detritus | Multidisciplinary Journal for Circular Economy and Sustainable Management of Residues

CISA

TOWARDS EVALUATING THE CIRCULAR ECONOMY IN THE BUILT ENVIRONMENT: INSIGHTS FROM THE CIRCULARITY ASSESSMENT PROTOCOL (CAP)

Amy Brooks [1], Nicole Bell *[,1], Jenna Jambeck [2], Madison Werner [2] and Melissa Bilec [1]

[1] *Department of Civil & Environmental Engineering, University of Pittsburgh, 153 Benedum Hall , Pittsburgh, Pennsylvania 15261, USA*
[2] *School of Environmental, Civil, Agricultural and Mechanical Engineering, University of Georgia, STEM2 Building, Athens, Georgia, USA*

Article Info:
Received:
6 May 2024
Revised:
23 September 2024
Accepted:
28 October 2024
Available online:
31 December 2024

Keywords:
Circular economy
Construction
Demolition
Built environment
Waste management
Pollution

ABSTRACT

The built environment requires extraction and consumption of enormous quantities of raw materials, water, and energy. While these materials remain in use for several years or decades, growing global populations and aging infrastructure are driving widespread generation of one of the largest and most challenging waste streams to manage. There is growing interest from communities in integrating circular economy (CE) strategies in the context of construction & demolition (C&D) material management. Many approaches for doing so focus on small-scale CE applications like individual products, materials, or projects. However, greater understanding is needed at the city-scale given communities' complex position at the frontlines of local development, resource consumption, and waste management. This study summarizes the development of an evaluative framework for community-based C&D circularity at a city or regional level. The framework expands upon a mixed methods approach called the Circularity Assessment Protocol (CAP), which integrates aspects of urban metabolism, geospatial analysis, and qualitative research methods to examine plastic waste management in communities. To advance convergent CE research, here, we aim to adapt the CAP framework to C&D. We describe our adaptation of the CAP to C&D through a conceptual review describing research, methods, and strategies related to seven elements of a local CE context: C&D Analytics, Building Material and Design, Community, Use, Collection, End-of-Cycle, and C&D Emissions. This work describes a novel yet preliminary conceptualization for developing a baseline understanding of circular C&D material management and a holistic examination of barriers, affordances, and opportunities for improving city-wide circularity.

1. INTRODUCTION

Integration of diverse expertise, disciplines, and research methodologies will be crucial for addressing increasingly complex environmental and sociotechnical issues the world faces. Though convergence research is not new, recent efforts have begun calling for such integration of scientific disciplines and researchers to develop strategies for tackling compelling topics ranging from natural hazards and disasters (Peek et al., 2020), to healthcare (Sharp & Hockfield, 2017), and nanotechnology (Roco & Bainbridge, 2013). With at least two billion metric tons of municipal solid waste (MSW) generated globally every year, research in sustainable waste management similarly needs integrated expertise and research methodologies given the economic, social, governmental, and technical aspects of managing materials. While all waste streams are salient, much attention has been given to plastic waste in the last decade, with elevated public visibility derived from the estimated 8 – 15 million metric tons entering the ocean annually (Forrest et al., 2019; Jambeck et al., 2015), primarily from land-based sources (Jambeck et al., 2020; Law, 2017). As a lightweight material, plastics comprise a small portion of construction & demolition (C&D) debris by mass (a typical metric for reporting waste quantities) relative to higher-density materials such as concrete, metal, lumber, etc. However, substantially greater quantities of global waste are from the C&D context, with nearly twice as much C&D waste generated (1.68 kg per capita) compared to municipal solid waste (0.74 kg per capita per day; (Kaza et al., 2018)). As a result, material from the built environment (BE) in which plastics are managed may be a ripe context for convergent research to develop complex interventions. In particular, the circular economy (CE) has been one of the leading concepts in both plastics and BE

* Corresponding author:
Nicole Bell
email: nicolebmascaro@gmail.com

https://doi.org/10.31025/2611-4135/2024.19444

material management, aiming to shift traditional linear (take-make-waste) systems into looping systems that efficiently maximize material use and minimize, if not completely remove, waste.

Given the integration of plastics and C&D materials, this paper reports on the progress of adapting a holistic, community-based assessment of plastic material management, called the Circularity Assessment Protocol (CAP), to the wider context of C&D materials to uncover ways to leverage community knowledge, research methods, and varying expertise related to plastics to better understand how to sustainably measure materials regardless of context or waste stream. We define C&D materials to include the materials during all the phases of the BE, from raw material extraction to production, construction, use, deconstruction, demolition, and reuse. Through integrating CE concepts in the BE, C&D waste management practices, and the CAP (herein, we refer to CAP as the original CAP developed for plastics), we aimed to develop a convergent approach for C&D that incorporates aspects of building design and planning, community interactions with the BE, C&D waste collection and treatment, and losses of material to the environment. We incorporate aspects of the original CAP that include a synthesis of the role of local government, economics, and technology. To this end, this work aims to answer the primary research question: How can the Plastics CAP be adapted and expanded for the C&D sector?

1.1 Abbreviations

MSW: Municipal solid waste
C&D: Construction & Demolition
CE: Circular Economy
BE: Built Environment
CAP: Circularity Assessment Protocol
EOC: End-of-Cycle
NGO: Non-Governmental Organization
LCA: Life Cycle Assessment
LCC: Life Cycle Costing
CBA: Cost-Benefit Analysis
MFA: Material Flow Analysis
MSA: Material Stock Analysis
BIM: Building Information Modeling
DT: Digital Twin
PET: Polyethylene terephthalate
PP: Polypropylene
NSI: National Structure Inventory
CBPR: Community-Based Participatory Research
PESTEL: Politics, Economy, Social, Technology, Ecology, and Law
EPA: Environmental Protection Agency
UN: United Nations

2. BACKGROUND & LITERATURE REVIEW

2.1 Summary of the CAP

The CAP is a standardized assessment tool used to aid decision-makers through collaboratively collecting community-level data on material usage and management of plastics. The CAP consists of seven spokes: Input, Community, Material and Product Design, Use, Collection, End-of-Cycle (EOC), and Leakage. At the center, the system is driven by policy, economics, and governance with key influencers including non-governmental organizations, industry, and government. International or national fieldwork for CAP is conducted by compensated local implementation partners, who have input on the context-sensitive design of CAP, are trained virtually on the methods of data collection, and then contribute to the analysis and dissemination of the data. For a CAP focused on the material of plastic packaging, quantitative data collected through the CAP process includes documenting the types of materials available for the packaging of fast-moving consumer goods (i.e. tobacco products, chips, candy, and grab-and-go beverages) in stores and restaurants; articulating common alternatives to plastic packaging (such as organic and compostable materials); quantifying the distance of the parent companies and manufacturers of these products; documenting the broader context of frequency and availability of various disposal methods throughout the community; and quantifying the amount of litter found in random sample sites throughout the area using the free and open data app developed at the University of Georgia, Marine Debris Tracker (herein referred to as "Debris Tracker") (Jambeck & Johnsen, 2015). Interviews with key stakeholders, including government officials, plastic manufacturers, non-governmental organizations (NGOs), grassroots groups, activists, and waste management experts are conducted. These interviews are thematically analyzed to provide a complementary qualitative analysis of the quantitative data collected.

To date, CAPs focused on plastic packaging have been conducted or are underway in 56 cities in 16 countries. Successful applications of the CAP process and results include use in the Urban Ocean program with multiple partners and many stakeholders in 11 cities around the world. An example of an intervention from the first six cities includes the creation of a waste sorting facility based on community input in Semarang, Indonesia after engaging with CAP data (150 jobs created; (Maddalene et al., 2023). Similarly, the CAP in Metro Manila revealed prominent patterns of plastic material attributes in the city, such as a high concentration of products sold in single-use multilayer film format that offers low value for recycling, which could be connected to the high prevalence of food packaging litter documented by the study (Jambeck et al., 2024). Plastics are interwoven with and are the backbone of many materials and products. Thus, we explored, in this paper, how to expand beyond plastics. We focused on construction and demolition based on the findings from our report (Bilec et al., 2020). We anticipate that this newly developed C&D CAP will continue to evolve as we pilot in regions around the world, along with exploring additional materials such as textiles and electric vehicle batteries.

2.2 Circular economy in the construction & demolition context

The concept of CE is wide-ranging, which leads to a variety of ways in which the CE is defined, applied, and measured over time (Kirchherr et al., 2018). Broadly, the CE has been defined as an economic system that shifts away from a traditional and extractive linear economy toward a looping system that ultimately reduces or eliminates the concept of waste through systems that return products and materials back into production and distribution for re-consumption. Historically, the CE has largely focused on manufactured goods and products with relatively short lifespans (Singh & Ordoñez, 2016), while CE in the built environment remains relatively underdeveloped, yet emerging, due to the individuality of construction projects, long lifespans, and unique life cycles of buildings, which themselves comprise a multitude of composite materials or products assembled into components (Pomponi & Moncaster, 2017). Unlike plastic packaging which has an average lifetime of one year, construction materials and products are designed for decades of useful life, emphasizing the substantial lag between production and manufacturing of building components and their end-of-life collection and management (Aktas & Bilec, 2012; Geyer et al., 2017). These innate phases mean that assessing or applying CE strategies must also encompass a range of dimensions such as early feasibility, planning, and design efforts, material manufacturing, construction activities, building operation, and ultimately end-of-cycle management (Çimen, 2021), which all occur over decades and potentially experience periodic changes due to building renovations, refurbishments, and even ownership.

In translating CE from an abstract concept to an applied framework, the CE can be assessed at the micro- (products, companies, consumers), meso- (eco-industrial parks), and macro-scales (city, region, nation) (Kirchherr et al., 2018; Pomponi & Moncaster, 2017). Within the built environment, there are also generally five dimensions of circularity including governmental, economic, technological, environmental, societal, and behavioral (Cruz Rios et al., 2021; Ossio et al., 2023; Pomponi & Moncaster, 2017). Interventions within these dimensions can further be oriented as top-down approaches led by national or regional entities such as market incentives for salvaged materials, extended producer responsibility policies and regulations, and green building rating systems, or bottom-up approaches such as marketing initiatives, material tracking, and prefabrication and modularization that might be led by individual businesses or grassroots organizations (Cruz Rios & Grau, 2020; Pomponi & Moncaster, 2017). Ossio et al. (2023) also identified five clusters of conceptual approaches to assessing circularity in the BE, which included focusing on C&D waste management systems, the "R" framework ("reduce, reuse, recycle"), life cycle assessment, building design approaches, and/or business models or networks that can be applied across the three scales (Figure 1). Further, ARUP & EMF (2024) developed four key principles on circularity specific to the built environment which focus on closing the loop for building materials including 1) Build nothing, 2) Build for long-term value, 3) Build efficiently, and 4) Build with the right materials. Among each of these, they have developed indicators and metrics that can be used to target specific interventions and measure impacts. This framework is adaptable across scale (i.e., micro, meso, etc.) as well as specific BE components (e.g., lighting systems, timber structures, etc.) and digital solutions (e.g., material passports), emphasizing the diversity of how CE can be evaluated in the C&D context.

