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Review Article/ Perspective Article

Towards Viable Retrofitting: A Review of Sustainable Strategies In Portuguese Social Housing

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Abstract

Contemporary premises in construction focus on sustainable solutions that reduce environmental and social impacts while improving functionality and affordability. The refurbishment of building stocks plays a crucial role in reducing carbon emissions from the built environment. Conventional Portuguese social housing, characterised by masonry and reinforced concrete, has resulted in inflexible and spatially unattractive structures with limited potential for material reuse, often leading to landfill disposal. Much of this housing, built between the 1960s and 1980s, is now reaching the end of its lifespan, requiring innovative strategies to address liveability, affordability, and sustainability. Prefabricated and Modular Systems (PMS) can extend a building's lifespan by enabling disassembly, material recovery, and adaptability. Evidence from European case studies shows that circular design strategies reduce waste, embodied carbon, and on-site disruption while enhancing flexibility and reuse opportunities. This research analyses sustainable retrofitting practices and develops an integrated framework linking Portuguese housing typologies with retrofit strategies grounded in circular design, prefabrication, and Design for Assembly and Disassembly (DfAD) principles. Life Cycle Assessment (LCA) is discussed as a tool to compare renovation scenarios and quantify environmental impacts and costs. This work aims to provide guidelines for retrofitting Portuguese social and collective housing in line with contemporary sustainability principles. Although such a contextualised approach has received limited attention in the literature, it holds significant potential for improving the existing housing stock. In this study, a sustainable retrofitting framework is proposed and qualitatively validated, and future research will focus on pilot testing to assess its technical and economic feasibility in practice.

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Highlights

- Sustainable retrofitting can reduce waste and enables adaptability in social and collective housing when incorporating circular design, prefabrication, and Design for Assembly and Disassembly (DfAD) principles.
- Prefabricated solutions can improve efficiency while minimising on-site disruption, while enhancing spatial quality, flexibility, and liveability.
- Framework links Portuguese housing typologies with scalable retrofit strategies.

1 Introduction

The building sector is recognised as one of the largest contributors to global resource consumption and greenhouse gas emissions, accounting for nearly 40% of total energy use and CO_2 emissions worldwide (IEA, 2022). In Europe, the social housing stock is particularly vulnerable: a large share of buildings constructed between the 1960s and 1980s now perform poorly in terms of energy efficiency, thermal comfort, adaptability (UNEP, 2024), and liveability. Similarly, Portuguese social housing, often built with reinforced concrete structures and subject to limited maintenance, face pressing challenges of energy poverty, physical degradation, and lack of functional diversity (Desvallées, 2022).

Sustainable retrofitting has therefore become a critical priority. Yet conventional approaches, typically centred on insulation upgrades or HVAC systems, often neglect long-term adaptability, circularity, and material efficiency and spatial sensitivity. Recent research points to strategies such as circular design (CD), Prefabricated and Modular Systems (PMS), Design for Assembly and Disassembly (DfAD), and Life Cycle Assessment (LCA) as ways of aligning retrofit practices with the objectives of the European Green Deal and the circular economy transition (European Commission, 2019; Nußholz & Bocken, 2023). Their application in Portuguese social housing, however, remains limited and fragmented (Krezlik, 2022).

In this study, Sustainable Retrofitting (SR) is understood as an overarching approach integrating environmental, technical, economic and social objectives. Within this, SR strategies form a subset that specifically focus on material circularity, adaptability, and reuse; DfAD and LCA are considered operational tools that enable and measure these circular aims—DfAD through design logic and LCA through quantitative evaluation.

This article presents a qualitative review of SR strategies and analyses their applicability to the Portuguese social housing context. Based on this review, it proposes a framework that integrates Circular Design (CD), Prefabricated and Modular Systems (PMS), Design for Assembly and Disassembly (DfAD) and Life Cycle Assessment (LCA) principles with the aim of enhancing environmental performance, economic viability, technical feasibility, and social value. By linking technical strategies with spatial and architectural design thinking, this research aims to qualify SR not only as an engineering process but as a holistic transformation of living environments.

2 Methodology

This article is based on a qualitative review of scientific literature, institutional reports, and architectural case studies. The review sought to identify sustainable retrofitting strategies with relevance for the Portuguese social housing context.

