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Research article

Industry and Literature Review of Urban Mining Applications in the United States: Gaps and Drivers for Implementation Towards a Circular Industrialized Construction Economy

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Abstract

Due to an increased awareness among stakeholders of the construction industry's detrimental environmental impacts, demand for circular and sustainable practices has increased significantly. The objective of this literature and industry scoping review is to analyze the current construction industry in the United States to determine emerging trends and developments in sustainable and circular design and construction, focusing on one of the concepts, Urban Mining, and its potential applications. In the context of this paper, Urban Mining is defined as the reclamation of materials, elements or components from existing decommissioned buildings which were not designed for deconstruction or adaptability with the goal to reuse (or recycle) these elements in new construction projects.

As this paper provides an outlook on technologies, materials, and practices that are emerging, there is a gap in available literature (reviewed or scientific sources) on the selected topic. Market reports, case study reports, and/or governmental and company websites are used to identify legislation, stakeholders, and changing practices pertinent to Urban Mining. By synthesizing deconstruction prospects for material groups and building components, gaps in Urban Mining practices are identified, including the documentation of building components, processing tools for reclaimed material, and technological, logistical, and legal infrastructures for reuse.

Keywords: Urban Mining, Circular Economy, Deconstruction, Material Recovery, Waste Reduction, Adaptive Reuse

1. INTRODUCTION

Due to an increased awareness among stakeholders of the construction industry's detrimental environmental impacts, demand for circular and sustainable practices has increased significantly (Guerra & Leite, 2021). The United States produces approximately 600 million metric tons of construction and demolition debris (CDD) annually, of which only 20-30% is reprocessed and repurposed (US EPA, 2023). This demand is catalyzed by existing and emerging legislation and policy at the federal, state, and local level, as well as by professional organizations such as the American Institute of Architects (AIA) and sustainability benchmarking foundations such as the Passive House Institute which publish guidelines, reports, certifications, and other market incentives to support sustainable practices (IMT, 2023). Consequently, circular and sustainable architecture, engineering, and construction (AEC) practices are approaching market maturity and implementation in the United States. However, because these practices are on the brink of implementation, there is a substantial gap in literature covering the newest and projected developments in the AEC industry. Existing literature is generally theoretical, or specific to one material or aspect within a larger sustainable practice (Ghisellini

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et al., 2022). This study contributes to the existing literature by providing a holistic overview of practical opportunities and gaps for Urban Mining in the United States AEC industry (Park, 2017).

This literary and industry review scopes the current US construction industry utilizing a variety of sources (market reports, case study reports, governmental and company websites) to determine emerging trends in sustainable and circular design and construction practices. The paper then synthesizes concepts and materials that are entering the construction industry within the next ten years and subsequently focuses on one of the topics, Urban Mining, and its potential applications within this scenario.

In the context of this paper, Urban Mining is defined as the reclamation of materials, elements or components from existing decommissioned buildings which were not designed for deconstruction or adaptability with the goal to reuse (or recycle) these elements in new construction projects. Processes of recycling, reuse, repair, and remanufacturing of existing material in the built environment (building components, appliances, systems) for new construction uses are included in Urban Mining (Koutamanis et al., 2018). As anthropogenic stocks of various minerals and materials begin to outweigh their natural reserves, prioritizing the recovery of these resources represents an essential circular economy strategy (Nakamura & Halada, 2015).

The objective of the review is to analyze related legislation, stakeholder roles, and strategies for the implementation of Urban Mining (such as Adaptive Reuse and Deconstruction prospects for different building components and materials) to present the main takeaways, gaps, and drivers for this concept in the United States AEC industry.

2. METHODOLOGY

The scope of this paper is defined geographically and legally by the United States of America, and by AEC industry activities spanning 1900 to 2050, more specifically projecting 5-10 years into the future with respect to planning and design and 30 years for policy ambitions.

An initial evidence inventory was conducted to identify search terms for emerging technologies, materials, and practices, using initial key terms to restrict the search included “topics,” “trends,” “tech,” and “materials,” combined with terms related to the area of research, such as “construction,” “sustainable,” and “circular.” Webpages and publications were filtered based on the scope outlined above. The broad results were evaluated and categorized manually and used to create summary sheets (Heisel, Farley-Thomas, et al., 2023) separated by materials and concepts.

As part of the evaluation, two variables were determined for each of the identified materials and concepts: the estimated amount of time in years to reach market maturity within the United States, and a ranking from 1-5 reflecting the expected impact on the AEC industry. Several characteristics were identified for each topic to determine the performance and generate the estimate of time to maturity, including scale of supply chain and product/ resource availability, progress in standardization for widespread application, and progress/ development of complementary technologies.[2] The impact on the construction market was estimated based on scale of application and sustainability benefits (role in the circular construction model, effect on building performance, reuse or reprocessing potential, etc.)

Materials and concepts were then mapped according to the quantitative variables concluded from the above characteristics: impact on a scale of 1-5, and time to maturity ranging from 0-10 years. Figure 1 organizes the results within four quadrants ranging from low impact and a low time to maturity to topics with high impact and a high time to maturity.[3] Topics with high impact and low time to maturity on this chart represent a special interest to this review.

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[2] On this scale, a topic or material with impact level 1 would indicate a construction method or material that either has a small-scale application (ie. small building components); can only be applied in select projects or locations within the US; has a limited impact on the building’s carbon footprint or reprocessing potential. A topic or material with impact 3 would impact larger scale building components, a local scale application, and/or significant progress in a project’s sustainability. A topic or material with impact 5 indicates an impact on whole building systems, widespread application, or standardization in the US, and/or a circular model.

