Post-Urban Mining Automation and Digitalisation for a Closed-Loop Circular Construction

Arghavan Akbarieh, arghavan.akbarieh@uni.lu
University of Luxembourg, Luxembourg, Luxembourg

Markus Schäfer, markus.schaefer@uni.lu
University of Luxembourg, Luxembourg, Luxembourg

Danièle Waldmann, daniele.waldmann@uni.lu
University of Luxembourg, Esch-sur-Alzette, Luxembourg

Felix Norman Teferle, norman.teferle@uni.lu
University of Luxembourg, Luxembourg, Luxembourg

Abstract

The large volume of in- and out-flow of raw materials to construction projects has a huge potential to be optimised for resource efficiency and waste reduction. With the recent awareness of the importance of the circular economy, construction actors are aligning their practices to be more circular and sustainable. The concept of material banks is born out of this awareness in order to document the lifecycle information of materials and facilitate re-using them. The introduction of new cycles before individual materials reach their final lifecycle stages results in reduced negative environmental impacts.

This paper presents a workflow by positioning different digital technologies to automate the procedures for reuse assessment: from the deconstructed building to M/C bank to new construction projects. This automation supports a practical material and component reuse, while it provides the necessary infrastructure to digitise and digitalise the post-deconstruction materials to be visualised, selected and used by future designers in Building Information Modelling (BIM)-based design and management environments. To this aim, the coupling of BIM, reality capturing technologies, additive manufacturing techniques, IoT and RFID sensors is also anticipated.

Keywords: Material Bank, Building Information Modelling, Reality Capturing Technologies, Additive Manufacturing, Re-use, Recycle, Deconstruction, End-of-Lifecycle, RFID, Industry 4.0

1 Introduction

The combination of global trends such as the drastic rise of the global population, climate crisis as well as resource depletion is pushing the global society towards overstepping the planetary boundaries. To avoid this, industries are shifting from the linear economy paradigm towards the Circular Economy (CE) in which, extract, produce, use, reuse, repair and recycle is promoted. CE strategies aim to keep a material in the economic value chain for as long as possible with the highest possible quality. A circular and closed-loop material use lowers the environmental externalities, resource extraction and waste generation (European Commission 2015).

As one of the most resource-consuming and emission producing industries, the construction sector is particularly under huge pressure to circularise its activities. On the one hand, a solution must be found to host an additional two billion people by 2050 and beyond (United Nations 2019). On the other hand, sustainable and circular workflows must be developed to avoid further resource depletion, waste and brownfield land generation. To overcome the above challenges, construction material reuse and recycling are in the spotlight of researchers. In many cases an element has a longer lifecycle span than a single building. Previous studies have shown that material reuse in multiple lifecycles reduces material's negative environmental impacts and lowers their embodied energy and carbon (Akbarnezhad et al 2014).

The research groups can be divided into two categories: the first group investigates the potentials of material reuse and recycling after the End-of-Lifecycle (EoL) of buildings, while the second group is invested in early design stage strategies to either Design out Waste (DoW) or Design for Deconstruction (DfD) (WRAP 2009). The common denominator of these two early design strategies is the lower waste output, known as Construction and Demolition Waste (CDW), and higher material reuse rate in the EoL phase.

Dow offers a set of principles for reducing the overall waste production of a construction project, including design for material optimisation, design for waste efficient procurement, design for off-site construction and design for recovery and, subsequently, reuse. DfD, however, focuses on developing a project, in which all building components and materials can later be demounted from the building and reused in a new project. DfD strategies might incur a higher initial cost in the first service life. Nevertheless, it reduces the construction cost in the second cycle of service life by almost 80%. Additionally, DfD can cut the overall cumulative construction cost of two cycles of service life by 11% (Akbarnezhad et al 2014). In the same study, DfD-based designs proved to produce 40% less carbon emission in comparison with conventional designs.

The early design strategies are highly effective in limiting waste production and strengthening the materials and components (M/C) reuse later in the EoL phase of buildings. Meanwhile, M/C must be diligently chosen and designed in order to be able to carry on further lifecycles after the building decommissioning. However, once the materials are taken out of the first building, they need to be recertified for the second lifecycle. Ultimately, new designers must use them in their designs, potentially, for a second DoW-, DfD-based design. To close the material loop and to realize the explained DfD-deconstruction-recertification-reuse cycle, a material reuse management body is required, which is conventionally known as material bank. A material bank links the early design stage and the EoL stage by facilitating the transfer of M/C extracted from a decommissioned building to a new structure. The material bank is also responsible for certification of reusable materials (Cai and Waldmann 2019).