2.3 Evaluating construction & demolition circularity at the city scale

There are several frameworks for evaluating the CE in the built environment at scales such as circularity of buildings (Bozeman et al., 2023; Honarvar et al., 2022; Khadim et al., 2022), construction projects (Tokazhanov et al., 2022), and building materials and products (Dräger et al., 2022). Common tools for assessing CE in construction and other sectors include life cycle assessment (LCA), life cycle costing (LCC), cost-benefit analysis (CBA), material flow analysis (MFA), or a combination of these, but historically they have focused on waste management, building design,

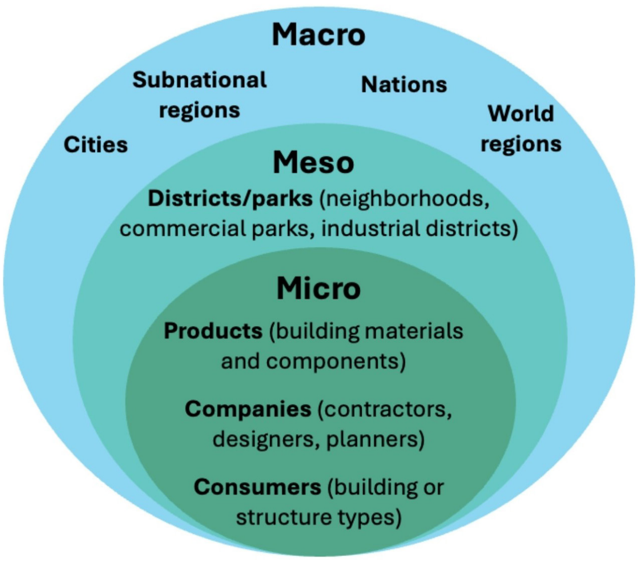

FIGURE 1: Evaluation scales for Circular Economy in the Built Environment and Construction and Demolition contexts (adapted from Kirchherr et al. (2018) and Çimen (2021).

or product design, with lagging attention on environmental impacts (López Ruiz et al., 2020; Lovrenčić Butković et al., 2023). At the city scale, CE applications have been published in recent years, though few incorporate the full life cycle of materials and products to account for losses of C&D materials to the environment (Table 1). In mapping recent city-scale CE assessments across the CAP spokes, some studies incorporate multiple aspects of material lifecycles, but these tend to be concentrated in waste applications. Additionally, few studies integrate community-based information into their material management assessments, and only one recent CE assessment accounted for losses of material (Zhu et al., 2022).

While focusing broadly on circular material management, the CAP aims to elevate aspects of the community in identifying specific interventions, filling a key gap in CE assessments in the C&D context. Place-based assessments are useful for supporting the just transition to and feasibility of local C&D CE. For example, Yung et al. (2014) focused on community-led research examining a bottom-up model of adaptive building reuse in a Shanghai historic district, finding that residents experienced an overall improvement to quality of life in connection with the preservation of historic structures and heritage, highlighting the value of interviews in retaining knowledge within communities. Other city and community-focused frameworks review completed technical assessments of the building and land use within a city as well as reviewing community efforts for sustainability (Sharifi & Murayama, 2014; Yigitcanlar et al., 2015; Zheng et al., 2017). Similarly, Doughty and Hammond (2004) reviewed "linear metabolisms of cities compared to "circular metabolisms of cities," illustrating the importance of sustainable city planning to reverse the current linear use of materials. While these approaches provide utility within a specific locale and geographic scale, aspects of waste management, such as collection and emissions of debris to the environment, were not considered.

3. ADAPTING THE CAP TO CONSTRUCTION & DEMOLITION

We identified gaps in key areas to advance C&D circularity – authentic engagement with community, pragmatic solutions derived from quantitative and qualitative methods, and holistic elements from policy, governance, and economics. Thus, we adapted the proven CAP for C&D. The development of the C&D CAP involved six iterative steps (Figure 2). Step 1 included developing a deep understanding of the CAP and building familiarity with previous applications through publications and working with the original developers. Steps 2 and 3 (the scope of this paper), included a literature review assessing circularity in the C&D context (summarized in Section 2), and the conceptual development of the C&D CAP (this section). Future publications focus on Steps 4 through 6.

While balancing our adaptation of the existing CAP, we conceptualized our translation of each CAP spoke to the C&D context through Patil et al.'s (2023) four key phases of circularity assessments including 1) goal setting and scoping based on stakeholder interests, 2) data acquisition from reliable sources, 3) circularity measurement against reference points and benchmarks, and 4) assessment of circularity impacts on system and relative stakeholders under investigation. Since the CAP and C&D CAP are intended to be conducted concurrently, we aimed to retain the underlying essence of the CAP spokes (i.e., Input, Material

TABLE 1: Examples of recent construction & demolition (C&D) circularity assessments in cities mapped across Circularity Assessment Protocol (CAP) spokes (IN = Input; CM = Community; PD = Product design; CL= Collection; EOC = End of cycle; LK = Leakage).

Reference	City, Country	CAP Spokes						
		IN	CM	PD	USE	CL	EOC	LK
Barbaro et al. (2022)	Sicilian municipalities, Italy	X			X			
De Medici et al. (2018)	Ortigia, Italy	X						
Corral et al. (2022)	Almócita, Spain	X	X					
Bao and Lu (2020)	Shenzhen, China		X				X	
Bao et al. (2019)	Suzhou, China		X					
Lederer et al. (2020)	Vienna, Austria			X	X	X	X	
Mohammadiziazi et al. (2021)	Pittsburgh, USA			X				
Arora et al. (2019)	Singapore			X				
Pearlmutter et al. (2019) [a]	Negev, Israel Rende, Italy Malmo, Sweden Freiburg, Germany			X				
Lynch (2022)	Vancouver, Canada				X	X	X	
Yu et al. (2022)	Nanjing, China Shanghia, China Hangzou, China					X	X	
Oliveira et al. (2021)	Manaus, Brazil					X	X	
Zhu et al. (2022)	26 cities, China							X

[a] *Evaluation conducted at building project scale*

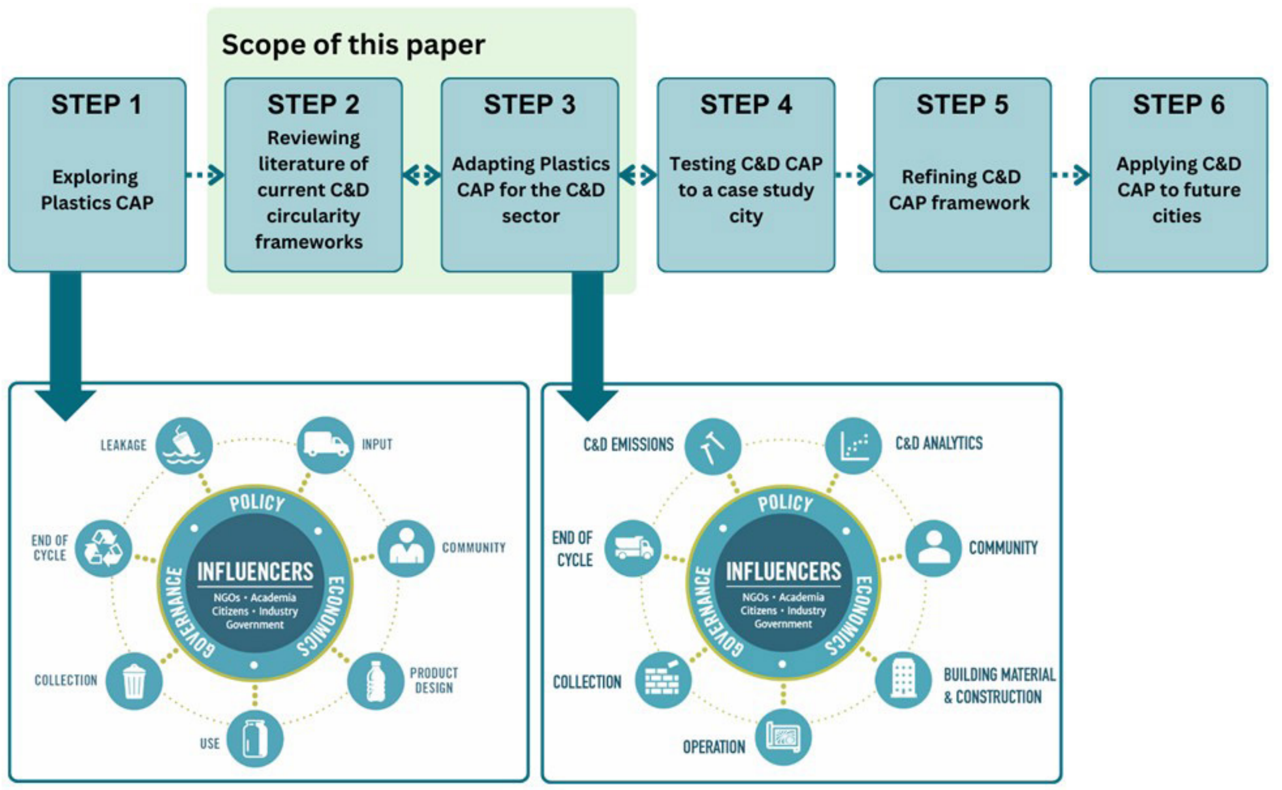

FIGURE 2: Process of adapting the Circularity Assessment Protocol (CAP) on the bottom left to the newly developed construction & demolition CAP on the bottom right. The scope of this paper is focused on Steps 2 and 3. Table 2 details changes.

& Product Design, Leakage, etc.), but adapt them to make practical sense in our sectoral application. Due to the inherent structural variation between the plastic and C&D contexts, we modified some spoke names, methods, and approaches where applicable to reflect characteristics most relevant to C&D materials in this initial version (Table 2). For example, we retained attributes such as rates of landfilling and recycling from the original CAP as criteria for the End-of-Cycle (EOC) spoke, but we modified the original Input spoke, which encompasses field surveys at retailers throughout the city under investigation to generate a profile of common plastic consumer packaging. In contrast, for the C&D CAP, we translated the Input spoke to C&D Analytics which aims to reflect attributes such as construction rates relative to city or community growth and common materials used in local construction projects and applications (i.e., residential, commercial, etc.). Finally, as we developed modifications of the CAP, we explored the availability of relevant data (including global, national, and local datasets), published scientific and grey literature related to circular C&D material management city, and sought regular discussions with the original CAP developers.

TABLE 2: Summary of conversion of the Circularity Assessment Protocol (CAP) to the construction & demolition CAP.

Spoke *	Plastic CAP approach [a,b,c]	C&D CAP approach
C&D Analytics (*Input*)	Identifying local vs. non-local producers of fast-moving consumer goods through retail sampling	Rates of new construction, demolition, and deconstruction, geographic trends, key sectors
Community	Thematic analysis of semi-structured interviews with relevant stakeholders (Local knowledge, education and awareness campaigns, etc.)	
Building materials & construction (*Product design*)	Attributes of common retail or takeaway consumer goods (e.g., weigh, material, brand, product type, etc.)	Common building materials, local regulations for green building design, local building examples
Operation (*Use*)	Identification of plastic alternatives or product delivery systems for common retail or food goods	Land use, building and property utilization rates, rate of renovations
Collection	Municipal solid waste collection practices, regulations, and infrastructure; Surveys of waste bins and collection status	Construction & demolition waste collection practices, regulations, and infrastructure; Deconstruction activities
End-of-Cycle	Plastic waste generation, composition, treatment methods	C&D waste generation, composition, treatment methods
C&D Debris Emissions (*Leakage*)	Litter density and composition via Debris Tracker [d] surveys, pollution abatement and prevention measures	Locations and issues related to illegal dumping and C&D littering via Debris Tracker [d] surveys; pollution abatement and prevention measures

** Original CAP spoke names in italics; [a] Maddalene et al. (2023); [b] Jambeck et al. (2024); [c] Youngblood et al. (2022); [d] Jambeck and Johnsen (2015)*

4. DESCRIPTION AND DEVELOPMENT OF EACH C&D CAP SPOKE

Because of the variability in methodologies, study contexts, and research objectives, we found some similarities and distinctions that helped inform the C&D CAP spokes criteria in relation to the CAP. We compiled examples of previously reported measures of circularity relevant to C&D and collated them based on the CAP spokes. We found that metrics related to 'hard' infrastructure were commonly represented in previous literature, which supported our metrics applied in the Operation, Collection, and EOC spokes such as reported waste treatment rates, composition studies, and identification of existing or needed local waste management facilities to draw CE conclusions. For example, many C&D CE studies have focused on adaptive reuse (Sharifi & Murayama, 2014; Yung et al., 2014; Zheng et al., 2017). However, few studies reported direct connections to environmental losses of C&D material despite ubiquitous recognition of the role the CE may play in preventing emissions of waste debris into the environment. Few studies incorporated mismanaged debris as criteria informing the overall assessment of the circularity of a city, district, building, or material. As such, we have adapted each CAP spoke to leverage various approaches for data collection and analysis as described in detail in the following sections. We first summarize the overarching goals, approaches, and examples from previous plastic-based applications of the CAP. We then make recommendations for the C&D CAP structured around Patil et al.'s (2023) key phases of circularity assessments by 1) defining applicable goals and/or scope of each spoke, 2) identifying outlets for relevant data acquisition and relevant reference points or benchmarking for measurement, and 3) considering potential impacts to the community and relevant stakeholders.