[3] “Time to maturity” is a metric which projects the time in years estimated for the concept or material to reach full market maturity, and widespread application in the United States, as well as become readily available for purchase/ implementation.

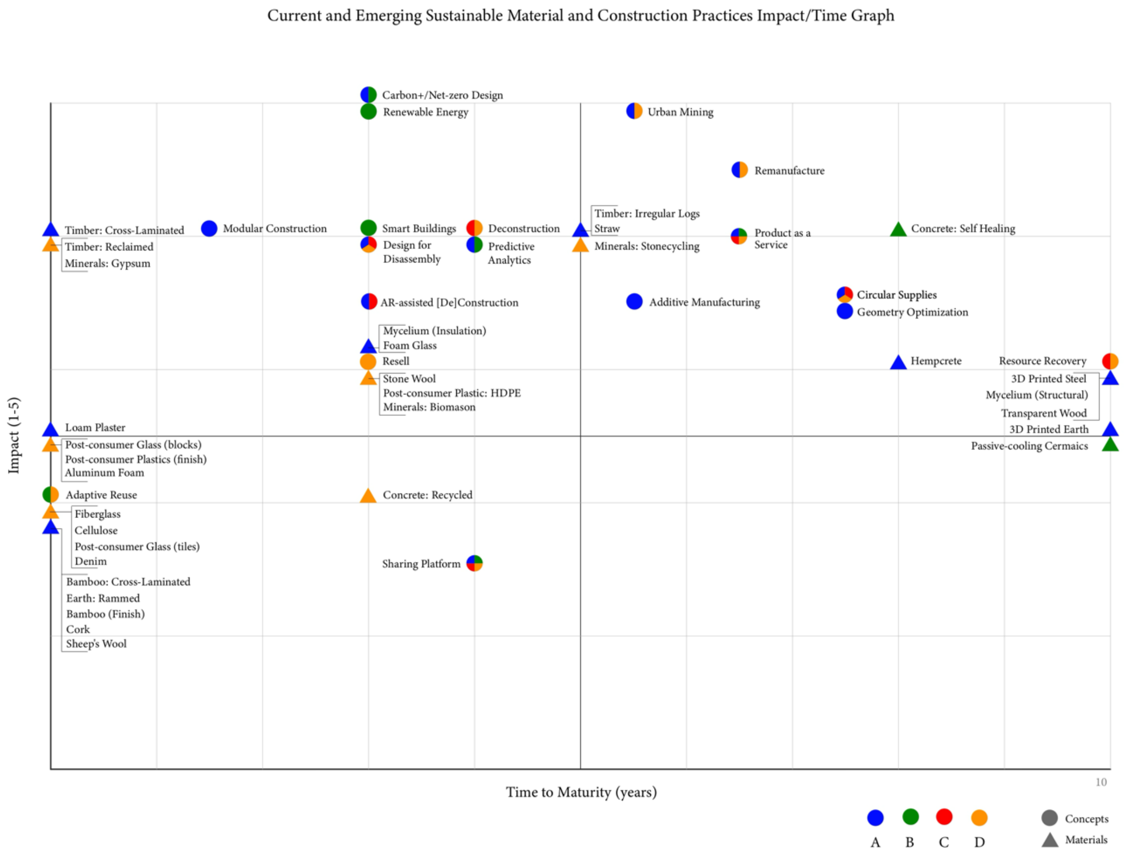

Figure 1. Impact vs. Time for Current and Emerging Sustainable Material and Construction Practices

The wider evidence mapping identified three topics for a deep dive into their application potential: Urban Mining, Design for Disassembly, and Modular Construction. This paper focuses on Urban Mining specifically. As the impact of Urban Mining is classified higher than the other two topics, yet the concept has a longer estimated time to maturity, it is a valuable focus for the paper to scope the current construction and industry gaps and drivers and synthesize considerations and guidelines that accelerate its implementation.

An initial review using Scopus and the search terms “circular construction” and/or “urban mining” and filtered by topical and geographic relevance yielded no comprehensive literature reviews about the United States context. To account for different terminologies in the US context, Scopus searches for “salvage” and “material reuse” offered high quality articles with very local geographic focus (as is to be expected in circular economy applications), however no industry level reviews. In comparison, the European and Asian context offers several comprehensive literature reviews (Mhatre et al., 2021) (Aldebei & Dombi, 2021), as well as city or building specific urban stock analysis (Verhagen et al., 2021) (Heisel, McGranahan, Ferdinando, et al., 2022).

Consequently, the scoping review for this paper was conducted using the search terms “circular construction” and/or “urban mining” using the online search engine Google to capture a wider range of sources. Filtered for geographic relevance to the US and publication dates within the past 5 years, 50 articles, reports and applications were selected for further analysis and comparison, spanning from material research to product development, policy development, architecture/ manufacturing company websites, organization, and institutional websites, as well as market reports.

Synthesizing this information, the paper first summarizes pertinent, emerging legislation (Section 3.1) that targets circular practices in the US, as these regulations create a necessity and incentive for the development and adoption of practices such as Urban Mining. Then, an outline of stakeholders (Section 3.2) and implementation strategies (3.3 Adaptive reuse, 3.4 Deconstruction by component, 3.5

Deconstruction by material) are discussed. Section 4 describes takeaway guidelines (Section 4.1) as well as industry gaps and drivers (Section 4.2) towards an applicable Urban Mining framework. Section 5 provides an analysis of research limitations, while Section 6 offers some further research suggestions.

