A COMPARISON OF CIRCULAR CONSTRUCTION & DEMOLITION DEBRIS MANAGEMENT IN TWO US CITIES USING THE CIRCULARITY ASSESSMENT PROTOCOL (CAP)

Amy L. Brooks, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
Jenna R. Jambeck, University of Georgia, Athens, Georgia, USA
Madison Werner, University of Georgia, Athens, Georgia, USA
Melissa M. Bilec*, University of Pittsburgh, Pittsburgh, Pennsylvania, USA,
*Corresponding author. Email: mbilec@pitt.edu; Phone: +1(412) 648-8075

Abstract

With their position at the frontlines of local consumption and waste management challenges, cities are critical to advancing the global circular economy (CE). As research continues to advance our understanding of how the CE can be translated into practice, there is growing recognition that circular interventions must consider the unique attributes of local economies, policies, and cultures. The Circularity Assessment Protocol (CAP), developed to meet this need, provides a standardized and adaptive assessment for evaluating the full life cycle of material management to develop context-sensitive CE strategies in cities. CAP was originally developed to focus on fast-moving consumer goods such as single-use plastic packaging; this original 'plastics' CAP has been implemented in 56 cities and 16 countries. Because CE works across sectors, we developed a construction and demolition (C&D) CAP, aimed at C&D materials, which account for one of the largest waste streams globally. Here, we briefly summarize the C&D CAP and report pilot findings in two US-based case studies: Atlanta, Georgia, and Pittsburgh, Pennsylvania to demonstrate the utility of the C&D CAP.

Our comparative analysis of Atlanta and Pittsburgh revealed distinct challenges and opportunities in advancing C&D circularity in these respective contexts. Atlanta's rapid growth and development in recent years presents opportunities for implementing circular design principles focused on integrating recovered materials into new construction and developing a local appetite for concepts like deconstruction and design for disassembly. In contrast, Pittsburgh's shrinking/stabilized population growth emphasizes the need for reducing new construction, strengthening the city's existing deconstruction ordinance. Both cities face unique barriers in material recovery and reuse, as well as illegal dumping and abandoned properties, all of which are influenced by local policy frameworks and market conditions. This research advances the understanding of community-scale CE implementation by integrating principles of urban metabolism, geospatial analysis, and qualitative research methods. The adapted CAP framework also provides these municipal cases with a comprehensive tool for baseline assessment and identification of intervention strategies in C&D waste management. This work contributes to the growing body of knowledge on local-scale CE applications and offers a replicable methodology for other cities transitioning toward circular building practices.

Introduction and Motivation

As urban populations continue to grow, with projections indicating that 68% of the world's population will live in cities by 2050, the traditional linear "take-make-waste" model is becoming increasingly unsustainable. With growth in urban populations, comes growth in construction activity and infrastructure development. The built environment accounts for approximately 40% of global resource use and generates nearly one-third of the world's waste, making the transition to circular economy principles in construction and demolition (C&D) activities not just ideal but imperative. The adoption of circular principles in urban C&D activities can help cities meet their sustainability goals, enhance resource security, create new jobs in the material recovery, recycling, and remanufacturing sectors,

and build resilience against resource scarcity and price volatility. Baseline assessments and context-sensitive design can help to support local transitions to circularity in the C&D context.

We have expanded our previously developed Circularity Assessment Protocol (CAP) for cities. Initially designed to assess fast-moving consumer goods, particularly single-use plastic packaging, the original 'plastics' CAP has been successfully implemented in various cities and countries. Detailed information about this protocol has been published [1-3]. Recognizing the cross-sectoral nature of circular economy (CE) principles, we have now developed a Construction and Demolition (C&D) CAP. This new protocol targets C&D materials, which represent one of the largest global waste streams [4, 5]. The C&D CAP, like its predecessor, utilizes a hub-and-spoke model encompassing seven key elements: C&D analytics, building materials & construction, community engagement, usage, collection, end-of-cycle processes, and C&D emissions [6]. Also like the original CAP, the central hub brings together considerations of local policy, economics, and community influences from stakeholders including industry, academia, NGOs, and government entities. Here, we present an overview of translating the framework of the CAP to the C&D waste context and report pilot findings in two US-based case studies: Atlanta, Georgia and Pittsburgh, Pennsylvania.

