The digital potential in creating a circular construction economy

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Globally, the challenge of accelerating sustainable transitions to ensure the continued thriving of the human population, natural environment and world economy is well-acknowledged. In the Netherlands ambitious targets have been set to achieve 55% emission reduction when compared to 1990 levels by 2030[1] and, in line with the European Green Deal, to move towards a climate-neutral society where economic growth is decoupled from environmental degradation and resource use[2].

A key sector that is critical in making this transition is the construction sector. According to the latest *Circularity Gap Report*[3], while the construction and maintenance of housing, offices, roads and other infrastructure represent the third largest resource footprint in the Netherlands (at 32 million tonnes), the sector also accounts for the highest level of raw material consumption across all sectors (at nearly 29 million tonnes). Scenarios for creating a more circular construction economy have to date included two main strategies – calls for zero demolition and radical changes in the ways we produce buildings.

In this paper, we consider these scenarios and explore the potential for digital technologies to make a difference in developing a more circular construction economy in the future. In what follows, the paper will first present a brief overview of current achievements to introduce circularity in construction. This highlights three key accomplishments, including the drive to document and inventorise building materials that can be recovered, reused and recycled; the development of prototypes, pilots and processes for circularity with a strong focus on designing for deconstruction, and; the creation of knowledge sharing platforms to build a network of actors to take forward lessons learnt on circular building processes. Thereafter, the second part of this paper will focus on identifying the possibilities and current problems faced with using digital technologies to support efforts to create a more circular construction economy.

Current achievements: documentation, pilots and prototypes, and knowledge sharing

In Europe, one of the major initiatives to radically transform the sector into a circular construction economy is the EU funded Buildings as Material Banks (BAMB)[4]. The vision of BAMB is to change the ways materials in buildings are valued so as to promote a greater extent of reuse of materials thereby reducing waste and reliance on virgin materials. Involving 15 partners from knowledge institutes, consultants, contractors, and municipalities across 7 countries, BAMB engaged with a stakeholder network of producers/suppliers of building materials and installations, construction firms, developers, property and building owners, facilities managers, architects,

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[1] https://www.government.nl/topics/climate-change/eu-policy
[2] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en
[3] The Circle Economy (2020) *The Circularity Gap Report – The Netherlands: Closing the circularity gap in the Netherlands*, accessed through https://www.circularity-gap.world/netherlands.
[4] See www.bamb2020.eu/about-bamb, funded through the European Union's Horizon 2020 research and innovation programme (grant agreement number 642384).

engineers, logistics managers, real estate consultants, recycling and deconstruction companies, policy makers and researchers to develop pilots that demonstrated the feasibility of systemic change in the sector. Four pilots were eventually delivered, including: the Build Reversible in Conception (BRIC) wooden building built by young trainees; a transformable steel-framed building module in the Green Transformable Building (GTB) Lab; a Reversible Experience Modules (REMS) to create a flexible indoor interactive and modular exhibition space, and; the Circular Retrofit Lab (CRL) to renovate prefabricated student housing modules for multiple uses.

Three guiding principles underpin the pilots in BAMB. First, design for deconstruction enables materials to be installed in such a way that these can later be dismantled and reassembled in another building or location. Through standardisation and using dry connections, coupled with prefabrication of reconfigurable modules, design for deconstruction can thus facilitate reusing of components and modules thereby extending the useful life of materials. Second, by creating a database of materials known as materials passports, information about the type, configuration, volume and location of materials can then be captured and shared across the value chain, thereby creating the potential for developing a market for the reuse of building materials. Third, circular business models that shift the focus from a product-dominant logic to a service-dominant logic can also encourage the reuse of building materials, components and modules. Take-back and leasing schemes are typical approaches conceived to move the focus away from ownership to freeing up access to building materials to facilitate reuse.

Notwithstanding the demonstration of these pilots, there are still a number of critical challenges that need to be addressed. On design for deconstruction, it is worth noting that this is still in a nascent stage of development. Less than 1% of existing buildings are fully demountable[5]. While design for deconstruction can provide a viable way forward when producing new buildings, the challenge remains as to how to deal with existing building stock. Indeed, even in BAMB, three out of four of the pilots were about new constructions, with CRL as the only pilot that deals with the context of refurbishment. When it comes to renovating buildings, attempts to reuse and recycle materials can be further complicated by the fact that materials in existing buildings are often in composite form where supply chain and logistical processes to disaggregate materials and components are still immature thereby adding further challenges to ensuring the quality of reused materials[6].

