Urban mining in buildings for a circular economy

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Urban Mining in Buildings for a Circular Economy: Planning, Process and Feasibility Prospects

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Abstract

The construction industry remains under immense pressure to reduce its material and climate related impacts. Increasing material demand and reduced building lifetimes have therefore motivated efforts for urban mining in buildings. Even though urban mining has been projected as a crucial measure for improving resource efficiency, its adoption as a practice in the construction industry remains at a very symbolic stage. Upscaling secondary resource recovery and reuse in the construction sector requires further efforts to understand urban mining feasibility from the perspective of project timelines, salvage time, skills and costs. Hence, this study develops an empirical research approach to measure urban mining feasibility and applies it to demolition-ready urban residential buildings stock in Singapore with semi-skilled construction workers. It develops indicators for urban mining feasibility based on planning stages, process change, behavioural practices and reuse-driven economic considerations. Based on urban mining of over 350 building components from 34 categories, results show an average of 1 to 12 min recovery time with an estimated urban mining cost from S$0.8 to S$9 per building component. Further, regulatory requirements for demolition permits can provide sufficient time for urban mining without affecting project timelines. Even though the mining skills of workers seem important, results highlights significant improvement in mining skills based on repeated salvage of specific building components. Results also provide robust evidence of reuse-driven urban mining feasibility in the case under study with significant prospects for embodied carbon savings. Overall, urban mining of buildings can contribute to net-zero targets and climate mitigation efforts with greater multi-stakeholder involvement and market push for reuse in the construction sector.

Keywords: Deconstruction, Secondary Resources, Reuse, Decarbonisation, Material Efficiency, Net Zero Targets

1. Introduction

Recent IPCC reports highlight the need for accelerated efforts to reduce material consumption to limit global warming to 1.5° above pre-industrial levels (IPCC, 2018). Based on the increasing emissions from the production of primary materials and associated natural resources depletion, the need for greater material efficiency and extended use has become rather imminent (Hertwich et al., 2019; Olivetti and Cullen, 2018). One of the key strategies has thus been towards recovering materials stockpiled in cities by treating cities as an urban mine (Arora et al., 2020; Koutamanis et al., 2018). Material consumption and associated embodied energy from the construction sector are a significant climate burden. Additionally, over a billion people lack adequate housing, in-part due to the costs associated with construction materials. Urban mining and reuse, in this context, are major climate mitigation strategies for the construction sector as it reduces the primary material demand and associated embodied emissions and environmental impacts.

Previous studies have highlighted that there is an increasing momentum towards urban mining across geographical boundaries and sectors (Arora et al., 2020; Koutamanis et al., 2018; Stephan and Athanassiadis, 2018; Zeng et al., 2018; Zhang et al., 2019). Sectors such as electronic waste have seen significant efforts in developing advanced methods for recovery of metals to a limit where it seems to compete with virgin mining (Zeng et al., 2018). Remanufacturing and reverse logistics efforts have long been practiced with a reuse perspective for material and environmental benefits in sectors such as automobiles, electrical and electronic products and equipment (Casper and Sundin, 2018; Gutowski et al., 2011; Hertwich et al., 2019; Kwak and Kim, 2016; Saavedra et al., 2013). However in buildings sector, urban mining has largely been focussed on recycling efforts for concrete and metals (Brunner, 2011; Cossu and Williams, 2015; Koutamanis et al., 2018; Stephan and Athanassiadis, 2018). Unfortunately, urban mining efforts for recovery of metal scrap and concrete undermine the potential for component reuse.

From an end-of-life perspective, urban mining in buildings can follow different approaches and processes to recover materials and components (Arora et al., 2020; Cossu and Williams, 2015; Koutamanis et al., 2018). Thomsen et al. (2011) proposed the emerging manifestation of buildings as future resources and thus ‘urban mines’ and argued for three predominant notions of building’s end-of-life: i) Deconstruction- *the careful planning and highly controlled deconstruction process producing a differentiated assortment of components and materials for reuse,* ii) Demolition- *an undifferentiated process of taking apart and compressing a building* *with potential for recycling and disposing the waste as landfill,* iii) Destruction- *destroying the buildings with no or minimal resource recovery (e.g. using explosives).* Tatiya et al. (2018) recently compiled a detailed differentiation between deconstruction and demolition to highlight the benefits that can be derived from building deconstruction. This is in line with greater push towards Design for Disassembly- an approach intended for modular construction with ease for components replacements/recovery. Urban mining of resources (e.g. metals), from buildings, can theoretically occur based on all three end-of-life processes, however, reuse of mined resources may best be achieved through a combination of methods including the deconstruction process (Couto and Couto, 2010; Rios et al., 2015; Thomsen et al., 2011).

Recently, several studies have argued for a component specific reuse focus within urban mining, instead of traditional 'construction and demolition waste (C&DW)' driven approach, due to both the environmental benefits and the structural arrangements of building materials within a building (Arora et al., 2020; Koutamanis et al., 2018). As an upcycling practice, reuse has often been associated with greater climate mitigation benefits, including higher embodied carbon savings and greenhouse gas emissions reduction (Allwood et al., 2012; Mayer et al., 2019; Nußholz et al., 2020; Williams and Shaw, 2017; Zhang et al., 2020). The reuse of building components requires careful salvage which must be carried out at site with skilled labour (Addis, 2006; Gorgolewski, 2008). However, traditional demolition practices rely on heavily a mechanised process and prioritizes rapid site clearance. In the developing world, by contrast, informal urban mining practices are conducted by a semi-skilled workforce involved in the recycling industry for daily wages and livelihood (Arora et al., 2017; Grant and Oteng-Ababio, 2016). The unavailability of advanced technologies or a highly mechanised process increase the prospects of components recovery without breakage for reuse. However, labour costs in developed economies and strict time schedules for construction projects form a major challenge for deconstruction exercises (Akinade et al., 2017; Akinade et al., 2015; Couto and Couto, 2010; Dantata et al., 2005).

From an experimental point of view, Dantata et al. (2005) provided a detailed analysis of deconstruction-associated on-site costs and time durations at a project level in Massachusetts, USA, with the conclusion that deconstruction costs could be 17–25% higher than demolition costs. This was after accounting for the prospects of selling salvaged building components, avoided disposal costs and additional labour costs. Tatiya et al. (2018) proposed a deconstruction cost calculator and concluded that lower net deconstruction costs than the costs of demolition could be achieved primarily based on sale of recovered materials. Similar feasibility studies exist for e-waste such as hard disks (Talens Peiró et al., 2020), but there remains a lack of detailed studies focused on the building components level in which costs, skills and feasibility are assessed to support urban mining decision making.

