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Buildings as material banks using RFID and building information modeling in a circular economy

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ABSTRACT

Currently, the Architecture, Engineering, and Construction community operates in an environmentally problematic linear economy by consuming non-renewable virgin materials, producing landfill waste, and increasing the overall environmental impact. A solution to mitigate these problems is the implementation of a circular economy, an economic model that decouples economic growth and depletion of resources by minimizing waste. Technology opportunities explored to foster these relationships include building as material banks (BAMB), building information modeling (BIM) software, radio-frequency identification (RFID) tags, and blockchain. This paper presents a conceptual diagram and framework for implementing a circular economy utilizing the promising technologies and concept.

1. Introduction

Currently, the Architecture, Engineering, and Construction (AEC) industry operates in a linear economy which can be depicted by the "take, make, waste" model (Babbitt et al., 2018). In this model, virgin materials are extracted from the earth, manufactured into a product, and disposed as waste via landfill. Through this system, the AEC accounts for up to 40% of carbon dioxide emissions worldwide, construction and demolition waste accounts for 40% of solid waste in the US, and the AEC industry is the largest consumer of raw materials (Pomponi and Moncaster, 2017; Ghisellini et al., 2018; S.C.C.R. and Philipp Gerbert, 2016). Due to the industry's and worldwide consumption of materials, it has been speculated that by 2050, it will take two Earths to endure the current rate of resource use (Piscicelli and Ludden, 2016; Commission, 2011). One solution to mitigate this problem is the implementation of a circular economy (CE). The circular economy is an economic model that aims to decouple economic growth and depletion of resources by minimizing waste and increasing the utilization period of products (Kozminska, 2019; Bocken et al., 2016). Applying this economic model to the AEC industry may result in a decrease of virgin materials, landfill waste, and overall environmental impacts.

Within the circular economy, one strategy is the use of buildings as material banks (BAMB) projects at the local, regional, and national scales (Gepts et al., 2019). BAMB projects focus on establishing and maintaining a building stock of recoverable and reusable building components (Rose and Stegemann, 2019). With an emphasis on BAMB projects in the circular economy, this paper produces a framework and proposes a geospatial solution to apply current technology to BAMB projects to facilitate CE strategies.

2. Objectives

The aim of this paper is to explore circular economy strategies and principles for the implementation of BAMB projects as well as to explore existing methods connecting demolition and construction projects. We investigate technology that can foster these relationships as well as proposing a framework that integrates past and present technologies. Technology opportunities that are explored include building information modeling (BIM) software, radio-frequency identification (RFID) data tags, and blockchain. Although other programs and technologies are available, optimization in these specific technologies may catalyze the transition into a circular economy for the AEC industry. A conceptual diagram is proposed connecting the fragmented AEC industry.

3. Current Research

3.1. Circular Economy

Several definitions of circular economy have emerged, and the overall idea is to minimize the use of virgin resource and the

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amount of landfill waste through reusing resources. Some of these challenges to the implementation to the circular economy include the transformation of business strategies and the financial risk of converting to a different business model, and the idea of materials seen to be “free” commodities because their economic value is not integrated in the overall market (Piscicelli and Ludden, 2016; Commission, 2011).

Different organizations that have been popularizing the transition into a circular economy include the Ellen MacArthur Foundation and the European Union’s Project BAMB program (Bocken et al., 2016; BAMB. BAMB 2020; T.E.M. Foundation 2017). Project BAMB is a collaboration between 15 partners from 7 countries that strive to create system-level shifts through circular economy while aiming to increase the value of used building components and materials (BAMB. BAMB 2020). This partnership has created material passports, business models, and policy agendas to aid in the implementation of the circular economy. Material passports are datasets aimed to define and describe material characteristics focusing on value for recovery and reuse (BAMB. BAMB 2020). With the evaluation of material flows, these passports can be useful to determine the market value of used building materials of different qualities (BAMB. BAMB 2020).

