
SMART AND CIRCULARITY DECISIONS IN A BUILT-UP ENVIRONMENT

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Abstract. The construction sector is increasingly recognized as one of the most resource-intensive industries, responsible for significant environmental pressures while at the same time serving as a key driver of economic development. In the context of rapid urbanization, where cities concentrate over half of the world's population and consume the majority of global resources, construction and demolition waste (C&DW) emerges as both a challenge and an opportunity. This paper advances an integrated vision for the transition from linear to circular models in urban construction. It focuses on three mutually reinforcing strategies: localized recycling of construction materials, the application of additive manufacturing particularly large scale 3D printing and the deployment of digital twins coupled with artificial intelligence for life-cycle resource management. By examining systemic barriers, technological innovations, and practical applications, the study outlines a pathway toward an intelligent, circular, and resource efficient built environment. The findings emphasize not only the environmental, but also the economic and social benefits of adopting such a paradigm, thereby positioning circular construction as a strategic necessity for sustainable urban development.

Keywords: Circular economy; construction and demolition waste; urban mining; 3D printing in construction; digital twin; sustainable construction; additive manufacturing; life-cycle management; resource efficiency; urban sustainability.

JEL: M11, L70, O18

1. Introduction

The urban environment of the twenty-first century stands at a critical juncture. Today, more than half of the global population resides in urban areas, and this proportion is projected to reach nearly two-thirds by 2050 (United Nations, 2017) (Fig. 1). This demographic concentration significantly amplifies the environmental footprint of cities, which already consume over 75% of global resources and generate more than half of the world's waste. This concentration of people, activities, and consumption has turned cities into both engines of innovation and epicenters of environmental pressure. At the heart of this imbalance lies the construction sector an industry that underpins economic growth yet remains one of the largest contributors to resource depletion and waste generation.

Buildings, whether newly erected or approaching the end of their service lives, embody vast reservoirs of materials – concrete, steel, bricks, and glass that retain significant residual value. Nevertheless, the prevailing linear model of construction, often described as “take – make – dispose,” results in the irreversible loss of millions of tons of potential secondary raw materials each year (Maury-Ramirez, 2022). This paradigm not only accelerates the depletion of natural resources but also perpetuates waste accumulation and greenhouse gas emissions.



Fig. 1. Global share of the urban population in 1980, 2015, and projected for 2050. Source: United Nations, Department of Economic and Social Affairs, Population Division (2014), World Urbanization Prospects: The 2014 Revision.

Against this backdrop, the concept of circular construction emerges as a compelling alternative. Instead of discarding materials at the end of a building’s life cycle, circularity envisions their recovery, transformation, and reintegration into new projects, thus closing the material loop. More than a technical adjustment, this transition requires systemic rethinking of how buildings are designed, built, operated, and dismantled (Pomponi, F&Moncaster, A. 2016).

The present study advances a vision for circular construction based on three mutually reinforcing strategies. First, on-site recycling of construction and demolition waste reduces transport needs and retains value within local economies. Second, large-scale 3D printing enables efficient use of recycled materials while allowing unprecedented architectural flexibility. Third, digital twins and artificial intelligence provide the means to monitor, simulate, and optimize resource flows across the entire life cycle of buildings (Sacks et al.,

2020). Together, these approaches outline a paradigm of construction that is not only sustainable but also intelligent, adaptive, and resource-efficient.

2. Construction and Demolition Waste as a Resource

Construction and demolition waste (C&DW) represents one of the most critical challenges and at the same time one of the greatest opportunities in the transition to a circular built environment. While materials such as concrete, bricks, metals, and wood are technically recyclable, the actual recovery rates remain modest across most regions of the world (Cynthia G (et al.) 2025). Instead, a large proportion of C&DW is disposed of in landfills, perpetuating resource loss and environmental degradation.

The barriers to effective C&DW management are multifaceted. A lack of standardized infrastructure for separate collection and sorting at construction sites often results in mixed waste streams that are costly and inefficient to process. In addition, reliable information about the material composition of existing buildings is frequently missing, particularly in older structures constructed prior to the widespread adoption of Building Information Modeling (BIM). Without accurate data on the quantity, location, and condition of embedded materials, selective demolition an essential prerequisite for clean material recovery, becomes impractical. Economic and logistical challenges further exacerbate the problem. High transportation and landfill costs, especially in densely populated urban areas, discourage recycling even where technical solutions exist (Gálvez-Martos, J. (et al.), 2018).

