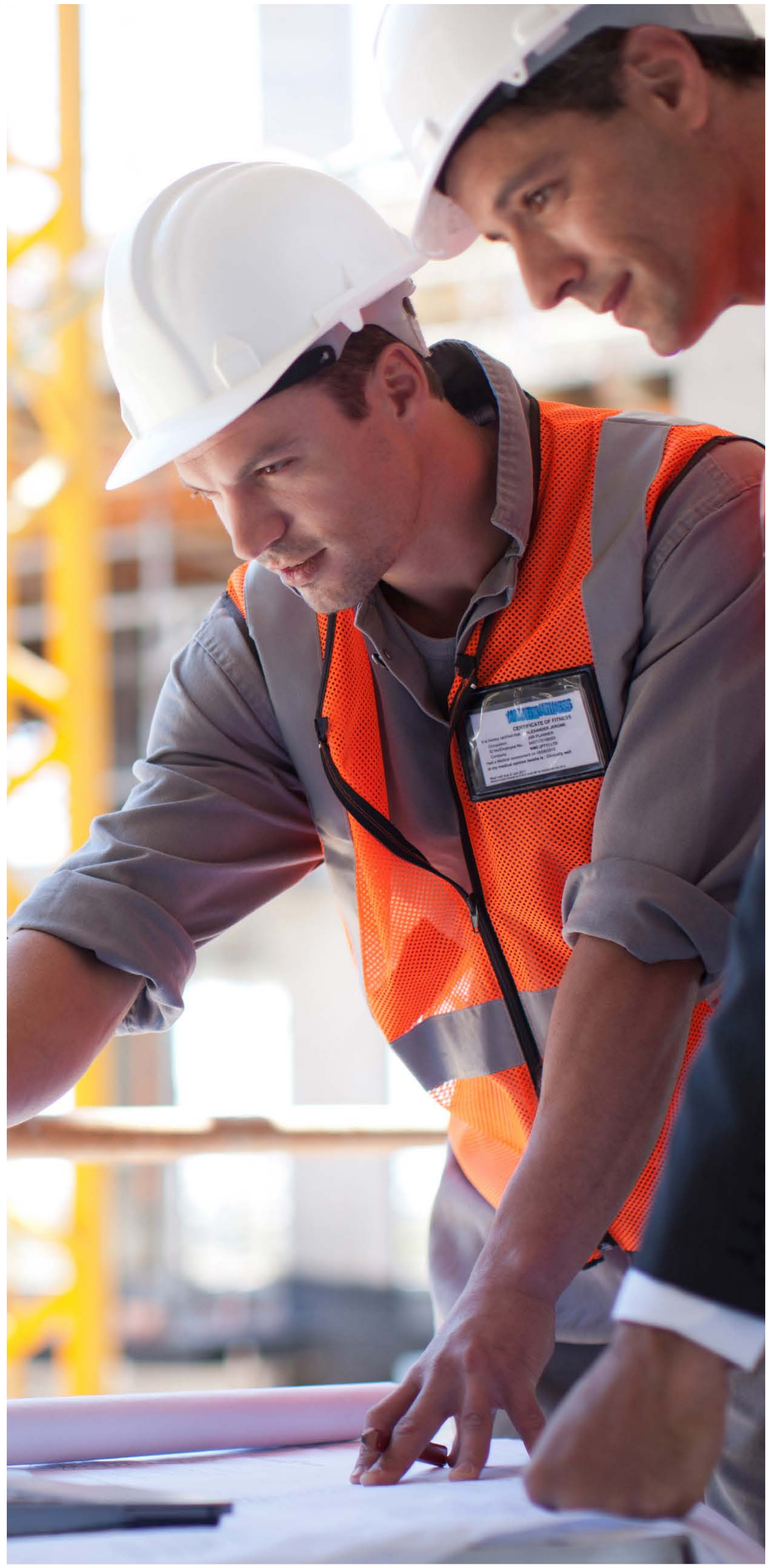
Other similar platforms to Podium are in development elsewhere in the industry and will be essential to deliver what is being demanded by some of today's mega-projects. Projects such as NEOM[32], which have aspirations to be built using sustainable, circular principles, will necessitate the use of innovative digital platforms and new technologies to realise. As these methodologies and platforms filter down through into the sector we can expect a greater uptake in holistic, connected, circular design and construction approaches.

