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LEAN-DIGITAL-PLACE INTEGRATION FOR CIRCULAR HOUSING DESIGN

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ABSTRACT

Circular economy strategies are increasingly promoted to reduce material waste, embodied carbon, and lifecycle environmental impacts in the built environment. However, practical adoption in housing remains limited due to fragmentation across process, information, and regional infrastructures. Existing studies emphasise design strategies or digital tools but do not appropriately consider the production system conditions required for circular workflows. A structured narrative literature review was conducted across three domains: Lean Construction, digital construction technologies (including BIM, Digital Twins, and AI), and circular economy. Based on this synthesis, the paper proposes a Lean-Digital-Place (LDP) framework that conceptualises circularity as an emergent property of aligned production processes, digital information infrastructures, and regional material ecosystems. The framework extends Lean Construction thinking from the project-level toward lifecycle and regionally embedded production systems. A research agenda and evaluation indicators are proposed to guide empirical validation and support the development of scalable circular housing systems.

KEYWORDS

Circular economy, BIM, Digital Twins, AI, Lean Construction, lifecycle analysis.

INTRODUCTION

Construction faces major environmental challenges due to high material consumption, waste and embodied carbon. As climate impacts intensify, transitioning to a zero-carbon and circular built environment has become a global priority (Pomponi & Moncaster, 2017). Circular economy strategies, such as material reuse, remanufacture and closed-loop systems, offer pathways to reduce these impacts (Moustafa et al., 2025). However, circularity adoption in construction, and particularly in housing, remains limited (Leising et al., 2018).

Lean Construction aims to reduce waste, improve flow, and maximise value (Koskela et al., 2002). Recent work indicates that Lean can help operationalise circularity practices, while digital technologies, including Building Information Modelling (BIM), Digital Twins (DTs),

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and Artificial Intelligence (AI), can enhance data flow, lifecycle information and decision support (Morseletto, 2020). Despite this potential, digital support for circular housing remains fragmented (Kirchherr, 2023).

This paper argues that limited circularity results from systemic fragmentation across construction processes, information flows, and regional infrastructures. These interdependencies and their impact on circularity are examined in detail in Section 4.

To address this, the paper proposes the Lean-Digital-Place (LDP) framework, integrating Lean Construction, digital technologies and place-based production systems. Lean provides coordinated and reliable workflows; digital technologies offer lifecycle transparency; and place-based ecosystems supply the physical and institutional capacity for material circulation.

The paper contributes by: (i) synthesising Lean, digital and circular economy research to identify systemic barriers to circular housing; (ii) proposing the LDP framework, which positions circularity as an emergent property of aligned process, information and regional systems; and (iii) outlining a research agenda and evaluation indicators to advance circular housing production systems. Circularity is framed as a production systems challenge requiring coordinated flows of work, information and materials.

Theoretically, the paper extends Lean research beyond project-level workflow optimisation toward lifecycle and regional production ecosystems. The LDP framework reconceptualises circularity as emerging from the alignment of production processes, digital information systems and place-based infrastructures.

The remainder of the paper is structured as follows. Section 2 reviews relevant literature; Section 3 outlines the narrative literature review methodology; Section 4 presents the conceptual foundations and the LDP framework; Section 5 proposes a research agenda; and Section 6 discusses limitations and concludes the paper.

METHOD

A narrative literature review (Rumrill & Fitzgerald, 2001) was conducted to synthesise knowledge across three domains relevant to circular housing production: Lean Construction, digital construction technologies and circular economy in the built environment. The approach combined database search, data extraction, narrative synthesis, gaps analysis and conceptual framework development. Figure 1 presents the methodological approach in the study.

The review was guided by the following research question: *How can Lean Construction, digital technologies, and place-based ecosystems be integrated to support circular housing at scale?*

Literature Search: Searches were carried out using Scopus, Web of Science, ScienceDirect and Google Scholar, covering publications between 2000 and 2025, terms related to:

- Circularity (“circular economy”, “material reuse”, “design for disassembly”),
- Digital (“BIM”, “digital twin”, “AI”, “lifecycle modelling”), and
- Lean (“lean construction”, “TFV”, “production flow”, “waste minimisation”).