Review of Related Work

Defining the circular economy in the construction and demolition context

While the definition of the circular economy is often self-evident among scholars and practitioners, through a systematic review of definitions, Kirchherr, et al. [7] describe the CE as “an economic system that replaces the ‘end-of-life’ concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes” (p. 229) that operates on various scales such as micro (e.g., products or companies), meso (e.g., institutions or industrial parks), or macro (e.g., cities, regions, nations). While this definition is broadly applicable to the C&D context, there are some sector-specific considerations spanning design, environmental, social, technical, and policy domains [8-10]. Further, CE in the building sector tends to span not just material cycles but also energy efficiency in buildings and sustainable development [11], emphasizing the importance of considering aspects such as permitting and construction specifications, technological limitations, quality and performance, and costs associated with adopting CE principles throughout a building life cycle [12]. Taken together, approaches for assessing circularity in this sector are wide-ranging.

Tools for assessing circularity of construction & demolition materials in cities

The evaluation of circular economy implementation in urban and construction contexts has evolved various approaches and indicators that typically emphasize local environmental considerations [13]. Material Flow Analysis (MFA) has emerged as a fundamental tool for quantifying resource flows to identify circular opportunities in cities, particularly when combined with urban metabolism studies [14]. In the construction sector, Life Cycle Assessment (LCA) frameworks have been adapted to incorporate circularity metrics, enabling the evaluation of environmental impacts across the entire building lifecycle while accounting for material recovery potential [15]. The Ellen MacArthur Foundation's Circular Buildings Toolkit has provided a standardized framework that has been modified by researchers to assess building-level circularity, measuring aspects such as recycled content, reused components, and design for disassembly at the product, building, and city scale [16].

More recently, integrated assessment frameworks have emerged that combine multiple approaches, such as the Building Circularity Index (BCI) developed by Verberne [17], which evaluates both technical and biological cycles in construction, and the National Circularity Assessment Framework for Buildings developed by the One Planet Network, which uses mixed methods approaches to evaluate circularity of buildings at the national scale [18]. Geographic Information Systems (GIS) have also been increasingly utilized to map and analyze material stocks in the built environment, enabling a better understanding of future urban mining opportunities and facilitating strategic

planning for circular material flows [19]. Despite these advances, researchers note the ongoing challenge of standardizing evaluation methods and the need for more comprehensive frameworks that can capture both quantitative and qualitative aspects of circularity in the built environment; also of note is the need for authentic community engagement.

The Circularity Assessment Protocol

The CAP is a standardized framework developed by the Jambeck Research Group at the University of Georgia to evaluate circular materials management at the community level and address aspects that are often lacking in CE assessments such as social and governmental considerations [13]. The CAP uses a systems-based approach with seven interconnected components or "spokes": Input, Community, Product Design, Use, Collection, End-of-Cycle, and Leakage. At its center are policy, economics, and governance influences from stakeholders like NGOs, academia, citizens, industry, and government. Altogether, the framework aims to provide a holistic snapshot of how materials flow through a community - from their entry as products, through their use and disposal, to potential leakage into the environment, culminating in context-specific recommendations.