3. RESULTS

Urban Mining takes place at a range of scales, spanning from the salvage and reuse of individual building materials and products to the systematic deconstruction of existing buildings. It extends to building reuse and adaptive reuse strategies through the reuse of existing structures or elements of decommissioned buildings in-place, and the replacement/ renovation/ retrofitting of e.g. their envelopes, finishes, MEP systems, or other technologies in the effort to extend the buildings and materials lifetime.

3.1 Urban Mining Legislation

One of the mechanisms opening an opportunity for Urban Mining is emerging legislation that targets waste diversion and deconstruction. Table 1 outlines such legislation recently passed at the federal, state, and city levels in the USA.

Table 1. Existing Legislation (Us DOE, 2023) (Fritzberg & Rimoldi, 2022) (Armstrong & Lamore, 2018)

Scale	**Name**	**Implementation**	**Focus**
Federal	Executive Order 14057: Federal Sustainability Plan	By 2045	(1) Reducing greenhouse gas emissions in buildings
	2030 Challenge	By 2030	
State	Landfill Material Restrictions	CA, MA, RI	(2) Diverting specific materials from landfill
	Extended Producer Responsibility for Packaging	CA, CO, OR, ME	
State	Return Deposit Recycling Programs	NY, MI, MA, ME	(3) Economic compensation for recycling
	Regional Greenhouse Gas Initiatives (RGGI)	Yearly cap by state CA, CT, DE, ME, MD, NH, NJ, NY, RI, VT, VA, WA	(4) CO2 cap and invest
	International Green Construction Code (IgCC)	RI, OR, NC, OR	(3) Diverting % of materials from landfill
		RI, OR, NC, OR	(1) Reducing greenhouse gas emissions in buildings
	International Energy Conservation Code (IECC) 2021, 2018	VT, CT, NJ, CA, WA (2021) NH, MA, NY, PA, MD, DE, NE, OR (2018)	

City	Climate Action Plan	36 cities across multiple states[4]	
		Pittsburgh, PA	(5) Requiring deconstruction of select projects
	Deconstruction Ordinance	Portland, OR San Antonio, TX Milwaukee, WI (suspended) Baltimore, MD Palo Alto, CA	
	Construction Demolition Diversion Ordinance	Milwaukee, WI Portland, OR	
		Lee County, FL Fitchburg, WI	(2) Diverting specific materials from landfill
		Palo Alto, CA Cook County, IL Fitchburg, WI Austin, TX	(3) Diverting % of materials from landfill

Current legislation focuses mainly on operational and decommissioning policies at the end-of use, with less focus on reimplementation strategies for salvaged materials at the beginning of a new construction project. Policies such as the Buy Clean procurement policy (implemented in the Federal Climate Action Plan, several state legislations, and at the city scale), which requires purchasing of low-carbon construction materials to reduce construction greenhouse gas emissions, are beginning to address these initial phases of the building lifecycle (Carbon Leadership Forum, 2020). Furthermore, diversion of waste and materials from a decommissioned building can be significantly facilitated by the choice of demolition and deconstruction methods. The emerging legislative framework outlined in Table 1 supports the implementation of Urban Mining, as deconstruction is becoming an effective method for meeting the legal requirements of some of the outlined waste diversion mandates.

To improve streamlining the applicability of salvaged materials in new construction, regrading and certification policies must be implemented and/or deregulated. To this extent, the states of Oregon and Washington recently have changed their code specifically with regards to the reuse of reclaimed timber. The change allows reclaimed lumber to be assumed either spruce-pine-fir stud grade or hem-fir No. 2 grade, depending on the dimensions of the piece. Structural properties would therefore be assigned to the reclaimed piece consistent with the adopted standards for that type of wood, eliminating the cost and time for an accredited grader to inspect the pieces (Washington State Legislature, 2020) (Kavanagh, B., 2023).

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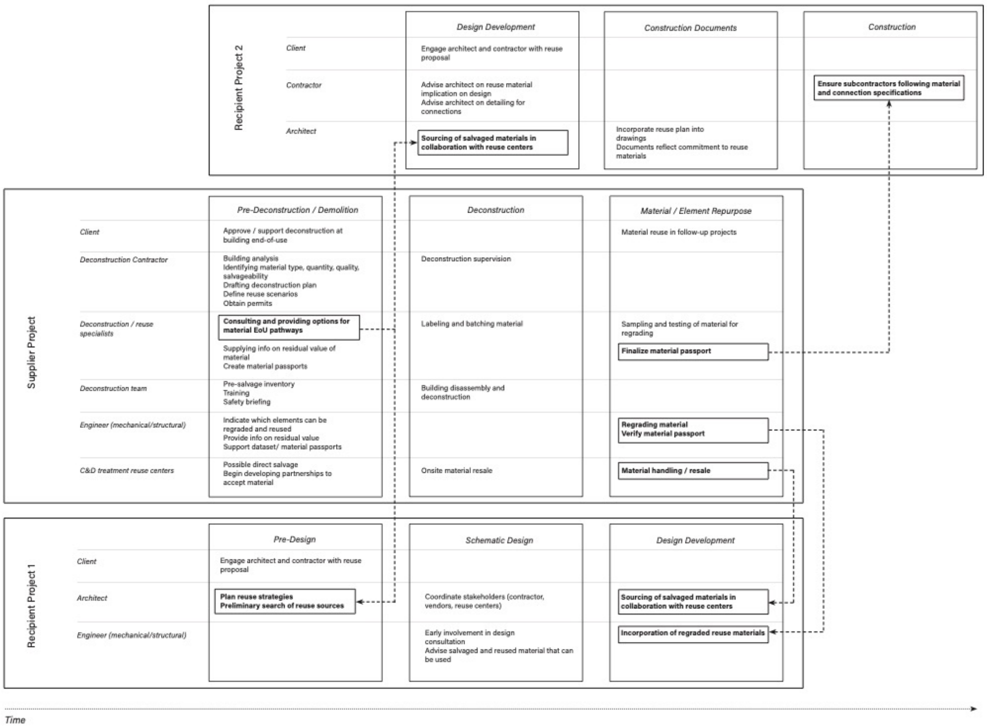
[4] Albuquerque, NM: Atlanta, GA; Austin, TX; Baltimore, MD; Boston, MA; Charlotte, NC; Chicago, Il; Cleveland, OH; Columbus, OH; Dallas, TX; Denver, Colorado; Detroit, MI; Honolulu, HI; Houston, TX; Indianapolis, IN; Ithaca, NY; Kansas City, MO; Los Angeles, CA; Louisville, KY; Memphis, TN; Miami, FL; Minneapolis, MN; New York, NY; Oakland, CA; Oklahoma City, OK; Philadelphia, PA; Pittsburgh, PA; Phoenix, AZ; Portland, OR; Raleigh, NC; Sacramento, CA; San Antonio, TX; San Diego, CA; San Francisco, CA; San Jose, CA; Seattle, WA