Figure 1: Methodological approach adopted in the study

The initial search retrieved approximately 140 publications across the selected databases. Titles and abstracts were screened for relevance to circularity, Lean processes, or digital lifecycle technologies. After removing duplicates and non-relevant items, 40 publications remained for full-text analysis. These were coded against four analytical categories—circularity strategies, place-based ecosystems, Lean processes, and digital information infrastructures—to identify overlaps, contradictions, and integration gaps.

Framework Development: Insights from the synthesis informed the development of the Lean-Digital-Place (LDP) framework, which conceptualises circular housing production as a socio-technical system emerging from the alignment of process, information and regional infrastructures. These dimensions were mapped against challenges and opportunities identified in literature. Areas requiring theoretical development, empirical validation or technological-institutional integration informed the research agenda. A key methodological limitation is that the narrative literature review is not fully systematic or reproducible, which may limit the robustness of the framework. Empirical studies, e.g. studies and pilots, are needed to validate and refine the LDP framework.

THEORETICAL FOUNDATIONS

CIRCULARITY IN THE BUILT ENVIRONMENT

Circular economy (CE) relates to reducing waste, resource consumption, and environmental impact of the built environment (Kirchherr, 2023). In housing, two emerging construction trends support the integration of circularity principles: industrialised construction (IC) and design for disassembly (DfD). IC involves the systematic production of buildings both on-site and off-site, to allow continual improvement. DfD extends resource-efficiency considerations beyond the initial assembly to include building maintenance, adaptability, and End-of-Life (EoL) scenarios (Davis et al., 2025). CE emphasises designing buildings and components for disassembly, adaptability, reuse, and closed-loop material flows. (Morseletto, 2020).

However, the adoption of circularity in housing is challenged by the construction industry's practices (Kirchherr, 2023). These include: (i) technical barriers, related to material traceability, incomplete lifecycle data and poor documentation (Akinade et al., 2015; Akanbi et al., 2018) (ii) organisational barriers, caused by fragmented supply chains, low trust, and limited capacity for circular practices (Adams et al., 2017; Sajid et al., 2024)(iii) infrastructure and market barriers: insufficient reuse facilities, lack of refurbishment centres and weak secondary material markets (Leising et al., 2018; Anastasiades et al., 2022) and (iv) regulatory barriers that embed linear practices into procurement and design standards (Munaro & Tavares, 2023).

PLACE-BASED PRODUCTION ECOSYSTEMS

Circularity requires not only improved design and data but also regional infrastructures that support material recirculation. Place-based perspectives view regions as production ecosystems, comprising reuse and refurbishment hubs, off-site industrialised construction facilities, demolition and recovery services, local supply chains and logistics networks, and governance structures (Ranasinghe et al., 2024).These regional systems are essential because circularity depends on geographically proximate, operationally reliable loops for sorting, processing, redistributing, and reusing materials. Without them, CE strategies remain theoretical or isolated.

LEAN CONSTRUCTION

Lean Construction treats construction as a production system aimed at improving flow, reducing waste, and delivering value. In the TFV theory, flow reliability, transformation efficiency and value generation underpin coordinated and predictable production (Koskela, 1997; Koskela et al., 2007). Approaches such as the Last Planner® System, value stream mapping, and just-in-time delivery have been shown to significantly reduce variability and inefficiencies across project phases (Formoso et al., 1999).

Although Lean Construction and Circular Economy stem from different traditions, they share a commitment to eliminating waste and improving system performance (Awwal et al., 2024). Lean strengthens production reliability and coordination, reducing process variability that undermines lifecycle-oriented design. Circularity complements this by extending material value through design for disassembly, reuse and closed-loop flows. Mapping the TFV model onto circularity highlights this alignment: transformation relates to resource optimisation; flow corresponds to stable circular supply chains; and value expands to include lifecycle and environmental performance, see Figure 2.