A key strength of the CAP is its emphasis on community partnership and local context, working with local implementation partners who help collect data and provide cultural insights [2]. Several applications of the CAP have revealed meaningful city-scale patterns. For example, in a study on plastic pollution in cities along the Ganges River, Youngblood, et al. [3] found that areas with lower populations had higher per capita litter densities than more populated areas, challenging assumptions about population density as a predictor of pollution. Another CAP application among six cities, Maddalene, et al. [1] found that over 90% of fast-moving consumer goods used plastic packaging, with 78% of to-go items and 69% of litter items being plastic. While most products were manufactured locally, approximately 40% of brands were owned by international companies, highlighting a disconnect between product design decisions and local waste management challenges. The framework has proven particularly useful for understanding the complex relationships between product design, consumer behavior, waste management infrastructure, and environmental impacts, while emphasizing the importance of community engagement in developing effective CE solutions. Most recently, Brooks, et al. [6] have begun adapting the CAP to explore circularity of the C&D waste stream in cities, which evaluates ways to adapt the CAP to reflect unique needs of the circular built environment such as reducing new construction, design across scales, design for longevity, durability, and eventual disassembly, deconstruction, and losses of C&D materials via illegal dumping.

Technology Approach

While the conversion of the CAP to the C&D context is detailed in Brooks, et al. [6], here, we provide details about how the approach was applied into specific city cases, Pittsburgh, Pennsylvania and Atlanta, Georgia, characteristics of which are summarized in Table 1. We note that the CAP spoke names have been adapted to reflect C&D as shown in Figure 1. Case study methodology is useful for uncovering contextual nuances of complex systems, provides a flexible approach to accommodate new information as they emerge, and can uncover transferrable insights that bridge theory to practice [20]. Data collection and analysis for each case relied largely on document analysis, field observations, and semi-structured interviews. Documents included municipal, county, and state reports, as well as government and local business websites and scientific literature where available. Field observations included litter transects in 2023 (see Youngblood, et al. [3] for procedural details) as well as site visits to selected C&D waste infrastructure facilities throughout 2024. Semi-structured interviews were held with N = 19 with pertinent government, academic, nonprofit, and business representatives from Atlanta and Pittsburgh. We primarily used content analysis to evaluate documents, descriptive statistics for processing field data, and thematic analysis for interviews.

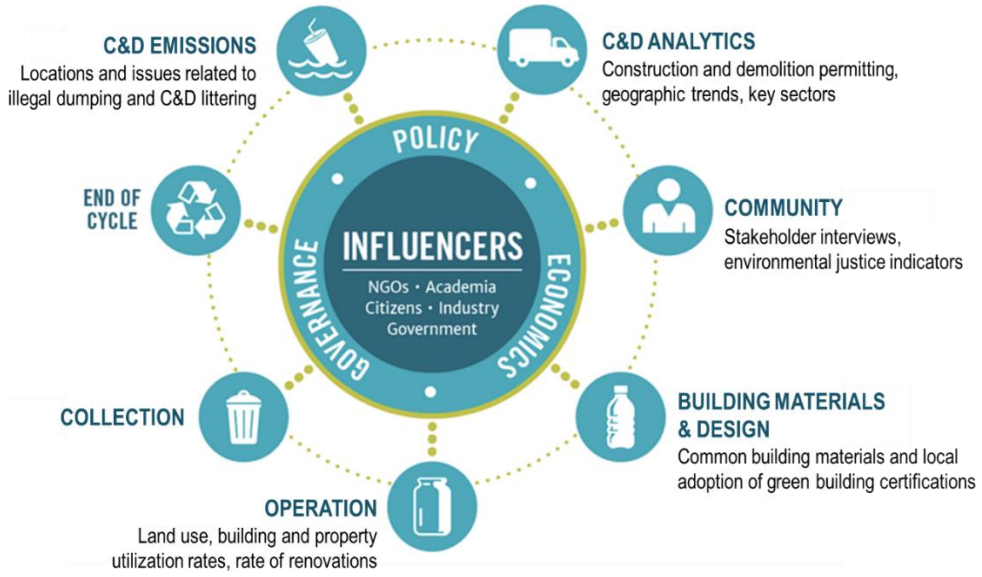

Figure 1. Overview of C&D CAP spokes and descriptions (Adapted from Brooks, et al. [6]).