3.2 Stakeholders and Roles in Deconstruction/ Reuse

When seeking input on deconstruction, material reuse, and end-of-life scenarios for re-activating a building's material value, a specialist or deconstruction consultant is generally required. These specialists have skills and experience in surveying buildings and construction sites to determine the most appropriate method of deconstruction to minimize damage to materials while meeting project deadlines and goals. They also are experts in the logistics required for a deconstruction project, which differ from typical demolition. At present, these experts are not found at larger AEC firms, but instead run independent companies and practice locally (Cruz-Rios & Grau, 2020).

Figure 2 outlines the relationships between stakeholders, as well as the coordination between deconstruction specialists and architects across different projects. Because circular practices are not yet mature, extensive planning for salvaged material end-of-use (EoU) scenarios may be required (Iacovidou & Purnell, 2016). The figure presents three project scenarios: the Supplier (or Donor) Project is in the Deconstruction Phase, Recipient Project 1 is in the Design Phase, and Recipient Project 2 is in the Construction Documents and Administration Phase. Because Urban Mining practices source materials for a new project from an existing deconstructed project, collaboration amongst stakeholders across building phases is required. For example, architects designing a project with the objective to construct with reclaimed material will have to determine its appropriate sourcing and specifications. Once the architect is producing construction documents, collaboration with an engineer to determine material grading and technical specifications is required. The deconstruction contractor/ specialist working on a decommissioned project organizes EoU pathways for the salvaged material, hence finding appropriate reuse centers or projects that can receive the material.



Recipient Project 2	Design Development	Construction Documents	Construction
Client	Engage architect and contractor with reuse proposal		
Contractor	Advise architect on reuse material implication on design Advise architect on detailing for connections		**Ensure subcontractors following material and connection specifications**
Architect	**Sourcing of salvaged materials in collaboration with reuse centers**	Incorporate reuse plan into drawings Documents reflect commitment to reuse materials	

Supplier Project	Pre-Deconstruction / Demolition	Deconstruction	Material / Element Repurpose
Client	Approve / support deconstruction at building end-of-use		Material reuse in follow-up projects
Deconstruction Contractor	Building analysis Identifying material type, quantity, quality, salvageability Drafting deconstruction plan Define reuse scenarios Obtain permits	Deconstruction supervision	
Deconstruction / reuse specialists	**Consulting and providing options for material EoU pathways** Supplying info on residual value of material Create material passports	Labeling and batching material	Sampling and testing of material for regrading **Finalize material passport**
Deconstruction team	Pre-salvage inventory Training Safety briefing	Building disassembly and deconstruction	
Engineer (mechanical/structural)	Indicate which elements can be regraded and reused Provide info on residual value Support dataset/ material passports		**Regrading material** **Verify material passport**
C&D treatment reuse centers	Possible direct salvage Begin developing partnerships to accept material	Onsite material resale	**Material handling / resale**

Recipient Project 1	Pre-Design	Schematic Design	Design Development
Client	Engage architect and contractor with reuse proposal		
Architect	**Plan reuse strategies** **Preliminary search of reuse sources**	Coordinate stakeholders (contractor, vendors, reuse centers)	**Sourcing of salvaged materials in collaboration with reuse centers**
Engineer (mechanical/structural)		Early involvement in design consultation Advise salvaged and reused material that can be used	**Incorporation of regraded reuse materials**

Figure 2. Current and Anticipated Stakeholder Roles in Phases of Deconstruction (Delta Institute, 2018) (Guy & Ciarimboli, 2007)

Circular construction at present is not a significant enough consideration for architecture firms to consistently require deconstruction consulting, and therefore firms currently rarely have in-house specialists for internal advising. This further increases the need for material passports and technical specifications to be property documented and shared with all independent stakeholders involved in a deconstruction project (Vefago & Avellaneda, 2013).