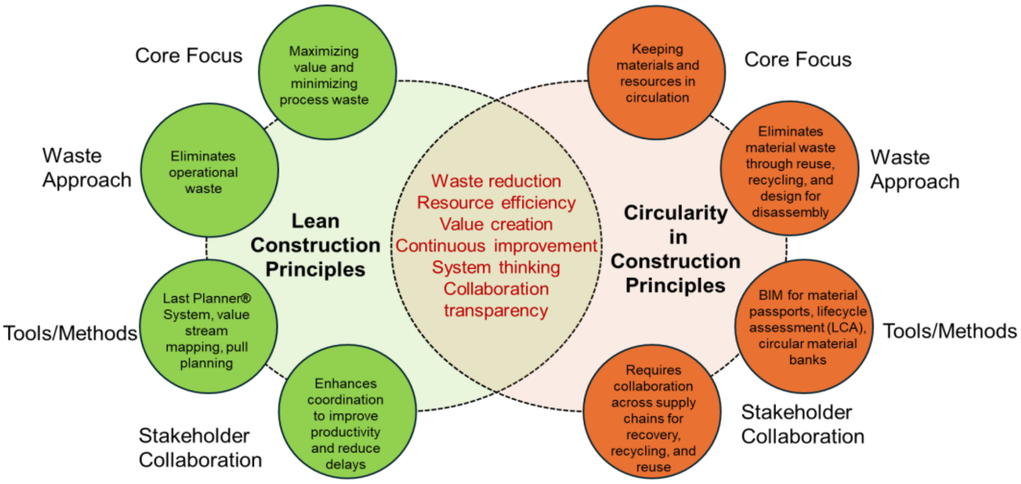

Figure 2: Conceptual synergy between lean principles and Circularity in Construction

Thus, lean supports circularity by strengthening operational efficiency within a framework that enables responsible material use and lifecycle analysis. Digital platforms provide the data and analytical capability needed to assess circular design options.

DIGITAL TOOLS FOR CIRCULAR DESIGN

Digital technologies, such as BIM, DTs, and AI, are increasingly seen as key enablers for embedding circularity into housing design.

BIM

In circular design, BIM can manage materials, components, and systems across the building lifecycle (Pomponi & Moncaster, 2017). It supports analysis of material flows, durability, and end-of-life pathways, enabling reuse, recycling and modularity (Akanbi et al., 2018). Embedded in early design workflows, BIM supports decisions on long-term material performance, disassembly, and adaptation within a digital environment (Sacks et al., 2018).

BIM also supports material passports, which store material composition data and potential reuse options, thereby improving traceability for deconstruction, refurbishment, and recycling (Pomponi & Moncaster, 2017). Linking BIM with automated Life Cycle Assessment (LCA) enables real-time evaluation of embodied carbon, energy use, and environmental impacts, helping compare materials and construction methods (Basbagill et al., 2013).

BIM's automated clash detection prevents coordination errors, which can lead to material waste. When combined with modular or prefabricated construction strategies, BIM's coordination capabilities enhance circularity by minimising scrap and ensuring components can be reused with minimal processing (El Hafiane et al., 2025). BIM enables transparent modelling of joints, fasteners, and modular components.This allows designers to adopt modular, reversible construction, fostering a shift from linear to circular building practices. (Durmiševic, 2018).

Several challenges limit BIM's ability to support circularity goals; e.g. insufficient metadata requirements for circular materials, limited representation of end-of-life scenarios within BIM tools (Akinade et al., 2015), and persistent gaps in practitioner training and capability (Chong et al., 2016). Technical fragmentation remains a key issue, as BIM tools might not interoperate well with material inventories or LCA platforms.

Digital Twins (DTs) in Circularity

DTs integrate live data from sensors and operational systems to create real-time digital replicas of physical assets (Bolton et al., 2018). DTs extend into operation, maintenance, refurbishment, and end-of-life planning, aligning with circularity principles of material performance and building adaptability (Pehlken et al., 2024).

IoT-enabled DTs collect real-time sensor data on building conditions, material performance, environmental parameters and occupancy patterns. This real-time data provides insights to support decisions about the entire lifecycle, from installation to demolition to replacement (Fuller et al., 2020). It links physical and digital data, enabling monitoring of structural integrity and energy consumption, that minimise waste and maximise efficiency (Pehlken et al., 2024).

DTs allow designers to simulate retrofitting scenarios by enabling strategies that reduce the need for new materials by forecasting how buildings and materials will perform under changing conditions (e.g. shifts in occupancy, climate, or technology) (Erkoyuncu et al., 2020). This capacity supports circularity principles by promoting reversible material assemblies and adaptable layouts in retrofitting.

The adoption of DTs is still at an early stage, especially in the housing sector. Challenges include high implementation costs (Peng et al., 2024), low interoperability between BIM and IoT, and limited knowledge and facilities management systems (Karan & Irizarry, 2015). Many organisations are not aware of DT's role in circularity outcomes, limiting strategic investment.