4.1 C&D analytics

CAP Input summary: The original CAP Input spoke aims to explore what products are sold in the community under investigation and where they originated. To understand local plastic production and input of plastic goods, the CAP involves field surveys of products sold in common retail environments (e.g., grocery stores, convenience stores, restaurants, and food vendors) and desktop research to identify local producers of plastic products. For example, Youngblood et al. (2022a) surveyed plastic-packaged fast-moving consumer goods across retailers in communities in India and Bangladesh, with a focus on snacks, candy, beverage, and tobacco items, ultimately creating a distribution map of producers and manufacturers and determining that many brand decisions were made in high-income locations away from where goods are sold, consumed, and impact participating communities.

Defining C&D Analytics goals and scope: In the C&D context, individual products and materials are difficult to survey as they are often in composite formats, difficult to access, or manufacturing information is unavailable or unfeasible to gather at the city-scale. There are two primary goals of this C&D spoke. The first goal is to take a 'pulse' of a city's C&D activity, exploring how population, geography and topography, and industries play into trends related to urban planning, a key component to circularity in cities (Petit-Boix & Leipold, 2018). The second goal is to explore the relationship between population trends and construction activity; thus, we refer to this spoke as 'C&D analytics' to reflect our focus on the city's growth/degrowth and urban planning trends used to understand the general needs and flow of building materials, which includes collecting available data on C&D trends. The geographical scope of this spoke is the city or community under consideration.

Data acquisition and benchmarking: Avoiding new construction and building for long-term value are key aspects of the EMF framework for evaluating CE in the built environment (ARUP & EMF, 2024), which uses metrics such as percent of reused floor area and building occupancy to determine if buildings are reaching their maximum utility. At the city scale, some recent studies have examined the interplay of urban development and planning issues with CE, as the volume or rate of construction compared with the rate of population change may be an indicator of circularity. Some qualitative case studies have been conducted such as De Medici et al. (2018), who documented the role of CE in the historic urban landscape of Ortigia, Italy by evaluating how knowledge and decision-making among educational, industrial, and governing institutions reflected in the broader cultural and historical development. Corral et al. (2022) similarly conducted an analysis in Almócita, Spain, a rural community dealing with depopulation, to examine how the CE has been implemented across the PESTEL elements: Politics, Economy, Social, Technology, Ecology, and Law (PESTEL). In another study, an analysis of social and economic circularity in Sicily, Italy, Barbaro et al. (2022) used the ratio of land consumption rate to the population growth rate as an indicator to explore the balance between development, population, and building use, ultimately finding that a surplus of underutilized buildings was failing to meet residential needs, potentially leading to building deterioration, decay and reduction in urban services, and threatened community identity.

Building on the work of Barbaro et al. (2022), we recommend assessing rates of construction relative to population change. By comparing construction rates and population, larger systemic issues can be revealed regarding building material management within a community. Depopulation within cities can also cause social, economic, and environmental challenges (Sutradhar et al., 2024). For example, if the population is decreasing within a community while new construction is increasing there may be an excess of raw material extraction, unnecessary site clearing and development, and ultimately construction waste, particularly if there are existing available and developed properties, structures, and buildings that are otherwise unoccupied or underutilized due to population shrinkage or migration out of the community.

Thus, we recommend informing the C&D CAP Analytics spoke with publicly available population datasets. For historical assessments, as well as consistency between CAP cases, population data can be sourced from national or international population datasets (e.g., US Census Bureau (2023) or the United Nations Statistics Division), or global geospatial datasets for estimating (e.g., Oak Ridge National Laboratory LandScan population data (Sims et al., 2023)). Many cities also collect data on building, demolition, and renovation permitting. In the US, for example, the US Census compiles residential building permit data through the Building Permit Survey, which reports national, state, and municipal building quantities and values part of its annual economic statistics (US Census Bureau, 2024). Lastly, depending on the level of detail or data availability, construction permits or value of construction put in place on a more granular spatial scale (e.g., neighborhood or zip code) and displaying this information geospatially can be used to elucidate potential material stocks, storage, and disparities in where construction is occurring.

Impact and stakeholders: Understanding a community's C&D 'pulse' can effectively highlight systemic planning issues that can help or hinder advancing local circularity. As mentioned, depopulation within cities can cause social, economic, and environmental challenges (Sutradhar et al., 2024). Key stakeholders relevant to the C&D Analytics spoke can encompass a wide range of professionals, government representatives, and the public. In particular, government representatives such as legal authorities, local development agencies, and civic institutions can raise awareness around circularity, encourage circular business practices, and use fiscal or regulatory tools to encourage sustainable development (Munaro & Tavares, 2023).

4.2 Community

CAP Community summary: The original CAP Community spoke aims to explore what conversations are happening around plastic consumer goods and what are stakeholders' attitudes and perceptions. Rooted in mixed methodology design, the CAP leverages knowledge from the community to better understand local perceptions of operations, affordances, and challenges to complement typically quantitative and technical data collected in other spokes. In previous CAP applications, researchers and local implementation partners have led interviews with key stakeholders and 'influencers' on the management of plastic consumer goods such as retail and food business owners, plastic and waste industry representatives, local government and regulatory officials, NGO operations, community leaders, informal waste workers, and members in local academia (Jambeck et al., 2024; Maddalene et al., 2023). Some CAP applications have also included social media analysis and workshops, aiming to uncover important community beliefs, attitudes, and values related to consumption and waste management behaviours (Jambeck et al., 2024).

Defining C&D Community goals and scope: The goal of the C&D community spoke, in alignment with the original CAP, is to work with the community to ensure the community's voice is heard and represented using a Community-Based Participatory Research (CBPR) framework, which aims to build trust and foster collaboration between the community. CBPR focuses on producing actionable outcomes that benefit the community directly, sharing power and resources fairly, and developing local capabilities. A crucial element of CBPR is jointly identifying problems and solutions with the community, rather than simply generating knowledge for academic purposes (Rickenbacker et al., 2020). The CBPR framework aims to not only support the community but also provide the community with technical expertise to co-create authentic solutions that are long-lasting through shared knowledge and action.

Data acquisition and benchmarking: There are several approaches to working with the community ranging from community action teams to conducting interviews (Shackleton et al., 2021). Interviews are regularly used in the C&D waste management context for developing holistic assessments of communities that are in complex social-ecological system. Several studies have used semi-structured interviews to explore the adoption of low-waste technologies at various stages of construction projects in Hong Kong (Zhang et al., 2012), determine the effect of a national green building strategy on C&D waste (Bao et al., 2020), and examine barriers and countermeasures experienced by Chinese C&D recycling enterprises (Ding et al., 2023). Similarly, Ottosen et al. (2021) used semi-structured interviews to build understanding related to scaling CE principles in Danish C&D contexts, citing the need for robust terminology in the sector, methods for documenting progress toward CE, incorporating technology such as digitalization and building passports, and supporting CE transition with improved value chains. Nghiem et al. (2020) similarly complemented their quantification of C&D waste in Vietnam with interviews investigating demolition contractors' awareness of and challenges associated with policies regulating C&D waste.

For adapting the CAP to C&D, we recommend utilizing the CBPR framework. As a first step, we suggest leveraging semi-structured interviews guided by a protocol designed to elicit participant responses related to their role and experience in their C&D context and local processes related to C&D debris management (Table S1). Like previous literature, interview participants could be selected based on input from the local implementation partners and snowball sampling (Parker et al., 2019). Similar to the CAP, C&D CAP participants should include representatives from a range of roles in academia, government, non-profits, and local businesses, and interviews should be designed to gain insight from community members to understand what efforts have already been made, what has worked, and what has not been attempted, ultimately strengthening a holistic co-understanding of gaps and opportunities. In future publications, we will consider broadening the scope to explore additional strategies for CBPR consideration.

Impact and stakeholders: The focus of the aforementioned surveys was pragmatic and expansive, yet they may have not considered authentic community outcomes. Engaging with societal complexities is needed for evaluating and advancing CE strategies in the BE (Cruz Rios et al., 2021). Including the public, in particular, can increase trust and visibility of the CE, while also encouraging greater participation in the CE agenda and local projects (Munaro & Tavares, 2023). Given the participatory nature of CBPR, CAP Community stakeholders can encompass a wide range of professionals, government representatives, and the public. In particular, community representatives, academic researchers, environmental authorities improve local CE awareness and lead CE-related projects that can advance more mindful consumption behaviors and attitudes (Munaro & Tavares, 2023).

4.3 Building materials & construction

CAP Product design summary: The original CAP Product design spoke aims to explore what materials, formats, and innovations are found in products, particularly packaging. Materials and design are critical aspects of the circular economy as upstream systemic changes in the design phase can reduce material dependencies, reduce waste, and attempt to harness it as valuable material inputs for circularity. To explore product materials and design, the CAP product samples collected during the retail and food business surveys are used to identify types of plastic packaging material and attributes such as mass, material type, and brand. Analysis of these products illuminates common formats of plastic products as well as prevalent materials. For example, Maddalene et al. (2023) found that polypropylene (PP), a low-value plastic in terms of recyclability (Moss, 2017), was prevalent among to-go packaging, representing the need for appropriate waste management strategies such as education around how to properly segregate PP items to avoid contaminating the recycling waste stream.

Defining C&D Building materials & construction goals and scope: In the C&D context, procuring and evaluating products and materials this way is less practical, as the BE comprises a range of materials, components, and products that provide specific, and often large-scale, utility such as structures, roofing, flooring, waterproofing, etc. Further, in-stock material quantities in the C&D context can be difficult to measure as the primary components of C&D materials are particularly heavy (e.g., concrete, asphalt, masonry, etc.), which can eclipse other materials like lightweight plastics used for interior and exterior finishes, waterproofing, etc. (Mohammadiziazi & Bilec, 2022). This overshadowing is evident in US estimates of C&D material consumption with concrete making up 68% of C&D debris by mass in 2018, followed by asphalt concrete (18%) and wood products (6.8%) (US EPA, 2019). As such, the goal of this spoke is to examine the existing building material stock, and the scope is within a defined time period in the geographical region of the city.