3.3 Adaptive Reuse

Adaptive reuse is a highly effective sustainability practice that reutilizes existing building stock for new developments. It is a mature practice in the US AEC industry and especially implemented in cities with high building density, such as New York City (Logan, 2019). At its core, adaptive reuse is Urban Mining at the largest scale, with the onsite reuse of an existing building's structural system, including its foundation, other systems, and equipment, in the design and construction of a "new" building. The "adaptive" component requires a change in occupancy, which generally requires more significant changes to the building's spatial organization than building reuse, retrofit or renovation. Adaptive reuse can result in a 50-75% reduction of the building's carbon footprint compared to demolition and new construction (Strain, 2017).

As a sustainable design strategy, adaptive reuse has reached full maturity in the United States, with many examples of its successful implementation in various contexts across the nation (Kolomatsky, 2020). Over the past decade, there has been a 50% increase in unused office space nationwide (Logan, 2019). Many developers are responding to this low demand and are employing architects who specialize in adaptive reuse strategies to lead these build outs (for example, in New York City converting office buildings to residential) (Sweeney, 2021).

Given these trends in the US market, special attention should be given to products that are compatible with existing structures or facilitate connections between new and existing structures. Table 2 links potentials for adaptive reuse across building types based on Energy Intensity Usage (EUI) trends.

Table 2. Building Types and Potential for Adaptive Reuse Based on EUI Impact (Logan, 2019)

Type	Timeline with Highest Potential	Energy Intensity Usage (EUI)
Office	1946-1979	Largest Energy Use Intensity, demanding energy efficient intervention, largest opportunities for reducing environmental impact
Hospitality and healthcare	2000 onward	Hospitality buildings have increasing EUIs, opportunity for implementation of upgraded, energy efficient systems
Education	2008 onward	Educational buildings built in past decade have performed better, indicating large opportunity for improvement in 20th century buildings
Retail	N/A	Generally low EUI

3.4 Deconstruction Prospects for Component/ Element Types

The potential for Urban Mining can vary based on the type of component or element in question. In Table 3, various elements are separated based on their corresponding shearing layer. (Brand, 1995). The shearing layers roughly correspond to how frequent these layers are replaced or renovated within buildings, ranging from Site and Structure, which rarely change, to Space Plan and Stuff, which are less permanent and more easily removed or reconfigured. Within these categories, it is important to consider barriers to Urban Mining that are specific to these elements, which may delay deconstruction timelines or render an otherwise reusable material unsalvageable.

Table 3. Components and Urban Mining Potential (Guy & Ciarimboli, 2007)

Layer	Material/ Component	Mining potential	Barriers	Takeaways
Site	Foundations	No current application for relocation / onsite reuse possible	Compromising structural integrity, weight/ value	Modular applications increasing reprocessing potential
Structure	Concrete (cast in place)	Recycling, Reuse	Cut and preserve as slab/ column element during removal, otherwise recycling	Limited by cast in place connections
	Precast concrete	Reuse	Reuse component with same application	Steel connections
	Wood	Reuse	Connections that are difficult to remove/ damage component	Reducing amount of components
	Steel	Reuse, Recycling	Reuse component with same application	Steel components can help keep MEP layers separate
Skin	Masonry	Reuse	Wet connections	Alternatives to cement mortars
	Timber	Reuse	Wood sidings, modular elements	Overlapping system so each discrete panel can be removed for maintenance
Services	MEP	Reuse, Recycling	Integration in other systems	Separation from other layers (raised floor system, etc.)
Space Plan	Partition walls, floor systems	Reuse	Lifespans of components and damage over time	
Stuff	Appliances, scrap metal	Most common application of Urban Mining to date		

Within each shearing layer, the different elements of a building require different strategies and create different opportunities for Urban Mining. Hence, different building components not only have different functions, but also different timelines of use, methods of installation and maintenance, and different end-of-use options. For example, larger components such as structural elements (columns, beams) generally have a high opportunity for the reuse of the whole unit in a similar application. However, components of MEP systems or smaller appliances are potentially sources of scrap material that can be recycled to create new building components.

Therefore, projects with shearing layers that are constructed separately from other layers have more potential for Urban Mining, as each component can be refurbished or deconstructed without causing damage to adjacent materials or systems and can be reprocessed according to its specifications.

3.5 Deconstruction by Material Family

The reuse potential of different elements is also material specific. Steel and timber have high potential for reuse, while concrete presents material specific challenges which need to be considered for reuse. The following section outlines such challenges and opportunities.

Overall, recycling/ reuse infrastructures in the US are still underdeveloped and ineffective in sustaining large scale deconstruction practices. Most recycling practices are local and depend on the individual client as a consumer and project manager to catalyze this process, hence lacking progress on institutional and industrial scales (MacBride, 2012).

3.5.1 Concrete

The most common applications of concrete in the US are cast-in-place, which produces monolithic elements that cannot be separated, or precast concrete elements, which are usually also connected by cast-in-place concrete. This connection cannot be separated efficiently for the reuse of each individual element. Hence, the predominant use cycle for concrete construction ends in demolition and recycling instead of disassembly and reuse (Salama, 2017).

The US has the recycling infrastructure to support increasing concrete recycling, including the separation of steel reinforcements. For new and non-structural uses, concrete aggregate mixtures can be composed of 100% recycled concrete before introducing new cement. The potential for downcycling and use in industrial applications is highly relevant for mined concrete. For new structural uses, aggregate can be composed of 20-40% recycled concrete before introducing new cement. However, there is still a low supply of high-quality recycled aggregate in the United States to incentivize increased structural use (F. Ernst & P. Leutiger, personal communication, 2023).