With growing adoption of Building Information Modelling (BIM), a significant effort within the academic community remains focussed on Design for Disassembly benefits that may arise due to urban mining at the end-of-life of buildings. From a modelling perspective, there are several studies which have looked at prospective benefits of deconstruction through the Design for Disassembly approach (Akbarnezhad et al., 2014; Akinade et al., 2017; Akinade et al., 2015; Huuhka et al., 2015; Rios et al., 2015). Further, studies of urban mining and deconstruction in the construction sector have primarily taken a theoretical focus (Akbarnezhad et al., 2014; Akinade et al., 2017; Couto and Couto, 2010; Koutamanis et al., 2018; Sanchez and Haas, 2018; Tatiya et al., 2018; van den Berg et al., 2021; Ventura and Trocmé, 2018), often oversimplifying the complexity of the process at the demolition site and eventual potential 'reuse'. Adopting a similar rationale to industrial ecology based built environment stock-flow studies, previous studies of urban mining suggest that end-of-life flows will substitute for primary material and components demand (Arora et al., 2020; Deetman et al., 2020; Han et al., 2018).

Even though modelling for assumed material recovery benefits, deconstruction and building components salvage remains an important academic priority, practical realities in the construction industry differ from such assumptions on the end-of-life of buildings. These practices are prevalently demolition-driven, with established opinions that building components salvage would take longer time (Boyd et al., 2012), require extensive effort, and incur additional costs with uncertain possibilities of finding a market for salvaged components (Couto and Couto, 2010; Koutamanis et al., 2018; Tatiya et al., 2018; Thomsen et al., 2011). Even though most studies argue for and rely heavily on Design for Deconstruction, buildings at the end-of-life today were not designed for disassembly and thus require additional investigation into recovery efforts. Answers to these perspectives from the construction industry can best be provided through primary data generated by experimental field research on demolition sites.

This study therefore undertakes an experimental approach for the urban mining of building components. Using end-of-life buildings ready for demolition in Singapore, a south-east Asian city state, this study investigates qualitative and quantitative aspects of urban mining feasibility from the perspective of actual costs and practices. It focuses on three important considerations of urban mining in buildings: planning, process and feasibility. Based on quantitative and observational datasets from demolition sites, this study aims to answer a single, unified question: How to measure the feasibility of urban mining in buildings in terms of efficiency and costs? Specifically, the objectives of this study include the development of a method to measure urban mining feasibility from demolition-ready urban residential building stocks. In this pursuit, the study develops indicators of urban mining feasibility from (a) project timeline perspective, (b) salvage time requirements for individual building components mining practice and (c) the behavioural aspects of construction stakeholders including construction and demolition workers. This study further discusses the challenges associated with urban mining of building components based on connection types (e.g. nails vs. screws), behavioural practices in the construction sector, and the prospects of greater adoption of urban mining and reuse.

2. Methodology

2.1 Urban mining site and building typology

This study focuses on urban built stock of the city of Singapore, home to over 5.6 million residents and over 1.3 million residential housing units (Arora et al., 2020). Singapore has one of the most advanced construction and real estate sectors with an exceptionally high degree of off-site construction practices due to labour and productivity considerations. Singapore aims to make Design for Manufacturing and Assembly (DfMA) technology as the default building construction method for large projects, with national adoption targets of 70% by 2025 for new built construction (BCA, 2021). Currently, public sector residential buildings provide housing for over 80% population within predominantly high-rise building typologies (Arora et al., 2019). For carrying out the urban mining study, six end-of-life residential buildings of 12 story height, comprising of over 120 flats in each building, were chosen based on availability and access (Figure 1). The majority of flats were two-bedroom, followed by one- and three-bedroom units. Such units make up the largest residential building typologies in Singapore and have uniformity in building plan and floor plans layout due to single government agency control over the public housing sector (Arora et al., 2019).

Typically, urban mining strategies need to go beyond residential typologies to cover other buildings from an evolved secondary resources supply chain perspective. The representative typologies and focus on non-structural building components ensure that the study can be applied to other building typologies including multipurpose buildings, office buildings, commercial buildings and/or industrial buildings.

Figure 1. Urban mining site and building typologies used for building components recovery

2.2 **Stakeholder engagement**

There are several aspects of urban mining in buildings including technical (such as the typology and design of the building, material type and components quality), regulatory and policy considerations (such as building codes, demolition permits etc.), labour requirements (need of specialised workers) as well as the market demand for the mined components. For a flourishing urban mining practice, a variety of stakeholders are required to facilitate the availability of end-of-life buildings for urban mining, and customers in the construction market to use the mined components. Many studies note the apparent lack of salvage markets and demand for urban mined building components/materials in cities due to a variety of reasons including consumer acceptance and construction practices. Arora et al. (2018) carried out a demolition case study in Singapore to conclude that metal scrap remains the only income stream for demolition contractors. With the absence of building components reuse, and the lack of a building components reuse market, contractors prefer traditional demolition over the deconstruction process. This situation is not unique to Singapore and other studies cite the lack of salvage markets and challenges in absorbing recovered resources from urban mining exercise in cities (Bertino et al., 2021; CIB, 2001; NAHB, 2021; Tatiya et al., 2018). In practice, urban mining for reuse fundamentally requires bringing construction and demolition stakeholders on board for site access and potential reuse.

In this study, several companies involved in building demolition activities were contacted for potential collaboration. Two companies eventually agreed: the first is involved in small scale renovation and demolition activities; while the second focuses on large-scale demolition. Second, the availability of demolition sites for urban mining is another challenge. Even though several demolition activities may be going on around the city, it is not necessarily possible that a site can be accessed to perform experimental studies. For this study, a collaboration with a demolition contractor was established in Singapore that spanned over two years in duration. Based on the availability of a newly accepted tender for demolition, access to the demolition site was gained for initial visits. Six blocks of public residential buildings that were planned for demolition, namely block 167-172 Boon Lay Drive, Singapore, were selected for experimental urban mining study (Figure 1). Subsequently, planning for the urban mining experiments was carried out with the local building demolition company in Singapore.

2.3 **Urban Mining experiment design**

The process of urban mining was investigated through a hands-on experimental approach. Two sets of experiments were performed at residential building demolition sites in Singapore. To ascertain the typical demolition process, a previous case study carried out at 371 Beach Road, Singapore (Arora et al., 2018) helped in determining the business-as-usual process (Fig. 2A). Following discussion with the demolition company, additional steps for urban mining building components were planned to be carried out for the experimental study (Fig. 2B).

Figure 2. A represents the Business-As-Usual steps involved in building demolition process while B highlights the additional steps added into the process under experimental study design.