An important aspect is the material flows between supply and demand projects as the total product ecosystem (Kasulaitis et al., 2019). In the product ecosystem, demands for products can be impacted by increasing consumption and technological innovation. As an example, the average U.S. household increased the average amount and consumption rate of products from 3 products to 16, and from 0.5 new products per year to 3.5, respectively, in a 20-year span. On the other hand, the average product mass decreased from 16kg to less than 4kg (Kasulaitis et al., 2019). Increasing consumption and technological innovation affect the circular economy due to the dilution and dispersion of product materials. Dilution refers to the phenomenon where the amount of a material found in an individual product is decreasing while the total amount of material in the same product’s waste stream is increasing. On the other hand, dispersion refers to the concept where a valuable material is found among many types of products. With dispersion and dilution inhibiting the recovery of used materials, the circular economy cannot progress.

3.2. Buildings as Material Banks

There are two main types of demolitions: conventional or selective (Ghisellini et al., 2018; Coelho and de Brito, 2011). Conventional demolition (CD) is the stereotypical demolition using mechanical equipment to demolish a site. Selective demolition (SD) is the practice of selectively disassembling building components, also known as deconstruction. Comparing SD with CD, SD reduces more landfill waste and retains building materials despite the higher operational and labor costs.

By retaining and designing used building materials into new buildings, new projects like the Hal7, a former industrial building, can be constructed and transformed into a mixed activities building for the community (Manelius et al., 2019). Within this project, three crucial details emerged: architectural experience, availability of construction materials, and reluctance for profit. To the first point, architectural experience, because the architects were designing a building from shipping containers and had another similar experience, the architects were familiar with reusing building materials. In a similar project found in the same study, they found that a city administrator was able to map, stockpile, and store materials for reuse (Manelius et al., 2019). Through the mentality of putting the environment ahead of economic costs, the role of the city or community was illuminated as a key driver to the implementation of BAMB projects.

Similar to the city administrator’s responsibility, Rose and Stegemann investigated Superuse Studios due to their reused material marketplaces (RMMs) as a connection between supply and demand projects (Rose and Stegemann, 2019). Superuse Studios is a Dutch architectural organization that hosts a website that maps and documents reusable secondary material waste streams (S. Studios and WoodGuide.org 2020). This website allows for a user to search for waste streams and access a material catalogue within a radius of a site. RMMs are a virtual platform for the construction industry where supply projects can sell their used materials to demand projects (Rose and Stegemann, 2019). Currently, designers require information on a used material early in the design stage, thus RMMs are not an established practice.

Other challenges and barriers for the implementation of BAMB projects stem from the economics of reusing building components (Gorgolewski, 2008). Few deconstructions occur due to the low cost of virgin materials and high cost of labor to conduct the physical deconstruction (Gorgolewski, 2008). With a small supply and demand for used materials, these materials will incur an additional storage cost as well as become more expensive than virgin materials. Possible solutions to this problem are optimizing costs of deconstruction projects as well as strengthening and increasing a market for reused building material to increase material flow.

3.3. Current Technology

In this section, the current technology relating to the construction industry that can optimize deconstruction and transactions between supply and demand projects like Building Information Modeling and other technologies are presented.

3.3.1. Building Information Models and RFID

Building information modeling (BIM) software is a tool that is used to load, edit, and manage virtual building data over its entire life cycle like Autodesk Revit (Volk et al., 2014). Benefits of BIM include cost estimations, a medium for information transfer, and a consistent visualization of a project’s design (Volk et al., 2014; Sattineni and Azhar, 2010; Meadati et al., 2010; Motamedi and Hammad, 2009). New buildings often use BIM technology; on the other hand, most the existing buildings did not use BIM technology during the design phase, but using data capture, building surveys, and pre-existing building information, the operators of the building can develop a BIM model for its benefits (Volk et al., 2014).

Some advances in BIM software include the use of range-based and tagging techniques like scan-to-BIM methods and RFID data tags, respectively (Rose and Stegemann, 2019; Volk et al., 2014; Sattineni and Azhar, 2010; Meadati et al., 2010; Motamedi and Hammad, 2009). Scan-to-BIM is a promising laser scanning and object recognition process that transforms the scan of a building into an accurate BIM model (Rose and Stegemann, 2019; Volk et al., 2014). Primary barriers of scan-to-BIM are cost and operability (Volk et al., 2014). On the other hand, RFID data tags are memory storage devices that use radio frequencies to identify and track items (Sattineni and Azhar, 2010; Meadati et al., 2010; Motamedi and Hammad, 2009). In the past, RFID tags have been used in construction management to monitor construction projects, materials, and workers as a visual aid to improve productivity. While other technologies can be used, RFID was chosen as an option to help demonstrate the framework.