On creating materials passports, challenges still persist in gathering accurate information about materials in existing building stock. Knowing what and where materials exist is not sufficient to guarantee that actions can be taken to recover and reuse the materials. At best, current estimations are unreliable, particularly at the localised context and in relation to renovation projects; there is a knowledge gap in knowing the precise context of a building component so that information about how it is assembled and the changes to its condition can be collected to facilitate the

[5] Kanters, J. (2018) Design for deconstruction in the design process: State of the art, *Buildings*, **8**, 150, https://doi.org/10.3390/buildings8110150.
[6] Buser, M. and Bosch-Sijtsema, P. (2018) Attributing value to waste: the difficult road to efficient waste management for renovation projects, *in*: C. Gorse and C. J. Neilson (Eds.) *Proceeding of the 34th Annual ARCOM Conference*, 3-5 September 2018, Belfast, UK, Association of Researchers in Construction Management, pp. 119-128.

extraction for reuse, repurposing, remanufacturing or recycling[7]. Moreover, databases that capture the quality, quantity and temporal availability of construction demolition and waste materials are limited. This limitation thus stymies the potential for knowing not just what and where materials can be found in existing building stock, but also when such materials will be available for reuse. Attempts have been made, for instance, in Singapore where building materials from existing public housing stock were mapped spatially and temporally[8]. Nevertheless, in this example, a number of challenges remain, including: the interoperability of data representations (e.g. aerial images or LIDAR data) with digital 3D models of buildings and cities, scalability of modelling efforts beyond a site-specific location, and the challenge of transforming the supply chains to build using reused material resources.

These challenges are also reflected in the area of circular business models. In developing the feasibility analysis for circular business models, participants in BAMB expressed concerns and doubts around current limitations in the industrial ecosystem where manufacturers and suppliers do not already have take-back or leasing schemes, in part because of limited knowledge about the financial aspects of their products, logistical constraints in taking-back and storing materials, a limited market for reselling used materials, and regulatory constraints that mean there is no certifying system that can guarantee the technical performances of reused materials[9]. It is important to differentiate between different lifecycles of product reuse, namely those that are short-lived (e.g. materials used in furniture) and those that have a longer lifespan (e.g. materials used in structural elements)[10]. Clearly, durability is an essential factor to take into account as materials and components must remain intact during cycles of disassembly and reassembly[11]. Yet, as new building codes and user requirements call for higher, more stringent specifications, it is highly unlikely that current stock of materials become less durable to meet the quality requirements, especially where structural elements are concerned.

This is further exacerbated by the lack of robust certification systems that can assure designers and contractors of the quality of materials extracted during a building's end-of-life, and the viability in terms of increasing and improving the training and education of workers in materials recovery (disassembly and reassembly)[12]. Where

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[7] Koutamanis, A., van Reijn, B. and van Bueren, E. (2018) Urban mining and buildings: A review of possibilities and limitations, *Resources, Conservation and Recycling*, **138**, 32-39.

[8] von Richthofen, A., Zeng, W., Asada, S., Burkhard, R., Heisel, F., Arisona, S. M. and Schubiger, S. (2017) Urban mining: Visualizing the availability of construction materials for re-use in future cities, *in*: *21st International Conference Information Visualisation*, London, pp. 306-311, https://doi.org/10.1109/iV.2017.34/.

[9] Buildings as Material Banks (2017) *D12 Feasibility Report + Feedback Report: Testing BAMB results through prototyping and pilot projects*, 31 August, https://www.bamb2020.eu/wp-content/uploads/2017/09/D12-feasibility-report-and-feedback-report_web.pdf.

[10] See Leising, E., Quist, J. and Bocken, N. (2018) Circular economy in the building sector: Three cases and a collaboration tool, *Journal of Cleaner Production*, **176**, 976-989, https://doi.org/10.1016/j.jclepro.2017.12.010.

[11] Antonini, E., Boeri, A., Lauria, M. and Giglio, F. (2020) Reversibility and durability as potential indicators for circular building technologies, *Sustainability*, **12**(18), 7659, https://doi.org/10.3390/su12187659.

[12] See e.g. Mayer, M. (2020) Material recovery certification for construction workers, *Buildings and Cities*, **1**(1), 550-564, https://doi.org/10.5334/bc.58. In this recent review, Mayer (2020) noted that only certification systems in Germany, namely the Deutsche Gesellschaft für Nachhaltiges Bauen e.V. (DGNB) and the Bewertungssystem Nachhaltiges Bauen für Bundesgebäude (BNB), place a strong emphasis on closing material cycles and assessing the end-of-life materials recovery potential.

existing buildings are concerned, there is generally a lack of information and documentation about the building structure and materials that detail the maintenance, testing and inspection routine; significant financial, human and technological resources will be necessary to build a reliable data record and this may imply the use of invasive surveys where parts of existing buildings are opened up for inspection[13]. Digital technologies can be helpful, but only if there is a culture of compliance with a comprehensive system of documentation, including e.g. pre-demolition audit, materials passports and construction logbook[14].

