Towards Circular Architecture. The Role of Digital Twin for the Quantification and Valorization of Waste Management

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Abstract. As a key urban innovation and a cornerstone of sustainable initiatives, Digital Twins (DT) serve as enabling instruments for data-informed, evidence-based transitions, connecting the social, ecological, and spatial dimensions of urban transitions, aligning with European ambitions ranging from promoting energy efficiency to the 2050 decarbonization roadmap. Moving from linear to circular design models, the study fosters adaptive solutions for developing dynamic, learning-oriented circular approaches to construction waste management. Along with a scientific and replicable decision-support tool, the study promotes closed-loop systems in spatial transformations and stark contrasts to the traditional economic models of "take-make-dispose" technocratic solutions and architectural conceptions. The research develops a systematic review of tools for both building-level renovation and district-scale regeneration, mapping reusable resources, quantifying waste, and reducing new material extraction. The research will conclude by determining its applicability in site-specific locations and complex environments through evaluations of the impacts of design interventions and the promotion of mutual understanding of its utility. By bridging the gaps in technical modeling, the collaborative DT processes will leverage sustainability and co-develop and test actionable insights in real-time settings, not only as technological demonstrators but also as participatory instruments for inclusive urban transformations.

Keywords: Circular Economy, Digital Twin, Architecture, Waste management, Decision-support tool

1 Introduction

Construction is one of the major contributors to global waste, accounting for more than 30% of worldwide generation, over 40% of resource use, and 25% of global waste, leading to unsustainable models and emerging alarming situations amid complex, growing environmental challenges. Integrating efficient waste management practices is pivotal to advancing sustainable practices in the construction sector. The built environment is responsible for more than 40% of raw material extraction, and more than one-third of this extraction occurs within European borders [1].

Moving from traditional models of “take-make-dispose" models towards green transformative shifts and reuse, recycling, and circular models seems imperative to face challenges related to natural depletion, energy consumption, or soil artificialization due to massive urbanization pressures [2]. Proposed by Ellen MacArthur Foundation [3] as a catalyst for the reduction of the building carbon footprint, while promoting efficient strategies for cost, and resources' optimized use [4], Circular Economy (CE) has been increasingly studied as a promising and sustainable concept as opposed to the linear approaches [5], whereas its potential applications in various processes of life cycle (production, consumption, distribution), and its principles of material recycling, and reuse are commonly acknowledged, being closely aligned with the United Nations Sustainable Development Goals (SDGs) in an integrated and transformative framework and promote innovative design strategies supporting resource reutilization and realignment and sustainability. In recent years, the concept of circularity has gained rising scientific and policy interest with the adoption of the First Circular Action Plan in 2019, and continued being institutionalized through European engagements, as the new Circular Economy Action (CEAP) (2020), or Green Deal towards the 2050 decarbonization pathway ([6], [7]). In fact, the transition from 'linear' to 'circular' strategies poses a range of new challenges for designers, requiring the acquisition of specific knowledge, resources, and management skills, as well as the development of novel methods, that operate within closed-loop flows and consider the entire project lifecycle.

Recent research, e.g. ([5], [8]), has been conducted to conceptualize circular design and identify knowledge gaps in construction standards, and still, developments are in an infant stage with significant technological uncertainty. Current trends and standalone and siloed tools have been developed to support circular design and the required skills for designers, with limited, nevertheless, empirical investigation and case-study evidence [9], which have led to fragmented practices and communication inability due to the absence of unified, clarified policy structures or misinterpretations, creating a lack of effectiveness. The study aims to bridge learning outcomes on standardized grounds and promote digitalized tools for practitioners of cleaner production with standardized ontologies and common language, guiding decision-making processes towards greener and resilient practices by exploring the 'digital twinning' strengths and potential in environmental engagements, and restructuring the narrative of current construction models and their disastrous environmental effects.

Circular economy is an umbrella term that encompasses synthetic processes and relevant principles for the use and reuse of materials, operating at different scales of implementation. The concept draws on interdisciplinary roadmaps documented in grey and scientific literature that combine diverse viewpoints from industrial and academic stakeholders. Some of them describe the concept in single conceptualized frameworks, whereas others explore the interconnectivity of its dimensions in more holistic viewpoints of a “restorative”, resilient, and long-lasting architectural and urban design and an instrument for sustainable development practices ([9], [10]).

Construction-intensive activities intensify soil artificialization, leading to major contributions to environmental degradation through excessive waste management and exacerbating serious ecological imbalances. To understand the distribution of the circular economy in scientific research, a selected sample of 1,597 scientific publications from the Lens.org database was analyzed. To focus the results on the circular economy and related topics, these publications were selected based on the occurrence of the keywords “circular economy” and “architecture”. The sample publications were chosen based on their publication year, from 2010 to 2026, because of their increasing mention in the literature since the 2010s ([11], [12]). To specify the sample, a field of study was chosen: waste management, engineering, circular economy, and architecture. To ensure comprehensive cluster outcomes, a minimum benchmark of five (5) occurrences was set. Fig. 1 shows clusters in different colors, with node sizes representing keyword co-occurrence and lines representing affinity between them.