Artificial Intelligence (AI) in Circularity

AI is emerging as a transformative enabler because of its analytical, predictive, and generative capabilities. By integrating AI with BIM and DTs, circularity considerations can be embedded throughout the housing (Akanbi et al., 2018). AI methods, e.g., neural networks, evolutionary algorithms, and reinforcement learning, can generate design options that reduce material use and carbon while improving disassembly(Asadi et al., 2012). AI supports multi-objective optimisation that accounts for environmental, economic, and operational factors (Nguyen et al., 2014), to accelerate decision-making and promote circularity from the early design stage.

When integrated with DTs or smart recycling systems, AI enhances the traceability of materials, ensuring they can re-enter supply chains in accordance with circular principles (Farshadfar et al., 2024).Machine learning models can simulate deterioration patterns, structural fatigue, and maintenance requirements based on historical real-time data (Brito & Silva, 2020). Predictive analytics also supports cost-effective lifecycle planning, enabling circularity.

AI-based evaluation systems may automatically analyse BIM or DT models to verify compliance with circular design guidelines, including disassembly potential, material reuse pathways, and LCA documentation. This automation reduces the need for time-consuming manual assessments, ensures consistency across projects, and allows for continuous feedback loops that improve design decisions (Akanbi et al., 2018).

AI adoption in construction is still in its infancy, and issues may occur due to inconsistent data standards across the construction sector, and the current limited integration between AI tools and mainstream BIM platforms (Yang et al., 2024). Addressing these challenges is essential for these technologies to serve as a reliable enabler of circularity.

Barriers to Circularity

Table 1 provides a comparative overview of the contributions and limitations of BIM (Building Information Modelling), DT (Digital Twins), and AI (Artificial Intelligence in supporting circular housing.

Table 1: Comparison of digital tools for circular design in housing

Tools	Contributions to Circularity	Current Limitations	References
BIM	-early design decisions -Supports material passports -Integrates real-time LCA -Automated clash detection -Models disassembly strategies	-limited circularity metadata -Limited end-of-life scenarios -Interoperability gaps with LCA and material databases -digital maturity variability	(Sacks et al., 2018); (Akanbi et al., 2018); (Basbagill et al., 2013); (Durmiševic, 2018)
DTs	-integrate real-time sensor data -track Lifecycle performance -Predictive maintenance -adaptability and refurbishment	-High operational costs - BIM Interoperability gaps -Low adoption -Limited awareness of benefits	(Bolton et al., 2018); (Fuller et al., 2020); (Karan & Irizarry, 2015); (Peng et al., 2024)
AI	-Multi-objective design optimisation for material -Automated material classification for recycling -Predictive modelling	-Insufficient datasets -limited transparency -limited data standardisation -Limited integration with BIM/DT workflows	(Asadi et al., 2012); (Brito & Silva, 2020); (Pomponi & Moncaster, 2017)

GAPS AND OPPORTUNITIES

WHY CIRCULARITY FAILS: THREE FORMS OF FRAGMENTATION

Across the reviewed literature, three interdependent forms of fragmentation consistently undermine attempts to achieve circularity: (i) process fragmentation; sequential workflows, late decisions and rework inhibit lifecycle planning; (ii) Information fragmentation: incomplete or incompatible datasets undermine traceability and environmental assessment, and (iii) spatial fragmentation, lack of regional reuse hubs, refurbishment facilities and reverse logistics prevent materials from circulating (Anastasiades et al., 2022; Sajid et al., 2024)

These forms of fragmentation (See Figure 3) interact through reinforcing causal mechanisms that limit circular implementation. Fragmented production processes reduce opportunities for early lifecycle coordination, which limits the effectiveness of digital information systems that rely on reliable upstream data. Weak lifecycle information constrains the development of regional reuse infrastructures and secondary material markets (Leising et al., 2018). This weakens the potential of digital information systems, since tools such as BIM and lifecycle assessment depend on early design coordination and reliable data flows(Akanbi et al., 2018). Limited information on material characteristics and availability constrains the development of regional reuse infrastructures and secondary material markets (Anastasiades et al., 2022).