Other concepts for material banks include Buildings as Material Banks (BAMB). In this concept, the whole building stock can be re-thought as a lay-off source of valuable reusable materials (Gepts et al 2019). This is not far from the truth. UK's Green Building Council states that more than two-thirds of the operational buildings in 2050 are already built (UK Green Building Council, 2021). Similar concepts such as Existing Buildings as Material Banks (E-BAMB) or Cities as Material Banks (CAMB) have been developed by other research groups (Manelius et al 2019; Rose and Stegemann 2018). Exploiting the existing building stock as a reservoir of secondary material for the future construction projects is the base of all these concepts. This is called Urban Mining; extracting the reusable M/C from buildings that are to be decommissioned.

However, a deconstructable component is not necessarily reusable unless the material bank certifies it. Various research studies discuss the central role of material banks to circularise the construction projects (Akbarieh et al 2020; Cai and Waldmann 2019; Gepts et al 2019; Jayasinghe and Waldmann 2020; Manelius et al 2019; Rose and Stegemann 2018, among others). Nevertheless, no previous study explored the feasibility of M/C reuse before and after a material bank's certification. To close this gap, the present paper conceptualises a workflow for practical M/C reuse. Owing to the large volume of materials in the building stock, a synergy of modern digital technologies is required to digitise, automate and digitalise the post-urban mining processes in the Architecture, Engineering, Construction, Owner and Operator (AECOO) sector. Without these technologies, material reuse cannot scale up.

This paper presents the necessary steps in the post-urban mining phase where the disassembled building M/C are already sent to the material bank and recertified by it. Development of an assessment strategy is not the focus of this study, but how to get the deconstructed parts from an old building to a new user. The suggested workflow demonstrates how disruptive technologies automate the on-site practices for a closed-loop a) building deconstruction to material bank phase, on the one hand, and b) from the material bank to new construction projects on the other hand. In this paper, deconstruction refers to complete disassembly of parts to achieve maximum reassembly and reuse potentials as well as minimum CDW. The choice of deconstruction strategy affects the overall (de)construction cost, energy use, carbon emission, generated CDW as well as M/C reclamation and further reuse potentials. The significance of crucial deconstruction factors, which preserve the quality of salvaged M/C and ensure high recovery rates are discussed in (Queheille et al 2019). However, going into the details of deconstruction practices are beyond the scope of this paper. We focus on what technologies are needed when and in what order to facilitate material reuse after the building deconstruction and prior to reuse in the second service life. The envisioned automation supports a practical M/C reuse, while it provides the necessary infrastructure to digitalise the post-deconstruction materials to be visualised, selected and used by future designers. Building Information Modelling (BIM), reality capturing technologies, additive manufacturing techniques, Radio Frequency Identification (RFID) and humanoids are among the technologies that are used in this study.

Throughout this paper, the term “digitalisation” serves as an envelope term for both digitisation and digitalisation despite the distinction between the two. Digitisation refers to the conversion of analogue data into digital format. In the context of this paper, digitisation implies acquiring the 3-dimensional geometry of real-world objects through reality capturing technologies. Digitalisation, however, happens when the digitised information along with a layer of information, e.g., material, are used within digital ecosystems in order to model and optimise processes. A prime example is object-oriented BIM. Modelling the materials or various construction processes is possible in BIM ecosystems where both geometry and semantics complete the digital representation of a construction project. In short, digitisation deals with information whereas digitalisation concerns the processes.

This paper is structured in 5 sections including the current section, i.e., Introduction. In the next part, section 2, background information about the prominent digital technologies in the construction sector is rendered. These technologies construct the proposed framework that is explained in section 3. In this part, the focus is on the vital procedures after building deconstruction. Section 4 further discusses the idea and section 5 concludes the discussions.

2 Technological Background and Related Works in the Construction Sector

In this section, digital technologies that serve for delineating the post-urban mining material reuse automation and digitalisation are briefly introduced.

2.1 Material and Component Bank (M/C Bank)

The concept of the Material and Component bank (M/C bank) is proposed by (Cai and Waldmann 2019). An M/C bank considers the reuse potential of a whole component or an assembly and does not solely focus on the constituent materials within an urban stock. The M/C transition from old building deconstruction to new construction hinges over M/C bank. To facilitate material reuse, the M/C bank has a digital, BIM-based platform where it receives elements’ lifecycle information from BIModels but also from other BIM compliant formats (Jayasinghe and Waldmann 2020).