Subsequent site visits were performed for surveying the quality, quantity and inventory development for recoverable building components. Various building components were measured for their dimensions and marked for recovery. This helped in creating a database of building components with all required information that could potentially be used by designers for a new construction. For building components recovery experiment design, all non-structural building components were considered. Broadly, building components were divided into five main categories:

i. Doors (including metal gates, wood doors, PVC doors etc.)
ii. Windows (Different material, size and frame combinations)
iii. Grille (Different material, size and frame combinations)

iv. Toilet and Kitchen Components (Sink, Basin, Bowl of different material and sizes)
v. Electric and Furniture components (Air conditioners, Fans, Water heaters, lights, plugs etc.)

Overall, more than 350 building components were identified for recovery. Detailed dimensions and specification of all building components can be found in the Supporting Information (SI). To perform the actual mining exercise, two semi-skilled demolition workers were hired to perform recovery, transfer, and storage of building components in a temporary warehouse. Previous studies have cited the need for specialised manpower with specific skills in deconstruction process, leading to very high labour costs. To understand how non-specialised workers gain the ability to salvage different building components, this study chose non-specialised construction workers to perform urban mining and gain skills based on 'learning while doing'. The salvage exercise was planned based on the typical work routine from morning to evening. Each workday started with planning the targeted number of building components to recover from different flats because the number of recovered building components was huge and couldn't be recovered from a single apartment. Within an 8-hour workday, 6.5 hours were aimed at building component recovery by two workers and documentation by lead researcher. Once the recovery of building components was completed for 6.5 hours, the remaining 90 minutes were spent transferring the recovered building components from different apartments to a common temporary storage house within the demolition site.

As several hundred building component recovery experiments were carried out to estimate man-hours needed to salvage specific building component types, three main aspects were of importance in the urban mining experiments:

i. Time needed to recover specific building component
ii. Skills improvement of workers in repeated recovery attempts
iii. Challenges in recovery of building components due to joints and connections

Even though all three aspects can be analysed based on time taken in recovery over repeated attempts, skills improvements for urban mining and role of joints and connections in end-of-life recovery were also noted as observations by the lead researcher. Decreasing trend in time were looked for in the recovery of similar building components until a stagnant range of recovery time was reached to see learning influence on labour time. As the urban mining was carried out with an eventual goal of reuse of recovered building components in subsequent construction projects, non-destructive methods of recovery and dis-assembly were prioritised based on use of simple tools. Observations regarding ease of recovery, damage and construction practices were documented to gain insights into behavioural practices at the construction stage which cause challenges for the safe/damage-free recovery of building components during the end-of-life deconstruction and salvage. These practices were validated based on observations of the damage to recovered building components and/or additional time taken for recovery.

2.4 **Estimation of Salvage time**

Based on the selected building components type for salvage, specific building components (e.g., window, door etc.) were chosen for sequential recovery so that the learnings from one salvage experiment can aid in reducing the time taken in the next salvage attempt. Timing for salvage ($T_{recovery}$) was measured using a digital timer for each experiment. Measured time includes the time from beginning of the salvage attempt until the building component was successfully recovered. Time required for recovering each building component was then documented in the physical logbook. As two workers were jointly involved in the exercise, the observed time of recovery should be multiplied with the number of workers involved. Further, duration for transfer ($T_{transfer}$) of building component from specific apartment from which it has been recovered to the temporary storage location needs to be added into the recovery time to account for total man-hours needed for urban mining. Hence the total urban mining time (T_{UM}) for a specific building component can be estimated by:

$$T_{UM} = n \times T_{recovery} + T_{transfer} \tag{1}$$

Where n is the number of workers.

2.5 **Economic Cost Estimation for urban mining**

Economic costs remain one of the biggest concerns in building-scale urban mining efforts. Traditionally, the overall costs of demolition and deconstruction have been estimated at a project level. However, this study focuses on urban mining of building components driven by the consumer demand and/or interest of clients. Within that frame, costs of recovering a building component can be assessed based on the time required for salvaging specific building components given in equation 1. At a component level, the cost of urban mining (C_{UM}) can be determined by:

$$C_{UM} = C_{labour} \times T_{UM} + C_{transport} + C_{tools} \tag{2}$$

Where C_{labour} represents the cost of worker in a given location, $C_{transport}$ denotes the proportionate cost of transport to a warehouse or construction site and C_{tools} denotes the proportionate cost of tools used in the process of urban mining of specific building component. However, at the project level, in some cases the urban mining exercise may influence the overall timeliness of the demolition project schedule. If urban mining of building components causes delays in the usual demolition time frame and/or site clearance, that cost can be divided proportionally over all the recovered building components and added to the urban mining cost.

2.6 **Criteria for urban mining feasibility**

The fundamental metric of urban mining feasibility is *time* which should be understood in two senses: a) time as *cost* of labour (which can be quantified based on recovery experiments); b) time as *timeliness in a project timeline*, i.e., whether recovery can be squeezed into a *project schedule*. The previous steps detailed within the methodology such as stakeholder engagement, demolition site access, inventory of components and salvage of building components at a demolition site overall create a case study driven experimental *method for how one could measure the urban mining* feasibility based on the *required time (i.e., costs)* and timeliness indicators. Another important consideration from an economic point of view is to look at the feasibility from economic benefits point of view to highlight the advantages for involved stakeholders in monetary terms. Previous studies have shown that deconstruction can lead to economic savings due to the earnings made by sale of salvaged materials and components. To estimate the costs related to building components recovery, the salvage time for specific building component is enough. But the total cost of urban mining includes costs of additional project delays, costs of transportation, and costs of temporary storage until a suitable buyer is arranged. Assuming that the urban mining exercise is driven purely based on economic consideration, the feasibility can be assessed based on the calculation of economic savings.

There are two potential scenarios for assessing the economic feasibility of urban mining a particular building component: one in which the recovered building component can be reused (i.e. ability to replace a new component); and another in which it can only be recycled in material form (such as metal scrap, plastic, wood, glass etc.). If the total cost of urban mining for a building component is less than the cost of a new building component ($C_{New\ Component}$) of similar dimension, then the urban mining exercise becomes feasible. However, if the prospects of reuse are low and if there is a lack of reuse market and/or customers, selective urban mining becomes a financial risk. Currently, the recycling income stream plays an important role for demolition contractors and is predominantly driven by metal recovery from buildings. Under reuse-driven urban mining scenario, such feasibility requires that:

$$C_{UM} \ll C_{New\ Component} \qquad (3)$$

Under recycling scenario, for urban mining to become economically feasible, the costs of urban mining should be less than the economic value of all scrap materials (V_{Scrap}) in the specific building component:

$$C_{UM} < V_{Scrap} \qquad (4)$$

Alternatively, apparent economic value difference between the recycling and reuse of each building component can also highlight benefits of building component salvage. Overall cost savings due to urban mining and reuse can thus be given by:

$$C_{Savings} = C_{New\ Component} - C_{UM} - V_{Scrap} \qquad (5)$$

3. Results and Discussion

3.1 Planning for Urban Mining

As previously highlighted, there are two important aspects of planning an urban mining exercise: i) demolition site (supply side) and ii) consumer/client (demand side). Currently, tthe demolition process in general is driven by recovery of metals. To change the focus of demolition from metal scrap to building components, there is a need for an appropriate market and/or consumer with demand for the building components. Thus, even though a demolition site may be available and ready, the urban mining for building components relies heavily on engagement with stakeholders to get access to demolition site and to find potential customers. The experiment described in this study aimed to include building component recovery within the context of the existing process of building demolition in a city, an experimental intervention which would necessarily affect the way demolition works in the business as usual case (Figure 3). The changes in the project strategy and planning can be significant at the outset, however, collaborative planning can help in parallel progression of urban mining efforts as highlighted in Figure 3.