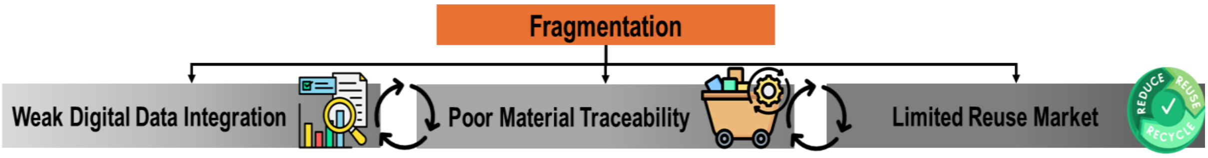

Figure 3: Casual mechanism of fragmentation hindering circularity

Furthermore, regulatory frameworks often do not provide strong incentives for circularity (Adams et al., 2017). Lastly, many practitioners have limited digital literacy, which restricts their ability to leverage BIM, DTs, or AI effectively (Yang et al., 2024). These interdependent mechanisms restrict circular practices to isolated projects rather than scalable production.

CONCEPTUAL DEFINITIONS: ALIGNMENT AND EMERGENT CIRCULARITY

We present Key constructs in Table 2 to address these gaps.

Alignment: The concept of alignment draws on research in production systems and Lean Construction, emphasising coordinated workflows, reliable planning and early stakeholder involvement to reduce variability and improve system performance (Koskela, 1992). Alignment also relates to the integration of technical and organisational subsystems required to achieve coherent socio-technical outcomes (Geels, 2004).Within circular housing systems, alignment can be observed through several operational indicators: early design coordination for circular strategies (DfD); interoperability and continuity of lifecycle data (BIM, Digital Twins); regional infrastructures and logistics networks that enable material reuse, and refurbishment.

Emergent Circularity (EC): The concept of emergence originates from systems theory, which explains how complex outcomes arise from interactions between interconnected elements (Checkland, 1999; Sterman, 2001). In the built environment context, circularity depends on design decisions and reliable production processes, transparent lifecycle information and operational infrastructures capable of supporting material loops. Table 2 presents the operational indicators and possible empirical measures.

Table 2: Indicator and measures for Alignment and Emergent Circularity

Construct	Operational indicators	Possible empirical measures
Alignment	early design coordination	stakeholders' number before concept freeze
Alignment	lifecycle data interoperability	BIM–DT integration level
EC	material reuse flows	% reused components

LEAN–DIGITAL–PLACE (LDP) FRAMEWORK

To address the systemic barriers to circular housing identified in the literature, this paper proposes the Lean-Digital-Place (LDP) framework (Figure 3).

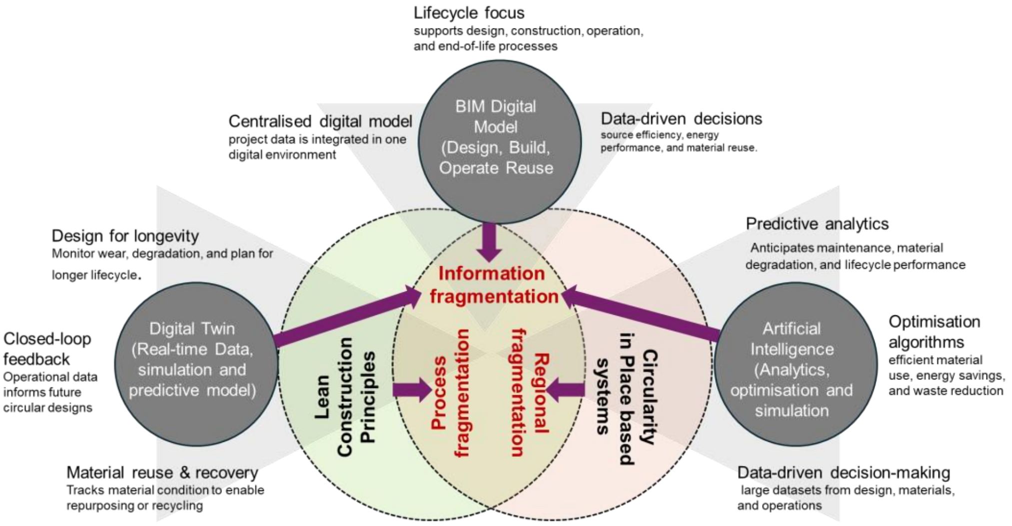

Figure 4: Lean-Digital-Place (LDP) framework for circular housing production systems

The framework conceptualises circularity not as a discrete design intervention but as an emergent property of a coordinated production system. Circularity arises when process flows (Lean), lifecycle information infrastructures (Digital), and regional material ecosystems (Place) are aligned to support the continuous circulation of materials across project and regional scales.