Table 1. Population, geography, and industrial characteristics of cases; EPA = Environmental Protection Agency.

Case characteristics	**Pittsburgh, Pennsylvania**	**Atlanta, Georgia**
Region	Mid-Atlantic (EPA Region 3)	Southeast (EPA Region 4)
County	Allegheny	Fulton
Area (sq. mi.)[a]	55.5	135
City population (2023)[a]	303,300	510,800
Population per sq. mi. (2020)[a]	5,470	3,690
Population trend[b]	Moderately decreasing	Moderately increasing
Major sectors and businesses	Steel, healthcare, technology, and education, with major corporations including US Steel, Kraft-Heinz, and PNC Bank	Transportation, film and television, with major corporations including Coca-Cola, Home Depot, and Delta Airlines
Geographical features	Situated at confluence of Ohio, Monongahela, and Allegheny Rivers. Features steep hillsides and plateaus.	Based in the foothills of the Appalachian mountains, and proximal to the Chattahoochee River. Features rolling hills and dense tree canopy.

[a] US Census Bureau [21]
[b] Sutradhar, et al. [22]

Construction & demolition analytics

There is no standard definition of C&D debris in the United States, but the category can include inert, hazardous, or composite materials. Additionally, inconsistent regulations lead to commingling of C&D waste with municipal solid waste (MSW), making measurement of C&D components challenging. Taken together, solid waste data can be inconsistent and influenced by data collection methods, or lack of dates, units, defined assumptions, or methodologies used [5].

Here, we defer to the local community's solid waste definitions. Specifically, the City of Pittsburgh uses the following definition: "*Waste resulting from the construction or demolition of buildings and other structures, including, but not limited to, wood, plaster, metals, asphaltic substances, bricks, block and unsegregated concrete"*

(Pittsburgh Municipal Code § 619.01h). Meanwhile, the City of Atlanta defines C&D waste as follows: "*Construction and demolition waste means discarded waste building materials and rubble generally resulting from construction, remodeling, repair and demolition of buildings and pavements, including but not limited to processed wood, metal, bricks, concrete, wallboard, paper and cardboard. Construction and demolition waste does not include materials and rubble resulting from construction, remodeling, repair and demolition or buildings and pavements, that contain or have been contaminated by hazardous materials which must be handled and disposed of separately"* (Atlanta Municipal Code § 130-1b). While the cities' municipal definitions of C&D waste are similar, Atlanta differentiates C&D waste from hazardous wastes, specifying that those wastes are classified differently and require special handling. Both cities list construction and demolition as C&D waste-generating activities, but Atlanta also mentions remodeling and repair projects. Both cities also mention common building materials such as wood, metals, concrete, and bricks, but neither explicitly mentions plastics, which are increasingly being adopted in building design and materials.

Pittsburgh and Atlanta demonstrate divergent demographic and construction trends that influence their circular economy potential. While Atlanta's population continues to grow, Pittsburgh has faced depopulation, which both have implications regarding urban development and construction activity. Pittsburgh's population in 1990 was 370,139, and there was a continued decline until about 2020, reaching a population of 299,226. Since 2020, there has been a very modest uptick in population of 303,255 in 2023 [23]. Despite Pittsburgh's population, both cities exhibit increasing construction spending, suggesting opportunities for material reuse and circular practices. The building stock composition varies between the cities - Atlanta has approximately 160,000 buildings compared to Pittsburgh's 118,000, though both cities maintain similar proportions of residential structures (86-87% of total building stock). Masonry emerges as the primary construction material in both cities' residential sectors, though Atlanta shows greater material diversity in its predominantly wooden commercial structures compared to Pittsburgh's primarily steel commercial buildings.