Data acquisition and benchmarking: For our adaptation to develop the C&D CAP, we explored proxy outlets for estimating common building materials and design norms in the community depending on data availability. To account for all building materials used for construction in communities, we recommend three major considerations: (1) existing buildings, (2) material origins, (3) examination of construction sites, and (4) adoption of green building standards in the community.

For determining the material composition of existing buildings, a multi-level system based on readily available data and information is recommended, largely focusing on the core and shell of the buildings (Figure 3). The first and most basic level of assessment is a visual inspection of buildings. We harness the random stratification approach used by the CAP to determine sampling locations throughout the community (See for example, (Maddalene et al., 2023); Youngblood et al. (2022)). Additionally, visual inspections should span various building types and occupancy classifications such as commercial businesses, education, industrial, residential, institutional, and utility buildings. This approach fosters active data collection and detailed observations of buildings, however, depending on the city size, the sample may not be representative.

The second level utilizes the publicly available National Structure Inventory (NSI) generated by the US Army Corps of Engineers, which at this time is limited to locations in the US. The NSI database was developed for hazard planning and includes a wide range of attributional data for buildings such as occupancy type, structure value, construction material types, foundation type and height, and square footage and number of stories (US Army Corps of Engineers, 2022). For the C&D CAP, the NSI provides spatialized data including categories for material types used per building that can be extracted based on community administrative boundaries in ArcGIS Pro. While this approach provides a spatially broader sample for analysis for the city compared to visual inspections the accuracy is limited to the material categories offered by the NSI (e.g., concrete, masonry, steel, wood, and manufactured).

Regarding levels one and two, a tiered approach should be considered. First, the top five local "heavyweight" materials (e.g., concrete and brick) should be identified through semi-structured interviews and/or searches of local construction commodities as typically heavy-weight material is more local. For example, concrete aggregate, bricks, and metals may have a more local footprint. Second, regional specifications should be identified through online sources such as governmental building codes, and if possible, obtaining specifications on specific projects is recommended to garner additional levels of depth. The material type and manufacturers should be noted and reviewed to show where materials are being manufactured and imported.

The third level is urban building material stock analysis (MSA), which is a stock-driven tool for quantifying the total available stock of material within a system (Augiseau & Barles, 2017), typically within a defined boundary such as building type, building components, geospatial, and/or the temporal scale (Mohammadiziazi & Bilec, 2022). Similarly, material flow analysis (MFA) focuses on the circulation of material through a system, that is, the sources, pathways, and sinks of material (Brunner & Rechberger, 2016), while MSA focuses on the material quantities. One way that can be utilized for C&D CAP is the MSA process developed by Mohammadiziazi and Bilec (2023), which estimated quantities of building materials used for existing buildings and renovations using geospatial and remote sensing data (e.g., LiDAR scans). A detailed analysis can provide a more in-depth overview of in-stock building material. For example, this model can account for interior flooring that cannot be seen during visual inspections.

The fourth level incorporates modeling technology, such as Building Information Modeling (BIM) or digital twins (DT) at the city scale. BIM is a process that generates

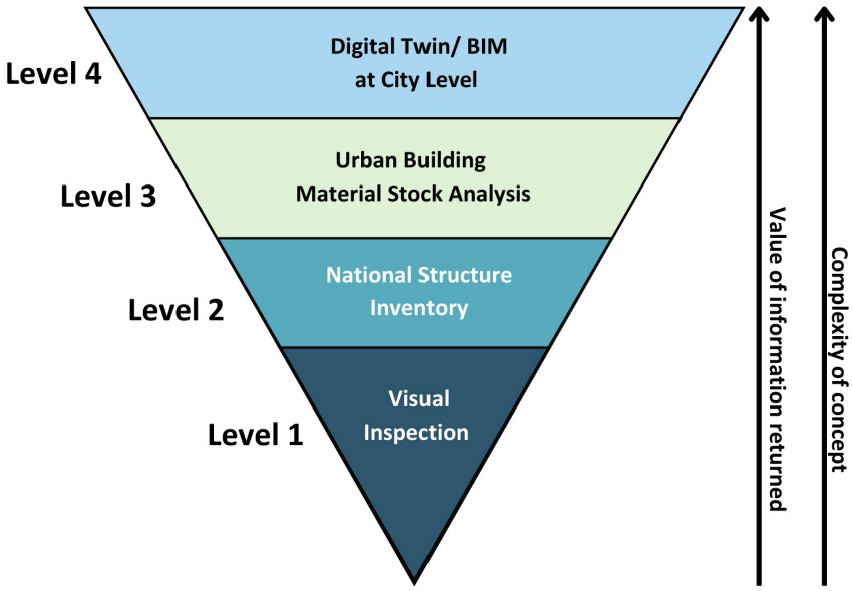

FIGURE 3: Levels of implementation for the building materials & construction spoke.

a computer-simulated building model that can be used to manage the planning, design, construction, or operations (Azhar et al., 2012). These models can be useful for estimating material stocks as they can aggregate a bill of materials, specifically listing the material type and quantity for all building components, including interior and exterior components (Zima, 2017). Similarly, a DT is a virtual representation of a physical entity that exchanges data in a real-time (Singh et al., 2021). DTs can be developed from different data streams, including but not limited to laser scanning and BIM, and "can make BIM a living instrument" (Lee et al., 2021), allowing for predictive modeling related to deconstruction and renovations (Kineber et al., 2023). While BIM has become an industry standard in recent years, DTs are a rapidly developing technology and have yet to become fully operationalized in the field of urban metabolism applications (Geremicca & Bilec, 2024). While BIMs and DTs offer promise, communities may not have the technical expertise, data, and digital infrastructure to support these models.

Impact and stakeholders: Implementing circular designs in the built environment can have many positive impacts not only on building systems in use but also in terms of sustainable materials management, for example, through uptake of bio-composite materials, prioritizing nature-based solutions in design, and selecting green building sites (Pearlmutter et al., 2019). By exploring existing building materials and design culture in CAP cities, we can identify outlets for improving the adoption of green building designs and advanced building stock management to aid in material recovery at the end of buildings' useful life. Relevant stakeholders include design, building, and construction professionals, as well as waste management subcontractors, who can integrate low-waste building techniques, specify construction waste audits, advance a culture of sustainability materials management in the local building industry, create integrated information systems through BIM or DTs, and implement design criteria to better manage C&D debris generation (Munaro & Tavares, 2023).

4.4 Operation

CAP Use summary: In a review of macro-scale circularity assessments, Harris et al. (2021) found indicators from the use phase has largely been lacking from existing literature, with a major focus on raw materials, waste generation, and recycling and recovering indicators in evaluation frameworks. Filling this gap, the original CAP Use spoke aims to explore community trends around use and reuse of various product types. The Use spoke assesses how products are procured and consumed throughout a community, including identification of broad efforts to engage the public to use alternatives to plastic or participate in plastic reduction schemes such as refill stations or bulk buying. For example, previous CAPs have surveyed if and how retailers and food businesses offer packaging alternatives such as reusable bags or implement reduction strategies such as product bans or fees. Maddalene et al. (2023)documented examples of non-plastic alternatives for to-go packaging, which may have resulted from city responses to national bans on certain plastic items.

Defining C&D Operation goals and scope: Translating this spoke to the C&D context, the goal of the Operation spoke is to understand what is occurring in the collective "use" phase of the community's building stock. In the EMF Circular Buildings Toolkit reuse, renovations, and repurposing an existing asset are key to avoiding new construction and building efficiently. Previous studies have explored land consumption and unused buildings as a critical feature of circularity. For example, along with examining land consumption rates relative to population changes in Sicilian municipalities in Italy, Barbaro et al. (2022) also evaluated unused building stock based on the Italian census data. For the C&D CAP, we suggesting using indicators such as use and rate of land development, building and property utilization rates, and rate of renovations.

Data acquisition and benchmarking: Determining vacant land locations can be useful for cities because it provides the potential for reuse or bringing community members together, for example, by creating a community garden. The next aspect to review is the building and property utilization rates. The goal is to determine what already exists within a city, what is needed, and what is excess. If available, buildings will be determined to be in use or vacant. Determining the building's occupancy status can better inform cities about what type of construction or deconstruction is necessary for growth. For example, if there is an excess of vacant homes or apartments, cities could take advantage of existing but under utilized building materials to construct more housing units. Lastly, the rate of renovation is considered. Commercial and residential renovation permits will be examined to see the frequency of renovation compared to new construction within a city. If renovation is being utilized, it can indicate cities are reducing their environmental impact by limiting new construction.

Impact and stakeholders: Strategic land usage can impact the community's heat island effect, promote biodiversity, and help a city withstand the impacts caused by climate change (Colding, 2007; Coseo & Larsen, 2014; Sachs et al., 2019). If cities are physically expanding while also experiencing land vacancies and abandoned structures, it may indicate that they are experiencing urban sprawl and missing sustainable growth opportunities. Governmental authorities and organizations can play several important roles relevant to the Operation spoke. For example, government stakeholders can improve awareness among construction professionals, waste management servicers, and the public, provide financial aid, and manage fiscal and regulatory actions to advance circularity of local C&D materials (Munaro & Tavares, 2023).

4.5 Collection

CAP Collection summary: While the upstream aspects of the CAP diverge for the two material streams (i.e., plastic consumer goods versus C&D materials), properties of material management begin to converge in downstream phases such as waste collection, treatment, and emissions. The CAP Collection spoke aims to explore how much and what types of waste are generated in communities, as well as how much waste is collected and by what means. When relevant, the approach also gathers information related to informal waste collection processes that contribute to a community's waste management system. For example, Jambeck et al. (2024) identified collection challenges associated with maintaining public waste receptacles throughout Manila as well as household waste segregation that led to inefficiencies in recovering potentially recyclable waste.

Defining C&D Collection goals and scope: We define the goal of the C&D Collection spoke to encompass documentation of quantities and types of waste from C&D activities and corresponding collection practices. C&D waste is historically challenging to quantify due to several factors such as inconsistent C&D material definitions, whether there is infrastructure in place to measure and report quantities, and how contractors operate relative to the other waste streams (i.e., MSW) (Clark et al., 2006; Kaza et al., 2018). Further, waste generation and respective collection activities can vary widely due to local economic conditions, location seasonality, and occurrence of disasters or manmade events. Additionally, C&D waste stream composition can vary from place to place due to climate-specific needs, local availability of materials, building costs, and aesthetics (Townsend & Anshassi, 2023).

Beyond quantifying waste generation and composition, identifying local systems, regulations, and organizations that contribute to collection of waste can uncover gaps or inefficiencies throughout the C&D waste management system. In the MSW context, waste is commonly collected door-to-door at a pre-determined frequency or deposited by households in central containers or locations for pick up and transport for disposal (Kaza et al., 2018). In the C&D context, debris generated on-site, including unused or scrap material, as well as packaging, can be managed through a range of options based on the phase of construction and is primarily overseen by building contractors and/or waste management servicers. Common approaches for waste collection during construction include placement of material-specific containers on site that are regularly hauled to a disposal facility, hiring of a job-site clean-up service that stages and removes debris periodically, direct utilization of primary contractor crew and equipment, and requiring subcontractors to manage their own waste staging, processing, and transport for disposal (e.g., requiring an electrical subcontractor to manage their debris). Demolition waste differs from construction waste in that it includes whole components and/or composite building materials, and often these materials are in various conditions due to use and aging.