More importantly, the M/C bank is responsible for assessing M/C against proper chemical, environmental and structural performance criteria. Especially, structural robustness of structural components must be insured by the M/C bank before reuse. Throughout this paper, we position our concept assuming that a material bank is already fully operational. The reuse performance assessment of a material or component is difficult and complex. These reuse test methods and criteria are beyond the scope of this study. Once tests are done, the final vote for reuse can be: Pass, Aesthetic Fix, Deep Fix and Not Pass (i.e., Fail). Therefore, the vote determines whether an element can continue its second lifecycle. However, when an element does not meet the performance critical and consequently fails, it will be assessed against proper recycling criteria. In the section 4, Discussion, a final vote will be explained in more details.

2.2 Building Information Modelling (BIM)

Building Information Modelling (BIM) is a methodology to create a 3D, digital, object-oriented, intelligent representation of a building in which all the building information is stored, managed and exchanged between stakeholders. The resulting digital model is also known as BIM, or BIModel to remove the confusion. BIM can be utilised in various lifecycle stages; from the pre-construction phase to the construction, maintenance, and deconstruction phases (Sacks et al 2018). By having construction products and processes digitalised in one single model, repetitive tasks could be automated that would lead to fewer on-site and off-site human-induced mistakes in a construction project. Currently, BIM is the only well-known methodology to holistically digitalise the fragmented construction products and services in an interoperable manner. The digitalisation of construction information through BIM creates a gateway for the construction industry to be linked with other digital technologies such as Artificial Intelligence (AI), Internet of Things (IoT), Blockchain and other central databases.

BIM can and must interact with the M/C bank to exchange the lifecycle information of materials. This interaction between a primary BIModel, the M/C bank, and a new BIM-based design is shown in Figure 1. Two parallel processes are carried out simultaneously. In the physical process, elements are deconstructed from the building, sent to M/C bank for assessment and recertification, and finally reused in a new building. In a parallel digital process, material lifecycle information will be transferred to the digital M/C bank after building deconstruction. After an update, lifecycle information as well as reuse certification and assessment results are available for new designers. For the reusable material design phase and the transition of information from the M/C bank to a new BIModel, designers must foster a new mindset: “Design with Reusable Materials” (Akbarieh et al 2020). This will be further

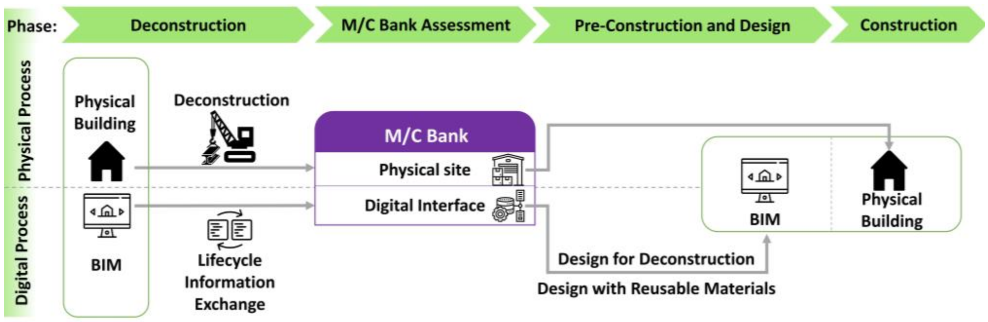

Figure 1 The interaction between BIM and M/C bank. The two, physical and digital, parallel processes enable material and component reuse.

discussed in section 4.

2.3 Reality Capturing Technologies

Reality capturing technologies are devices and processes with which real-world objects, buildings, or areas (such as a road or a city) can be captured for a detailed 3D data acquisition. The capturing devices may use laser pulses to record the distance, angles and other physical attributes such as colour or intensity from the desired elements. Others may use optical digital imagery from a single or a multitude of cameras. Different types of laser scanning methods include Terrestrial Laser Scanning (TLS) and Airborne Laser Scanning (ALS). High accuracy mobile or handheld scanners have also been introduced to the market in order to ease the work of scanning professionals for locations with limited access or small objects. Unmanned Aerial Vehicle (UAVs) can also be equipped with scanners. On the other hand photogrammetric analyses have become very popular with the availability of various digital cameras, UAVs and cloud-based processing services. As these methods complement each other, modern sensor systems, e.g. mobile mapping systems, often comprise both these types of capturing technologies.

From both data types subsequently a point cloud is created, which needs to be further processed by specialised software in order to represent the desired digitised elements. Through BIM-based methods, it is possible to reconstruct a real-world object from these data for modelling and visualisations.

Currently, many research groups use these methods for condition assessment or corrosions and cracks detection in M/C the belong to steel and concrete structures (Ribeiro et al 2020; Yang et al 2020). Tracking and updating the status of construction progression based on BIModels are among other practical use-cases of capturing technologies (Han and Golparvar-Fard, 2017). Moreover, Hamledari and Fischer (2021) proposed using such technologies on construction site in order to automate the progress monitoring and realising construction payments through blockchain-based smart contracts.