The scientific literature was collected through Scopus, Web of Science and Google Scholar and using keywords and Boolean operators such as [“circular” OR “sustainable” AND “renovation” OR “retrofitting” OR Rehabilitation” AND “building” OR “housing” AND “prefabrication” OR “design for disassembly” OR “life cycle assessment”]. Publications were restricted to the period 2000–2025. In parallel, policy documents from the European Union, the International Energy Agency (IEA), and the United Nations Environment Programme (UNEP) were consulted. Importantly, the review bridges architectural and engineering perspectives, combining design-oriented approaches with technical performance analysis, an asset that allows a more comprehensive understanding of sustainable retrofitting strategies.

The research design evolved through three iterative stages: (1) a state-of-the-art review across CD, PMS, DfAD, and LCA in retrofitting; (2) analysis of Portuguese social housing typologies to define applicability and constraints; and (3) synthesis into an integrated framework that structures the retrofit process into diagnosis, strategy, validation, and implementation phases.

3 Sustainable Retrofitting Foundations

Recent literature emphasises that SR requires strategies that address multiple dimensions simultaneously (Toosi et al., 2020). As a result, from literature review, four contemporary approaches are particularly relevant: **Circular Design (CD), Prefabricated and Modular Systems (PMS), Design for Assembly and Disassembly (DfAD), and Life Cycle Assessment (LCA)**. Figure 1 illustrates how these strategies interact with four sustainability dimensions—environmental, economic, social, and technical. While the first three correspond to the established sustainability pillars, the technical dimension is frequently incorporated in construction-related frameworks to reflect performance and feasibility considerations (Alam Bhuiyan & Hammad, 2023). Each approach contributes to more than one dimension, and their overlap defines the integrated scope of SR. CD connects strongly to environmental, economic and technical aspects through resource efficiency and circular economy principles. PMS respond mainly to technical and social requirements by enabling rapid, cost-controlled interventions, while also supporting environmental goals when combined with DfAD through reversible assemblies, and ever economical concerns by enabling material efficiency. LCA primarily addresses environmental impacts but also incorporates economic and social considerations.

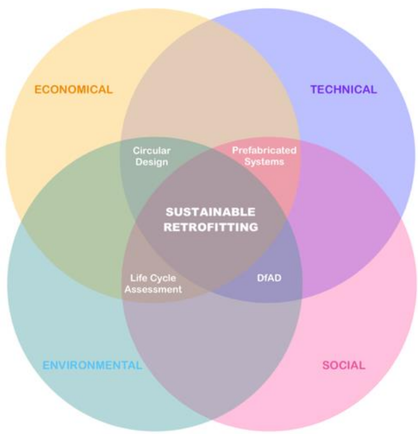


Figure 1. Main concepts within Sustainable Retrofitting. Source: Authors

CD applies circular economy principles to construction, aiming to maximise material value and minimise waste. It replaces the linear "take–make–dispose" logic with closed loops of reuse, repair and recovery (Pomponi & Moncaster, 2017). Applied to retrofitting, circular design enables buildings to act as material banks, where components are documented, recovered and reintegrated into new cycles. Examples such as the Circular Retrofit Lab in Brussels demonstrated how modular façades and dry connections can turn student housing into adaptable, demountable systems (Cambier, Nys & Glorieux, 2022). These practices underline both the technical feasibility and economic potential of large-scale reuse. These circular strategies naturally complement prefabricated and modular systems, as components designed for reuse can be efficiently produced and assembled off-site.

PMS involve producing building components off-site under controlled conditions and assembling them on-site (Gibb, 1999). By reducing construction time, improving quality and minimising disruption, these systems have become increasingly relevant for occupied housing retrofits (Almeida, Barbosa, & Malheiro, 2020). A relevant project is the Cité du Grand Parc Renovation in Bordeaux, where prefabricated exoskeletons expanded space and improved energy performance without displacing residents (Lacaton & Vassal, 2017). Prefabrication also aligns with circularity when designed for disassembly, enabling modules to be reused and thereby reducing embodied carbon (Nußholz & Bocken, 2023). When combined with Design for Assembly and Disassembly (DfAD), prefabricated systems can be reversed, upgraded, or replaced, further extending their life and aligning with circular principles.