Nevertheless, alongside the development of pilots, there have been a growing number of knowledge sharing platforms designed to bring together stakeholders to raise awareness of, and to develop new processes and ways of working in, the circular construction economy. In the Netherlands, examples of platforms include Platform 31 on the theme of the circular society[15], and the construction-specific Platform CB'23 which aims to draw up national construction sector-wide agreements on circular construction before 2023[16]. CB'23 has engaged with a number of strategic partners including, among others, a number of government agencies (including Rijksvastgoedbedrijf, Rijkswaterstaat, Ministerie van Infrastructuur en Waterstaat, Ministerie van Binnenlandse Zaken en Koninkrijksrelaties), De Bouwcampus, Bouwend Nederland, and Cirkelstad. CB'23 has to date produced guidance on measuring circularity in the building sector, based on quantifying the use of materials, environmental impacts, and end-of-life availability of reusable materials. At the time of writing this paper, CB'23 is also coordinating a number of action teams that will develop agreements on an integrated purchasing process and on effective design processes that incorporate the measures of circularity in objectively definable criteria.

The prospects (and potential bottlenecks) of digital technologies in developing a circular construction economy

In this section, we turn to the prospects and potential bottlenecks of using digital technologies to develop a circular construction economy.

BIM, Materials Passports, and Digital Twins
Prospects: The last decade has seen the global architectural, engineering and construction (AEC) sector develop capabilities in building information modelling (BIM). In a number of countries (e.g. the UK, Ireland, Singapore), BIM Level 2, where information models are coordinated to enable collaborative working and

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[13] This recommendation for creating a 'golden thread' of information that covers the design, construction, and operations and maintenance of buildings was made in the Hackitt (2018) review, following the Grenfell Tower disaster, in which 72 people died in a fire that spread through the cladding of the building façade in June 2017. See Hackitt, J. (2018) *Building a Safer Future: Independent review of building regulations and fire safety final report*, https://www.gov.uk/government/publications/independent-review-of-building-regulations-and-fire-safety-final-report.
[14] There are a number of developments at European level, e.g. the EU Construction and Demolition Waste Management Protocol (September 2016) and discussions on the future of the Construction Products Regulation in view of encouraging circular economy in the construction sector (see circular number 13814/19 ENT 246 MI 772; https://data.consilium.europa.eu/doc/document/ST-13814-2019-INIT/en/pdf).
[15] https://www.platform31.nl/thema-s/thema-circulaire-maatschappij.
[16] https://platformcb23.nl/over-platform-cb-23.

decision-making across different disciplines and project participants, has been mandated as the minimum standard for all work in the public sector. To some extent, BIM Level 2 has led to greater integration between design and construction. In future, there is scope to extend this further in BIM Level 3 to enable a more dynamic process of managing the built asset over the lifecycle. Another promising area of development lies in the creation and use of digital twins. Digital twins are virtual replicas of the physical world, and these have been used in other sectors such as aerospace, automotive and process industries to model and simulate performance. The consulting firm, Arup, produced a framework for how digital twins can be meaningfully deployed in the AEC sector. Drawing on the capabilities maturity framework, Arup articulated 5 levels of digital twin capability, including[17]:

- Level 1: a digital model with limited functionality for learning and autonomous decision-making;
- Level 2: a digital model with some capacity for feedback and control, with data from sensing systems fed back to a human operator;
- Level 3: a digital model that is able to provide analytics and insights for predictive maintenance;
- Level 4: a digital model that is able to (machine) learn from various sources of data to enable autonomous decision-making, and;
- Level 5: a digital model that is able to autonomously reason and act on behalf of users to coordinate across numerus independent systems to provide feedback to a central decision-making network (e.g. at city level).

Recall the two possible scenarios for creating a circular construction economy; that is, to reduce or even remove the need for building demolition on the one hand, and to radically transform the ways we produce the built environment. To move towards zero-demolition would imply the need to extend the useful life of the physical structures and materials in buildings. For instance, in a recent attempt to model the impacts of extending the in-use life of cement-based materials in the USA – one of the most-consumed materials in constructing buildings and infrastructure – Miller[18] suggested that an extension of 50% in the longevity of in-use period would lead to a 14% reduction in cement production. Yet, extending the in-use life of building materials in turn means that closer attention must be paid to renovation, an important and significant aspect of maintaining the existing building stock which is often less regulated and more informal. Despite the longevity of buildings in general, there are parts, such as bathrooms and kitchens, that are subject to more frequent renovations, which involve materials with high replacement rates[19].

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[17] Arup (2019) *Digital Twin: Towards a meaningful framework*, https://www.arup.com/perspectives/publications/research/section/digital-twin-towards-a-meaningful-framework.

[18] Miller, S. (2020) The role of cement service-life on the efficient use of resources, *Environmental Research Letters*, **15**, 024004.

[19] See e.g. Stephan, A. and Athanassiadis, A. (2018) Towards a more circular construction sector: Estimating and spatialising current and future non-structural material replacement flows to maintain urban building stocks, *Resources, Conservation and Recycling*, **129**, 248-262, https://doi.org/10.1016/j.resconrec.2017.09.022. Stephan and Athanassiadis (2018) developed a model to estimate non-structural material replacement flows for the City of Melbourne, Australia (from 2018-2030) and found that plasterboard, carpet, timber and ceramics have the highest average annual replacement rates.