A note of caution about the environmental impacts of recycled concrete: Replacing virgin aggregate with recycled aggregate results in environmental benefits as it reduces the impact of gravel quarrying on natural landscapes and shortens transport distances to construction sites - however, recycling concrete has no significant carbon savings as it requires the same (if not sometimes more) cement compared to regular concrete. To significantly reduce the carbon impact of concrete, renewable energy sources for the manufacture of clinker and new cement recipes as alternatives to common Portland cement need to be developed. More importantly, the direct reuse of existing concrete elements requires no new cement to be added and retains the value and utility of the existing when applicable (Salama, 2017).

3.5.2 Timber

Prerequisites for salvage are similar to other material types. The timber must be in good condition and not severely damaged by environmental factors such as heat or moisture, and not be coated or contaminated by toxic substances such as lead or asbestos. Timber structures which are mechanically fastened together with bolted or screwed connections, require the least labor to salvage, followed by timber structures connected via nails (Guy & Ciarimboli, 2007).

The greatest challenge in these cases is minimizing any damage created from the removal process of these connections. Timber structures or finishes which are primarily connected by adhesive products are not ideal candidates for salvage, as these adhesives damage the material and require labor potentially greater than the value of the material to deconstruct (Smith, 2012).

Structural timber is a key material type which can be salvaged via Urban Mining strategies. The majority of timber which exists in the urban mine is embedded in residential structures, where elements are typically nailed together in stud-frame construction. This presents a unique, material specific challenge in the processing of this material for reuse, as the denailing of the material adds an additional step to processing for reuse. There are multiple approaches to tackle this problem. Some see it as a workforce development opportunity to support a green labor force (Bluedorn et al., 2022). Others see it as an opportunity to test new technologies, such as AI and computer vision, building machines that can spot and remove nails and screws from boards without human labor (Pozzi, 2019).

3.5.3 Steel

Steel occupies a unique niche in that it is a relatively carbon intensive material, but it is also readily available for reuse and recycling. Already, the supply chain for the recycling of structural steel is robust. Given that steel components are commonly separated based on their metal grades during demolition, recycling rates up to 90% can be achieved for a building. If separated to high standards, the quality of steel can be retained during the recycling process.

From an environmental perspective, steel recycling requires high energy input that is today only rarely provided through renewable sources such as hydropower. Reuse of steel components thus produces much less processing emission. Steel sustains minimal damage due to connections between components and/ or their removal. The quality of steel as impacted by atmospheric deterioration or changing load scenarios during the use phase are more relevant criteria for assessing components for reuse and need to be documented accordingly (Silverstein, 2008) (Cooper & Allwood, 2012).

3.5.4 Glass

Insulated glazing units, or hybrid glazing systems, which use a combination of materials and assemblies, are currently unable to be reprocessed into new glazing units. The focus on improving operational qualities of glazing systems through additives such as films or coatings negatively impacts the end-of-use potential for these components. Specifically, the increased use of plastic films, which subsequently require delamination for reprocessing, reduces the feasibility of high-quality component recycling.

Downcycling processes currently provide a multitude of building products made from pre- and post-consumer glass wastes. At the same time, disassembling and separating components, or removing entire glazing systems, can lead to the direct reuse of components (glass and frame) or systems in a new project (Hartwell & Overend, 2019). Changes to building policy and energy codes are aspects limiting the direct reuse of glazing units and require innovative design solutions (Marshall, 2019) or the remanufacture of windows through take-back programs or circular business models (DeBrincat & Babic, 2018).

3.5.5 Brick

The main barrier for salvaging masonry components is the use of mortar in construction, specifically concrete-based mortar. Prior to the 20th century, brick was a circular material in practice and buildings that were demolished would be rebuilt with reused bricks. In pre-war masonry construction, lime-based mortar was used, which was weaker than the bricks and able to be dissolved chemically. However, the ubiquity of concrete in post-war construction led to the substitution of lime for cement in mortar mixes. This made the mortar stronger than the brick itself, and when demolishing post-war brick walls bricks would fragment before the mortar, making the bricks unusable (Brick Industry Association, 2023). Additionally, surface contamination of masonry components (i.e. mortar) must be cleared completely for use with new mortar to avoid water penetration and exposure to atmospheric conditions. Because of the difficulty in separating brick without damaging the components, exterior facade masonry components today are more readily reused in interior applications (Ritchie, 1971).

Emerging production processes such as StoneCycling adopt the process of upcycling construction and demolition waste to produce construction material (StoneCycling, 2023). The StoneCycling start-up in the Netherlands produces brick units for interior and exterior finishes. In the US, this process is beginning to be adopted for single projects, with the potential to evolve into product manufacturing (Redling, 2021).

4. DISCUSSION

By reviewing existing Urban Mining literature, reports and products in the United States, this paper synthesizes existing practices to create an overview of current legislation and application strategies of this concept.

In summary, the legislative landscape in the US is largely focused on end-of-use diversion of building materials, currently incentivizing (mostly) recycling and (some) reuse of materials. These legal policies will increase demand for cost-effective methods of meeting material diversion requirements, which can be met through appropriate deconstruction planning and implementation involving suitable stakeholders. These processes will require increased organization and collaboration with deconstruction specialists, deconstruction teams, project contractors and engineers, and the recipient stakeholders of the reclaimed material.