In the context of CE, there are several demolition methods ranging from unselective demolition such as mechanical and implosive demolition, as well as hand demolition, selective salvaging, deconstruction, and soft stripping, which follow strict methods for abatement of hazardous materials that are managed separately (Townsend & Anshassi, 2023). The adoption of circular C&D waste collection methods can vary substantially, with local governance often driving uptake through incentives and ordinances as well as strategic funding or partnerships that encourage the development of local markets for salvaged materials. For example, deconstruction, which encompasses planned building disassembly to maximize recovery of reusable and recyclable materials, is required in only a few cities across the US (CR0WD, 2023), highlighting the lack of widespread integration of this important circular materials management strategy.

Data acquisition and benchmarking: Despite these challenges, there are some established and widely adopted approaches for estimating C&D waste generation and composition to help approximate demolition job costs, inform governance and policy approaches, and anticipate community planning needs (Table 3 summarizes US-based estimation methods). Such approaches include relying on historically reported data when available, taking physical measurements and sorting, correlative statistics using building and economic statistics, and MFA (Townsend & Anshassi, 2023). For the case of estimating waste generation and composition at the city or regional scale, mathematical modelling approaches may be better suited and are commonly used in extant literature. For example, Lederer et al. (2020) conducted a city-scale MFA of construction mineral wastes in Vienna, Austria, finding that the city consumed 4.4 metric tons of concrete, masonry, asphalt, and aggregate in 2014, which they ultimately used to explore various scenarios advancing local CE efforts.

Impact and stakeholders: The C&D CAP will document how C&D waste generation and collection are managed and monitored in local cities to ultimately inform steps to create more sustainable outlets that are appropriate for the community. By identifying quantities and types of C&D waste generated in a community, the CAP can help identify targeted waste reduction interventions. Similarly, CAP C&D findings can inform strategies for segregation and collection operations such as regulating or incentivizing on-site waste segregation to maximize material recovery. Relevant collection stakeholders include construction professionals such as designers, contractors, and builders, as well as waste management suppliers such as haulers and service providers (Munaro & Tavares, 2023). Together, these stakeholder groups lead jobsite management decisions, the development of guidelines related to on-site waste generation and segregation, and hauling and processing operations that are key to efficient C&D debris management and material recovery. Additionally, government stakeholders play an important role in incentivizing deconstruction activities that contribute to advancing CE at the city scale.

4.6 End-of-cycle

CAP EOC Summary: The original CAP EOC spoke aims to explore how waste is disposed in (or near) the community. While waste reduction is a high priority, effectively treating waste that is generated is critical for recovering reusable or recyclable goods and preventing losses to the environment. To understand the CAP community's solid waste management system as part of the local CE, the CAP maps the local treatment infrastructure related to consumer plastic goods, such as landfills, material recovery facilities, or composters. Additionally, this spoke can uncover the role of alternative treatment streams and local systems. For example, in addition to identifying both formal and informal waste collection outlets in Manila, Jambeck et al. (2024) also uncovered the role that informal junk shops played in recovering rigid plastics and clean PET which could be sold for recycling.

Defining C&D EOC goals and scope: In alignment with the original CAP developed for plastics, we similarly define the goal of the C&D EOC spoke to explore how C&D waste is managed and treated in the community under investigation. Broadly, non-hazardous C&D waste is often collected and treated in conjunction with MSW, however, some municipalities and countries require separate collection, sorting, and treatment. EOC treatment for C&D debris includes similar treatment outlets as plastic goods, such as recycling, landfill and permanent storage, and energy recovery. When C&D debris is not recovered for salvage, reuse, and refurbishment, there are several treatment methods that are driven by material type as well as local levels of infrastructure and economic development. In the US, 52% of C&D debris is managed via conversion to aggregate, followed by landfill (24%), and conversion to manufactured products (22%). A small fraction (<1%) is managed via conversion to fuel, soil amendments (excluding composting), and compost and mulch (US EPA, 2020). Like other phases of C&D material life cycle, the treatment of C&D waste can vary drastically from place to place. For example, in the US, regulations of C&D waste are largely under the purview of each state, resulting in a wide range of policies targeting the management of C&D waste ranging from how it is defined, how C&D landfills are designed, requirements for C&D facility permitting, and whether proximal groundwater monitoring is required (Clark et al., 2006). Additionally, recycling is heavily dependent on local drivers such as costs of recovering and market conditions, the presence of green building programs, regulatory programs or requirements, and local desire to work toward environmental or sustainability goals (Townsend & Anshassi, 2023). Taken together, understanding how various types of waste are managed can help to inform reduction targets and alternate treatment options.

Data acquisition and benchmarking: The modeling approaches to estimate C&D waste generation quantities and composition as described in the previous section (Collection) can also inform waste treatment targets. As such, we recommend using common data sources for the Collection and EOC spokes, with additional EOC-specific input from stakeholder interviews, inventories of local infrastructure, potential salvage or resale markets, and waste treatment facilities to determine where C&D waste is disposed of and

TABLE 3: Examples of US-based approaches for estimating quantities of construction & demolition waste generation, composition, and end-of-cycle management (Adapted from Townsend and Anshassi 2023).

Approach	Source	General method description
Construction statistics	US EPA, Franklin Associates (1998)	Estimates building-related debris using correlation of production statistics for six construction & demolition sectors: residential and non-residential construction, demolition, and renovation.
Consumption statistics-based material flow analysis	Cochran and Townsend (2010)	Estimates total construction & demolition debris generation based on type of construction project (e.g., new vs. renovation) with consideration of material input
Disposal statistics-based material flow analysis ("CDDPath")	Townsend et al. (2019)	Estimates construction & demolition debris generation and incorporates end-of-life management pathways (e.g., landfill, recycling, etc.) and secondary feedback and markets for 12 material types

identify outlets for landfill diversion and improved recycling and reuse. Like the Collection spoke, waste quantities can be used as benchmarking metrics to help examine how various EOC interventions are impacting waste treatment over time.

Impact and stakeholders: The EOC spoke can help identify gaps in the local waste management system, as well as identify potential outlets for material recovery. Improving EOC waste treatment encourages efficient use of material resources and prevents C&D debris emissions to the environment. For example, Blengini (2009) showed that recycling of building materials can be environmentally beneficial by offering reductions in energy consumption and greenhouse gas emissions. Further, improving the capture and treatment of C&D debris that cannot be recycled or reused can lead to reduced environmental impacts such as land degradation and pollution. Relevant EOC stakeholders include government authorities and establishments, who might advance integrated CE processes, guidelines, and funding into the local waste management system, as well as waste management suppliers such as haulers, processers, and service providers (Munaro & Tavares, 2023), who may lead decision-making around waste operations, including data collection and reporting.

4.7 C&D Emissions

CAP Leakage summary: The CAP Leakage spoke aims to explore what materials end up in the environment and relevant leakage pathways. To do so, the CAP documents litter via field transect surveys and observations, establishing a litter density and composition which can then be connected with findings from interviews with local stakeholders and literature to develop strategies for intervention. Both Maddalene et al. (2023) and Youngblood et al. (2022a) found variation of litter densities across sampled cities and population densities in south and southeast Asian communities, finding that higher populations did not necessarily correspond to higher litter densities. Similarly, the CAP revealed that the proportion of plastic in litter found in Manila, Philippines (Jambeck et al., 2024), was less than that found in cities with relatively developed economies located in the United States (UN Environment, 2021).

C&D Emissions goals and scope: In the case of C&D, we similarly define the scope of the C&D Emissions spoke to explore what and how C&D materials end up in the environment. First, C&D debris emissions can encompass a wide range of materials including such as concrete, roofing, lumber and wood products, gypsum board, steel, finishes and components such as carpeting, paint, appliances and electronics, insulation, ducting, and inert waste such as aggregate, dirt, and sand (Townsend & Anshassi, 2023). Additionally, there are a range of emission pathways for C&D debris throughout the building life cycle (Figure 4), such as littering and illegal dumping/fly-tipping (Du et al., 2021), natural disasters (Dubey et al., 2007), and building wear and tear (Müller et al., 2020). Active C&D job sites may be an important source of lost materials (Zadjelovic et al., 2023), though most construction pollution research is focused on managing particulate emissions (Cheriyan & Choi, 2020) rather than solid waste debris losses, which may often be presumed to be collected and managed. As such the scope of the C&D Emissions scope must be expanded to include various leakage pathways relevant to the C&D life cycle.

Data acquisition and benchmarking: The C&D CAP can leverage similar approaches as the CAP to document debris losses (i.e., transect surveys), but due to the variation in seasonality and building and construction lifetimes, other supplemental methods might include surveys of C&D jobsites and illegal dumping hotspots. Few methods have been established to specifically target C&D macro-debris losses, potentially due to unclear definitions delineating C&D emissions from other sources and sectors. However, few studies exist that specifically document jobsite losses,

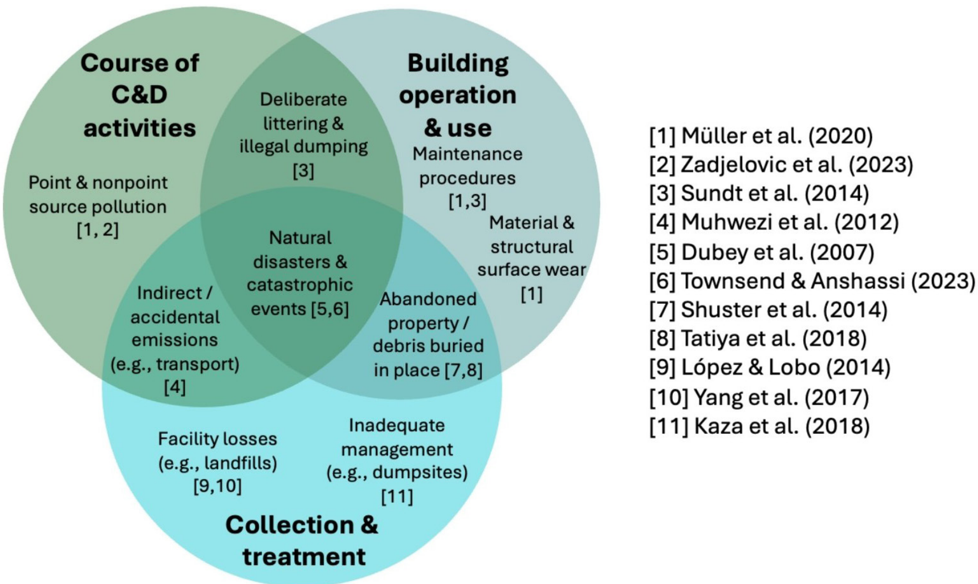

FIGURE 4: Sources of C&D debris emissions and exemplary references.

highlighting a need for establishing survey procedures. Zadjelovic et al. (2023) conducted field surveys proximal to a construction site in Chile to document losses of expanded polystyrene material used in sidewalk expansion joints, while Järlskog et al. (2021) sampled stormwater inlets, street swept debris, and road dust to examine pollutants lost from a reconstruction project in Gothenburg, Sweden. The C&D CAP could similarly track losses adjacent to active construction areas, in addition to documenting other potential pathways for construction losses to the environment. Findings from the C&D CAP can be referenced against previous surveys that may have been conducted by the community, local nonprofits, or academic researchers. Additionally, C&D CAP cases can be compared based on leakage density or product and material composition. In cases that have not yet established litter surveys, the C&D CAP will act as a benchmark, providing critical knowledge around C&D material losses such as materials or products that can be targeted, hotspots or community areas that can be mitigated via enforcement or continued monitoring activities, etc.