Unlike existing circular construction approaches that emphasise design strategies, isolated material flows, or digital tools (e.g., Leising et al., 2018; Lessing et al., 2015; Morseletto, 2020), the LDP framework integrates insights from Lean Construction, digital lifecycle technologies, and place-based production ecosystem research to articulate the socio-technical conditions required for circular housing. From this perspective, circularity is a system property that emerges from interactions between coordinated production processes (Koskela et al., 2002), interoperable information systems (Sacks et al., 2018; Bolton et al., 2018), and the availability of regional material infrastructures such as reuse hubs and refurbishment centres (Leising et al., 2018; Davis et al., 2025).

Lean as Enabler of Lifecycle Coordination

Lean Construction contributes the process logic needed to support circular housing by reducing variability, improving flow and ensuring early, reliable coordination across the production system (Koskela, 1992; Koskela et al., 2007). By strengthening workflow stability, Lean enables the timely integration of design for disassembly, reusable components, and lifecycle-oriented decisions, requirements consistently highlighted in circularity research (Amarasinghe et al., 2024; Dara et al., 2024).

Lean's emphasis on early stakeholder involvement, collaborative planning, and continuous improvement directly addresses the process fragmentation that prevents circularity from scaling. Through predictable and transparent workflows, Lean provides the foundation upon which circular strategies can be systematically embedded throughout the lifecycle. Thus, within the LDP framework, Lean is positioned not as a complementary approach but as a critical enabler of lifecycle-oriented design and production.

Digital Tools as Lifecycle Information Infrastructure

Digital technologies, BIM, Digital Twins, and AI, form the information backbone of the LDP framework, providing the structured, accurate and continuous data streams needed to operationalise circularity. BIM enables material passports, disassembly modelling and automated LCA integration (Pomponi & Moncaster, 2017; Akanbi et al., 2018; Basbagill et al., 2013), while Digital Twins extend information feedback loops into operation, maintenance and end-of-life phases (Awwal et al., 2023; Bolton et al., 2018; Fuller et al., 2020). AI enhances this infrastructure by supporting prediction, optimisation and automated verification of circular design principles (Asadi et al., 2012; Brito & Silva, 2020).

Within the LDP framework, digital tools strengthen and extend Lean processes by improving information continuity, interoperability, and decision reliability across design, construction, use, and deconstruction. They mitigate information fragmentation, enabling lifecycle transparency and forming a coordinated information system that supports circular flows of materials, knowledge and decisions.

Place-Based Ecosystems as Material and Institutional Infrastructure

Even with strong Lean processes and robust digital information systems, circularity depends on regional infrastructures capable of supporting material recirculation. Place-based ecosystems comprise reuse and refurbishment facilities, logistics networks, secondary material markets, regulatory actors and governance frameworks (Leising et al., 2018; Davis et al., 2025). These elements address the spatial fragmentation that restricts circularity to isolated projects.

Within the LDP framework, Place situates Lean and digital strategies within regionalised production and circulation systems, highlighting how local institutional capacities, market structures and logistical networks enable or constrain circular flows of materials. This perspective extends Lean Construction beyond project-level optimisation to the coordination of regional socio-technical systems, aligning construction processes with the physical and institutional infrastructures required for material recovery, reuse and redistribution.

RESEARCH AGENDA

The paper proposes a research roadmap for supporting the implementation of CE (See Figure 4). It outlines five interlinked research areas that collectively advance theoretical development, methodological innovation, capability building, and regional scaling. These provide a structured agenda for empirical investigation and practical implementation: S1 establishes analytical foundations → S2 designs physical systems → S3 develops information systems → S4 builds organisational capabilities → S5 evaluates and scales regional systems. Evaluation indicators include the proportion of components designed for disassembly, the percentage of refurbished materials, lifecycle embodied carbon reduction, interoperability of digital material data, and the operational capacity of regional reuse.

Stage 1 (S1): Analytical Foundations**:** Develop analytical techniques that integrate BIM metadata with Lean process analysis. Indicators: proportion of components with lifecycle data, early-stage coordination metrics, and coverage of material loops.

Stage 2 (S2): Design of Physical Production Systems: Simulate production hub flows within regional circular economies. Indicators: percentage of reused/refurbished materials, efficiency of logistics networks, and throughput of material hubs.