Digital twins that connect BIM with materials passports can therefore have the potential to lead on decisions relating to predictive maintenance. At the same time, the ways we design buildings will likely change. Apart from design for deconstruction, it is likely that spatial configuration in buildings will facilitate more flexible, multifunctional use. Examples include flexible workspaces in office buildings, and the growth in co-living spaces where residents share communal areas such as living rooms and kitchen/dining rooms. Here again, there is the possibility to use digital twins to provide (near) real-time decisions on managing space use and facilities. For instance, digital twins have been developed to help manage the flow of people in public spaces such as the London Underground; while these twins were initially designed to monitor overcrowding in stations, an unintended though useful consequence of the COVID-19 pandemic is that these twins were able to be repurposed to monitor safe distancing between commuters[20].

Potential bottlenecks: Notwithstanding the promising potential of digital technologies to help automate decisions about predictive maintenance of space use in buildings, there are still a number of challenges faced when integrating BIM, materials passports and digital twins. First, the use of BIM for managing the built asset post-handover is still relatively new. There is still a lack of a structured framework that can deliver asset information models from distributed data sources, validate these models against the requirements, and facilitate the use of information in the operations and maintenance phase of the building life cycle[21]. Second, the drive towards achieving BIM Level 2 has driven practice to focus on the creation of BIM models rather than to use the models for effective decision-making. In a recent analysis of the effort put into various tasks when implementing BIM, there is some evidence to show that while 3D models have the potential to drive collaborative decision-making, an enormous amount of effort is still expended in producing 2D drawings because these are what is expected by clients and authorities from whom approvals are required[22]. In comparing between cases of how BIM was implemented in two different metro projects in Chennai in India, it was found that when the focus was on creating the BIM model then it was less likely that the model was used to facilitate collaborative decision-making; conversely, in the case where the project team first focussed on transforming their practices and in bringing in new partners to the team that the BIM model was used to draw new visualisations to address new questions and unfamiliar perspectives[23].

Similarly, on digital twins, there has been a growing focus on creating more precise virtual models of the physical world. Creating and subsequently updating the twin can be a very costly exercise. At present, there are numerous data difficulties that can generate problems in producing accurate models of the real world; these include

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[20] See e.g. https://open-space.io/, and; also https://cp.catapult.org.uk/2020/07/27/ai-technology-to-reduce-covid-transmission/.

[21] See e.g. Patacas, J., Dawood, N. and Kassem, M. (2020) BIM for facilities management: A framework and a common data environment using open standards, *Automation in Construction*, **120**, 103366, https://doi.org/10.1016/j.autcon.2020.103366.

[22] Aibinu, A. A. and Papadonikolaki, E. (2020) Conceptualizing and operationalizing team task interdependences: BIM implementation assessment using effort distribution analytics, *Construction Management and Economics*, **38**(5), 420-446, https://doi.org/10.1080/01446193.2019.1623409.

[23] Mahalingam, A., Yadav, A. K. and Varaprasad, J. (2015) Investigating the role of lean practices in enabling BIM adoption: Evidence from two Indian cases, *Journal of Construction Engineering and Management*, **141**(7), 5015006, https://doi.org/10.1061/(ASCE)CO.1943-7862.0000982.

inter alia the lack of a unified data and model standards to deal with disparate data types, scattered ownership of data from across the value chain, and current limited capacity to handle massive volumes of data efficiently[24]. These challenges are further exacerbated by the scale and complexities faced when developing digital twins for cities and the built environment. Thus, there is a need to view digital twins not as accurate models representing the real world, but as "a container for models, data, and simulations [that] is not only a novel way of using smart technologies for collaborative planning processes, but also facilitates consensus-building among participants with different backgrounds"[25]. A good example of such container for models, data and simulations can be found in the digital infrastructure of the smart city efforts in Singapore, where 3D topographic mapping, city models, and BIM represent, in combination, buildings, relief, vegetation, city furniture, transportation, water bodies, bridges, tunnels, land use and underground built structures. Rather than to treat the digital twin as a technical model, it is important to note that Singapore has also developed a whole-of-government approach to coordinate the production of datasets on a 'collect once, use by many' principle that can be shared across multiple government agencies to support the development and operation of a smart city[26].

Digital Platforms

Prospects: In the data-driven world that is required to capture the value of buildings as materials banks, digital platforms will play an increasingly important role in future. A platform society is defined as an ecosystem where datafication can capture and circulate value representations, commodify value propositions and turn these into tradeable entities and value offerings for mass personalisation[27]. In the AEC sector, product platforms have enabled the transformation of construction from an on-site production system to one that uses increasingly modularised production systems that are simultaneously standardisable and customisable. Examples include modular bathroom pods, façade systems, and even prefabricated housing systems (e.g. Boklok concept developed by Skanska and Ikea). Thus, platforms provide organisations with the opportunity to create value by enabling the meeting of market demand for variety while benefitting from economies of scale and scope[28].