29 https://identify.bsigroup.com/blog/be-like-lego-r/

30 https://www.wsj.com/articles/lego-megaprojects-bent-flyvbjerg-big-things-11675280517

31 https://www.lendleasepodium.com/

32 https://www.neom.com/en-us/ourbusiness/sectors/design-and-construction



5. Circularity as a waste management strategy for the built environment

Circular construction is an emerging business strategy that promotes the reuse and recycling of as many raw materials as possible in a bid to minimise CO2 emissions and waste to landfill. Circular construction, as an important component of sustainable development, is focused on promotion of the maximum reuse and recycling of raw materials and products to reduce waste and CO2 emissions. Reduce, reuse, recycle and recover are essential interventions for a circular construction, with a systemic shift in the culture and mind-sets of stakeholders. This section focuses on Construction and Demolition Waste (CDW) and how potential new technologies developed for other applications can be utilised to bring circularity to CDW management.

Reduced carbon production of raw materials with less imperfections and better circular construction models are at the forefront of the built environment's agenda. However, technical issues, such as price, legal barriers and regulations that stand in the way of the solutions being rolled out more widely must be overcome. The new CDW management systems are designed to maximise the recycling of construction, demolition and excavation waste and maximise the production of high quality, high value recycled sand and aggregates which can be used as a replacement for natural resources in a range of products including concrete and asphalt production.

New digitised platforms and innovative technologies are being developed and implemented for efficient waste management practices to reach full circularity. The target is systems that could be used in waste treatment plants or machines to make collection, sorting, treatment and recovery of secondary raw materials from waste more efficient. Systems that are capable of carrying out the sorting of mixed waste using robotic technologies are paramount. Smart bins with sensors for material detection or level measurement, methods for digital image analysis and new business models are already being developed. For example, K-project: Recycling and Recovery of Waste 4.0 - "ReWaste4.0" showcases developments in projects that focus on digitalization and the use of robotic technologies in waste management. Collection and logistics, machines and waste treatment plants, business models and data tools are four important pieces of achieving circular waste management within the built environment.

Circular CDW management is best represented as the 4R framework of 1) reduce, 2) reuse, 3) recycling and 4) recover.

01

Reduction means waste minimisation at sources,

02

Reuse is when the same material/ product is used at least twice,

03

Recycling is the end-of-life treatment of waste to create a new life for further use and

04

Recovery is the process of producing secondary raw materials from the waste for the use in the manufacturing of a new product.

"New digitised platforms and innovative technologies are being developed and implemented for efficient waste management practices to reach full circularity."

Many countries have made significant progress in developing circular practices and strategies for their CDW management. For example, the nation-wide circular economy program in the Netherlands, Circular Dutch Economy by 2050 specifies that the construction industry should adopt more innovations, e.g., circular and modular construction to reduce the construction waste. Many CDW management initiatives are also emphasised in the European Union's Action Plan for the Circular Economy, including promoting sorting systems, encouraging recycling and design improvements to contribute to circular construction across Europe. It is important to focus more on developing cutting-edge recycling technologies to have more upcycling options for construction waste into high-performing products, rather than just focusing on processing construction waste with a view to relieving the burden on their environment, for which more down-cycling options may emerge.

"It is important to focus more on developing cutting-edge recycling technologies to have more upcycling options for construction waste into high-performing products."

Instead of simply knocking buildings down and sending the CDW to landfill, circular construction would turn building components that are at the end of their service life into resources for others, minimising waste. It would change economic logic because it replaces production with sufficiency: reuse what you can, recycle what cannot be reused, repair what is broken, and re-manufacture what cannot be repaired. It will also help protect businesses against a shortage of resources and unstable prices, creating innovative business opportunities and efficient methods of producing and consuming. Materials scientists, for example, are currently developing products that use processed CDW for manufacturing building components – for example, by crushing up CDW and using it to make new building materials. It is, however, illegal to use products that haven't been certified for construction. This is one of the main obstacles standing in the way of the more widespread reuse of materials, particularly in a structural capacity. Testing the performance of materials for certification can be expensive, which adds to the cost of the material and may cancel out any savings made from reusing them. For the construction, demolition and waste management industries to remain competitive in a global marketplace, they must continue to develop and implement supply chain innovations that improve efficiency and reduce energy, waste and resource use. To achieve this, substantial research and development into smart, mobile and integrated systems of CDW management is necessary. Radically advanced robotic AI systems for sorting and processing CDW must be developed. Advanced sensors and AI that can detect quickly and determine accurately what can be used among CDW and efficient robotic sorting could aid circular construction by vastly improving the recycling of a wide range of materials. The focus should be on the smart dismantling of buildings and ways of optimising cost-effective processes.