Figure 3. Inclusion of urban mining planning and process into the demolition project strategy

One of the first planning steps is to identify potential urban mining sites. However, information regarding such sites may be hard to obtain without the proper network or insider business connection. Typically, once the decision to demolish a building is made, there are natural efforts for engaging demolition contractors. A key step in planning an urban mining practice (or an experimental exercise) remains building close collaboration with demolition site stakeholders which can include site owners, real estate developers and/or demolition contractors. In this study, previous attempts for assessing the status of demolition waste management in the Singapore city had helped in finding regulatory stakeholders. However, demolition activities are typically performed by medium and small-scale industries (Arora et al., 2020; Arora et al., 2018; Tatiya et al., 2018; Zaman et al., 2018). Once the demolition company receives a tender for demolition project, it must wait for the handover activities where the company is formally given custody and access to the building. Once handover is complete, the demolition company prepares documents for regulatory clearance from regulatory authorities (Building and Construction Authority in Singapore).

Operationally, the requirements for these regulatory conditions can take up a significant length of time. Typically, a demolition site, after handover, must be disconnected from water and electricity supply. All the sewer lining and open holes must be sealed so that the site can be prevented from becoming a breeding ground for mosquitoes, rats etc. This is predominantly part of the public health and safety plan. In addition, the entire demolition site must be cordoned off with noise barriers. This is important due to the loud noise of building demolition activities. In addition, the building is tested for the presence of asbestos which can be a health hazard for workers on the site. Singapore has mandated asbestos survey on any building demolition or renovation activity for buildings built before 1st January 1991 (MOM, 2019). The reports for identifying asbestos presence in building can take a few weeks to arrange and be processed.

All these activities are crucial from the point of view of regulatory clearance, and they also provide a sufficient time frame for urban mining activities to be performed. This time is ideal for planning the surveying and inventory development for urban mining. Even though variations in demolition timelines and completion may vary based on the urgency in site clearance and construction type, in the city of Singapore regulatory requirements for demolition permits allow sufficient time for building component recovery. In this case study, the time range from the decision to demolish until regulatory approval ranged from 2-4 months for six different buildings assessed in this study.

There exists a significant perception in existing literature and construction community that urban mining in buildings may affect the timelines of demolition and subsequent construction

(Densley Tingley et al., 2017; Gorgolewski, 2008; Rios et al., 2015; Salama, 2017). On the contrary, regulatory clearance formalities from the point of time when a decision is made to demolish a building may take a few months' time. Some may argue that it is a very short time span for urban mining, but the practicality of building component salvage only requires four steps, namely, identification of demolition site, survey of building to identify building components of interest, actual urban mining i.e., salvage of components followed by transfer to a construction site or warehouse where further processing, if required, can be done. In current study, all these steps were performed well before the mechanical demolition of the building started, with no effects on project timelines.

The next step in planning requires an understanding of which and how many building components are required to be urban mined. Demand for building components can be driven by a variety of consumers/clients such as new construction project demands; selling through salvage business; or donation to charities. Based on the scale of urban mining requirements, manpower and warehouse space needs to be arranged. In this study, urban mining was driven by experimental investigations and potential construction projects. Hence, a warehouse area was secured within the demolition site. Demolition contractor planned for a sequential demolition of buildings which allowed certain buildings to be free from heavy machine activities until the very end. Initially three housing units at the ground level were used as warehouse. Additional building components were stored at a carpark which was scheduled for demolition after residential blocks. After initial site visit, a survey was arranged to look at the stock of building components in different housing units. An initial inventory was developed with expected number of building components to be salvaged (Table 1). This inventory included taking a representative photographic image of each building component and overall quantity to be reclaimed. This was followed by a paste-it note on certain building components to identify the blocks at the time of recovery.

Table 1 Inventory developed during the survey of end-of-life building

Serial Number	Building Components	Expected Salvage Quantity
1.	Doors	25 units
2.	Outside Doors	10 units
3.	Kitchen Windows	15 Sets
4.	Room Windows	20 Sets
5.	Sliding Glass Doors	15 Sets
6.	Kitchen Sink	10 Sets
7.	Hand Wash Basin	10 Sets
8.	Toilet Bowls	10 units

9.	Gas Stoves	8 units
10.	Wood flooring	100 m^2
11.	Kitchen Cabinet	10 Sets
12.	Room Cabinet	10 Sets
13.	Marble Flooring	$80m^2$
14.	Switch and Plugs	50 units
15.	Hanging Lights	16 units
16.	CFL Light bulbs	40 units
17.	Shower heater	15 units
18.	Outdoors Cement Tiles	$80m^2$
19.	Wall-mounted Fans	15 units
20.	Roof Fans	10 units
21.	Air-conditioner	6 units
22.	Corrugated Roofing Sheet	32 Sheets
23.	Glass Tiles	40 units
24.	Hand railings	8 units
25.	Expanded Metal Mesh Frame	16 units

3.2 Process of Urban Mining

Once this inventory was developed, two semi-skilled workers were hired to undertake the urban mining exercise. Significant evidence suggests that selective demolition can lead to superior building components recovery from construction sites (Arora et al., 2020; Vitale et al., 2017). Even though the workers were previously involved in the demolition activities, salvage of building components was a new assignment for both. This activity hence started focus on each building component with a learning while doing approach. The process started with the salvage of wooden doors, which appeared easy since crew drivers could be used on the door hinge. It was followed by the salvage of metal gates, windows, window grilles, sliding glass doors, washbasin, toilet bowls, kitchen fixtures etc. Figure 4 shows the salvage activities performed during the urban mining exercise.

Figure 4. Workers involved in mining various building components namely A. wood doors, B. lights, C. metal gate, D. metal frames, E. toilet bowl, F. kitchen furniture, G. window, H. kitchen top, from residential building apartments.