Apart from product platforms, another development in the horizon is the platform ecosystem. This is where a network of users – on both the demand and supply sides – coalesce around a focal platform organisation. Well-known examples include the ride-sharing app Uber and the vacation rental platform Airbnb. Platform ecosystems disrupt traditional production logics by shifting from the ownership of assets to the ownership of access; from conventional make-or-buy decisions to facilitating

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[24] Tao, F. and Qi, Q. (2019: 491) Make more digital twins, Nature, **573**, 490-491.
[25] Dembski, F., Wössner, U., Letzgus, M., Ruddat, M. and Yamu, C. (2020) Urban digital twins for smart cities and citizens: The case study of Herrenberg, Germany, *Sustainability*, **12**, 2307, https://doi.org/10.3390/su12062307.
[26] Lim, T. K., Rajabifard, A., Khoo, V., Sabri, S. and Chen, Y. (2021) The smart city in Singapore: How environmental and geospatial innovation lead to urban livability and environmental sustainability, *In*: H. M. Kim, S. Sabri and A. Kent (Eds.) *Smart Cities for Technological and Social Innovation: Case studies, current trends, and future steps*, London: Academic Press, pp. 29-49.
[27] Van Dijck, J., Poell, T. and de Waal, M. (2018) *The Platform Society: Public values in a connective world*, Oxford: Oxford University Press.
[28] Mosca, L., Jones, K., Davies, A., Whyte, J. and Glass, J. (2020) *Platform Thinking for Construction*, Digest Series, No. 2, London: Transforming Construction Network Plus.

approaches to employ-or-enable, and; from solely focussing on managing supply to also managing demand[29]. In the context of the circular economy, two examples illustrate the emergence of a platform ecosystem – Madaster, and the Excess Materials Exchange. Both these platforms are designed to capture data about the quantity, quality and location of reusable materials, along with their financial and circular values. The vision of these platforms is to attract the owners of reusable materials to register their portfolio of assets in order to create a digital marketplace that can then be matched with the requirements of demand-side users.

<u>Potential bottlenecks</u>: While digital platforms have the potential to grow in their role as intermediaries in the marketplace for reusable materials, this is still at a nascent stage of development. Current efforts by platforms like Madaster and Excess Materials Exchange can be characterised as documenting through materials passports what materials are available and where. The challenge for such platforms is their ability to grow their pool of users so that a thriving marketplace for circular materials can be developed. In a recent review of research into platforms in the AEC sector, it was found that platform thinking is currently restricted to the creation of technical tools; for platforms to flourish in the sector, there is a need to shift attention to more strategic concerns[30]. To strategically grow the pool of users, platforms must develop innovation capabilities so that complementary services can be offered that attract (and sustain) new users to the platform[31]. An example of this can be found in platforms such as Uber or Amazon – Uber started out as a ride-sharing app that grew include complementary services of delivering food and groceries, while Amazon grew from its humble beginning as an online bookstore into the digital marketplace it is today.

Knowing what materials are available for reuse and where is not sufficient. For digital platforms to thrive in the circular construction economy, platforms like Madaster and Excess Materials Exchange must constantly innovate to build more complementary services that can grow the pool of demand-side and supply-side users. This implies a need to go beyond documenting and inventorising, to become a catalyst and intermediary (matchmaker) that connnects a network of firms across the value chain that can process the recovery, reuse, recycling and reassembly of secondary materials. There are already examples of platforms that attempt to connect designers with fabricators, such as Wikihouse and Katerra. Inspiration can be drawn from these platforms on digital fabrication so that connections between key players (e.g. building owners, product suppliers, fabricators) on the demand and supply sides can be made to enable a cradle-to-cradle approach to designing, constructing and managing the lifecycle of the built assets.

[29] Grabher, G. and van Tuijl, E. (2020) Uber-production: From global networks to digital platforms, *Environment and Planning A: Economy and Space*, **52**(5), 1005-1016.
[30] Chan, P. W. (2020) Construction in the platform society: New directions for construction management research, *In*: L. Scott and C. J. Neilson (Eds.) *Proceedings of the 36th Annual ARCOM Conference*, 7-8 September 2020, UK, Association of Researchers in Construction Management, 396-406.
[31] See e.g. Gawer, A. (2014) Bridging differing perspectives on technological platforms: Toward an integrative framework, *Research Policy*, **43**(7), 1239-1249, and ; Helfat, C. E. and Raubitschek, R. S. (2018) Dynamic and integrative capabilities for profiting from innovation in digital platform-based ecosystems, *Research Policy*, **47**(8), 1391-1399.