ZenRobotics[33] is an example of industry enterprises contributing to circular construction, they were one of the first companies to use AI and robots in a demanding waste processing environment (see figure 4). To extract recyclables from waste, the company uses combined Artificial Intelligence (AI) and robotics technologies. ZenRobotics's technology enables increased waste sorting flexibility, which leads to enhancing the efficiency of secondary material recovery and purity. Cameras and sensors coupled with AI technology were employed to monitor the Waste. ZenBrain, an AI software, examines sensor data to produce a precise real-time analysis of the waste stream. The heavy-duty robots make autonomous decisions on which pieces to remove based on this analysis, which leads to a rapid and precise separation of waste. As a result, it enhances the secondary raw materials recovery efficiency. Recycling robots transform the economics of material recovery facilities by automating sortation. Metal, wood, plastic, stone and concrete are relatively easier for recycling and robotic sorting can play a significant role in yield ability of recovered materials for recycling. Manufacturers can use recycled plastic to create a wide variety of construction materials, including, roofing/flooring tiles, concrete, indoor insulation, structural lumber, PVC windows, bricks, and other relevant products.

33 https://www.terex.com/zenrobotics/

Figure 4 – ZenRobotics waste recycling robots, (images taken from https://www.terex.com/zenrobotics/)

The implementation of AI is undoubtedly one of the most significant developments in the field of CDW management, but there is still a lot of potential unfolding. As the waste industry's embracing of computer vision, machine learning and robotics raises, more innovative solutions will be streamlined to accelerate the sorting process, the recycling and the recovery of secondary raw materials which can lead to both financial and environmental benefits. Overall, AI-powered waste sorting and processing robots will help the realization of a truly circular economy. Recent advances in AI-based data analysis techniques, especially in smart sorting systems, provide a solution for automated on-site classification methods. On-site sorting has many advantages and developing mobile machines and plants that can operate on-site is one of the innovative developments that has potential in contributing to circular construction. Since on-site operations require less workforce and resources than sorting at recycling facilities. It can also improve the reusability and recyclability of CDW, therefore contribute to production of high-quality products[34]. Wang et al. proposed simultaneous localisation and mapping (SLAM) technology and the instance segmentation method, which enable the robot to deal with complex site environments, resulting in enhanced on-site CDW sorting accuracy[35].

Combining new technologies with advanced sensors and robotic sorting, recycling systems offer a unique upcycling approach that can be utilised for a selection of input materials whilst consistently maintaining the ability to produce high quality outputs, i.e. circular products. Pre-demolition audits and mobile on-site operations can be critical to the success of circular construction, while remanufacturing process aligned with modern methods of construction, such as pre-fabrication and 3D printing can assist with the circular product developments[36]. Issues around quality management and certifications require policymakers, scientists, and practitioners to come together and make responsive policies and regulations that allow and enforce circularity within the built environment sector.

34 https://doi.org/10.1016/j.scitotenv.2020.138264

35 https://doi.org/10.1016/j.jobe.2020.101769

36 https://doi.org/10.1016/j.autcon.2018.05.005

More specifically, practitioners in the sector must be inspired and encouraged to be passionate about changing the mind-sets of stakeholders and the public and showcase the potential of new paradigms. This can be driven by a combination of: (1) creative design, (2) focused academic research and applied technology, (3) external industry engagement, and (4) flexible, responsive regulation[37].

The successful implementation of the circularity concept in the built environment depends on the use of cutting-edge technologies as a decision support tool.

To achieve circular construction, novel strategies and methodologies from Industry 4.0 are being developed and implemented in the field of waste management. Digitalization and the use of robotic technologies in waste management can pave the way for a circular construction. The main concerns should be set on systems that can be implemented in CDW treatment plants, such as intelligent robotic sorting and sensing technologies or machines with smart tools to make treatment of CDW more efficient. Moreover, smart dismantling as opposed to complete demolition could provide higher chances of better quality secondary raw materials recovery. However, smart dismantling requires pre-demolition audits and individualised plans for each project which might make the whole process less convincing for the stakeholders. Therefore, systems which carry out the sorting of mixed CDW via robotic technologies are crucial. Next generation of CDW skips with sensors for material detection, harmonised with Internet of Things (IoT) technologies, and methods for digital image analysis would certainly help the circular construction developments.

The technological alignment between technical innovation and scalable real-world application is hampered by the absence of system architectural design. The degree of technological integration is insufficient to handle the complex activities involved in implementing the circularity concept. Different technologies are still not naturally linked into a comprehensive decision support system to enable circular CDW management due to the complex operational issue and their interdependency for the system to work. Moreover, the lack of databases hinders advanced CDW management because the effectiveness of the decision support tools is highly dependent on the digital information about the existing or demolished constructions[38]. The rebuilding of end-of-life (EoL) databases for existing structures can be time-consuming, inaccurate, and even inconsistent because many of them are neither circularly designed nor supplemented by material information in a suitably digital form. In addition, stakeholders pay little attention to EoL information since there are no financial incentives. Because of this, the present uses of big data analytics, IoT, and blockchain are still in the trial phase, with only conceptual frameworks being proposed to boost the effectiveness of fundamental building processes and little attention to the circularity concept.