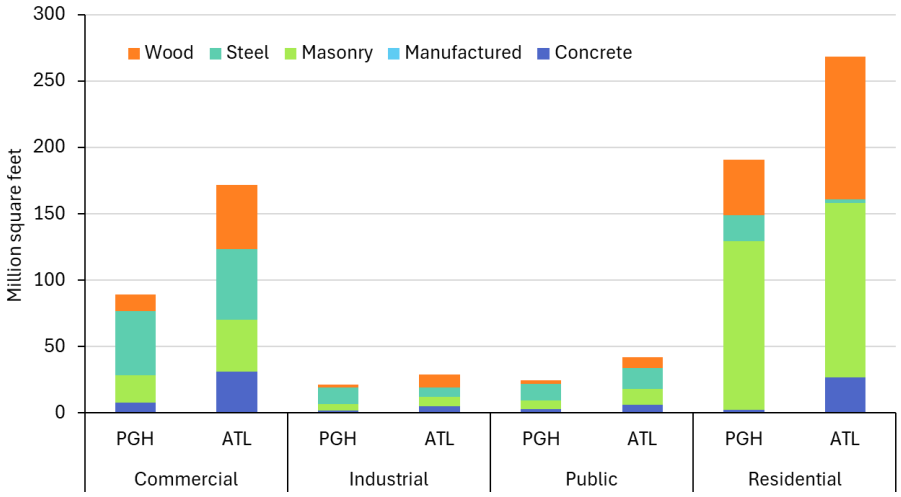

Figure 2. Comparison of building materials by sector in Pittsburgh and Atlanta. Source: [24]

Community

Stakeholder interviews revealed two common themes across both cases related to educational needs and economic barriers to advancing CE of building materials. Education of local building and design professionals was particularly prominent in both cases. For example, an Atlanta industry representative stated, *"…subs [are] the actual workforce that handles the material. That has different accountability, responsibility, awareness, and education."* Similarly, a Pittsburgh industry representative said, "*I think education has a lot to do with it. We have developers that…would*

love to do the right thing. They haven't had that light bulb moment when sustainability clicked, and they don't know where to get started. So, we'll see engineers and designers that we partner with where education is lacking and so is understanding materials." Beyond education and awareness needs, local economic barriers in both cases may be disincentivizing more circular recovery of building materials for reuse and recycling, with one Atlanta government representative stating, *"landfill tipping fees are historically low--it's a lot more feasible to throw away than recycling."* In this same vein, a Pittsburgh government representative similarly stated, *"The bar barriers have always been the low tipping fees in Pennsylvania, so that hasn't really…[made] it economical to pull anything out of the waste stream."* These similarities in barriers experienced by both cities highlight the value of finding cohesion across cities despite their broad differences and ultimately could lead to shared insight or best practices between them.

Additionally, communities within cities grapple with ongoing impacts from historical industrial, political, and economic development initiatives that cause environmental and social vulnerabilities in inequitable ways. From an environmental injustice standpoint, about 18.6% of Allegheny County (Pittsburgh) residents live in highly burdened areas, which is slightly lower than the 22.6% of Fulton County (Atlanta) residents [25]. Environmental burdens and social vulnerability contribute to both of these cities' EJ challenges, but Pittsburgh is particularly burdened by a high burden from houses built before 1980, which points to implications regarding exposure to lead-based paint for both residents and building and waste management contractors [25]. Nonprofit organizations are involved in both cities in building awareness and engaging communities around issues within the built environment that connect to community thriving and well-being.

Building materials & construction and Operations

While both Pittsburgh and Atlanta have a history of green building adoption [26, 27], the cities show different approaches to adoption of green building standards. Atlanta has a slight 'lead' in terms of LEED projects per resident, with about 46% more projects than Pittsburgh. Both cities significantly outperform the other locations shown in the graph, with the third-highest city having less than half of Pittsburgh's rate.