On digital fabrication, though, the AEC sector has been slow in adopting digital technologies, especially since building design projects are often complex multi-variant problems addressed by numerous parties working in separate disciplinary and professional silos. Digital innovations applied in other sectors such as robotic manufacturing in industrial design can be used in the AEC sector in order to augment the skills of construction workers. Promising initiatives exist in using computer numerical control (CNC), 3D printing, and robotic manufacturing in the built environment[32]. One of the reasons contractors turn to demolition rather than deconstruction/disassembly for reuse of the components and materials is the lack of time and the high price of labour. Using digital fabrication techniques on site could potentially reduce the time and cost of disassembly. To do so, robotic manufacturing needs to be mobilised in radically different ways; instead of using robotics to replace construction workers, there is a need to develop new ways in which robots can collaborate with humans more effectively (e.g. cobots) to adapt to each individual bespoke building not only in construction but also in deconstruction. More advanced robotics coupled with virtual reality diagnostics and applications can help survey and deconstruct existing building stock that was not built in standardised ways. Nevertheless, making this process universal and upscalable with the existing building stock can be technologically challenging, and it is thus unsurprising that current attempts tend to focus on new buildings.

As already mentioned, the challenge remains in matching supply and demand of secondary materials. The low proportion of existing building stock that is designed for deconstruction coupled with the challenges of organising logistics around recycling of materials[33], and the mismatch between when materials are made available and when they are needed[34], are currently key inhibitors for creating a thriving (digital) market for circular construction. That said, there are already some inroads made on certain secondary materials, e.g. masonry and steel, where recovery and reusable rates are high[35]. It would therefore be sensible to focus on and strengthen (digital) platforms that connect supply of and demand for these materials[36].

A further challenge with the growth of digital platforms is an ethical, values-based one. A key principle building a circular (construction) economy is to include more localisation of economic activity. Thus, this would imply the need for more decentralised solutions where we target waste where it is generated in the local community rather than to resort to centralised processing systems. Yet, digital

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[32] See, for example, the National Centre of Competence in Research (NCCR) on digital fabrication in Switzerland (https://dfab.ch); the Robotic Building Lab at Technische Universiteit Delft (http://www.roboticbuilding.eu/about/what/); MX3D, an innovation leader in 3D printing of large-scale metal objects including a 12-metre long stainless steel pedestrian bridge to be installed in Amsterdam (https://mx3d.com/projects/mx3d-bridge/), and; 3D printed canal house in Amsterdam (https://3dprintcanalhouse.com).
[33] See e.g. Ghaffar, S. H., Burman, M. and Braimah, N. (2020) Pathways to circular construction: An integrated management of construction and demolition waste for resource recovery, *Journal of Cleaner Production*, **244**, 118710, https://doi.org/10.1016/j.jclepro.2019.118710.
[34] See von Richthofen *et al.* (2017).
[35] For example, Stephan and Athanassiadis' (2018) estimation indicated that 79% of masonry materials and 93% of metals are recoverable.
[36] There are already platforms for trading reused brick (e.g. http://www.gamlemursten.eu/), and construction steel (e.g. http://www.zhaogang.com/). Building on lessons learnt from these platforms can then facilitate expansion as knowledge about and interest in other secondary materials grows.

platforms have the potential to centralise (and globalise) the digital marketplace. An example of a digital platform ecosystem that have become a centralised powerful force can be found in Google's attempt to enter the field of urban mobility. By creating the internet infrastructure to collect data about people's movements in cities like Detroit, Google through its subsidiary Sidewalk Labs were able to rationalise data about citizen movements and influence the decision to spend public money to integrate players like Uber; this in turn reduced citizen choice and removed more affordable options[37]. Sidewalk Labs was of course involved in creating the masterplan for Toronto's Quayside smart city, a project that was rejected in 2019 in part because of fear of what Google would do with citizen data. The promises of more open and democratic forms of innovation with end-user engagement is delivered with prescriptive solutions by a few mega-corporations like Google; the rhetoric of data democracy translates to the reality of data dictatorship[38].

Role of the public sector
Prospects: The public sector plays a crucial role on two fronts. First, as a major client, government agencies have tremendous power in specifying the need for circular designs in the public procurement process. Moreover, as owner and custodian of a sizeable portfolio of buildings and infrastructure, the public sector is in a prime position to engage with digital platforms like Madaster and Excess Materials Exchange to document their buildings as materials banks. Second, the government also acts as regulator. We have seen how government mandates on BIM have led to transformation of practices. Therefore, the public sector can pave the way as frontrunners by promoting circularity in the procurement of new buildings and in the renovation and maintenance of existing stock.

There are already developments in which public bodies are already participating in developments in industry and its platforms (e.g. CB'23 in the Netherlands, mentioned above). By bringing together multiple agencies in government, this goes some way to create a whole-of-government approach to (public procurement for) developing a circular construction economy. Nevertheless, current efforts and developments to platforms are often based on incremental adjustments to existing toolkits[39]. Such developments often focus on representing the physical material world rather than broader organisational aspects that can radically transform the production process. There is also a need to connect developments with fundamental research that can offer a clearer understanding of what can be achieved, what the alternatives are, and the purpose and performance outcomes of such radical transformation. Consequently, this not only requires reviewing and evaluating the past, but also for recommending designs for the future. The public sector (e.g. RVO) can stimulate closer cooperation between academic researchers and industry platform development through specific calls and programmes.