Impact and stakeholders: Ultimately, knowing the profile and locations of C&D debris losses can help inform upstream efforts to curb them such as monitoring, enforcement of litter and dumping policies, and education efforts that are adapted to the local community. As one of the most impactful issues of material management, reducing impacts from pollution can bring important change to communities. Losses may be prevented by integrating CE-based strategies into construction and building policies, with one recent study finding that CE policies may reduce construction-related air pollution by 2.92% (Zhu et al., 2022). Further, connecting upstream strategies to leaked materials could aid in offsetting costs for cleaning up illegal dumpsites (Du et al., 2021). Key stakeholders for this spoke include community members who may be impacted by inadequately managed C&D waste, local contractors or businesses who may contribute to illegal dumping, organizations that conduct cleanups and education campaigns, and policymakers who decide on local ordinances that encourage and regulate sound waste management systems and prevent leaked materials from reaching the environment in the first place (Santos et al., 2019).

5. RECOMMENDATIONS & CONCLUSIONS

Importantly, we propose an iterative process to allow for community empowerment, progressive assessment, and reflection. CE assessments offer an essential utility by generating baseline measurements that can be used as reference points to monitor impacts and make informed decisions (Patil et al., 2023). Therefore, we recommend the following: 1) compilation of initial findings/assessment; 2) review of the initial findings with the community and then refinement of the assessment; and 3) reporting of findings and identification of strategies (Figure 5). The initial assessment is the first phase of the C&D CAP providing a general overview of construction and demolition materials being used and discarded within a city. Information gathered from the initial assessment is presented to stakeholders within the community. Based on the objectives determined by groups, the C&D CAP will be reassessed within the city. Based on the results from the focused C&D CAP, opportunities are provided and implemented by stakeholders.

We note that in its current form, the C&D CAP has been conceptualized based on exploring data outlets and accessibility with a US-based and urban perspective given the authors' positioning. As a result, the initial concept of the C&D CAP presented here is based upon assumptions of data availability and access that may need to be adjusted in locations where reporting of construction, demolition, or general waste management data are not common or consistent. To address this limitation, future iterations of the C&D CAP will aim to explore ways to integrate the use of proxy representations or maximize the use of standardized, global datasets when needed.

Further, the CAP comprises a wide range of topics, knowledge, and methods. Here, we have generated a brief overview of potential evaluation tools relevant to each spoke, with the anticipation that future work will further investigate theory, methods, and relevant applications to fulfill C&D CAP needs in a robust manner, including application and testing of methods in C&D CAP case cities. Additionally, a key facet of the original CAP method is the co-creation of community knowledge with local implementation partners. As we examine outlets for generating understanding of C&D debris management at the city-scale, we anticipate identifying areas for inclusive and participatory ways for community members to be involved in the work beyond stakeholder engagement. For example, trained community members could lead visual inspections as part of the Building materials & construction spoke or could contribute to documenting C&D litter and illegal dumping locations as part of the C&D Emissions spoke.

We note that the approach used by the CAP aims to generate transferable, rather than generalizable findings, such that practical interventions are case-specific but can offer insights to other locales in the form of lessons learned or best practices. The nature of case studies means that the trajectory of evaluation is not always systematic or linear, which highlights the importance of considering data reliability, issues that the methodology has been criticized for in the past. However, these issues can be addressed throughout the case study research process by clearly defining the research goal and design, establishing a robust data collection and case analysis protocol, and elaborating on methods in reporting (Quintão et al., 2020). Additionally, validity techniques such as triangulation and member checking can help support validating study findings, while researcher reflexivity can help identify prior assumptions or biases that could influence qualitative data collection and analysis (Mays & Pope, 2000; Torrance, 2012). Lastly, relying on public datasets, such as those generated by municipalities or local contractors, could lead to inconsistencies in methods, reporting, units, and definitions that can make assessing solid waste challenging (Kaza et al., 2018). One recent project adapting climate change methods to the issue of plastic pollution called Project Drawdown created a rating system for various data sources used in their case evaluations that could be similarly useful in the application of the C&D CAP (Royle et al., 2022).

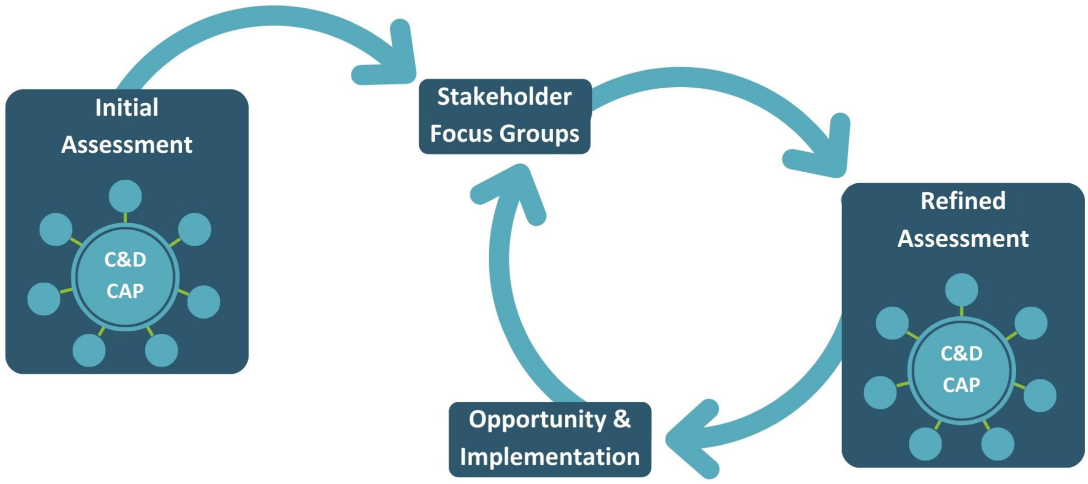

FIGURE 5: Iterative process of C&D CAP assessment.

By assessing the full life cycle of C&D materials at the macroscale (e.g., cities, communities), we can identify opportunities for aligning various parts of the local CE. For example, by understanding community needs, we can identify outlets for workforce development, capacity building, and potential issues of safety and well-being in relation to the C&D activities. Further, the nature of the CAP as a community-based framework portends that outputs and deliverables of the CAP are both specific to each case as well as accessible to a wide audience in order to foster open dialogue and collaboration. Supporting cities' transitions to the CE can be instrumental for advancing global circularity. The methodological concept presented here aims to strengthen implementation of such local transitions by looking across the full life cycle of C&D, while also paving a pathway for convergence among multiple sectors.

ACKNOWLEDGEMENTS

The authors wish to thank their partners in the City of Pittsburgh who helped to conceptualize the C&D CAP by sharing their local expertise, knowledge, and data with the team. These partners included representatives from Allegheny Cleanways, Construction Junction, Carnegie Mellon University, Green Building Alliance, and Grounded. This material is based upon work supported by the National Science Foundation under Grant Nos. 1934824, 2236080, 2345080.

REFERENCES

Aktas, C. B., & Bilec, M. M. (2012). Impact of lifetime on US residential building LCA results. The International Journal of Life Cycle Assessment, 17(3), 337-349. https://doi.org/10.1007/s11367-011-0363-x

Arora, M., Raspall, F., Cheah, L., & Silva, A. (2019). Residential building material stocks and component-level circularity: The case of Singapore. Journal of Cleaner Production, 216, 239-248. https://doi.org/10.1016/j.jclepro.2019.01.199

ARUP & EMF. (2024). Circular Buildings Toolkit. Arup. https://ce-toolkit.dhub.arup.com/framework

Augiseau, V., & Barles, S. (2017). Studying construction materials flows and stock: A review. Resources, Conservation and Recycling, 123, 153-164. https://doi.org/10.1016/j.resconrec.2016.09.002

Azhar, S., Khalfan, M., & Maqsood, T. (2012). Building Information Modeling (BIM): Now and beyond [Journal Article]. The Australasian Journal of Construction Economics and Building, 12(4), [15]-28. https://search.informit.org/doi/10.3316/informit.013120167780649

Bao, Z., & Lu, W. (2020). Developing efficient circularity for construction and demolition waste management in fast emerging economies: Lessons learned from Shenzhen, China. Science of The Total Environment, 724, 138264. https://doi.org/10.1016/j.scitotenv.2020.138264

Bao, Z., Lu, W., Chi, B., & Hao, J. (2020). Construction waste management performance in green building: Contextualising LEED in China. Detritus.

Bao, Z., Lu, W., Chi, B., Yuan, H., & Hao, J. (2019). Procurement innovation for a circular economy of construction and demolition waste: Lessons learnt from Suzhou, China. Waste Management, 99, 12-21. https://doi.org/10.1016/j.wasman.2019.08.031

Barbaro, S., Napoli, G., & Trovato, M. R. (2022). Circular Economy and Social Circularity. Diffuse Social Housing and Adaptive Reuse of Real Estate in Internal Areas. In F. Abastante, M. Bottero, C. D'Alpaos, L. Ingaramo, A. Oppio, P. Rosato, & F. Salvo (Eds.), Urban Regeneration Through Valuation Systems for Innovation (pp. 229-244). Springer International Publishing. https://doi.org/10.1007/978-3-031-12814-1_14

Bilec, M. M., Beckman, E. J., Jambeck, J., Locklin, J., Jiang, G., Cruz, F., & Ford, R. (2020). NSF convergence accelerator: Design for circular economy from molecules to the built environment workshop report.

Blengini, G. A. (2009). Life cycle of buildings, demolition and recycling potential: A case study in Turin, Italy. Building and Environment, 44(2), 319-330. https://doi.org/10.1016/j.buildenv.2008.03.007

Bozeman, J. F., Chopra, S. S., James, P., Muhammad, S., Cai, H., Tong, K., Carrasquillo, M., Rickenbacker, H., Nock, D., Ashton, W., Heidrich, O., Derrible, S., & Bilec, M. (2023). Three research priorities for just and sustainable urban systems: Now is the time to refocus. Journal of Industrial Ecology, 27(2), 382-394. https://doi.org/10.1111/jiec.13360

Brunner, P. H., & Rechberger, H. (2016). Handbook of material flow analysis: For environmental, resource, and waste engineers. CRC press.

Cheriyan, D., & Choi, J.-h. (2020). A review of research on particulate matter pollution in the construction industry. Journal of Cleaner Production, 254, 120077. https://doi.org/10.1016/j.jclepro.2020.120077

Çimen, Ö. (2021). Construction and built environment in circular economy: A comprehensive literature review. Journal of Cleaner Production, 305, 127180. https://doi.org/10.1016/j.jclepro.2021.127180

Clark, C., Jambeck, J., & Townsend, T. (2006). A Review of Construction and Demolition Debris Regulations in the United States. Critical Reviews in Environmental Science and Technology, 36(2), 141-186. https://doi.org/10.1080/10643380500531197

Cochran, K. M., & Townsend, T. G. (2010). Estimating construction and demolition debris generation using a materials flow analysis approach. Waste Management, 30(11), 2247-2254. https://doi.org/10.1016/j.wasman.2010.04.008

Colding, J. (2007). 'Ecological land-use complementation' for building resilience in urban ecosystems. Landscape and Urban Planning, 81(1), 46-55. https://doi.org/10.1016/j.landurbplan.2006.10.016

Corral, F. J., Vázquez, R. M., García, J. M., & de Pablo Valenciano, J. (2022). The Circular Economy as an Axis of Agricultural and Rural Development: The Case of the Municipality of Almócita (Almería, Spain). Agronomy, 12(7).