Another approach is the BIM-based, Whole-life Performance Estimator (BWPE), developed by Akanbi et al. (2018). BWPE has the ability to measure the salvage performance of a building directly from the design stage in a BIM model. This model from the study was developed to determine the recyclability and reusability of recovered building materials for specifically steel, timber, and concrete structures. In addition, this model can aid in architectural de-

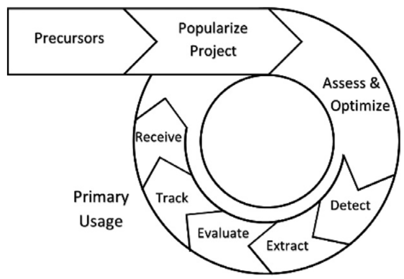

Fig. 1. Process flow diagram for building as material banks and circular economy.

sign while concentrating on recovering the most reusable and recyclable materials. Finally, with the use of pre-redevelopment audits, the model will illuminate deconstruction barriers and inefficiencies. The model has the potential to predict what and how many materials should be recovered from a deconstruction compared to the pre-redevelopment audit and physical deconstruction results. While BIM software has made significant progress, barriers like operability and cost have prevented the overall implementation of BIM software industry wide.

3.3.2. Other technology: Blockchain

Blockchain, the technology behind the digital crypto-currency Bitcoin, is a distributed and decentralized ledger that efficiently and irrefutably records transactions through secure and encrypted logs (Heiskanen, 2017; Turk and Klinc, 2017; Crosby et al., 2016). The appealing aspect of blockchain as a transaction ledger is that if a user changes a single block within the chain, the entire blockchain will be regenerated for only that particular user (Heiskanen, 2017). As a result, this user would be "highlighted" to convey that they changed the original blockchain in front of the users within this environment. Currently, blockchain is used to accurately record changes to a BIM model where a group of users have access (Turk and Klinc, 2017). Within this system, the group of users, will be able to know who made what change at a particular time. In BAMB projects, blockchain can be used to manage and create reliable transaction records between the supply and demand projects. In addition, the RFID data tag's information can be stored within a blockchain to track the material's location throughout its life cycle.

4. Framework

By integrating most of the technologies and accounting for various barriers surrounding BAMB projects and the circular economy, a process flow diagram has been developed using four phases (Fig. 1). In the proposed process flow diagram, the design was based on the transition from a linear to a circular economy. Although this is a theoretical framework, a case study will be presented in the future as well as a measurement of stakeholder engagement to verify the feasibility of this framework.

4.1. Phase 1: Precursors

From the current research on BAMB projects, there have been wide discussion about various challenges and barriers towards the adoption of BAMB projects. As examples, the information on existing buildings and recycled material availability is missing, incomplete, or scattered (Rose and Stegemann, 2019; McDonald, 2005). Thus, using these buildings as material banks requires an in-depth pre-redevelopment audit of the building to find recoverable materials (Rose and Stegemann, 2019). On the other hand, recycled material information, specifications, and availability is scattered without a unified database to search for a material stock. By addressing these barriers in the framework, blockchain databases storing materials, construction projects, and deconstruction projects information are necessary to accurately record data.

In this framework, material databases will be used for two purposes: to serve as a baseline of data and store RFID data. With the baseline of data, standards may be developed from trends of reused and recycled building materials to aid in the recertification and testing process. A current example of the material database would be Project BAMB's material passports. Next in the framework is a list of construction and deconstruction projects in a region to become a geospatial map linked to the BIM of a site and the blockchains relating to the tracked materials. As the interface for the geospatial map, the supply and demand of materials would be mapped out as construction projects, deconstruction projects, or as a waste steam. Between the geospatial map, BIM software, and blockchain users would be able to view the quantity and location of each building material at a supply or demand site within the BIM model. In addition to the two databases, there would be another layer within the geospatial map to plot and list out non-profits so users could test, recertify, and/or upcycle their used materials. By establishing these databases, collecting existing and new building will be unified.