The overall exercise was carried out over different days of the work week. In total two full workdays and four half days were spent for the salvage of 354 building components with two semi-skilled workers. In order to understand the efficiency gain in recovery process and the typical time expected to recover each type of building components, the time taken for the salvage of each building component was recorded. At the end of each day when salvage was completed, an additional 90 mins was spent transferring the reclaimed components to a temporary warehouse. In total, 1314 mins were spent on urban mining exercise of 354 building components by two workers, or 43.8 man-hours for urban mining and 12 man-hours for warehouse transfer. Once this exercise was completed, salvaged building components were loaded into a 15-foot transport vehicle for transfer to a construction site. 12 man-hours were spent on loading the vehicle in two trips. In total, the building components recovery exercise took approximately 68 man-hours to complete.

Figure 5 shows detailed distribution of building component specific urban mining time. It highlights the time taken in minutes for two workers on each building components recovery. A total of 33 categories of building components were analysed (Fig 5, see SI for data). Urban mining time for various building components ranged from 1-2 mins for window grilles to 14 mins for air-conditioner units to 15 mins for kitchen counters.

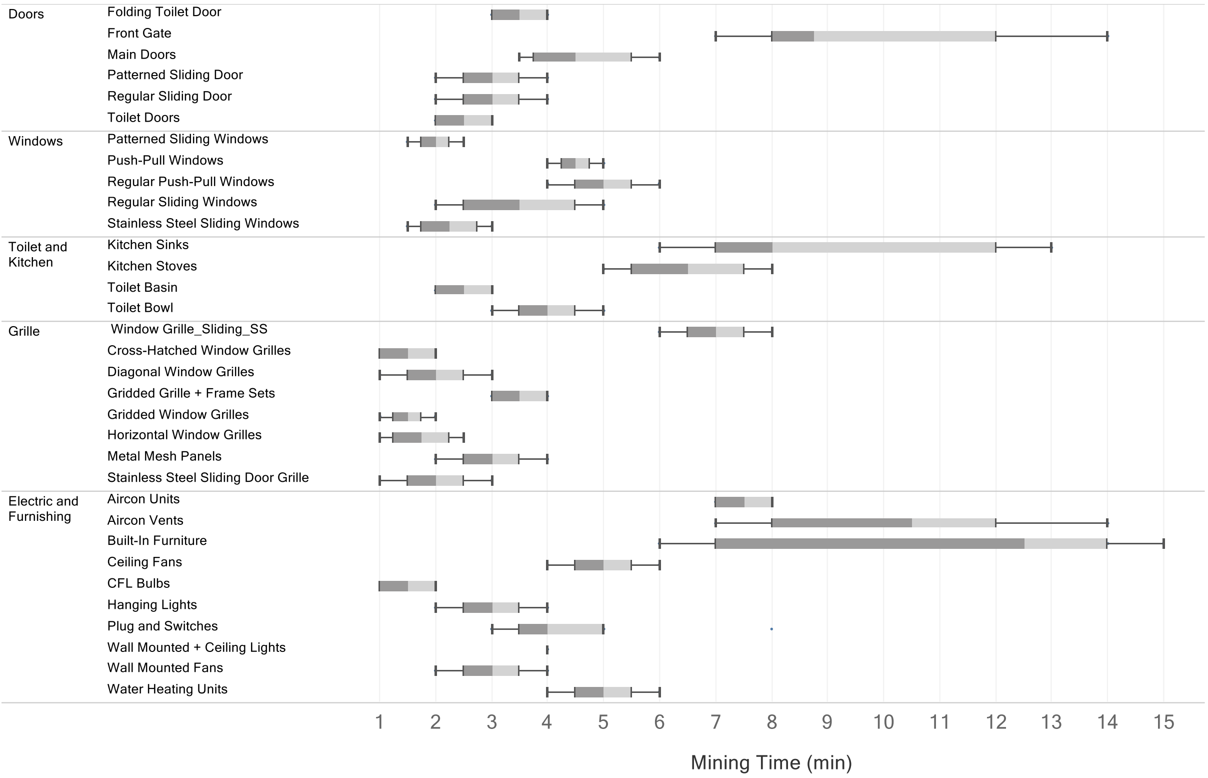

Figure 5. Time needed for urban mining of building components

The variation in mining time was due to two primary reasons. One important aspect of salvage time variation was associated with skill learning through practical experience. As previously discussed, it was a first-time experience for both workers in salvaging building components, and therefore skills for recovery were developed in repeated attempts. In careful observations on recovery times for building components of the same category, it was observed that the time taken to remove one component significantly decreased in later attempts with stabilisation after 3-4 recoveries. This can be associated with the typical skill gaining process in any sector. Additionally, some recovery attempts didn’t go as well as others due to physical differentiation in connection type. This is consistent with previous works on modular products and connection designs with ease for disassembly (de Aguiar et al., 2017; Kroll and Hanft, 1998; Sodhi et al., 2004; Vanegas et al., 2018). It was observed that the fastener design and material play a crucial role in disassembly of building components. Rusting was a major problem for removing screws which led to 4-5 mins additional time in unfastening. Uses of nails instead of screw was another problem which render disassembly process very difficult without physical damage to the components. Therefore, the prospects of reuse of building components and a future of circular buildings can potentially be realised by creating financial business case and climate mitigation evidences with experimental case studies (Heisel and Rau-Oberhuber, 2020; Nußholz et al., 2020).

During the urban mining exercise, an important observation was made regarding the behavioural tendencies of construction workers whose practice of adding cement, grout concrete and nails leads to severe challenges at end-of-life for deconstruction without damage. Several of the building components had nails in addition to typical slots a component had for fasteners. Nails were added for additional safety and/or satisfaction that a component will not disassemble easily. Similar practice was observed for adding cement at the base of toilet bowls even though the bowl has fasteners in place for secure set up.

Figure 6. Examples of avoidable behavioural practices which lead to breakage of building components during mining namely A. wash basin with white Portland cement (seen in B), C. (unnecessary) nails and white Portland cement at the base of toilet bowl, D. concrete below kitchen basin, E. nails instead of screws in electric boards F. concrete layer below window frame

Addition of white Portland cement and/or concrete at the base of building components was similarly seen for washbasins, window frames and even electric switches (Figure 6). Excessive usage of cement as a construction practice has been documented in other countries too (Shanks et al., 2019). Usage of cement and/or concrete at the base of building components makes component salvage tedious and time consuming. In most cases of cement adhesives, recovered building components were either completely broken or partially damaged. Usage of cement has also been seen as a bigger challenge for salvageability of common building materials such as bricks (Nordby et al., 2009). This prevalent practice in Construction sector can only be avoided with significant efforts to raise awareness about modularity and inculcate a disassembly driven mind-set. With millions of people involved in this sector across the globe, serious efforts are needed on re-skilling the construction workforce to avoid unnecessary and overly cautious practices such as adding nails or cement when already complete assembly systems are in place.