Despite these systemic obstacles, Existing buildings should increasingly be perceived not as waste but as repositories of valuable resources, a concept often referred to as urban mining. Through processes of selective demolition, sorting, and recycling, construction and demolition waste can be reintegrated into new projects, effectively closing material loops (Fig. 1) (Bender, A.P, (et al.), 2020). Concrete can be crushed and reused as aggregate in new mixes or 3D-printable composites. Bricks, once fragmented, can serve as ceramic fractions for construction or landscaping applications. Finely ground glass can be incorporated into specialized concretes, while metals retain high economic value through remelting and reuse.

This latent potential, although technologically accessible, remains underutilized. Unlocking it requires systemic transformation: regulatory incentives, integrated data management, and innovative on-site recovery technologies. In this way, what has traditionally been considered waste can be redefined as a renewable material resource, paving the way toward a genuinely circular construction sector.



Fig. 2. Conceptual representation of urban mining and the circular reuse of construction materials.

Source: Holcim (2023). What is urban mining? Available at: <https://www.holcim.com/who-we-are/our-stories/what-is-urban-mining>

3. Technologies for Circular Construction

The realization of a circular construction model relies on the integration of advanced technologies that enable the recovery, transformation, and reuse of materials within localized and efficient cycles. Three technological domains are particularly significant: on-site recycling, additive manufacturing through 3D printing, and digital twins.

On-site recycling: Mobile crushers, sieving stations, and mixing units allow demolition debris such as concrete and bricks to be processed directly at the construction site. This approach minimizes the need for long transport routes, reduces carbon emissions, and fosters local value creation. By transforming waste into reusable aggregates and composite mixtures on-site, it becomes possible to close material loops within the same urban context (Bonifazi G., (et al.), 2025).

3D printing in construction: Additive manufacturing enables the automated fabrication of building elements layer by layer, using cementitious composites that may include recycled aggregates, ground

glass, or other secondary materials (Wang,X. (et al.), 2024). The method significantly reduces waste, eliminates the need for formwork, and allows for rapid construction with considerable cost savings. At the same time, it enhances architectural flexibility, supporting organic and non-standard designs. Despite its promise, the technology faces regulatory and material certification challenges, particularly when recycled fractions are incorporated.

Digital twins: A digital twin is a dynamic model that integrates design, material data, and performance monitoring over the entire building life cycle. By linking to Building Information Modeling (BIM) and artificial intelligence, digital twins enable simulations of selective demolition, predictive maintenance, and precise calculation of materials suitable for reuse (Rabaia, M.K.H, (et al.), 2025). As such, they provide complete traceability of resources, allowing for efficient recovery and reintegration within circular construction processes.

Taken together, these three technological trajectories establish the foundation for a new paradigm in construction – one that is not merely sustainable but also intelligent, adaptive, and strategically managed.

The transition toward a circular construction paradigm is enabled by the convergence of three complementary technological trajectories: on-site recycling, additive manufacturing, and digital twins. Together, these approaches form an integrated framework that facilitates resource efficiency and minimizes waste across the entire building life cycle (Fig. 3).

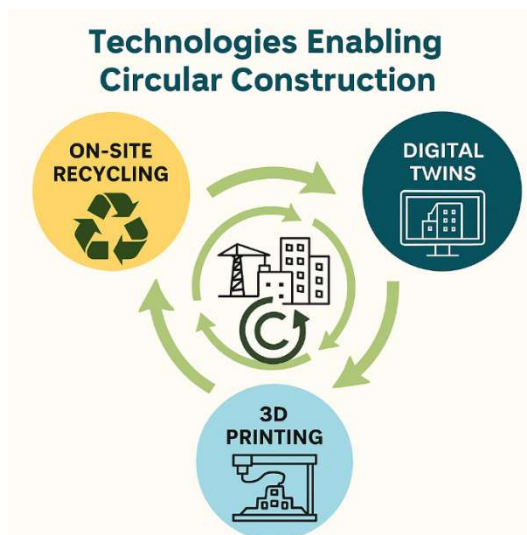


Fig. 3. Technologies enabling circular construction: on-site recycling, 3D printing, and digital twins.

Source: Author's illustration.

4. Benefits and Implications of the Circular Model

The integration of on-site recycling, 3D printing, and digital twins generates a set of benefits that extend beyond environmental performance and encompass economic and social dimensions. Compared with conventional construction practices, the circular model demonstrates clear advantages in terms of cost reduction, resource efficiency, and project delivery times.