Coseo, P., & Larsen, L. (2014). How factors of land use/land cover, building configuration, and adjacent heat sources and sinks explain Urban Heat Islands in Chicago. Landscape and Urban Planning, 125, 117-129. https://doi.org/10.1016/j.landurbplan.2014.02.019

CR0WD. (2023). Building Sustainable Communities and Circular Economies: A Local Government Policy Guide to Alternatives to Demolition through Deconstruction and Building Reuse. https://www.cr0wd.org/_files/ugd/52fa8e_7132447b0ded417bbdc657b3ee7abfae.pdf

Cruz Rios, F., & Grau, D. (2020). Circular Economy in the Built Environment: Designing, Deconstructing, and Leasing Reusable Products. In S. Hashmi & I. A. Choudhury (Eds.), Encyclopedia of Renewable and Sustainable Materials (pp. 338-343). Elsevier. https://doi.org/10.1016/B978-0-12-803581-8.11494-8

Cruz Rios, F., Grau, D., & Bilec, M. (2021). Barriers and Enablers to Circular Building Design in the US: An Empirical Study. Journal of Construction Engineering and Management, 147(10), 04021117. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002109

De Medici, S., Riganti, P., & Viola, S. (2018). Circular Economy and the Role of Universities in Urban Regeneration: The Case of Ortigia, Syracuse. Sustainability, 10(11).

Ding, Z., Wang, X., & Zou, P. X. W. (2023). Barriers and countermeasures of construction and demolition waste recycling enterprises under circular economy. Journal of Cleaner Production, 420, 138235. https://doi.org/10.1016/j.jclepro.2023.138235

Doughty, M. R. C., & Hammond, G. P. (2004). Sustainability and the built environment at and beyond the city scale. Building and Environment, 39(10), 1223-1233. https://doi.org/10.1016/j.buildenv.2004.03.008

Dräger, P., Letmathe, P., Reinhart, L., & Robineck, F. (2022). Measuring circularity: evaluation of the circularity of construction products using the ÖKOBAUDAT database. Environmental Sciences Europe, 34(1), 13. https://doi.org/10.1186/s12302-022-00589-0

Du, L., Xu, H., & Zuo, J. (2021). Status quo of illegal dumping research: Way forward. Journal of Environmental Management, 290, 112601. https://doi.org/10.1016/j.jenvman.2021.112601

Dubey, B., Solo-Gabriele, H. M., & Townsend, T. G. (2007). Quantities of Arsenic-Treated Wood in Demolition Debris Generated by Hurricane Katrina. Environmental Science & Technology, 41(5), 1533-1536. https://doi.org/10.1021/es0622812

Forrest, A., Giacovazzi, L., Dunlop, S., Reisser, J., Tickler, D., Jamieson, A., & Meeuwig, J. J. (2019). Eliminating Plastic Pollution: How a Voluntary Contribution From Industry Will Drive the Circular Plastics Economy [Perspective]. Frontiers in Marine Science, 6(627). https://doi.org/10.3389/fmars.2019.00627

Franklin Associates. (1998). Characterization of building-related construction and demolition debris in the United States (The US Environmental Protection Agency Municipal and Industrial Solid Waste Division Office of Solid Waste, Issue.

Geremicca, F., & Bilec, M. M. (2024). Searching for new Urban Metabolism techniques: A review towards future development for a city-scale Urban Metabolism Digital Twin. Sustainable Cities and Society, 107, 105445. https://doi.org/10.1016/j.scs.2024.105445

Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, use, and fate of all plastics ever made. Science Advances, 3(7), e1700782.

Harris, S., Martin, M., & Diener, D. (2021). Circularity for circularity's sake? Scoping review of assessment methods for environmental performance in the circular economy. Sustainable Production and Consumption, 26, 172-186. https://doi.org/10.1016/j.spc.2020.09.018

Honarvar, S. M. H., Golabchi, M., & Ledari, M. B. (2022). Building circularity as a measure of sustainability in the old and modern architecture: A case study of architecture development in the hot and dry climate. Energy and Buildings, 275, 112469. https://doi.org/10.1016/j.enbuild.2022.112469

Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., & Andrady, A. (2015). Plastic waste inputs from land into the ocean. Science, 347. https://doi.org/10.1126/science.1260352

Jambeck, J. R., & Johnsen, K. (2015). Citizen-Based Litter and Marine Debris Data Collection and Mapping. Computing in Science & Engineering, 17(4), 20-26. https://doi.org/10.1109/MCSE.2015.67

Jambeck, J. R., Maddalene, T., Youngblood, K., Oposa, A., Perello, H., Werner, M., Himelboim, I., Romness, K., Mathis, J., Keisling, C., & Brooks, A. L. (2024). The Circularity Assessment Protocol in Cities to Reduce Plastic Pollution. Community Science, 3(1), e2023CSJ000042. https://doi.org/10.1029/2023CSJ000042

Jambeck, J. R., Moss, E., Dubey, B., Arifin, Z., Godfrey, L., Hardesty, B. D., Hendrawan, I. G., Hien, T. T., Junguo, L., Matlock, M., Pahl, S., Raubenheimer, K., Thiel, M., Thompson, R., & Woodall, L. C. (2020). Leveraging Multi-Target Strategies to Address Plastic Pollution in the Context of an Already Stressed Ocean. https://oceanpanel.org/blue-papers/pollution-and-regenerative-economy-municipal-industrialagricultural-and-maritime-waste

Järlskog, I., Strömvall, A.-M., Magnusson, K., Galfi, H., Björklund, K., Polukarova, M., Garção, R., Markiewicz, A., Aronsson, M., Gustafsson, M., Norin, M., Blom, L., & Andersson-Sköld, Y. (2021). Traffic-related microplastic particles, metals, and organic pollutants in an urban area under reconstruction. Science of The Total Environment, 774, 145503. https://doi.org/10.1016/j.scitotenv.2021.145503

Kaza, S., Yao, L., Bhada-Tata, P., & Van Woerden, F. (2018). What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050. (Urban Development Series, Issue.

Khadim, N., Agliata, R., Marino, A., Thaheem, M. J., & Mollo, L. (2022). Critical review of nano and micro-level building circularity indicators and frameworks. Journal of Cleaner Production, 357, 131859. https://doi.org/10.1016/j.jclepro.2022.131859

Kineber, A. F., Singh, A. K., Fazeli, A., Mohandes, S. R., Cheung, C., Arashpour, M., Ejohwomu, O., & Zayed, T. (2023). Modelling the relationship between digital twins implementation barriers and sustainability pillars: Insights from building and construction sector. Sustainable Cities and Society, 99, 104930. https://doi.org/10.1016/j.scs.2023.104930

Kirchherr, J., Piscicelli, L., Bour, R., Kostense-Smit, E., Muller, J., Huibrechtse-Truijens, A., & Hekkert, M. (2018). Barriers to the circular economy: Evidence from the European Union (EU). Ecological Economics, 150, 264-272.

Law, K. (2017). Plastics in the Marine Environment. Annual Review of Marine Science, 9, 205-229.

Lederer, J., Gassner, A., Kleemann, F., & Fellner, J. (2020). Potentials for a circular economy of mineral construction materials and demolition waste in urban areas: a case study from Vienna. Resources, Conservation and Recycling, 161, 104942. https://doi.org/10.1016/j.resconrec.2020.104942

Lee, D., Lee, S. H., Masoud, N., Krishnan, M. S., & Li, V. C. (2021). Integrated digital twin and blockchain framework to support accountable information sharing in construction projects. Automation in Construction, 127, 103688. https://doi.org/10.1016/j.autcon.2021.103688

López, A., & Lobo, A. (2014). Emissions of C&D refuse in landfills: A European case. Waste Management, 34(8), 1446-1454. https://doi.org/10.1016/j.wasman.2014.04.004

López Ruiz, L. A., Roca Ramón, X., & Gassó Domingo, S. (2020). The circular economy in the construction and demolition waste sector – A review and an integrative model approach. Journal of Cleaner Production, 248, 119238. https://doi.org/10.1016/j.jclepro.2019.119238

Lovrenčić Butković, L., Mihić, M., & Sigmund, Z. (2023). Assessment methods for evaluating circular economy projects in construction: a review of available tools. International Journal of Construction Management, 23(5), 877-886. https://doi.org/10.1080/15623599.2021.1942770

Lynch, N. (2022). Unbuilding the city: Deconstruction and the circular economy in Vancouver. Environment and Planning A: Economy and Space, 54(8), 1586-1603. https://doi.org/10.1177/0308518X221116891

Maddalene, T., Youngblood, K., Abas, A., Browder, K., Cecchini, E., Finder, S., Gaidhani, S., Handayani, W., Hoang, N. X., Jaiswal, K., Martin, E., Menon, S., O'Brien, Q., Roy, P., Septiarani, B., Trung, N. H., Voltmer, C., Werner, M., Wong, R., & Jambeck, J. R. (2023). Circularity in cities: A comparative tool to inform prevention of plastic pollution. Resources, Conservation and Recycling, 198, 107156. https://doi.org/10.1016/j.resconrec.2023.107156

Mays, N., & Pope, C. (2000, Jan 1). Qualitative research in health care. Assessing quality in qualitative research. Bmj, 320(7226), 50-52. https://doi.org/10.1136/bmj.320.7226.50

Mohammadiziazi, R., & Bilec, M. M. (2022). Building material stock analysis is critical for effective circular economy strategies: a comprehensive review. Environmental Research: Infrastructure and Sustainability, 2(3), 032001. https://doi.org/10.1088/2634-4505/ac6d08

Mohammadiziazi, R., & Bilec, M. M. (2023). Quantifying and spatializing building material stock and renovation flow for circular economy. Journal of Cleaner Production, 389, 135765. https://doi.org/10.1016/j.jclepro.2022.135765

Mohammadiziazi, R., Copeland, S., & Bilec, M. M. (2021). Urban building energy model: Database development, validation, and application for commercial building stock. Energy and Buildings, 248, 111175. https://doi.org/10.1016/j.enbuild.2021.111175

Moss, E., Eidson, A., and Jambeck J. (2017). Sea of Opportunity: Supply Chain Investment Opportunities to Address Marine Plastic Pollution.

Muhwezi, L., Chamuriho, L., & Lema, N. (2012). An investigation into materials wastes on building construction projects in Kampala-Uganda. Scholarly Journal of Engineering Research, 1(1), 11-18.

Müller, A., Österlund, H., Marsalek, J., & Viklander, M. (2020). The pollution conveyed by urban runoff: A review of sources. Science of The Total Environment, 709, 136125. https://doi.org/10.1016/j.scitotenv.2019.136125

Munaro, M. R., & Tavares, S. F. (2023). A review on barriers, drivers, and stakeholders towards the circular economy: The construction sector perspective. Cleaner and Responsible Consumption, 8, 100107. https://doi.org/10.1016/j.clrc.2023.100107

Nghiem, H. T., Phan, Q. M., Kawamoto, K., Ngo, K. T., Nguyen, H. G., Nguyen, T. D., Isobe, Y., & Kawasaki, M. (2020). An investigation of the generation and management of construction and demolition waste in Vietnam. Detritus, 12, 135-149.

Oliveira, M. d. P. S. L., de Oliveira, E. A., & Fonseca, A. M. (2021). Strategies to promote circular economy in the management of construction and demolition waste at the regional level: a case study in Manaus, Brazil. Clean Technologies and Environmental Policy, 23(9), 2713-2725. https://doi.org/10.1007/s10098-021-02197-7

Ossio, F., Salinas, C., & Hernández, H. (2023). Circular economy in the built environment: A systematic literature review and definition of the circular construction concept. Journal of Cleaner Production, 414, 137738. https://doi.org/10.1016/j.jclepro.2023.137738

Ottosen, L. M., Jensen, L. B., Astrup, T. F., McAloone, T. C., Ryberg, M., Thuesen, C., Christiansen, S., Damø, A. J., & Odgaard, M. H. (2021). Implementation stage for circular economy in the Danish building and construction sector. Detritus, 16, 26-30.