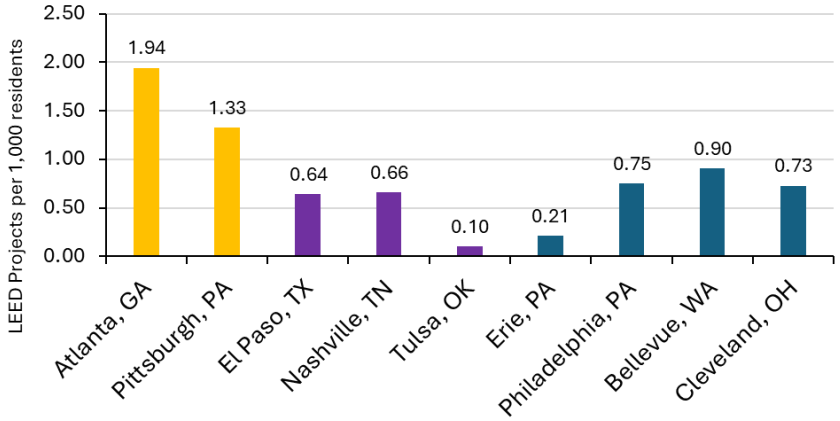

Figure 3. Comparison of LEED projects per 1,000 residents Atlanta, Pittsburgh, and other US cities (Source: US Green Building Council [28])

Land utilization patterns differ significantly between the cities as well. Atlanta maintains 65% tree cover with 27% of the area dedicated to built-up areas, while Pittsburgh's built environment accounts for 26% of the city's land cover (Figure 4). Both cities face challenges with vacant properties, though variation in reporting makes comparison between the two cities challenging. Pittsburgh has over 30,000 vacant parcels, 91% of which are residential, while

Atlanta reports 135 vacant properties available for resale through its local land bank. While this disparity suggests variations in reporting, it also highlights different opportunities and challenges for material reuse and urban renewal, with Pittsburgh having a large stock of vacant and abandoned properties that could be converted into utilized spaces via circular economy redevelopment projects.

Lastly, material reuse is a major component of advancing circularity in the built environment and both cities host organizations and facilities that are leading efforts in doing so. In Pittsburgh, a nonprofit group, Construction Junction, accepts a wide range of building materials including doors, flooring, masonry, plumbing, scrap metal, and windows, as well as a broad range of interior finishes and appliances. Similarly, in Atlanta, the Lifecycle Building Center (LBC) accepts building materials, doors, flooring, plumbing, windows, and scrap lumber, and one recycling center operates three facilities that accept a similar range of items.

Figure 4. Land cover in Pittsburgh (left) and Atlanta (right). (Source: Zanaga [29])

Collection & end-of-cycle

While C&D waste management systems are relatively similar across US municipalities, we found some important differences in C&D waste generation and treatment between Pittsburgh and Atlanta. Pittsburgh generates approximately 0.71 lbs (0.32 kg) of C&D waste per capita daily [30], while a C&D waste audit for Metro-Atlanta (includes the 10 counties surrounding the city) from 2010 shows a per capita C&D waste generation rate of approximately 1.90 lbs (0.86 kg) daily [31]. Comparatively, it is estimated that 3.70 lbs (1.68 kg) per capita per day of C&D waste are generated globally [5]. These differences likely emerge from variations in how C&D waste is measured and reported. Both cities maintain diverse waste management infrastructure, including transfer stations, recycling facilities, and material reuse centers. There are six and four landfills proximal to Pittsburgh and Atlanta, respectively, that accept C&D materials, suggesting well established landfill infrastructure available for C&D waste.