The circular economy is linked to many topics through scientific research. Its scope of application is broad and continues to expand. The co-occurrence of keywords in scientific research indicates that research density is higher around circular economy, sustainability, waste management, life cycle analysis, and recycling. The connections between keywords reveal links across disciplines, and the distribution of the cluster demonstrates the movement of scientific research. The main concepts emerging from this cluster are Building Information Modeling (BIM), digital twins, blockchain, and Industry 4.0 with weaker connections between architecture and this cluster.

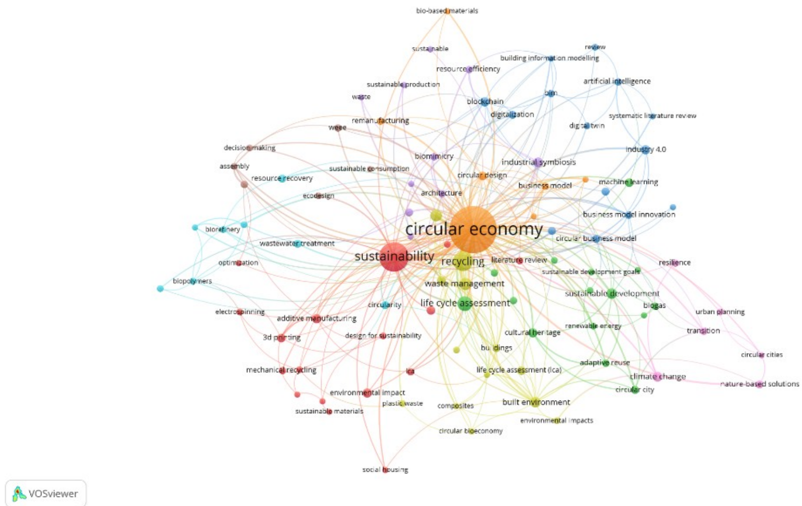

Fig. 1. Bibliometric analysis from Lens.org database, of the scientific research about circular economy and architecture in Europe from 2010 to 2026.

2 Tools. Addressing Gaps and Challenges

To support and enable circular design, a range of tools and methods has been identified and documented in the grey and academic literature; a systematic literature roadmap is provided in this section to identify innovations and relevant gaps. From the same lens, recent research on the conceptualization of the circular economy has systematically identified significant gaps arising from the lack of unified approaches, leading to misalignments, misunderstandings, and misinterpretations ([13], [14]). Most studies address the transferability of knowledge and common agreements across different methods and tools, and neglect the social implications, behavioral adaptations, and consumer-centric lifestyles, adopting systemic views of a circular mindset, while others focus on waste management and demolition waste [15].

The study revealed complementary difficulties in adapting "design personas," the need for innovative collaboration schemes and relevant competencies, and the need to assess and anticipate plausible environmental impacts and societal adoption challenges in advance. Digital highways synchronize data bidirectionally and bridge data and interoperability gaps on "what-if" scenarios, translating simulation insights into real-world applications in connected ecosystems. Kozminska [17] et al. explored architectural cases in circular design processes, by highlighting innovative standards and the need for interdisciplinarity due to the perplexing nature of stakeholders, emphasizing the role of architects as 'orchestrators' of the process as pivotal to coherent designs

Waste recovery takes place at various levels, depending on the possibility; it starts with prevention, followed by reuse, recycling, and energy recovery. Considering the **project lifecycle criteria** each tool offers a different approach to waste management categorized into nine criteria: tracking, quantifying, mapping, advising, modeling, interconnecting, analyzing, managing, and preventing (Table 1).

Table 1. Objective of the tool for waste management and circular economy in the construction industry

Tool objective	Description
Track	Waste flow tracking
Quantify	Waste quantification and inventory creation
Map	Location of deposits, waste recovery operators and materials
Advise	Inform stakeholders about methods for recovering construction waste
Model	Integrate construction waste into a 3D model
Interconnect	Facilitate exchange between stakeholders about suitable and easily accessible reusable materials
Analyze	Construction data, including its life cycle, performance at the scale of material and building
Manage	Management of construction waste on site, facilitating waste collection
Prevent	Prediction and anticipation of construction waste to reduce its quantity

Existing tools for waste management in the construction industry can be organized with these objectives to expose their roles in the recovery process. The study of a sample of

10 tools that are more often used or mentioned in the construction industry seems to demonstrate their broad scope.