3.3 Economic cost and feasibility of Urban Mining

As discussed in section 2.5, the costs of urban mining building components can be estimated based on equation 2 using the location specific daily wages for a semi-skilled construction worker. In Singapore, it costs 100 Singapore Dollar (1 SGD=0.75 USD) for 8 hours workday. In total, 56 man-hours were spent on reclaiming 354 building components alone. This time does not account for time involved in moving from one building components to another once a task is complete. Including all time spent in urban mining, walks and/or rest for the workers to initiate salvage of another component, a total of 10 workdays were consumed (i.e. 80 man-hours). A total cost of 1000 SGD was paid to recover all the building components. This cost can be distributed for each building component based on the average time of urban mining for each building component type based on equation 1 and 2. Total cost of 1000 SGD was distributed over 1314 minutes of spent on urban mining by two workers and thus the proportionate cost of urban mining was estimated to be 0.76 SGD per minute spent on building components recovery. Table 2 provides the average urban mining time and costs for each type of building components. It further compares the cost of urban mining with the market price of a new building component. Assuming that these building components can be reused, the urban mining feasibility under such scenario has been ranked as low or high.

Table 2 Building component specific salvage time, cost and feasibility of urban mining

Building Component	Average Salvage Time (x2)	Cost of Urban Mining (SGD)	Market Price	UM Feasibility
Front Gates	9.4	7.2	Much Higher	High
Main Doors	4.4	3.3	Much Higher	High
Regular Sliding Door	2.6	2.0	Much Higher	High
Toilet Doors	2.7	2.1	Much Higher	High
Folding Toilet Door	3.5	2.7	Much Higher	High
Regular Sliding Windows	2.7	2.0	Much Higher	High
Patterned Sliding Windows	2.0	1.5	Much Higher	High
Stainless Steel Sliding Windows	2.0	1.5	Much Higher	High
Regular Push-Pull Windows	5.0	3.8	Much Higher	High
Patterned Push-Pull Windows	4.5	3.4	Much Higher	High
Horizontal Window Grilles	1.5	1.1	Much Higher	High
Diagonal Window Grilles	1.0	0.8	Much Higher	High

Cross-Hatched Window Grilles	2.0	1.5	Much Higher	High
Gridded Window Grilles	1.2	0.9	Much Higher	High
Gridded Grille + Frame Sets	3.5	2.7	Much Higher	High
Window Frame	8.0	6.1	Much Higher	High
Window Grille_Sliding_SS	1.3	1.0	Much Higher	High
Stainless Steel Sliding Door Grille	2.5	1.9	Much Higher	High
Toilet Basin	3.8	2.9	Much Higher	High
Toilet Bowl	9.2	7.0	Much Higher	High
Kitchen Sinks	5.9	4.5	Much Higher	High
Kitchen Stoves	3.0	2.3	Much Higher	High
Metal Mesh Panels	7.8	5.9	Much Higher	High
Aircon Units	11.3	8.6	Much Higher	High
Aircon Vents	7.5	5.7	Much Higher	High
Wall Switches (Double)	4.4	3.4	Much Higher	High
Built-In Furniture	9.4	7.2	Much Higher	High
Wall Mounted Fans	3.0	2.3	Much Higher	High
Ceiling Fans	5.0	3.8	Much Higher	High
Wall Mounted & Ceiling Lights	4.0	3.0	Much Higher	High
Hanging Lights	3.0	2.3	Much Higher	High
CFL Bulbs	1.0	0.8	Higher	Low
Water Heating Units	5.0	3.8	Much Higher	High

Overall cost for urban mining ranges between 0.8 SGD for bulbs and grilles to 8.6 SGD for Air Conditioners. From a purely economic perspective there is less incentive for recovery of CFL bulbs from demolition site because the cost of urban mining is almost as much as the market price of a new bulb. However for other building components, Table 2 highlights that under a reuse scenario, there is a significant economic benefit and feasibility prospect for urban mining efforts. As an example, a window set costs between $100 - 220 in Singapore while its recovery cost is about 4$. If the same window broken down under demolition into metal, glass, rubber and polymers, only its approximate 6 Kg metal content would have been of value. Based on current rates of about 300$ per tonne scrap costs, it would mean less than 1$ value of a window set. The intact value of a building component by maintaining its functionality can hence play a crucial role in building components urban mining and eventual reuse.

3.4 Additional considerations for better circularity and net zero prospects

Creating enabling environments for the development of building components reuse markets is fundamental to see momentum towards secondary resource acceptance in the construction sector. As discussed, reuse prospects create significant value addition in building components as opposed to recycling routes. An important step in this direction remains policies for promotion of reuse and incentives for salvage practices at the end-of-life buildings. In the Singapore case, the focus on reuse of building components was driven by costs associated with the disposal of demolition waste. Materials such as wood, glass, plastic, and rubber do not have any domestic market and thus there is cost to demolition companies in dealing with these materials (Arora et al., 2018). To process these materials at a waste-to-energy plant or landfill, demolition contractor must pay a S$77 per-tonne fee As a result, in current practice metals are the only material of interest and metal recycling drives the building demolition revenue stream. Our results suggest the importance of changing from a material-level to a component-level focus. These findings are in line with Wu et al. (2017) who concluded that financial incentives and government regulations are the only considerations that may cause demolition contractors to consider changing construction & demolition waste management behaviour. Thus, these findings have an important significance for the creation of business models (Yli-Opas, 2016) that may help cost recovery (Nußholz et al., 2020) for traditional demolition stakeholders.

An additional aspect is predominantly driven by the net-zero ambitions of construction sector. Currently, there is a little consideration for environmental and embodied energy savings within construction standards and building rating schemes. Even though one may argue that embodied carbon savings and the costs involved must be balanced with the prospects of climate mitigation benefits, there exist enough evidence of embodied carbon savings from building components reuse (Nußholz et al., 2020; Seo et al., 2015; Zaman et al., 2018). Often, at a product level such savings seem small, however, given the scale of consumption and growth in the upcoming construction activities for buildings and infrastructure, supply chain level carbon emissions savings would be enormous. Estimations of such carbon emissions benefits at a building and a city level can help estimate the benefits of promoting urban mining policies at an urban and/or national scale.

4. Limitations

Findings in this study may be generalised and adopted for replication in other cities given an understanding that the localised context of construction ecosystem will play an important role. From planning perspective, city-specific policies and regulation can be a significant base for variation. From experimental perspective, the results may vary with different set of construction workers, their stress level, and their adaptability to the work environment. From materials quality perspective, building codes and the construction practices along with construction developer's choice of investment, all would affect the eventual quality and thus the market value of recovered building components. Additionally, some of the building components recovered in this study may not find acceptance in certain consumer communities due to individual preferences and/or cultural influences. Macro-social environments including the physical environment, social interaction, and social identity including life style, plays an important role in acceptance of urban mined building components for reuse and should be considered in making an assessment of the potential market scope within a localised context.