While demolition is the conventional approach to dismantling and recovering building materials at their useful end-of-life, deconstruction is a key component of CE in the built environment. Both cities benefit from robust networks of non-profit organizations supporting material reuse. Pittsburgh is one of only seven cities in the USA that have promoted deconstruction efforts [32], with an executive order put into place in 2021 that directed various city departments to contribute to a unified policy, pilot deconstruction efforts on condemned properties, and establish a Deconstruction Action Council. However, stakeholder interviews suggested that there has been some difficulty in implementing these efforts as city leadership has changed. In comparison, Atlanta has yet to adopt a city-wide ordinance, however, a nonprofit, called Build Reuse, has led deconstruction efforts in the city through raising awareness about recovery and recycling of building materials. Similarly, the LBC received a Sustainable Materials Management grant from the US Environmental Protection Agency grant in 2019 that funded a deconstruction pilot

program and the development of a community deconstruction toolkit, showing that there is some momentum for establishing and growing deconstruction efforts in the city.

Construction & demolition emissions

C&D emissions can emerge from a range of activities across all phases of construction [6], but there are few methods available for rapidly assessing the extent to which emissions may occur in a city. In the present study, we focus on emissions primarily from littering, illegal dumping, and potential building losses from natural disasters as points of comparison. Both cities face challenges with illegal dumping and C&D-related litter, though the nature and scale of these issues differ. Pittsburgh's litter surveys showed C&D materials comprised 4% of total litter items, while Atlanta reported 1.5%. Little public information was available regarding Atlanta's efforts to curb illegal dumping. In contrast, a statewide study by Keep Pennsylvania Beautiful reported an estimated $6.3 million in annual spending on prevention and abatement in Pittsburgh [33]. Similarly, a local nonprofit called Allegheny Cleanways has spearheaded efforts at reducing illegal dumping by mapping hotspots, remediating problem areas, and reporting on common products and materials found, with renovation waste consistently ranking among the most commonly dumped materials.

In addition to illegal dumping and littering, natural hazards provide a pathway for building materials to leak into the environment, though their specific vulnerabilities differ based on local geography and climate and directly measuring the relationship between the risk of natural hazards to C&D losses to the environment is currently lacking. To explore potential risks and pathways of C&D emissions to the environment, we explored the US Federal Emergency Management Agency (FEMA) National Risk Index, which reports estimated losses by natural hazards by US county. Compared to the rest of the United States, the potential for building losses due to natural hazards is relatively moderate in Atlanta and relatively low in Pittsburgh, with an estimated annual building loss of $37.3 million and $12.7 million in the cities, respectively [34]. The FEMA National Risk Index also estimates that building losses in Pittsburgh are typically driven by cold waves, ice storms, landslides, riverine flooding, and strong winds. Similarly, Atlanta is at relatively high risk of building losses due to lightning, tornadoes, riverine flooding, hail, and ice storms.

Discussion & Recommendations

Our comparative analysis of C&D circularity in Atlanta and Pittsburgh reveals how different urban contexts necessitate distinct approaches to advancing the circular economy in the built environment. While both cities demonstrate commitment to sustainable building practices, their divergent demographic trajectories—Atlanta's growth versus Pittsburgh's population's decline (1990 to 2020)—create unique challenges and opportunities. Pittsburgh's established institutional framework, including its deconstruction ordinance and robust material recovery infrastructure, positions it well for adaptive reuse and renovation of existing structures. Common challenges, such as low landfill tipping fees and illegal dumping, suggest areas where cities can share policy solutions despite their different contexts. The application of the adapted CAP framework has proven valuable in providing a comprehensive assessment tool that accounts for local conditions while maintaining comparability across cities.

Pittsburgh

- With the infrastructure to support a larger population [22], explore pathways toward reducing new construction projects through zoning changes, permitting processes, tax abatements, grants for redevelopment, etc. that could encourage adoption of green building certifications, refurbishment or renovation of legacy abandoned properties, or use of recovered or recycled building materials.

- As one of only a handful of US cities with deconstruction ordinance, Pittsburgh has the opportunity to be a national leader in this space. The city should make every effort to explore implementing the ordinance.
- While the city should continue investing in illegal dumping remediation and prevention, the high presence of abandoned, condemned, or vacant properties is likely driving illegal dumping. The city could investigate how recovery or redevelopment of such properties influences illegal dumping behaviors, particularly in known trouble areas like specific neighborhoods or land use types.