2.4 Extended Reality Technologies

Extended Reality (XR) XR is an umbrella term that refers for the three types of immersive technologies: Virtual Reality (VR), Augmented Reality (AR), as well as Mixed Reality (MR). Each of these technologies delivers a different immersive experience to the user (Alizadehsalehi et al 2020). Through XR, users experience a blend of the real and digital/virtual worlds, where audio and visual cues enable the user to either enter a completely digital world, although realistic, in VR, or to experience an addition to their immediate environment in AR. Therefore, XR is a useful technology to support design and decision making in construction projects by simulating different procedures in various lifecycle stages. In the context of this paper, directly observing the disassembly of reusable parts and reassembly of new parts in an XR environment hugely benefits designers and construction project team.

XR software and objects can be sourced from BIModels and created via BIM authoring tools, respectively. For reusable construction materials, creating XR-oriented objects are the next step after scanning with reality capturing technologies. Once the captured elements are turned into 3D objects; they can be visualised in XR environments to assist with assessing the design needs.

2.5 Internet of Things (IoT)

IoT systems compose of multiple sensors and cyber-physical systems, which collectively help with real-time information sharing and collection (Borgia 2014). Real-time data improves the efficiency of processes and the project. Moreover, within an IoT system, sensor devices, i.e., Smart Objects, can communicate with each other to exchange information. The data gathered by IoT devices can be further processed, integrated and modelled in BIM-compliant environments.

Radio Frequency Identification (RFID) is categorised as a communication technology which powers the IoT. As such, it a sought-after, low-cost technology in the construction sector with which data are automatically collected from objects and stored in the RFID tag. In this technology, radio waves transfer energy and data to an electronic transponder, i.e., tag. RFID sensors can be attached to different elements for tracking, locating, inventory and material management, health and status monitoring, progress management, quality control and logistics planning (Motamedi et al 2016).

RFIDs are becoming more popular with material banks as some studies envision the integration of material passports in RFID tags with information being logged in a blockchain network (Copeland and Bilec, 2020). Material Passports structurally document the composition of materials and their lifecycle information, including reuse and recycling potentials, and the environmental impact (Honic et a, 2019).

2.6 Humanoids and Robotic Machinery

Robotic machinery and Humanoids are among other Industry 4.0 spill-overs in the construction industry. Having sensor-fed digital twins on the one hand, and sensor-equipped sites on the other hand, it has never been an easier time for AECOO actors to explore the possibilities of humanoids in construction projects. Humanoids completely depend on all the above-mentioned technologies in order to autonomously move in the (De)construction site and to add a new layer of automation to the projects. However, the added value of on-site robotics is the increase in speed and efficiency of projects and reduction of errors and health hazards of workers.

Despite many advantages of robotic machinery in the construction sector, (Melenbrink et al 2020) briskly warned that the application of humanoids is suited for large scale and repetitive projects and might not be cost-effective for the majority of single construction projects or tasks.

2.7 Additive Manufacturing

Additive Manufacturing is widely deployed for repair and restoration in various industries including power plant, marine, manufacturing, railway and aircraft industries (Rahito et al 2019). However, it is not a common practice in the construction industry since reuse and recovery of construction M/C were not considered in the past. Additive manufacturing automates the restoration of parts only if material compatibility is met. Hence, not all materials in construction can be repaired by this technique. However, cementitious and metallic materials have proved to have high potentials (Delgado Camacho et al 2018). In fact, 3D concrete printing is an additive manufacturing procedure that could be useful for concrete parts' restoration.

Binder jetting, material extrusion and sheet lamination are common additive manufacturing principles. These principles can help to retain a product in the supply chain by introducing new sub-cycles for reuse. Figure 2 illustrates how a real-world object can be fixed and ready for reuse if the machine has the geometry of the damaged and original 3D object. Additive manufacturing rapidly produces complex structures with a rather low wastage rate of materials and energy. The variety of additive manufacturing techniques offers new reuse possibilities by repurposing the elements and creating new components from the deconstructed elements. Of course, this procedure completely depends on having access to initial design drafts, dimensions, and material compositions of the elements. This is another reason for having standardised material passports saved in secure databases during the first and second lifecycle of elements.