Potential bottlenecks: While the government as a major client and regulator of the AEC sector can shape a more circular construction economy, there are a number of

[37] Zuboff, S. (2019) *The Age of Surveillance Capitalism: The fight for a human future at the new frontier of power*, London: Profile Books.
[38] Ploeger, H. and van Loenen, B. (2018) 2050: The story of Urbidata, *in*: B. van Loenen, G. Vancauwenberghe and J. Crompvoets (Eds.) *Open Data Exposed*, The Hague: Asser Press, pp. 269-288.
[39] See e.g. Chan (2020).

critical challenges that remain. First, circularity is rarely the main goal or criterion in the procurement of building work. Often, transparency and public accountability means that the most economically advantageous tender gets awarded the contract. This may mean that tradeoffs are made that do not favour circular design solutions. Second, and related to the first point, there is stronger emphasis on capital expenditure with less attention paid on operating expenditure. As a result, decisions made on reducing capital expenditure could lead to the choice of materials and designs that are less durable. Furthermore, while regulation and information models are more developed for new-build, this is not the case for renovation and maintenance projects. As knowledge is still lacking about materials locked in existing building stock, this is an area that needs more attention.

As regulators, it would be tempting to suggest that further mandates can be put in place to capture information about materials stored in existing and new building stock. Yet, this must be approached cautiously. As mandates on BIM have shown, this can have the unintended consequence of goal displacement where efforts are put into creating information models that are detached from its potential for collaborative decision-making. Thus, a softer, voluntary code of practice where the public sector leads by example by putting circularity, design for deconstruction and traceability of information about materials firmly in the requirements of new-build and renovation projects.

Changing organisational processes
Prospects: In a recent McKinsey report, *The Next Normal in Construction*[40], future scenarios were proposed that construction could be transformed into a more integrated and coordinated industrialised process, where digital technologies coupled with new materials and new actors could disrupt and turn construction into a high-performing resilient sector. The emphasis in the *Next Normal in Construction* is one that revolves around change driven primarily by technological innovation. Yet, while new (digital) technologies may be a force for change, there is also a need to transform the organising logics and processes in the sector, particularly in terms of better procurement approaches or new business models for building strong partnerships.

As circularity demands taking a long-term lifecycle view in managing the built asset, one major change in the organising logic is to shift from a product-dominant logic to a service-dominant logic. There are already many pilots in this space. For instance, in Delft University of Technology, experimental research is ongoing with industry stakeholders to explore the possibilities of leasing building facades. This requires not only new techniques for designing and constructing facades, but also new financial mechanisms to ensure stable cash flows and a sustainable business model[41]. This

[40] Ribeirinho, M. J., Mischke, J., Strube, G., Sjödin, E., Blanco, J. L., Palter, R., Biörck, J., Rockhill, D. and Andersson, T. (2020) *The Next Normal in Construction: How disruption is reshaping the world's largest ecosystem*, June, McKinsey and Company, https://www.mckinsey.com/industries/capital-projects-and-infrastructure/our-insights/the-next-normal-in-construction-how-disruption-is-reshaping-the-worlds-largest-ecosystem.
[41] Azcarate Aguerre, J., Klein, T., den Heijer, A., Vrijhoef, R., Ploeger, H. and Prins, M. (2018) Façade leasing: Drivers and barriers to the delivery of integrated Façades-as-a-Service, *Real Estate Research Quarterly*, **17**(3), 11-22, https://www.vogon.nl/artikelen/proptech/facade-leasing-drivers-and-barriers-to-the-delivery-ofintegrated-facades-as-a-service.

also necessitates a shift in mindset from ownership of built assets to ownership of access in a sharing economy.

Potential bottlenecks: While moving from a product-dominant to a service-dominant logic has gained traction in recent times, accomplishing this transition is still challenging. In a study of mechanical, electrical and plumbing (MEP) services, where there was an example of shifting from selling MEP equipment to selling predictive performance, a number of critical challenges were documented, including: the lack of transparent and reliable information about lifetime performance of MEP equipment; limited incentive for MEP equipment suppliers to offer lifetime services; absence of design and data analytic capabilities, and; restrictive procurement practices that favoured lowest-price tender rather than most optimal (circular) design[42]. Indeed, the AEC sector is a mature industry with institutionalised ways of doing by established actors in the market revolved around key professions of AEC stakeholders. Thus, change can be slow. The role of the client – particularly public-sector client – is therefore paramount. This can also be seen in other sectors. For example, the aerospace sector is one of the sectors that have made the transition towards a service-oriented business model. Aero-engine companies like Rolls-Royce, through their TotalCare® scheme, leases engines on the basis of ensuring predictive performance. Yet, it is worth noting that this was a result of over 20 years to experimentation and exploration with data-driven intelligence, a journey that was initiated by one of their major clients in civil aerospace American Airlines[43]. Therefore, there is a need to focus on stimulating demand as a critical step to create a viable market for circular building solutions.