Stage 3 (S3): Development of Digital Information Systems: Create circularity-related ontologies for BIM, DTs and AI, enabling interoperability. Indicators: completeness and interoperability of digital material data, predictive accuracy for lifecycle performance, and digital traceability coverage.

Stage 4 (S4): Organisational Capability Building**:** Pilot training programmes that integrate digital tools with circular economy workflows. Indicators: number of trained stakeholders, adoption rate of circular workflows, and cross-functional collaboration metrics.

Stage 5 (S5): Regional Evaluation and Scaling: Develop policy evaluation and decision-support frameworks linking design choices to circular outcomes. Indicators: operational capacity of regional reuse/refurbishment hubs, regional material recirculation rates, and lifecycle carbon reductions.

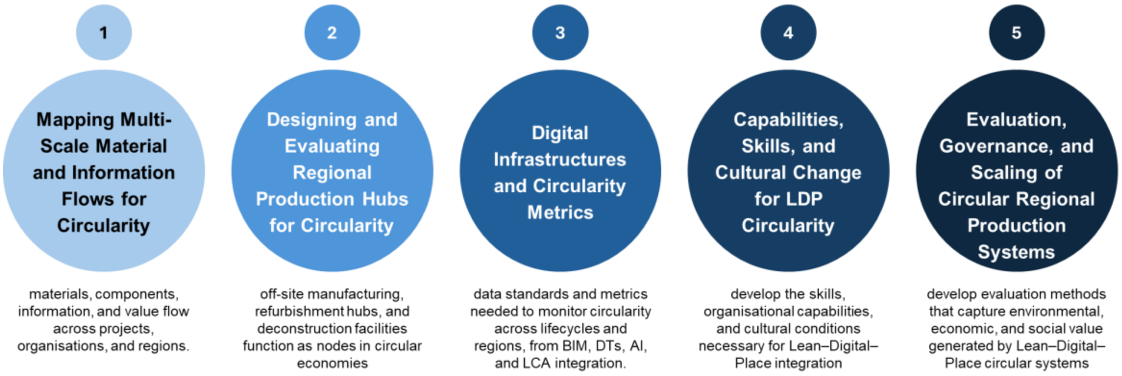

Figure 5: Research roadmap for the proposed LCD framework

Taken together, these stages articulate a progression from isolated digital tools to integrated lifecycle workflows, and from a design-centred perspective to fully coordinated regional circular systems. To support empirical assessment, future studies should develop evaluation indicators linking design, information systems, and regional circular infrastructures.

LIMITATIONS

A key limitation is that the LDP framework is primarily conceptual, based on a structured narrative review, and has not been empirically validated or compared to existing Lean or circular economy models. While the framework integrates insights from fragmented literature domains, it does not provide analytical testing, critical evaluation of contradictions, or direct assessment of measurable outcomes. Future research should operationalise the framework through case studies, pilot projects, and comparative analysis, using the evaluation indicators proposed in the research agenda to strengthen theoretical validation and practical applicability.

CONCLUSION

Achieving circularity in the built environment requires coordinated action across production processes, information infrastructures and regional material systems. This paper has brought these elements together by proposing the Lean–Digital–Place (LDP) framework, which integrates Lean Construction principles, digital lifecycle technologies and place-based production ecosystems into a coherent socio-technical model for circular housing. Through this integration, the paper reframes circularity as a system property that emerges when work flows, information flows, and material flows are aligned across lifecycle and regional scales.

The LDP framework extends Lean Construction theory beyond its traditional project-level focus by situating production flow and value generation within broader circular ecosystems. In doing so, it shows how Lean's process logic, digital transparency and regional material infrastructures can collectively address the process, information and spatial fragmentation that currently limits circularity in practice. This provides a conceptual foundation for understanding circular housing not as a set of isolated design strategies, but as a coordinated, multi-scalar production system.

To support further development, the paper advances a research agenda outlining five areas of inquiry spanning analytical integration, physical production systems, digital information infrastructures, organisational capability building and regional scaling. These areas provide a pathway for empirical validation of the LDP framework and for developing the capacities needed to deliver scalable circular housing systems.

Future work should focus on applying and testing the framework in real-world contexts, including case studies, pilot projects and cross-organisational collaborations, to evaluate how Lean, digital tools and regional ecosystems interact in practice. Such research will help refine the LDP framework, strengthen its theoretical foundations and contribute to the transformation of housing production systems toward circularity and environmental sustainability.

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