As existing buildings were not designed and built to be disassembled, architects and contractors seeking to implement Urban Mining strategies are faced with challenges in material deconstruction, preservation, and processing. This review consolidates several of the aspects that architects, contractors, engineers, and clients must be aware of and consider as they move forward with deconstruction projects or using reclaimed material. Different types of construction techniques or material connections (adhesives, some mechanical connections) can damage materials beyond repair. Standard methods for regrading reclaimed material are not yet widely used. Processes vary for different elements / materials during deconstruction and preparation for reuse (disassembling connections, reprocessing, reuse strategies) requiring adequate planning depending on the specifications of each project.

4.1 Takeaways

The following takeaways can be extracted as key points for deconstruction and Urban Mining of existing structures - and can be used as selection criteria for suitable projects:

● No adhesives: Buildings built prior to 1950 generally are absent of any adhesive products that gained popularity in post-war construction. These chemical fastening techniques damage the underlying material, reducing the material's value and generally make it more difficult to deconstruct such materials, increasing labor costs. However, renovations are common and there is no guarantee that these buildings will be totally absent of adhesives.

● Higher quality building materials: Structures built prior to 1950 typically contain materials of higher value. This is especially true for structural timber elements. Based on observation, timber salvage prior to this date generally was sourced from old-growth forests (where available regionally), and as a result is much denser and performs better in structural settings (Forrest, 2021). These buildings were also built before the development of composite and plastic materials, which are generally lower in quality and value.

● Significant elements and historic preservation: Often but not always, buildings built prior to 1950 and their materials are more valuable by reason of historic preservation. Certain fixtures and equipment are valued for their ornate detail, such as cast-iron radiators or door hinges. These elements are also more valuable as they are no longer in production, and building owners seeking to make repairs to structures from these dates will pay a premium for building elements that match the time period.

● Absence of toxicants: Buildings built before 1950 also exist within a sweet-spot of relatively toxicant-free construction. Though lead paint may still be present, many of these buildings were built prior to the widespread introduction of asbestos to the building industry. Asbestos is an especially pertinent barrier to Urban Mining, as the abatement process can delay salvage and deconstruction timelines past the point of profitability.

The following points synthesize the legislation which limited construction with toxic Substances in the United States (US EPA, 2015) (US DOS, 2022):

○ 1976 – Toxic Substances Control Act: Federal regulation on use and production of pollutants, limits (although not entirely banning) asbestos and other toxic pollutants;
○ 1978 - Federal government ban on lead paint: Pre-1940 lead-based paint was most commonly used prior to this;
○ 1979 - Toxic Substances Control Act (amendment): Polychlorinated biphenyls prohibited, regulations for light fixtures, heat transfer equipment, specialty paints;
○ 1987 - Montreal Protocol: Chlorofluorocarbons (CFC) banned, nonflammable and nonreactive coolants requirements for refrigeration units.

Once projects are selected, the following points are key to successful deconstruction to maximize the quality and quantity of reusable materials extracted:

- Visibility and access to identify building elements and components: The visibility and ease-of-access to elements and their connections within a building impacts the ability to plan for deconstruction. Surveys which document a building's material composition and construction facilitate the planning process, allowing a deconstruction contractor to plan the removal of different elements based on material and connection specifications (Heisel, McGranahan, & Boghossian, 2022).

- Component composition and quality: Both the material composition and the qualities of those materials impact the salvage and reuse of the component. Materials within a component that can be easily separated have potential for reprocessing and recycling. Alternatively, high quality components that sustain minimal damage from deconstruction can be reused within a similar application. This depends on the wear of the material and its timeline in terms of availability for reuse; the material may require further maintenance and regrading to fulfill a structural application. One business model supporting the potential for Urban Mining in buildings is Product Life Extension, increasing material durability and reparability, with material components designed for direct reuse, repair, refurbishment, and/ or remanufacturing (Milios, 2021).

  Repurposed materials must also meet aesthetic and functional requirements set by clients and architects. In some settings, materials that show wear and patina from their use over time have higher value than new or refurbished materials, but in other instances the opposite is true.

- Damage to materials/ systems/ components during deconstruction: Adhesive connections may damage entire sides of components, while mechanical connections may damage the ends of components, requiring them to be cut down to a new size. Any alterations to the component may compromise structural integrity. Materials that are contaminated (due to paints, adhesives, etc.) often cannot be reprocessed for recycling and may not be adequate for reuse (Abbott, 1996).

These concepts are exemplified in several case studies outlined in Table 4, for which the deconstructed components, materials, and their end-of-use cases are identified. The case studies provide examples of the different deconstruction strategies and end-of-use pathways for the acquired reclaimed materials. As evidenced by the salvaged components highlighted for each project, the existing implementations of Urban Mining are sensitive to the project's different shearing layers and their respective methods of deconstruction and reprocessing.

Additionally, the case studies provide evidence of stakeholder dynamics across projects in different stages of development. The collaboration between a project team which is decommissioning and deconstructing their project and a project team in the design phase is critical to maximizing the material recovery and repurposing potential of each project, essentially closing the loop in a circular material lifecycle.