Another aspect of this phase is advocacy around local, regional, and national legislation to create grants and establish an organization dedicated to BAMB projects. As an example, in the LEED v4 for BD+C (Building Design and Construction), BAMB project principles account for around 13 points out of the possible 110 points (USGBC Headquarters Scorecard 2019 July 10). On the other hand, storage, warehouses, incentives, and disincentives can be managed and levied by the regional and local legislation (Manelius et al., 2019; Leigh and Patterson, 2006). Incentives and disincentives include increased landfill taxes, the development of tax breaks for reused materials, and an increase in virgin material prices.

4.2. Phase 2: Popularize Project

In this phase, some of the beginning principles of BAMB projects like deconstructions and pre-redevelopment audits are integrated into the AEC industry. By increasing the number of deconstructions, the availability and variety of recovered building materials will increase while the initial price of the reused building materials will decrease which will induce a stronger market for secondary materials (Rose and Stegemann, 2019; Gorgolewski, 2008). In addition, by increasing both deconstructions and audits, it allows for a smooth transition within the AEC industry utilizing used building materials as well as help establish standards of practice. Before physically increasing the number of deconstructions and audits through the incentives and disincentives, the construction industry should be well informed and trained. It has been observed in one of the case studies by Gorgolewski et al. that using reused building components in a project results with an increase in price of construction bids (Gorgolewski, 2008). It has been observed that designers and contractors that have previously and successfully reused building components receive more attention than conventional counterparts due to their experience like the Hal7 project mentioned earlier (Manelius et al., 2019). Once contractors gain experience, the construction industry will begin to decrease their bids for BAMB projects.

4.3. Phase 3: Assess & Optimize

This phase is continuous throughout the entire cycle to ensure that BAMB projects are continually improving and becoming a more economically viable solution. Possible improvements to the system can include a feature similar to Rose and Stegemann that includes a repurposing feature that can relate and link alternative materials for different uses (Rose and Stegemann, 2019). Recalling the product ecosystem, material flows can be monitored to see if materials are getting reused as well as the trends of using primary or secondary building materials over time (Rose and Stegemann, 2019). With this information, new project benchmarks and goals may be established within industry and construction management (Rose and Stegemann, 2019). Finally, this phase verifies that everything is in place before the "Primary Usage" phase is initiated.

4.4. Phase 4: Primary Usage

In this phase, the bulk of the geospatial mapping system is carried out. Specifically, deconstruction and construction projects communicate as the supply and demand to easily locate and reuse building materials with the help of nonprofits or third-party organizations to recertify, upcycle, test, and track materials. While each stage of the system will be discussed further, the framework will be similar to the framework proposed by Rose and Stegemann, but this paper will add on RFID technology, the BWPE model, and nonprofit organizations while focusing on blockchain databases and geospatial mapping software to produce a more efficient and reliable user-interface between the supply and demand projects. The aforementioned approach focused on large-scale projects, which did not include local and regional governments, a driver in implementing BAMB projects.

4.4.1. Stage 1: Detect

As the first stage, pre-redevelopments audits must be finished at least two months ahead of the scheduled deconstruction. Two months is the chosen arbitrary time for demand projects to view the material on the BIM software and for nonprofits to receive and sample materials found throughout the building. As the second part to this stage, non-profit organizations will screen samples of materials found throughout the building that can be recertified or tested for their reuse. Materials that pass the screening procedures will be permitted to be sold while those that fail are not permitted. In this paper, the logistics and specifics for upcycling, recertifying, and testing techniques were not included thus can be used as a direction for future research.

4.4.2. Stage 2: Extract

In stage two, the physical deconstruction of a building starts and the passing screened materials go for sale through the blockchain and geospatial mapping interface. Before a user could buy said materials, a BIM model and an inventory must be submitted to the regional legislation to be added to the material bank database and map a demand source. With this submission, a feature within the program would be coded to connect sources of supply and demand with a minimal transportation distance because most of the global warming potential originates from the transportation of destruction waste (Ghisellini et al., 2018). After the submission of the BIM model and inventory, any user may buy up to half of the materials from the pre-redevelopment audit and place bids on the leftover material. The used building material is broken up into two categories as a clause in case material will be bought but not extracted from a building. So, through deconstruction practices, contractors must be able to extract half of the bought used materials and have leeway in case they are unable to extract out absolutely all of the materials of the building. With the other half of used materials that had bids, it will not be as pressing to extract out those materials but will continue to help the deconstruction project. Material not sold to bids could then be donated to nonprofits or be sold to third party organizations. By donating to the nonprofits, the deconstruction companies can receive a tax break to increase the profit of the deconstruction. Although third party organizations do not allow for the companies to receive a tax break, companies could instead sell the material which will continue to increase profit of a deconstruction. To improve the market of the third-party organizations, the organizations could use upcycling techniques on the building materials.