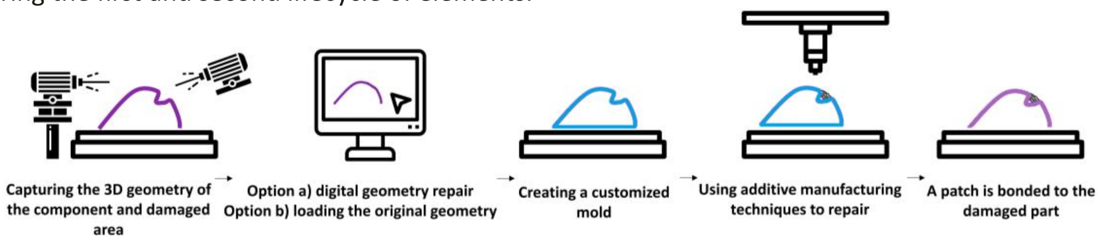

Figure 2 Digital processes for repair through additive manufacturing. The image is modified from (Türk, 2017).

3 A proposed workflow for post-urban mining automation and digitalisation of reusable materials and components

Urban mining provides us with secondary materials. It is vital to create efficient workflows to determine whether the obtained secondary materials can be reused and if not, how to improve their reuse potentials in the post-urban mining phase. The suggested workflow demonstrates automation of the on-site practices which prepares the deconstructed materials for reuse and digitalise the reusable M/C This workflow is still under development and it aims to create a closed-loop reusable material system with three steps: a) from building deconstruction to M/C bank, b) M/C bank assessment and certification for reuse or recycling and c) from the M/C bank to new construction projects. Figure 3 demonstrates the overall workflow.

A plethora of different M/C exist in the construction sector. However, the present study focuses on structural pieces, either load bearing or not. Most of these structural pieces are referred to as components. To explain by example, concrete reuse is not possible as a material, only a concrete component as beam or slab element can be reused. Hence, concrete material reuse is not impossible but not possible in a closed cycle. As a material, it can be reused as part of aggregates for production of new concrete; Nevertheless, reuse of insolation material, such as mineral wool, is possible and this is a material. As these materials need other reuse certification and analysis methods, they are not considered here.

Before the building deconstruction, a deconstruction audit must take place and the processes, required equipment and manpower or robotics must be planned. Exploring the pre-deconstruction audit and programming is beyond the scope of this paper. Nevertheless, after building deconstruction, on-site experts must visually inspect and control M/C to screen and separate obviously defective parts. This initial screening can be assisted by the information transmitted to the engineers through RFID or IoT sensors attached to the parts.

When the M/C arrive at the physical M/C bank location, they will go through a scanning process to capture their outer surface and 3D dimensions. This scanning process may benefit from the complementary nature of hybrid capturing data. It should be pipe-lined, standardised and automated in order to save costs and time. The resulting scans would be used for structural assessments, deformation and damage tracking and material recertifications. Scanning the surface may result in damage, crack and corrosion detection. However, if the element is not loaded, cracks will not be opened and damage may not be detected. Therefore, a control and crack detection before deconstruction or during the operation phase is crucial. All the scans will be stored in the digital M/C bank and remain there until the assessment vote is revealed. As explained before, the deployed structural, chemical and sustainable assessment methods and their results are beyond the scope of this research. For the time being, we consider that the combination of the assessment result will be communicated as final vote that could be: Pass, Aesthetic Fix, Deep Fix and Not Pass (i.e., Fail).

The “Pass” vote confirms that the material or component can be reused as it is. However, before exiting the M/C bank, or prior to being placed into storage, these M/C should go through a second capturing session. The first session detects visible surface issues. However, depending on the evaluation strategy, different destructive or non-destructive structural tests, X-Ray inspections, might be used to assess invisible cracks or defects inside the components. This is why a second capturing session is needed. This repetition ensures that the material took no damage during the M/C bank’s assessments. Despite the additional imposed time and costs, this session prevents future users from suing the M/C bank for obvious surface details that developed after M/C bank assessment or during transportation.

Both pre and post M/C bank assessment capturing results must be presented to designers to aid them with proper design. Meanwhile, the M/C bank must use the second set of scans to create a digital BIM object catalogue from the reusable M/C. These objects must be presented to designers to assist them with design with reusable materials.

If the final vote is “Aesthetic Fix”, components are structurally robust and environmentally sound to be reused. In this case, visible surface areas, punched areas, surface holes, cracks and discolourations require light aesthetics treatments through additive manufacturing or 3D printing. Aesthetic fixes might also target the edges of a component, e.g., a concrete column that has lost the sharpness of the edges during the first lifecycle. In this case, a comparison between the first set of capturing outcomes and the initial design of the deconstructed elements provides better inputs for choosing a suitable additive manufacturing technique to lightly fix the elements. These treatments make M/C visually suitable for a second service life and give new users a psychological assurance that these parts are as good as new.

If the final vote is “Deep Fix,” then M/C will go through recovery and reclamation procedures to achieve the desired performance levels set by the M/C bank. In this case, classification of damage is required to support the decision for refurbishment, e.g., new corrosion protection, epoxy or injection.