Table 4. Case Studies of Urban Mining Application in the Construction Sector (Wachter, 2000) (Heisel & Hebel, 2022)

Case Study	**Building Type**	**System**	**Components/ Elements**	**Materials**	**Connections** (where known)	**End-Use**
Warner Homes, Peoria, IL	Residential	Frame structure	Frame Structure	Wood	Mechanical	Materials reused by housing authority
			Facade	High quality brick	Low quality mortar (broke off)	

			Finishes	Hardwood flooring		
Riverdale Village, Baltimore, MD	Residential	Frame structure	Frame structure	Wood		Online sale
			Joists	Wood		
			Rafters	Wood		
			Finishes	Hardwood flooring		
			Facade	Brick		
Fort Ord Pilot Deconstruction Project, Monterey, CA	Residential	Frame structure	Roof system	Dimensional lumber		Onsite public sale, donated to organizations, lumber regraded and strength tested
			Sheathing	Plywood		
			Frame structure	Wood		
Walter Reed Medical Center, Washington DC	Institutional	Frame structure	Frame structure	Aluminum	Bolted and screwed	Reassembly of entire structure and glazing for complete building reuse at St. Elizabeth's Hospital
			Panel glass	Glass		
Catherine Commons Deconstruction Project, Ithaca, NY	Residential	Frame structure	Frame Structure	Timber		Material handling, post-processing and resale through local reuse center
			Substructure	Timber		
			Flooring	Timber		

4.2 Gaps and Drivers

Table 5 summarizes the gaps and drivers for the implementation of Urban Mining within the United States AEC industry. These points highlight the opportunities to increase the application and effectiveness of this concept in architectural and construction practices.

Table 5. Urban Mining Gaps and Drivers (Milios, 2021) (Deconstruction and Building Material Reuse, 2018) (Abott, 1996)

Field	**Gaps**	**Drivers**
Deconstruction	Identification of building elements and connections	Material passports and documentation of systems; Scanning technologies
	Damage to materials/ systems/ components during deconstruction	Separation of material systems; Panelized deconstruction
Processing	Material/ element composition and quality assessment, availability for reuse	Processing tools using robotics, scanning, AI tools designed to reverse connections; Restoring reclaimed materials
	Cost and time lag of processing	
Reuse	Gaps in supply chain, networks for disassembled materials	Reuse centers, third party resellers; Policy requiring diversion of demolition waste

Several of the points identified suggest practical approaches to implementing reuse and deconstruction within the Urban Mining framework, as well as broader strategies for sustainable architectural practices. Exemplary strategies are the inventory of separate material systems when creating a deconstruction plan, the development and use of scanning technologies and processing tools to preserve material quality, and collaboration with a variety of stakeholders during each phase of a (de)construction project. Approaches that are outside the scope of Urban Mining (which is addressing the existing built environment), and can be attributed to Circular Construction (addressing future constructions) (Hebel & Heisel, 2022) include the appropriate documentation and transfer of technical specifications between stakeholders for each component of a constructed system through material passports (Heisel & McGranahan, 2024) maximizes reprocessing potential for reclaimed materials by ensuring it is correctly deconstructed, graded, applied, and maintained. Another example is designing material systems that can be assembled separately to be accessed, maintained, and deconstructed without damage to other components. These strategies also facilitate building maintenance and building analyses (such as life cycle assessments, LCA) for marketing or certification purposes.

5. LIMITATIONS

The goal of the review is to look ahead to upcoming developments in the industry and practice of Urban Mining. To identify untapped potential, the review is partially built upon non-peer-reviewed information, such as start-ups developing innovative technologies, architecture office websites, or case study reports. Biases in market reports and company websites are to be expected, especially for unique products, material systems, and case studies. While a lot of care has been taken to verify information through second sources and/or first-hand information, these data sources represent a possible limitation to the paper’s results. However, due to the number of sources used and the synthesis of data points into industry-averages and general guidelines, the authors feel the publication overcomes possible pitfalls of the chosen methodology.

6. FURTHER RESEARCH

The Urban Mining practices explored throughout this paper are increasingly implemented in the United States. Legislative, technological, and economic infrastructures are simultaneously developing to support these practices. Circular construction, including circular use of resources, drives the shift within the AEC industry towards a circular economic framework.

Through an exchange of feedback between research of existing Urban Mining practices nationwide and internationally, and the implementation of take-aways in different deconstruction case studies, guidelines and applications, the maturity and impact of this concept can be refined and tested in practice. This study also forms guidelines and practical, implementable strategies for improving sustainable architectural and construction practices. By providing an overview of the current state of the industry and projecting into its near future, this study can equip professionals and other researchers with the insight to be innovative in their own practices. Thus, collective progress can be made to increase the maturity and impact of Urban Mining in the United States construction market.

One valuable application of the outlined guidelines is to case study deconstruction projects, to test out the practicality and shortcoming of these findings and the proposed solutions to identified gaps. Consequently, the authors are continuously working to organize deconstruction projects as case studies for Urban Mining practices. Through practical applications of the strategies researched above, the authors and collaborators seek to refine its understanding of stakeholder relationships, deconstruction techniques, material considerations, and reimplementation of salvaged materials back into the construction market. These projects involve contact with the property owners, demolition contractors, reuse centers, and design/ construction firms. The authors also work on documentation and cataloging practices to refine the analysis and deconstruction methodology for each component (Heisel, McGranahan, & Boghossian, 2022). One case study project, for example, implemented panelized deconstruction (cutting and removal of entire wall sections or floor compositions before transport to a secondary site for processing) to reduce time spent on site, achieve economic compatibility as well as provide better working conditions and increase control of material flows (Heisel, McGranahan, et al., 2023).

Further studies include a review exploration of the Design for Disassembly topic, identified in the first portion of this study. As deconstruction and reprocessing for building components is increasingly practiced in the construction industry, architectural design and engineering can provide solutions facilitating these practices. For example, projects can be designed with easy access to each separated building layer, facilitating maintenance and deconstruction. This future study will build upon the principles of Urban Mining.

DECLARATIONS

Competing interests The authors declare that they have no known competing interests or personal relationships that could have appeared to influence the work reported in this paper.

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