From an environmental perspective, the use of recycled aggregates and locally recovered materials reduces dependence on virgin resources and significantly lowers carbon emissions linked to extraction, processing, and transportation (Xing, W, (et al.), 2022). Moreover, additive manufacturing is an inherently low-waste process, generating less than 5% of waste compared with up to 30÷40% in conventional construction.

In economic terms, localized recycling reduces expenditures on raw materials and waste disposal while eliminating the costs associated with formwork and excess labor. 3D printing can shorten construction times dramatically small scale housing can be realized within days rather than weeks, thus reducing financing costs and increasing project feasibility (Sayegh, E., 2020).

The social dimension is equally significant. Accelerated construction timelines can support urgent housing programs, particularly in disaster recovery or affordable housing initiatives. Localized production strengthens regional economies by creating closed material loops and reducing reliance on centralized suppliers. At the same time, digital tools enable greater design flexibility, ensuring that buildings can better reflect cultural context and user-specific needs (Firoozi,A.A. (et al.),2024).

Collectively, these advantages underscore the transformative potential of circular construction, not only as an environmental imperative but also as a strategy for economic resilience and social equity in urban development.

A comparative summary of the main differences between conventional and circular construction practices is presented in Table 1.

Table 1. Comparison between conventional construction and the circular model with 3D printing.

Category	Conventional Construction	Circular Model + 3D Printing
Material costs	High, dependent on virgin resources	Significantly lower due to recycled inputs
Transportation emissions	Substantial, long supply chains required	Strongly reduced, localized material cycles
Construction time	Weeks to months	Days (for small-scale projects)
Waste generation	30–40% of input materials	<5%, near zero-waste process
Design flexibility	Limited, constrained by formwork and methods	High, enabling complex and organic forms

5. Conclusion

The transition from a linear to a circular construction model is no longer optional but a strategic necessity. The prevailing “take – make – dispose” paradigm accelerates resource depletion, amplifies waste generation, and exacerbates environmental pressures. By contrast, circular construction – anchored in on-site recycling, additive manufacturing, and digital twins, offers a transformative pathway toward a resilient, resource-efficient, and intelligent built environment.

On-site recycling enables the conversion of demolition debris into valuable secondary raw materials directly at the construction site, thereby reducing dependence on virgin resources and minimizing transport-related emissions. Additive manufacturing through 3D printing introduces rapid, low-waste, and cost-effective construction processes while expanding architectural freedom and design adaptability. Digital twins provide comprehensive material traceability, predictive maintenance, and life-cycle optimization, ensuring that resources are managed intelligently across all phases of a building’s existence.

The synergy of these technologies creates a closed-loop system in which resources are continuously recovered, transformed, and reused (Fig. 4). This integrated vision of circular construction underscores its potential not only as an environmental imperative but also as an economic and social opportunity. Lower material costs, shorter construction timelines, and localized value creation enhance resilience, while faster housing delivery and design flexibility address urgent social needs.

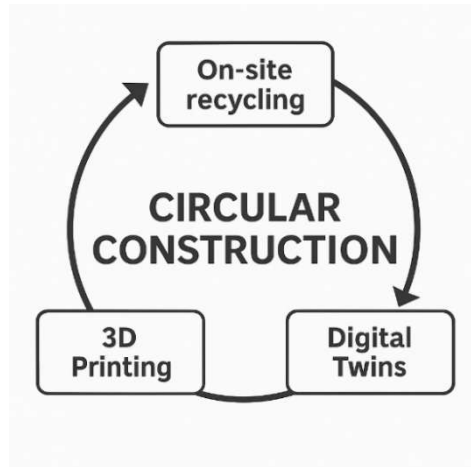


Fig. 4. Integrated vision of circular construction, enabled by on-site recycling, 3D printing, and digital twins.

Source: Author's illustration.

Realizing this paradigm, however, requires more than technological advancement. Regulatory frameworks, supportive business models, and educational initiatives must foster a culture of circularity in the construction sector. Only through such systemic transformation can circular construction evolve from an emerging concept into a cornerstone of sustainable urban development.

Future Research and Policy Implications. While technological innovation provides the foundation for circular construction, future research should explore scalable business models, regulatory frameworks, and financial instruments that can accelerate its mainstream adoption. Particular attention is needed on standardization of recycled materials, certification protocols for 3D-printed structures, and interoperability between digital twin platforms. At the policy level, incentives for localized recycling, investment in mobile processing infrastructure, and requirements for life-cycle transparency could provide strong levers for systemic transformation. By aligning technological advances with supportive governance and market mechanisms, circular construction can evolve from pilot projects into a cornerstone of sustainable urban development worldwide.