Conclusions and recommendations

In conclusion, this paper addresses the question of the digital potential in advancing a more circular construction economy. Our review indicates the promising potential of using digital technologies (e.g. in digital twins integrated with BIM and materials passport, digital platforms, and service-based business models) to better capture data about the quantity, quality, location and circular value of reusable materials in buildings and to create a viable (digital) marketplace for circular products and services. However, this is still at a nascent stage of development.

Efforts to date have largely focussed on the supply side. There is therefore scope to drive and strengthen demand for circular building solutions. To this end, the public sector and government agencies play a critical role, both as a major client of the AEC sector and as regulator that can shape, mandate and control information standards. In so doing, better (near) real-time decisions can be made that contribute to the extension of the useful life of buildings and building materials.

A number of recommendations can be summarised as follows:

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[42] Robinson, W., Chan, P. and Lau, T. (2016) Finding new ways of creating value: A case Study of servitization in construction, *Research-Technology Management*, **59**(3), 37-49, https://doi.org/10.1080/08956308.2016.1161405.

[43] See Johnston, P. (2017) The aero-engine business model: Rolls-Royce's perspective, in: K Richter and J. Walther (Eds.) Supply Chain Integration Challenges in Commercial Aerospace: A comprehensive perspective on the aviation value chain, Cham: Springer, pp. 237-248.

- Creating a thriving (digital) marketplace for secondary materials: There are already some successes on closing the loops on certain secondary materials (e.g. bricks and steel). Lessons can be learnt from these examples in order to build and strengthen (digital) platforms that connect supply-side and demand-side users. Clients and developers that manage a portfolio of built assets (e.g. corporate clients, housing associations) can play a significant role in registering and documenting their material assets in platforms such as Madaster. As a major client of the AEC sector, the public sector that manages a sizeable portfolio of buildings and infrastructure can also pull a number of levers, including: specifying the use of secondary materials in the requirements for new buildings, renovation and maintenance work; investing in surveying and documenting existing building stock; incentivise product manufacturers to build capacity in take-back and leasing schemes (e.g. by subsidising the storage of secondary materials); develop regulations and robust certification schemes for the reuse of secondary materials, especially where reuse for structural elements is concerned. Through its public expenditure, the government can also shape research and development activities so that evidence-based developments on digitisation for circularity can be targeted at alternatives that can work and scale up. It is important that fundamental research can inform on the performance outcomes – intended and unintended – of circular interventions.

- Through-life information management process for design, construction and asset management: The compulsory development of a gebouwdossier would be an answer to developing through-life information models that can inform design, construction and asset management decisions. The public sector can be a frontrunner in this regard, and such a dossier can be effective if coupled to (a) gradual development by means of integrating information with e.g. any activity that requires drawings, permits etc.; (b) an intelligent framework that harvests information or facilitates the above activities rather than add to the burdens of owners and contractors, and; (c) enable decisions that relate to achieving additional goals, e.g. energy transition, public health, and not just circularity. Lessons learnt and benefits should be researched and communicated to all stakeholders, including local authorities who are primary users of such information, so that there is cumulatively acceptance of such information management practices over time.

- Training and education: The AEC sector, and in particular designers and contractors, must be upskilled in a number of areas, including: communicating and operating within a through-life information framework, and; design for deconstruction. Furthermore, the certification system for secondary materials must also be accompanied by the training of a sufficient pool of assessors who are able to evaluate the quality and durability of reused materials. Only when there is confidence in the quality assurance systems will the circular construction economy flourish.

- Whole of government approach: The public sector is an influential actor in the AEC sector. Circularity necessitates the fostering of industrial symbiosis where networks of relationships are brokered across different sectors so that the waste from one can be used as the raw materials for another. Often, though, the focus in the circular construction economy emphasises the physical and material world within the AEC sector, downplaying broader influences from outside the sector that can also impact on decisions on circularity. For instance, there are other sustainable transitions at play, including the energy transition, the housing transition and urban transformations to accommodate demographic change. Policy choices to address these simultaneous and ongoing transitions will in turn affect decisions on transforming the built environment – including new-build and adaptations of existing building stock. Therefore, a whole-of-government approach where multiple agencies share and exchange data can facilitate joined-up systems thinking and enable the simulation of scenarios on e.g. building stock renewal in the context of rapid urbanisation. In so doing, a whole-of-government approach emphasises the production of large, usable datasets. This creation of datasets can also be facilitated through public-private partnerships, e.g. by collaborating with companies that specialise in technology platforms. However, caution must be exercised to safeguard the ethical use of data and to ensure high levels of privacy and security.