5. Conclusion

This study used a case study approach to highlight the process, timelines, costs and skills involved in urban mining of non-structural building components from end-of-life buildings. Briefly, two demolition sites were used as case studies. The first case study helped in understanding the planning and process of demolition, while the second used an experimental design to carry out building components recovery using semi-skilled construction workers.

- Over 350 building components were recovered from end-of-life buildings and time needed for recovery was measured as man-hours.
- Accordingly, the component specific economic costs for urban mining were estimated and compared with market prices for the same components if recycled, reused or bought as new.
- Further aspects, including the regulatory, logistical and salvage skills, have been examined.

Overall, this study provides evidence to support industry-wide adoption of urban mining practices. It highlights various aspects associated with the urban mining of building components for potential reuse and adoption in new construction for a greater circular economy. Even though the local context for recovering building components can vary significantly, conclusive evidence of the feasibility of building components recovery has emerged from the results of this study. The estimates of component specific man-hours and costs involved in salvage confirm the practicality of an urban mining business case and opens new opportunities for reuse practice in construction. As the labour costs vary based on locations and season, man-hours required for salvage provides a useful dataset for decision making by the academic and practice community.

However, there is a further need to assess location-specific embodied carbon savings in promotion of building components reuse in new construction. Such GHG emission estimates should include processing and transport related emissions for reuse markets and ascertain the extent to which such strategies can help in decarbonisation and net zero goals. As discussed previously, stakeholder engagement is crucial for urban mining exercise as a demolition contractor may only drive these efforts if there is a sufficient market demand. The best possible strategy would require engagement of potential consumers and real estate developers with the demolition contractors to salvage the required building components. These activities of urban mining will also create job opportunities for semi-skilled workforce and provide a financial and environmental win-win for built environment stakeholders. The projected growth of urban buildings and infrastructure can benefit from the wider adoption of urban mining practices within the built environment. With greater efforts on component-level recovery and reuse during the next decade, building components circularity can create pathways for low carbon-built environment and help reduce the climate burden.

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References

Addis, W. (2006) Building with reclaimed components and materials : a design handbook for reuse and recycling, Earthscan, London.

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

Akinade, O.O., Oyedele, L.O., Ajayi, S.O., Bilal, M., Alaka, H.A., Owolabi, H.A., Bello, S.A., Jaiyeoba, B.E. and Kadiri, K.O. 2017. Design for Deconstruction (DfD): Critical success factors for diverting end-of-life waste from landfills. Waste Management 60, 3-13.

Akinade, O.O., Oyedele, L.O., Bilal, M., Ajayi, S.O., Owolabi, H.A., Alaka, H.A. and Bello, S.A. 2015. Waste minimisation through deconstruction: A BIM based Deconstructability Assessment Score (BIM-DAS). Resources, Conservation and Recycling 105, 167-176.

Allwood, J.M., Cullen, J.M., Carruth, M.A. and Department, U.o.C.E. (2012) Sustainable Materials with Both Eyes Open, UIT Cambridge Limited.

Arora, M., Raspall, F., Cheah, L. and Silva, A. 2019. Residential building material stocks and component-level circularity: The case of Singapore. Journal of Cleaner Production 216, 239-248.

Arora, M., Raspall, F., Cheah, L. and Silva, A. 2020. Buildings and the circular economy: Estimating urban mining, recovery and reuse potential of building components. Resources, Conservation and Recycling 154, 104581.

Arora, M., Raspall, F. and Silva, A. 2018. Identifying Design Interventions in Cities for Urban Sustainability. (51791), V004T005A025.

Arora, R., Paterok, K., Banerjee, A. and Saluja, M.S. 2017. Potential and relevance of urban mining in the context of sustainable cities. IIMB Management Review 29(3), 210-224.

BCA 2021 Factsheet: Push for greener buildings and new support scheme to boost transformation efforts through industry alliances unveiled, Singapore, https://www1.bca.gov.sg/docs/default-source/docs-corp-news-and-publications/media-releases/bca-cos-2021-factsheets.pdf?Status=Temp&sfvrsn=4d7e29b4_5.

Bertino, G., Kisser, J., Zeilinger, J., Langergraber, G., Fischer, T. and Österreicher, D. 2021. Fundamentals of Building Deconstruction as a Circular Economy Strategy for the Reuse of Construction Materials. Applied Sciences 11(3), 939.

Boyd, S., Stevenson, C. and Augenbraun, J.J. 2012. Deconstructing Deconstruction: Is a Ton of Material Worth a Ton of Work? Sustainability 5(6), 391-400.

Brunner, P.H. 2011. Urban Mining A Contribution to Reindustrializing the City. Journal of Industrial Ecology 15(3), 339-341.

Casper, R. and Sundin, E. 2018. Addressing Today's challenges in automotive remanufacturing. Journal of Remanufacturing 8(3), 93-102.

CIB 2001 Deconstruction versus demolition. https://www.irbnet.de/daten/iconda/CIB1459.pdf (ed).

Cossu, R. and Williams, I.D. 2015. Urban mining: Concepts, terminology, challenges. Waste Management 45, 1-3.

Couto, J. and Couto, A. 2010. Analysis of Barriers and the Potential for Exploration of Deconstruction Techniques in Portuguese Construction Sites. Sustainability 2(2), 428-442.

Dantata, N., Touran, A. and Wang, J. 2005. An analysis of cost and duration for deconstruction and demolition of residential buildings in Massachusetts. Resources, Conservation and Recycling 44(1), 1-15.

de Aguiar, J., de Oliveira, L., da Silva, J.O., Bond, D., Scalice, R.K. and Becker, D. 2017. A design tool to diagnose product recyclability during product design phase. Journal of Cleaner Production 141, 219-229.

Deetman, S., Marinova, S., van der Voet, E., van Vuuren, D.P., Edelenbosch, O. and Heijungs, R. 2020. Modelling global material stocks and flows for residential and service sector buildings towards 2050. Journal of Cleaner Production 245, 118658.

Densley Tingley, D., Cooper, S. and Cullen, J. 2017. Understanding and overcoming the barriers to structural steel reuse, a UK perspective. Journal of Cleaner Production 148, 642-652.

Gorgolewski, M. 2008. Designing with reused building components: some challenges. Building Research & Information 36(2), 175-188.

Grant, R.J. and Oteng-Ababio, M. 2016. The Global Transformation of Materials and the Emergence of Informal Urban Mining in Accra, Ghana. Africa Today 62(4), 3-20.

Gutowski, T.G., Sahni, S., Boustani, A. and Graves, S.C. 2011. Remanufacturing and Energy Savings. Environmental Science & Technology 45(10), 4540-4547.

Han, J., Chen, W.-Q., Zhang, L. and Liu, G. 2018. Uncovering the Spatiotemporal Dynamics of Urban Infrastructure Development: A High Spatial Resolution Material Stock and Flow Analysis. Environmental Science & Technology 52(21), 12122-12132.