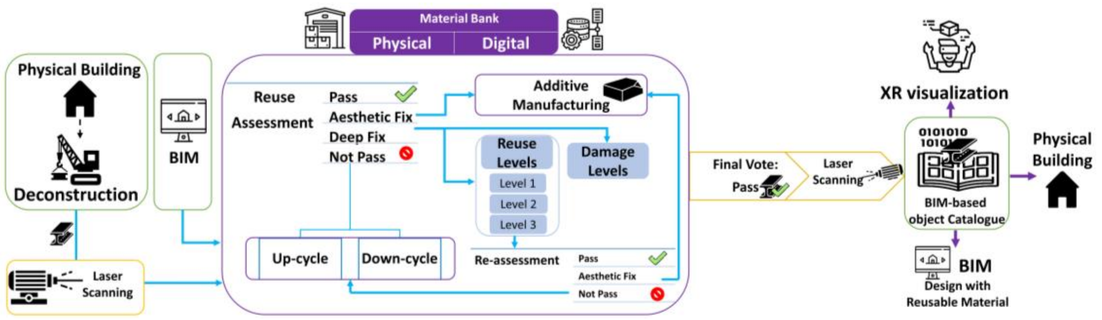

Figure 3 An overview of the proposed framework. Integration of BIM, capturing, additive manufacturing and material bank for automating, digitising and digitalising reusable materials and components.

After recovery, if they pass the reuse assessments, they will be assigned reuse level labels, e.g., level 1, level 2 and 3, to demonstrate how they compare with new elements in terms of structural performance and based on the legally binding building codes. This labelling could be based on the degree of corrosion or the results of chemical analysis if the structural robustness in confirmed. In this way, some components could be reused in the same position as before, while others can be repurposed and used in different or innovative ways. What is important is that these structures are still good enough to remain in the value chain and away from landfills. If needed, "Deep Fixed" elements go through an aesthetic fix before the final pass. Afterwards, they will be sent for the second scanning in order to be prepared for BIM object catalogues. Damaged RFID sensors must be replaced prior to the second capturing session. Subsequently, RFID information must be updated in the M/C bank and BIModels.

Finally, the group of materials that fails to pass the M/C bank assessment tests will be sent for recycling. A new procedure will be initiated, in which materials can be up- or down-cycled. No cycle is perfect. Having elements that are not suitable for reuse is inevitable. However, recycled parts can be reintroduced to the material cycle, for instance as concrete aggregates for concrete 3D printing (Bai et al 2021).

4 Discussion

Different studies expressed the necessity for fluidity and flexibility of design when it comes to the inclusion of reusable M/C in new designs after the M/C bank recertification. However, Akbarieh et al. (2020) suggested that two design approaches can be taken into account for buildings with reusable parts, namely, "Design First, Bank Second" and "Bank First, Design Second". In the former, designers and engineers freely plan and organise the project first and then look into the M/C bank to find suitable components for their design. In the latter, however, designers look into the M/C bank first, choose certain reusable products and develop their design based on them. This approach requires a reservation system to be added to the digital M/C bank platform for designers to secure a reusable element for their design. Otherwise, if the elements are given to another project, the designers must re-design the project. This imposes additional project costs and time delays that must be avoided.

Nevertheless, both of these approaches demand BIM-based objects of the reusable elements, which designers need to use in the BIModel before final project approval. While structural performance determines whether a material can be reused, physical attributes would be important for certain designers. Thus, future M/C banks must provide plugins or object catalogues to meet the design needs of engineers. After the elements are scanned and turned into BIM-based objects, designers have more freedom to use them in their design to make new design decisions to make the reusable products suitable for solid placement in the new lifecycle. Material passports, reuse vote, performance assessment methods and results, and other necessary lifecycle information must be presented to designers as attributes of the BIM-based reusable objects. Firstly, material passports assist with verification of existing information, such as concrete grade, steel grade, reinforcement degree and position. The M/C bank must verify this information as well as provide proof of the information. Afterwards, it should update or re-emit the material passports for the reusable products. To assure experts about the authenticity of the lifecycle information, the integration of M/C bank data and blockchain technology could be pursued. Secondly, since building deconstruction and reuse certification happen after one building lifecycle, e.g., 50 years, M/C bank must consider the design codes for the new situation in comparison with the outdated codes in order to properly assess the elements. Not only M/C bank, but future designers might need to access to both design codes for sound engineering judgements as well as building permission issuance.