Parker, C., Scott, S., & Geddes, A. (2019). Snowball sampling. SAGE research methods foundations.

Patil, R. A., van Langen, S. K., & Ramakrishna, S. (2023). Circularity Assessment: Developing a Comprehensive Yardstick. In R. A. Patil & S. Ramakrishna (Eds.), Circularity Assessment: Macro to Nano: Accountability Towards Sustainability (pp. 3-14). Springer Nature Singapore. https://doi.org/10.1007/978-981-19-9700-6_1

Pearlmutter, D., Theochari, D., Nehls, T., Pinho, P., Piro, P., Korolova, A., Papaefthimiou, S., Mateo, M. C. G., Calheiros, C., Zluwa, I., Pitha, U., Schosseler, P., Florentin, Y., Ouannou, S., Gal, E., Aicher, A., Arnold, K., Igondová, E., & Pucher, B. (2019). Enhancing the circular economy with nature-based solutions in the built urban environment: green building materials, systems and sites. Blue-Green Systems, 2(1), 46-72. https://doi.org/10.2166/bgs.2019.928

Peek, L., Tobin, J., Adams, R. M., Wu, H., & Mathews, M. C. (2020). A Framework for Convergence Research in the Hazards and Disaster Field: The Natural Hazards Engineering Research Infrastructure CONVERGE Facility [Original Research]. Frontiers in Built Environment, 6. https://doi.org/10.3389/fbuil.2020.00110

Petit-Boix, A., & Leipold, S. (2018). Circular economy in cities: Reviewing how environmental research aligns with local practices. Journal of Cleaner Production, 195, 1270-1281. https://doi.org/10.1016/j.jclepro.2018.05.281

Pomponi, F., & Moncaster, A. (2017). Circular economy for the built environment: A research framework. Journal of Cleaner Production, 143, 710-718. https://doi.org/10.1016/j.jclepro.2016.12.055

Quintão, C., Andrade, P., & Almeida, F. (2020). How to improve the validity and reliability of a case study approach? Journal of Interdisciplinary Studies in Education, 9(2), 264-275.

Rickenbacker, H. J., Collinge, W. O., Hasik, V., Ciranni, A., Smith, I., Colao, P., Sharrard, A. L., & Bilec, M. M. (2020). Development of a framework for indoor air quality assessments in energy conservation districts. Sustainable Cities and Society, 52, 101831. https://doi.org/10.1016/j.scs.2019.101831

Roco, M. C., & Bainbridge, W. S. (2013). The new world of discovery, invention, and innovation: convergence of knowledge, technology, and society. Journal of Nanoparticle Research, 15(9), 1946. https://doi.org/10.1007/s11051-013-1946-1

Royle, J., Jack, B., Parris, H., Elliott, T., Castillo, A. C., Kalawana, S., Nashfa, H., & Woodall, L. C. (2022, 2022/01/01/). Plastic Drawdown: A rapid assessment tool for developing national responses to plastic pollution when data availability is limited, as demonstrated in the Maldives. Global Environmental Change, 72, 102442. https://doi.org/https://doi.org/10.1016/j.gloenvcha.2021.102442

Sachs, J. D., Schmidt-Traub, G., Mazzucato, M., Messner, D., Nakicenovic, N., & Rockström, J. (2019). Six Transformations to achieve the Sustainable Development Goals. Nature Sustainability, 2(9), 805-814. https://doi.org/10.1038/s41893-019-0352-9

Santos, A. C., Mendes, P., & Ribau Teixeira, M. (2019). Social life cycle analysis as a tool for sustainable management of illegal waste dumping in municipal services. Journal of Cleaner Production, 210, 1141-1149. https://doi.org/10.1016/j.jclepro.2018.11.042

Shackleton, S., Bezerra, J. C., Cockburn, J., Reed, M. G., & Abu, R. (2021). Interviews and surveys. In The Routledge Handbook of Research Methods for Social-Ecological Systems (pp. 107-118). Routledge.

Sharifi, A., & Murayama, A. (2014). Neighborhood sustainability assessment in action: Cross-evaluation of three assessment systems and their cases from the US, the UK, and Japan. Building and Environment, 72, 243-258. https://doi.org/10.1016/j.buildenv.2013.11.006

Sharp, P., & Hockfield, S. (2017). Convergence: The future of health. Science, 355(6325), 589-589. https://doi.org/doi:10.1126/science.aam8563

Shuster, W. D., Dadio, S., Drohan, P., Losco, R., & Shaffer, J. (2014). Residential demolition and its impact on vacant lot hydrology: Implications for the management of stormwater and sewer system overflows. Landscape and Urban Planning, 125, 48-56. https://doi.org/10.1016/j.landurbplan.2014.02.003

Sims, K., Reith, A., Bright, E., Kaufman, J., Pyle, J., Epting, J., Gonzales, J., Adams, D., Powell, E., Urban, M., & Rose, A. (2023). LandScan Global 2022 Version 2022) [raster digital data]. Oak Ridge National Laboratory. https://doi.org/10.48690/1529167

Singh, J., & Ordoñez, I. (2016). Resource recovery from post-consumer waste: important lessons for the upcoming circular economy. Journal of Cleaner Production, 134, Part A, 342-353. https://doi.org/http://dx.doi.org/10.1016/j.jclepro.2015.12.020

Singh, M., Fuenmayor, E., Hinchy, E. P., Qiao, Y., Murray, N., & Devine, D. (2021). Digital Twin: Origin to Future. Applied System Innovation, 4(2).

Sundt, P., Schulze, P.-E., & Syversen, F. (2014). Sources of microplastic-pollution to the marine environment. Mepex for the Norwegian Environment Agency, 86, 20.

Sutradhar, U., Spearing, L., & Derrible, S. (2024). Depopulation and associated challenges for US cities by 2100. Nature Cities, 1(1), 51-61. https://doi.org/10.1038/s44284-023-00011-7

Tatiya, A., Zhao, D., Syal, M., Berghorn, G. H., & LaMore, R. (2018). Cost prediction model for building deconstruction in urban areas. Journal of Cleaner Production, 195, 1572-1580. https://doi.org/10.1016/j.jclepro.2017.08.084

Tokazhanov, G., Galiyev, O., Lukyanenko, A., Nauyryzbay, A., Ismagulov, R., Durdyev, S., Turkyilmaz, A., & Karaca, F. (2022). Circularity assessment tool development for construction projects in emerging economies. Journal of Cleaner Production, 362, 132293. https://doi.org/10.1016/j.jclepro.2022.132293

Torrance, H. (2012). Triangulation, Respondent Validation, and Democratic Participation in Mixed Methods Research. Journal of Mixed Methods Research, 6(2), 111-123. https://doi.org/10.1177/1558689812437185

Townsend, T. G., & Anshassi, M. (2023). Construction and Demolition Debris. Springer.

Townsend, T. G., Ingwersen, W. W., Niblick, B., Jain, P., & Wally, J. (2019). CDDPath: A method for quantifying the loss and recovery of construction and demolition debris in the United States. Waste Management, 84, 302-309.

UN Environment, U. (2021). Mississippi River Plastic Pollution Initiative: 2021 Science Report.

US Army Corps of Engineers. (2022). Technical Documentation. Retrieved April 10 from https://www.hec.usace.army.mil/confluence/nsi/technicalreferences/2022/technical-documentation
US Census Bureau. (2023). Annual Value of State and Local Construction Put in Place by State. https://www.census.gov/library/visualizations/interactive/state-local-construction-spending.html
US Census Bureau. (2024). Current Data (2019 - present). https://www.census.gov/construction/bps/current.html
US EPA. (2019). Advancing Sustainable Materials Management: 2017 Fact Sheet Assessing Trends in Material Generation, Recycling, Composting, Combustion with Energy Recovery and Landfilling in the United States. https://www.epa.gov/sites/production/files/2019-11/documents/2017_facts_and_figures_fact_sheet_final.pdf
US EPA. (2020). Advancing Sustainable Materials Management: 2018 Fact Sheet Assessing Trends in Material Generation, Recycling, Composting, Combustion with Energy Recovery and Landfilling in the United States. https://www.epa.gov/sites/production/files/2021-01/documents/2018_ff_fact_sheet_dec_2020_fnl_508.pdf
Yang, H., Xia, J., Thompson, J. R., & Flower, R. J. (2017). Urban construction and demolition waste and landfill failure in Shenzhen, China. Waste Management, 63, 393-396. https://doi.org/10.1016/j.wasman.2017.01.026
Yigitcanlar, T., Kamruzzaman, M., & Teriman, S. (2015). Neighborhood Sustainability Assessment: Evaluating Residential Development Sustainability in a Developing Country Context. Sustainability, 7(3), 2570-2602. https://www.mdpi.com/2071-1050/7/3/2570
Youngblood, K., Brooks, A., Das, N., Singh, A., Sultana, M., Verma, G., Zakir, T., Chowdhury, G. W., Duncan, E., Khatoon, H., Maddalene, T., Napper, I., Nelms, S., Patel, S., Sturges, V., & Jambeck, J. R. (2022). Rapid Characterization of Macroplastic Input and Leakage in the Ganges River Basin. Environmental Science & Technology, 56(7), 4029-4038. https://doi.org/10.1021/acs.est.1c04781
Yu, S., Awasthi, A. K., Ma, W., Wen, M., Di Sarno, L., Wen, C., & Hao, J. L. (2022). In support of circular economy to evaluate the effects of policies of construction and demolition waste management in three key cities in Yangtze River Delta. Sustainable Chemistry and Pharmacy, 26, 100625. https://doi.org/10.1016/j.scp.2022.100625
Yung, E. H. K., Chan, E. H. W., & Xu, Y. (2014). Community-Initiated Adaptive Reuse of Historic Buildings and Sustainable Development in the Inner City of Shanghai. Journal of Urban Planning and Development, 140(3), 05014003. https://doi.org/doi:10.1061/(ASCE)UP.1943-5444.0000174
Zadjelovic, V., Wright, R. J., Walker, T. R., Avalos, V., Marín, P. E., Christie-Oleza, J. A., & Riquelme, C. (2023). Assessing the impact of chronic and acute plastic pollution from construction activities and other anthropogenic sources: A case study from the coast of Antofagasta, Chile. Marine Pollution Bulletin, 195, 115510. https://doi.org/10.1016/j.marpolbul.2023.115510
Zhang, X., Wu, Y., & Shen, L. (2012). Application of low waste technologies for design and construction: A case study in Hong Kong. Renewable and Sustainable Energy Reviews, 16(5), 2973-2979. https://doi.org/10.1016/j.rser.2012.02.020
Zheng, H. W., Shen, G. Q., Song, Y., Sun, B., & Hong, J. (2017). Neighborhood sustainability in urban renewal: An assessment framework. Environment and Planning B: Urban Analytics and City Science, 44(5), 903-924. https://doi.org/10.1177/0265813516655547
Zhu, Y., Mao, C., Jia, Q., Barnes, S. J., & Yao, Q. (2022, 2022/01/01). Building Better Cities: Evaluating the Effect of Circular Economy City Construction on Air Quality via a Quasi-Natural Experiment. Journal of Environmental and Public Health, 2022(1), 3151072. https://doi.org/10.1155/2022/3151072
Zima, K. (2017). Impact of information included in the BIM on preparation of Bill of Quantities. Procedia Engineering, 208, 203-210. https://doi.org/10.1016/j.proeng.2017.11.039