Heisel, F. and Rau-Oberhuber, S. 2020. Calculation and evaluation of circularity indicators for the built environment using the case studies of UMAR and Madaster. Journal of Cleaner Production 243, 118482.

Hertwich, E.G., Ali, S., Ciacci, L., Fishman, T., Heeren, N., Masanet, E., Asghari, F.N., Olivetti, E., Pauliuk, S., Tu, Q. and Wolfram, P. 2019. Material efficiency strategies to reducing greenhouse gas emissions associated with buildings, vehicles, and electronics—a review. Environmental Research Letters 14(4), 043004.

Huuhka, S., Kaasalainen, T., Hakanen, J.H. and Lahdensivu, J. 2015. Reusing concrete panels from buildings for building: Potential in Finnish 1970s mass housing. Resources, Conservation and Recycling 101, 105-121.

IPCC 2018 Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, Shukla, P.R., Pirani, A., Moufouma-Okia, W., C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, Maycock, T., Tignor, M. and Waterfield, T. (eds).

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.

Kroll, E. and Hanft, T.A. 1998. Quantitative evaluation of product disassembly for recycling. Research in Engineering Design 10(1), 1-14.

Kwak, M. and Kim, H. 2016. Modeling the Time-Varying Advantages of a Remanufactured Product: Is “Reman” Better Than “Brand New”?1. Journal of Mechanical Design 138(5), 051701-051701-051718.

Mayer, A., Haas, W., Wiedenhofer, D., Krausmann, F., Nuss, P. and Blengini, G.A. 2019. Measuring Progress towards a Circular Economy: A Monitoring Framework for Economy-wide Material Loop Closing in the EU28. Journal of Industrial Ecology 23(1), 62-76.

MOM 2019 When do I need to conduct an asbestos survey?, Government of Singapore, Singapore.

NAHB 2021 Deconstruction: Building Disassembly and Material Salvage, https://www.fairmontwv.gov/DocumentCenter/View/1393/EPA-Deconstruction-Brochure?bidId=.

Nordby, A.S., Berge, B., Hakonsen, F. and Hestnes, A.G. 2009. Criteria for salvageability: the reuse of bricks. Building Research & Information 37(1), 55-67.

Nußholz, J.L.K., Rasmussen, F.N., Whalen, K. and Plepys, A. 2020. Material reuse in buildings: Implications of a circular business model for sustainable value creation. Journal of Cleaner Production 245, 118546.

Olivetti, E.A. and Cullen, J.M. 2018. Toward a sustainable materials system. Science 360(6396), 1396-1398.

Rios, F.C., Chong, W.K. and Grau, D. 2015. Design for Disassembly and Deconstruction - Challenges and Opportunities. Procedia Engineering 118, 1296-1304.

Saavedra, Y.M.B., Barquet, A.P.B., Rozenfeld, H., Forcellini, F.A. and Ometto, A.R. 2013. Remanufacturing in Brazil: case studies on the automotive sector. Journal of Cleaner Production 53, 267-276.

Salama, W. 2017. Design of concrete buildings for disassembly: An explorative review. International Journal of Sustainable Built Environment.

Sanchez, B. and Haas, C. 2018. A novel selective disassembly sequence planning method for adaptive reuse of buildings. Journal of Cleaner Production 183, 998-1010.

Seo, S., Kim, J., Yum, K.-K. and McGregor, J. 2015. Embodied carbon of building products during their supply chains: Case study of aluminium window in Australia. Resources, Conservation and Recycling 105, 160-166.

Shanks, W., Dunant, C.F., Drewniok, M.P., Lupton, R.C., Serrenho, A. and Allwood, J.M. 2019. How much cement can we do without? Lessons from cement material flows in the UK. Resources, Conservation and Recycling 141, 441-454.

Sodhi, R., Sonnenberg, M. and Das, S. 2004. Evaluating the unfastening effort in design for disassembly and serviceability. Journal of Engineering Design 15(1), 69-90.

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.

Talens Peiró, L., Castro Girón, A. and Gabarrell i Durany, X. 2020. Examining the feasibility of the urban mining of hard disk drives. Journal of Cleaner Production 248, 119216.

Tatiya, A., Zhao, D., Syal, M., Berghorn, G.H. and LaMore, R. 2018. Cost prediction model for building deconstruction in urban areas. Journal of Cleaner Production 195, 1572-1580.

Thomsen, A., Schultmann, F. and Kohler, N. 2011. Deconstruction, demolition and destruction. Building Research & Information 39(4), 327-332.

van den Berg, M., Voordijk, H. and Adriaanse, A. 2021. BIM uses for deconstruction: an activity-theoretical perspective on reorganising end-of-life practices. Construction Management and Economics 39(4), 323-339.

Vanegas, P., Peeters, J.R., Cattrysse, D., Tecchio, P., Ardente, F., Mathieux, F., Dewulf, W. and Duflou, J.R. 2018. Ease of disassembly of products to support circular economy strategies. Resources, Conservation and Recycling 135, 323-334.

Ventura, A. and Trocmé, M. (2018) Designing Sustainable Technologies, Products and Policies: From Science to Innovation. Benetto, E., Gericke, K. and Guiton, M. (eds), pp. 205-210, Springer International Publishing, Cham.

Vitale, P., Arena, N., Di Gregorio, F. and Arena, U. 2017. Life cycle assessment of the end-of-life phase of a residential building. Waste Management 60, 311-321.

Williams, I.D. and Shaw, P.J. 2017. Reuse: Fashion or future? Waste Management 60, 1-2.

Wu, Z., Yu, A.T.W. and Shen, L. 2017. Investigating the determinants of contractor's construction and demolition waste management behavior in Mainland China. Waste Management 60, 290-300.

Yli-Opas, R. 2016 Business models for consumer product reuse.

Zaman, A.U., Arnott, J., Mclntyre, K. and Hannon, J. 2018. Resource Harvesting through a Systematic Deconstruction of the Residential House: A Case Study of the 'Whole House Reuse' Project in Christchurch, New Zealand. Sustainability 10(10), 3430.

Zeng, X., Mathews, J.A. and Li, J. 2018. Urban Mining of E-Waste is Becoming More Cost-Effective Than Virgin Mining. Environmental Science & Technology 52(8), 4835-4841.

Zhang, C., Hu, M., Yang, X., Miranda-Xicotencatl, B., Sprecher, B., Di Maio, F., Zhong, X. and Tukker, A. 2020. Upgrading construction and demolition waste management from downcycling to recycling in the Netherlands. Journal of Cleaner Production 266, 121718.

Zhang, L., Zhong, Y. and Geng, Y. 2019. A bibliometric and visual study on urban mining. Journal of Cleaner Production 239, 118067.