BIM-based reusable objects can be visualised in XR environments. Not only the project team and designers, but clients in the first place, must agree with having reusable elements in their projects. If clients' doubts regarding the structural and environmental safety of load-bearing reusable elements are not addressed, they might refrain from using them, which in turn, will restrain the project team to use them (Rakhshan et al 2020). Therefore, XR technologies can be used in this phase to reassure designers and clients of the suitability of reusable materials for their built assets. For exposed reusable parts, clients might need to see them in XR before approving the design. Therefore, together with BIM, XR technologies play a huge role in spreading the "design with reusable materials" approach. Additionally, XR can help with the creative repurposing of elements that could be suggested by the project team or even clients through visual inspection of the reusable element within the virtual project. In the same vein, having reusable parts in 3D objects might help with cross-industry exchanges.

Employment of humanoids especially in the EoL phase of future buildings can be anticipated in the coming decades. If a designer anticipates that future deconstruction must be performed by a humanoid, this decision must be documented in the deconstruction guidelines or material passports. Otherwise, the element might not be deconstructed albeit being designed for deconstruction. Similarly, humanoids speed up the repetitive automation for the capturing of reusable parts, storage and relocation. The necessary codes for operating a deconstruction humanoid should be kept in the deconstruction guidelines and inserted in the BIM-based object attributes or RFIDs.

Additive manufacturing offer more than repair solutions. If clients or designers demand a certain reusable element for their design, it is possible to modify, customise or optimise the topography of the element for them. This possibility expands the horizons of design with reusable materials and encourage designers to adopt this design approach.

5 Conclusion

M/C banks are among the trendiest topics in the circular economy within the construction sector. However, few studies have conceptualised a BIM-based working model for presenting reusable materials to the market after M/C banks enable circulation of them from the EoL phase to the new design phase. Taking advantage of this gap, this paper describes a workflow for feasible material reuse after the reuse recertification by the bank. The above concept deals with the post-urban mining phase, where secondary materials have been already reclaimed from the building stock.

To create a truly circular solution and minimise the CDW, a combination of digital technologies is needed to provide digital, real-time and accurate information to assist project stakeholders in design decisions. In this paper, we explained how these technologies serve to automate the processes by which reuse information are later digitised and digitalised. Without the obtained technology-based automation, material reuse cannot scale up on a global level.

The proposed framework, which is still under development, integrates BIM, reality capturing technologies, additive manufacturing techniques, IoT and RFID sensors in order to provide an automated reuse workflow. In fact, BIM is the conjunction where all these technologies meet. It is through BIM that the outcome of one technology is modified, prepared and utilised as an input for another one in order to close the material loop in the construction sector. The suggested workflow delineates which technologies play what roles at what times to provide the necessary digital information regarding the M/C deconstruction, recertification and reuse in a new building.

In summary, every deconstructed element goes through a process to record their physical properties via modern 3D capturing technologies, before and after the material bank assessment. Based on the scan results, 3D, BIM-based reusable objects are reconstructed, which holds the lifecycle information, reuse assessment results. Designers can visualise the reusable materials in BIM-based environments, directly in the material catalogues or through XR technologies. Having the reusable material objects in BIM-based environments eases the design and decision making, boost the reusable material market and facilitates the transition from linear economy-based designs to circular designs in the AECOO sector.

Acknowledgements

The authors would like to acknowledge the funding received from the Investissement pour la Croissance et l'emploi—European Regional Development Fund (2014–2020), with the grant agreement 2017-02-015-15 for the Eco-Construction for Sustainable Development (ECON4SD).

References

Akbarieh, A., Jayasinghe, L.B., Waldmann, D. & Teferle, F.N. (2020). BIM-Based End-of-Lifecycle Decision Making and Digital Deconstruction: Literature Review. *Sustainability.* 12 (7). pp. 2670.

Akbarnezhad, A., Ong, K.C.G. & Chandra, L.R. (2014). Economic and environmental assessment of deconstruction strategies using building information modeling. *Automation in Construction.* 37, pp. 131-144.

Alizadehsalehi, S., Hadavi, A. & Huang, J.C. (2020). From BIM to extended reality in AEC industry. *Automation in Construction*. 116. pp. 103254.

Bai, G., Wang, L., Ma, G., Sanjayan, J. & Bai, M. (2021). 3D printing eco-friendly concrete containing under-utilised and waste solids as aggregates. *Cement and Concrete Composites*. 120. pp. 104037.

Borgia, E. (2014). The Internet of Things vision: Key features, applications and open issues. *Computer Communications*. 54. pp. 1-31.

Cai, G. & Waldmann, D. (2019). A material and component bank to facilitate material recycling and component reuse for a sustainable construction: concept and preliminary study. *Clean Technologies and Environmental Policy.* 21. pp. 2015-2032.