With the use of BIM software, the BWPE model can compare the accuracy of the model with pre-redevelopment audits and physical deconstruction. By adjusting the model using the data, designers of new buildings will predict the potential recoverable materials as well as perform cost analyses to better estimate the entire cost of the building with its payback period.

4.4.3. Stage 3: Evaluate

During this time, as the deconstruction project starts to finish, materials are transported to the nearest nonprofit to test and recertify the entire material for its mechanical and structural properties to ensure that the material passes current virgin material and future used material code standards (Gorgolewski, 2008). If the material fails for recertification, the material could be upcycled or recycled depending on the choice of the demand project managers. As an example, a project could recycle a slab of concrete by crushing the used concrete into an aggregate and using all the aggregate to form new concrete. On the other hand with upcycling, because upcycling is a topic that is underexplored, creating a market will catalyze research in the concept (Bocken et al., 2016). If a material passes the recertification and testing procedures, then the material has the additional option to be upcycled or to be stored at the non-profit, on-site of the next project, or off-site at another location. This storage could be worked with nonprofits as well as the local and regional governments to minimize the monetary costs of storing materials. As an example, in the Hal7 building mentioned earlier, the city project manager was able to provide and suggest empty facilities to store the used building materials (Manelius et al., 2019).

While this entire process occurs, designers and architects must be flexible in their designs to enable changes of design to occur in the building (Gorgolewski, 2008). The earlier the designers receive the information about the material properties, the easier it is to have the materials designed into the building as well as minimizing costs of changing a design of a building (Gorgolewski, 2008).

4.4.4. Stage 4: Track

In the fourth stage, all materials should be finished with the upcycling process or stored at some location. At this point, materials re-enter the material databases at the nonprofits to attach passive RFID tags. Information on the RFID's tag will include structural property data, history data, and location data (Motamedi and Hammad, 2009). This information will be housed in a blockchain to keep the data of the material secure and prevent any tampering. These tags are related to the "Detect" stage where used materials with RFID tags will be included into the BIM model at the same location the tag is in the physical building. With these tags, if another deconstruction occurs within the same structure, material data is easily accessible. A barrier of this system is tracking each data tag because a passive RFID tag has a small range. Therefore, a project manager or construction worker would have to manually walk around the site to scan each tag and verify that the tag is in the correct spot on the physical building and model.

4.4.5. Stage 5: Receive

As the last stage, the demand project receives the used building materials from the nonprofit and pays for the cost of upcycling, recertification, and/or storage. While there have been cost analyses of different demolition techniques, there is not a direct cost analysis of the cost of the used building components (Gorgolewski, 2008; Leigh and Patterson, 2006). In both analyses, deconstruction is projected to have a higher cost compared to conventional demolition when not accounting for the sales and savings from landfilling. When accounting for sales and savings, deconstruction projects cost up to 37% less than conventional demolition (Gorgolewski, 2008). From this point, the next possible deconstruction analysis could include a cost analysis that compares the projected cost of recertified, tested, and tracked materials to various used materials.

5. Conclusion

This study proposed a framework to initiate and catalyze the transition into a circular economy using BAMB projects from a regional and national perspective. With current research and studies, there is an informational and communicational gap between supply and demand projects. As the example, research and building data are decentralized and scattered throughout all types of mediums. By creating the geospatial mapping and BIM system, these gaps will close allowing for BAMB implementation.

Although the framework and the presented ideas have been theorized, a case study will be presented as future work to accompany the process flow model phases and stages to aid as a visualization for this process. This case study is projected to be on the Frick Environmental Center located in Pittsburgh, Pennsylvania. In addition, the physical software and system will be developed to provide an enhanced space to display the conceptual framework's layout. With the future case study and software system, the relationship between the material, construction, deconstruction, and nonprofit databases with the geospatial map will be demonstrated.

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