Industrial stakeholders need to go all-out for circular innovation together with the help of governments to formulate strategies and policies towards circular construction transition[39]. The mind-set and behavioural changes of stakeholders are critical to circular construction transition. Some stakeholders are hesitant to invest on long-term circular strategies because of the volatile economic situation in the built environment. It is challenging to change the conventional linear mind-set to a circular one and convince the stakeholders and engineers that innovative business models are essential to surviving in the forthcoming resource intensive market. If there is no active stakeholder involvement and collaboration, the new technology development will have minimal influence on the circular construction transition[40]. More interdisciplinary research is needed to drive the construction industry towards a more circular future by considering challenges from policy, governance, and behavioural aspects.

37 https://doi.org/10.1016/j.jclepro.2019.118710

38 https://doi.org/10.1007/s11367-020-01807-8

39 https://doi.org/10.1016/j.jclepro.2020.121134

40 https://doi.org/10.1007/s10098-020-02016-5

6. Concluding remarks and future perspective

With the global population rapidly increasing, it's essential to review current systems in the built environment sector. The built environment sector will be urged to preserve the environment and to support the growth of population by providing housing and infrastructures. The main goal of circular construction is to decouple infrastructure development from the consumption of finite resources, and to valorise in what today is considered as waste. Digitalization can unlock the huge potential of circular construction. Digitalization of processes and products to improve efficiency and sustainability within the built environment is at forefront of every stakeholder's agenda involved in the sector. Realising full circularity in this sector is not impossible, rather within reach if the full impact of the breakthrough technologies are realised and the bottlenecks are resolved through effective communication, creativity and collaboration. One of the biggest challenges for the newly developed technologies and solutions is their mass adoption in practice. Breakthrough technologies face the reluctance of various stakeholders in their implementation in individual projects. Digital solutions such as AI-based smart waste bin, collaborative design platforms, componentised and reversible design systems, use of product passports, robotics sorting and processing, and IoT can contribute to the achievement of responsible and circular consumption and production, leading to a new era of industry innovation for infrastructure development.

The key drivers for circular construction could be innovative technologies, flexible policies and regulations, market structures and skills of everyone involved in the built environment sector. To enable systemic change towards circularity through the development and implementation of digital innovations, the built environment is in dire need of a culture shift and mind set change of all the stakeholders.

To unlock the tremendous opportunities that the circular economy holds, information/data about resources, their specifications/characteristics and their usage along the product lifecycle and value chain is essential. Digitalization is the crucial to obtaining and leveraging this information. Digital solutions provide real-time data about a construction product's location, condition and availability. This improves the traceability of materials along with enabling easier access to products and making processes more convenient and effective.

It should be emphasised that a supportive government policies for circular models, could increase capital flows and public awareness. While inappropriately rigid policies and regulations could leave smaller businesses without the flexibility to try and implement circular models using breakthrough technologies. Political emphasis on the potential of digital/circular solutions boosts growth and improves awareness of new products and services among clients and suppliers.

Circular construction obtained through digitalization offer new paradigms for producing, consuming and living. This offers an invaluable opportunity for human society.

"The key drivers for circular construction could be innovative technologies, flexible policies and regulations, market structures and skills of everyone involved in the built environment sector."

Authors

Dr. Seyed Ghaffar
Associate Professor in Civil Engineering at Brunel University London

Dr. Seyed Ghaffar is an Associate Professor in Civil Engineering. He is a Chartered Civil Engineer, a Member of the Institute of Concrete Technology, and a Fellow of the Higher Education Academy. He has authored more than 70 peer-reviewed journal papers and edited a book titled “Innovation in construction”. His research covers several construction materials, with a focus on the development of low-carbon technologies suitable for new and retrofitting applications by combining materials sciences and innovative technologies.

He has been successful in attracting multi-million research grants on 8 projects funded by the Engineering and Physical Sciences Research Council, the British Council, and the European Commission.

Paul Mullett
Group Engineering and Technology Director at Robert Bird Group

Paul is the Group Engineering and Technology Director at Robert Bird Group. In this role he explores the strategic application of transformative technologies and looks at ways to identify and adopt value-adding innovations.

Paul is an award-winning engineer with over 25 years’ experience as a professional consultant in a variety of technical and managerial roles, and he has a proven track record of providing sound, considered advice to clients based on a practical, technically grounded approach to engineering with a commitment to quality and risk management. Paul’s project portfolio is highly varied including advanced structural analysis, high-rise buildings, bridge strengthening, forensic engineering, delivery of mega-projects and complex construction engineering.

Paul is a published technical author and editor with numerous journal papers, articles and book chapters to his name, and recently co-edited and co-authored the book ‘Innovation in Construction: A practical guide to transforming construction’. He is a Chartered Fellow of the Institution of Civil Engineers, a Fellow of the Chartered Institute of Arbitrators and a registered Professional Simulation Engineer with NAFEMS.

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