Copeland, S. & Bilec, M. (2020). Buildings as material banks using RFID and building information modeling in a circular economy. Procedia CIRP, 27th CIRP Life Cycle Engineering Conference (LCE2020) Advancing Life Cycle Engineering : from technological eco-efficiency to technology that supports a world that meets the development goals and the absolute sustainability 90. pp. 143-147.

Delgado Camacho, D., Clayton, P., O'Brien, W.J., Seepersad, C., Juenger, M., Ferron, R. & Salamone, S. (2018). Applications of additive manufacturing in the construction industry – A forward-looking review. *Automation in Construction*. 89. pp. 110-119.

European Commission. (2015). Communication From The Commission To The European Parliament, The Council, The European Economic And Social Committee And The Committee Of The Regions- Closing the loop - An EU action plan for the Circular Economy (No. COM (2015) 614 final). European Commission, Brussels.

Gepts, B., Meex, E., Nuyts, E., Knapen, E. & Verbeeck, G. (2019). Existing databases as means to explore the potential of the building stock as material bank. *IOP Conference Series: Earth and Environmental Science.* 225. pp. 012002.

Hamledari, H. & Fischer, M. (2021). Construction Payment Automation Using Blockchain-Enabled Smart Contracts and Reality Capture Technologies. ArXiv201015232 Cs. https://arxiv.org/abs/2010.15232

Han, K.K. & Golparvar-Fard, M. (2017). Potential of big visual data and building information modeling for construction performance analytics: An exploratory study. *Automation in Construction*. 73. pp. 184-198.

Honic, M., Kovacic, I., Sibenik, G. & Rechberger, H. (2019). Data- and stakeholder management framework for the implementation of BIM-based Material Passports. *Journal of Building Engineering*. 23. pp. 341-350.

Jayasinghe, L.B. & Waldmann, D. (2020). Development of a BIM-Based Web Tool as a Material and Component Bank for a Sustainable Construction Industry. *Sustainability.* 12 (7). pp. 1766.

Manelius, A.-M., Nielsen, S. & Kauschen, J.S. (2019). City as Material Bank – Constructing with Reuse in Musicon, Roskilde. *IOP Conference Series: Earth and Environmental Science.* 225. pp. 012020.

Melenbrink, N., Werfel, J. & Menges, A. (2020). On-site autonomous construction robots: Towards unsupervised building. *Automation in Construction*. 119. pp. 103312.

Motamedi, A., Soltani, M.M., Setayeshgar, S. & Hammad, A. (2016). Extending IFC to incorporate information of RFID tags attached to building elements. *Advanced Engineering Informatics*. 30. pp. 39–53.

Queheille, E., Taillandier, F. & Saiyouri, N. (2019). Optimization of strategy planning for building deconstruction. *Automation in Construction*. 98. pp. 236-247.

Rahito, Wahab, D.A. & Azman, A.H. (2019). Additive Manufacturing for Repair and Restoration in Remanufacturing: An Overview from Object Design and Systems Perspectives. *Processes*. 7. pp. 802.

Rakhshan, K., Morel, J.-C., Alaka, H. & Charef, R. (2020). Components reuse in the building sector – A systematic review. *Waste Management & Research*. 38. pp. 347-370.

Ribeiro, D., Santos, R., Shibasaki, A., Montenegro, P., Carvalho, H. & Calçada, R. (2020). Remote inspection of RC structures using unmanned aerial vehicles and heuristic image processing. *Engineering Failure Analysis*. 117. pp. 104813.

Rose, C.M. & Stegemann, J.A. (2018). Characterising existing buildings as material banks (E-BAMB) to enable component reuse. *Proceedings of the Institution of Civil Engineers - Engineering Sustainability*. 172. pp. 129-140.

Sacks, R., Eastman, C., Lee, G. & Teicholz, P. (2018). BIM handbook : a guide to building information modeling for owners, managers, designers, engineers and contractors. 3rd edn. New Jersey: Hoboken: Wiley.

Türk, D. (2017). *Exploration and validation of integrated lightweight structures with additive manufacturing and fiber-reinforced polymers*. PhD thesis. ETH Zurich.

UK Green Building Council. (2021). Climate change. UKGBC-UK Green Building Council. URL https://www.ukgbc.org/climate-change/ (accessed 4.20.21).

United Nations. (2019). World Population Prospects 2019: Highlights (No. ST/ESA/SER.A/423). United Nations, Department of Economic and Social Affairs, Population Division, New York.

WRAP. (2009). Designing Out Waste: A Design Team Guide for Buildings (No. A42: N462).

Yang, L., Cheng, J.C.P. & Wang, Q. (2020). Semi-automated generation of parametric BIM for steel structures based on terrestrial laser scanning data. *Automation in Construction*. 112. pp. 103037.