Table 2. Sample of 10 tools used in the recovery of waste in the construction industry

Tools	Track	Quantify	Map	Advise	Model	Interconnect	Analyze	Manage	Prevent
Track waste	X	X							
BAMB Materials Passports	X								
TOTEM					X		X		X
DEMOCLES						X		X	X
SimaPro							X		
VALOBIM		X	X						
RREUSE				X					
Opalis						X			
Level(s)							X		
OpenLCA							X		

Table 2 shows a disparity in the purposes of the tools in existing literature, presented with fragmented regard. Each of them is generally part of a post-production waste approach, seeking to manage what happens to waste, while only few of them target the first stage of recovery: prevention, as the case of TOTEM (Belgium) that analyzes the life cycle of a project from the design phase. Version 2020 of the method behind TOTEM was used in the study of Lam et al. (2022) [18].

At first glance, the industry appears well-equipped with tools and methods, but stakeholders face complex, too numerous, and siloed tools. As they are often costly, difficult to use, and time-consuming, it has become difficult for contractors and architects to incorporate them into their thinking. Furthermore, these tools are mainly intended for large-scale projects and large-scale companies. Along with the development of circular economy strategies, digitalization has been identified in diverse studies as an enabler of these practices, yet it is characterized by a significant lack of theoretical or technical background, a fragmented approach, and limited synergies that hinder the feasibility of circular models.

The concept of Digital Twin (DT) dates back to 2002, when industrial designers at the University of Michigan introduced it as a virtual representation of physical assets, aimed at design optimization, the integration of circular standards, and real-time monitoring and material flow [19]. It has progressively emerged as a key enabling technology that addresses design complexities in decision-making processes and is a promising strategy for reducing costs, facilitating innovation, and supporting the green transition, considering the combined information from multiple sources and scales in real-time ecosystems to improve efficiency and time savingsWhen combined with BIM, it enables material and knowledge flows throughout construction and waste management, facilitating the dynamics of automated processes in real-time ecosystems of architectural projects. In several endeavors and exemplary cases, DT enabled architectural performance through the evaluation of waste volumes and quality, the identification of reuse scenarios aligned with customer preferences, and the distribution of resources, exploring the operational option of DT integration to advance circular economic practices [20]. Despite the multiple assets on DT use, multiple barriers hinder the lack of transparency and traceability with fragmented and underused data and the need for intersections among different sectors, including the barriers of advanced skills and relevant training [21].

3 Discussion

Moving from linear to circular architectural conceptualizations fosters multilevel innovation and adaptive solutions in real-time ecosystems by optimizing time, costs, and resource use and distribution. In this study, a systematic review of existing tools for construction and demolition waste identified significant gaps in communication and collaboration, and the need for more inclusive designs that promote closed-loop systems and holistic support mechanisms, by adding new knowledge to the existing literature.

Moreover, each tool has advantages but also disadvantages that can hinder the development of waste recovery. These drawbacks result in tools that are time-consuming, costly and sometimes expensive, difficult to learn, difficult to apply in the field, often requiring high-performance equipment, and lacking educational value and awareness. BIM-related tools are developing, but small companies do not systematically model their projects, which can be an obstacle to the use of waste recovery software. As an example, some tools are developing into application, to facilitate their use in site to the most stakeholders as possible (for example the tools ValoDépôt, BatiTri, Cycle Zero in France). Developing these types of tools could promote waste recovery among stakeholders who find it difficult to implement, such as small construction companies.

Other factors come into play in waste recovery, such as the location of construction sites and their proximity to sorting and storage facilities, as well as the size of the sites, which, when too small, does not promote waste recovery because of the low rentability for the companies.

4 Perspectives and Future Work

Digital advancements the conceptualization, design, and implementation of architectural projects optimize visualization, data generation, and the development of synergies throughout the project lifecycle, thereby improving communication skills and collaborative schemes among the involved stakeholders. In the next steps of the study, to meet research objectives, empirical studies on benchmarking approaches (France and Belgium) will be conducted to provide avenues for further investigation that emerge from the current discussion. Empirical evidence will be collected towards an in-depth understanding of the DT ecosystem to demonstrate its feasibility and constraints in real-time architectural projects of different scales. . This will help reveal the potential of digitalization as well as its limitations related to technical patterns, participation instruments, and learning processes.

It seems relevant to consider key stakeholders and self-builders such as small construction companies, small design offices, and even, for example, individuals wishing to build and recycle their waste, who also have a role to play in the recovery of construction waste at their scale. The next phase of the study aims to develop a tool that best addresses the existing drawbacks, evaluating the possibilities and limitations of a comprehensive, holistic tool, such as a digital twin or a simpler and more accessible tool for the stakeholders concerned. While considering that these different tools will not be geared towards the same types of projects or stakeholders.

Various tools could be implemented, such as educational sheets for construction workers and self-builders, training sessions for construction companies and their staff, or applications that are easy to bring to the construction site and simpler to use. Waste recovery should target transport-related waste such as packaging, implementation-related waste such as losses, cuttings, and cleaning inherent to the construction site, and demolition and building dismantling waste.

Even though efficient tools exist today, there is a real gap between the birth of innovation and its adoption. Companies do not easily position themselves as leaders but prefer to follow what has already been done. This creates a gap between the creation of a tool and its application. In addition, project size comes into consideration, as tools are less often used in smaller projects.

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