Atlanta

- With the moderately increasing population in Atlanta, there is pressure for new developments to accommodate more people and businesses. The city should continue incentivizing the adoption of green building certifications, while also exploring the adoption of a local extended producer responsibility scheme for building materials to decrease reliance on new materials, which could be accomplished through regulatory or economic instruments such as product takebacks for building components and materials that can be reused or recycled depending on their condition and structural integrity.
- Atlanta has robust leadership on deconstruction from the nonprofit sector. The city could explore converting these efforts into a city-wide ordinance or identify ways to invest in aspects of Build Reuse efforts with workforce development and revitalization.
- Little information on the city's illegal dumping challenges is publicly available beyond news reports. The city could commission a study to investigate neighborhood or land use hot spots to inform targeting strategies ranging from low-cost deterrence equipment such as fencing, signage, and lighting, maintenance and upkeep operations (e.g., mowing, beautification), bulk material collection infrastructure or events, or enforcement technology like trail cameras.

Conclusion

These findings offer valuable insights for other cities seeking to develop context-appropriate strategies for transitioning toward a more circular built environment, ultimately also aiding in decarbonization. Providing pragmatic CE solutions with communities aids in the beneficial reuse of materials and reduction in life cycle energy use. As the C&D CAP is in the earlier stages of development, we have identified some potential avenues for future work and improving the methods. First, as the C&D CAP relies heavily on publicly available desktop information, ensuring data quality and consistency between cities is a challenge. For example, in our current application, there was more recent reporting available for Pittsburgh's waste management system and quantities, while there was less publicly available information for Atlanta's. Future work could incorporate a data quality procedure that ensures a systematic and transparent reporting structure. Additionally, future iterations of this work could incorporate a wider range of local stakeholders such as community and neighborhood representatives to integrate resident or business voices into the analysis. Finally, this iteration of the C&D CAP represents a limited analytical time frame. Expansion of this work could include longitudinal monitoring, which could be effective for determining effectiveness of local initiatives such as illegal dumping prevention or redevelopment of vacant property. Further, the present study presents a qualitative synthesis of findings across the two cases with respect to the C&D CAP framework. Future work will aim to incorporate metrics such as an index or scoring system to enable visualization via spider charts and facilitate cross case and longitudinal comparisons. Additionally, robust systems-based techniques such as LCA and MFA combined with future iterations of the C&D CAP could strengthen the framework's utility by accounting for metrics such as material or energy intensity at the city scale and environmental impacts beyond losses of materials to the environment at their end of life. This research advances our understanding of community-scale CE implementation by demonstrating how urban metabolism, policy frameworks, and local market conditions interact to shape circular building practices.

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About the Authors

Dr. Amy Brooks is a Research Scientist in Sustainable Engineering at the University of Pittsburgh. She obtained her PhD in Engineering from the University of Georgia in 2021. Her research spans topics including plastic waste management, circular economy, and engineering education.

Dr. Jenna Jambeck is the Georgia Athletic Association Distinguished Professor of Environmental Engineering at the University of Georgia. She is also the founder of the Circularity Informatics Lab with a research focus on waste management, plastic pollution and circular economy.

Madison Werner is an Environmental Anthropologist and the Director of Qualitative Research for the Circularity Informatics Lab at the University of Georgia. Her research involves topics relating to circular economy, plastic waste management, and gender.

Dr. Melissa Bilec (corresponding author, presenter) is the Special Assistant to the Provost for Sustainability, Co-Director of the Mascaro Center for Sustainable Innovation, and George M. and Eva M. Bevier Professor in the Department of Civil & Environmental Engineering at the University of Pittsburgh. Her research involves the built environment, life cycle assessment, and circular economy.