REFERENCES

- FIROOZI, Ali Akbar, FIROOZI, Ali Asghar, OYEJOBI, D.O., AVUDAIAPPAN, Siva and FLORES, Erick Saavedra (2024), Emerging trends in sustainable building materials: Technological innovations, enhanced performance, and future directions, *Results in Engineering*, 24, Available from <https://doi.org/10.1016/j.rineng.2024.103521>. [viewed 2024-11-24]
- BENDER, A.P., BILOTTA, P. (2020). Circular Economy and Urban Mining: Resource Efficiency in the Construction Sector for Sustainable Cities. *Sustainable Cities and Communities*. Encyclopedia of the UN Sustainable Development Goals. Springer, Cham. Available from https://doi.org/10.1007/978-3-319-95717-3_40 [paywall]. [viewed 2020-01-01].
- EL-SAYEGH, S. (2020) “A critical review of 3D printing in construction: benefits, challenges, and risks,” *Archives of Civil and Mechanical Engineering*. Springer Science and Business Media LLC. Available from <https://doi.org/10.1007/S43452-020-00038-W>. [paywall]. [viewed 2020-03-10]
- POMPONI, Francesco, MONCASTER, Alice (2016), Embodied carbon mitigation and reduction in the built environment – What does the evidence say?, *Journal of Environmental Management*, 181, Available from <https://doi.org/10.1016/j.jenvman.2016.08.036>. [paywall]. [viewed 2016-01-10]
- HASIBUAN, Gina Cynthia Raphita, AL FATH, Muhammad Thoriq, YUSOF, Naeemah, DEWI, Rezky Ariessa, SYAFRIDON, Gea Geby Aurora, JAYA, Indra, ANAS, M. Ridwan, Syahrizal (2025), Integrating circular economy into construction and demolition waste management: A bibliometric review of sustainable engineering practices in the built environment, *Case Studies in Chemical and Environmental Engineering*, 11, 2025, 101159, ISSN 2666-0164, Available from <https://doi.org/10.1016/j.cscee.2025.101159>. [viewed 2025-06-01]
- BONIFAZI, Giuseppe, GROSSO, Chiara, PALMIERI, Roberta, SERRANTI, Silvia (2025), Current trends and challenges in construction and demolition waste recycling, *Current Opinion in Green and Sustainable Chemistry*, 53, Available from <https://doi.org/10.1016/j.cogsc.2025.101032>. [viewed 2025-06-01]
- GÁLVEZ-MARTOS, José-Luis, STYLES, David, SCHOENBERGER, Harald, ZESCHMAR-LAHL, Barbara (2018), Construction and demolition waste best management practice in Europe, Resources, *Conservation and Recycling*, 136, Available from <https://doi.org/10.1016/j.resconrec.2018.04.016>. [paywall]. [viewed 2018-09-01]
- RABAIA, Malek Kamal Hussien, SEMERARO, Concetta, SOUDAN, Bassel, SALAMEH, Tareq Samir Zaki, ABDELKAREEM, Mohammad Ali, OLABI, Abdul Ghani (2025), Digital twin-driven sustainable energy life cycles: Technical review and Guidelines, *Energy Nexus*, 19, Available from <https://doi.org/10.1016/j.nexus.2025.100482>. [viewed 2025-09-01]
- MAURY-RAMIREZ, Anibal & MESA, Jaime A. (2022). Construction and Demolition Waste Challenges and Opportunities. Available from <https://doi.org/10.3390/books978-3-0365-5049-7>. [viewed 2022-08-01]

United Nations , 2018. *World Urbanization Prospects: The 2018 Revision. Department of Economic and Social Affairs, Population Division..* [Online] Available at: <https://population.un.org/wup/>

WANG, Xiaonan, LI, Wengui. GUO, Yipu, KASHANI, Alireza, WANG, Kejin, FERRARA, Liberato, AGUDELO, Isabel (2024), Concrete 3D printing technology for sustainable construction: A review on raw material, concrete type and performance, *Developments in the Built Environment*, 17, Available from <https://doi.org/10.1016/j.dibe.2024.100378>. [viewed 2024-03-01]

XING, Weiqi, TAM, Vivian WY, LE, Khoa N, HAO, Jian Li, WANG, Jun (2022), Life cycle assessment of recycled aggregate concrete on its environmental impacts: A critical review, *Construction and Building Materials*, 317, Available from <https://doi.org/10.1016/j.conbuildmat.2021.125950>. [paywall]. [viewed 2022-01-24]

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