DfAD combines principles of simplified assembly with strategies for dismantling and reuse at end of a building's useful life. It relies on mechanical fixings, stratified systems and material standardisation to ensure reversibility (Crowther, 2005). Applied to retrofitting, DfAD has been successfully implemented in European initiatives, such as the MeeFS project (Multifunctional Energy Efficient Façade System for Building Retrofitting), which used prefabricated façades designed for selective replacement and future upgrades (European Commission, 2015). Beyond environmental benefits, DfAD minimises disturbance to occupants and increases adaptability in collective housing blocks, linking technical feasibility with social value (Durmisevic, 2006). Assessing these systems through Life Cycle Assessment (LCA) ensures that environmental benefits from disassembly and modular reuse are quantified, guiding design decisions.

LCA provides a standardised method to evaluate environmental impacts of construction systems across their life cycle, accounting for both embodied and operational effects (Toosi et al., 2020). Studies have shown that deep retrofitting generally results in lower life-cycle emissions than demolition and rebuilding, even when the embodied impacts of materials are considered (Röck et al., 2020). Prefabricated retrofits, particularly timber-based systems, have demonstrated superior life-cycle performance through improved waste management, lower embodied energy, and enhanced recycling potential (Monahan & Powell, 2011; Dodoo, Gustavsson & Sathre, 2014). Global reports further reinforce the role of LCA in guiding policies towards low-carbon retrofitting (UNEP & IRP, 2020).

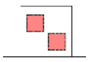
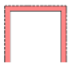
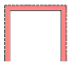
As highlighted CD, PMS, DfAD, and LCA are interdependent. CD informs PMS; DfAD enhances reversibility and LCA quantifies the environmental and economic trade-offs. Together, they create an integrated framework for sustainable retrofitting (figure 1).

4 State of the art in Housing Retrofitting

Housing retrofitting has become a central strategy to reduce the environmental footprint of the built environment (Ma et al., 2012). Rather than demolishing and rebuilding, rehabilitation of existing housing enables energy upgrades, material efficiency and improved living conditions while preserving social value (McGrath et al., 2012). In this context, research and practice increasingly converge on the need to integrate environmental, economic, technical and social dimensions in retrofit strategies (Röck et al., 2020).

In Portugal, where most social housing stock was built between the 1960s and 1980s under public programmes (INE, 2021), retrofits remain largely centred on energy performance through envelope upgrades such as External Thermal Insulation Composite Systems (ETICS), window replacement and HVAC improvements (Gomes, 2015). While effective in reducing energy demand, these solutions tend to lock buildings into rigid configurations with limited adaptability and limited spatial qualities compromising their liveability. Many of these buildings now face structural degradation, poor thermal comfort and high energy needs, reinforcing energy poverty (Desvallées, 2022). However, in recent literature, ambitious strategies are emerging: Table 1 summarizes selected Portuguese projects where innovative housing retrofitting approaches were explored.

Table 1. Comparison between different housing retrofitting projects in the Portuguese context.

Author	Housing Typology	Study focus	Retrofit type	Material / Technique	Performance results	Prefabrication level	Social / Spatial aspects
Almeida et al., 2014	single storey	Energy retrofit, low environmental impact	 Internal	Local wood-based materials, cork insulation	94% energy consumption reduction (1)	Low (conventional constructive methods)	Emphasises "architectural identity preservation"; indoor air quality improvement
Almeida, Barbosa & Malheiro, 2020	low-rise (4-storey)	Energy Retrofit	 Envelope (façade)	Prefabricated Insulated Façade Panel	86% energy consumption reduction (2)	Medium (prefabricated panels)	Reduced disruption to occupants, energy cost reduction, indoor air quality improvement
Krezlik, 2022	low-rise (4-storey)	Energy Retrofit, Low Environmental Impact	 Addition (balcony)	Conventional Materials (concrete); Cross Laminated Timber (CLT)	42% energy consumption reduction (3)	Medium (CLT panels)	Addresses "comfort and daylighting" and improved usable space
Lopes et al., 2024	Brick Masonry Buildings	Energy Retrofit, Circular perspective	 Envelope (façade)	Modular 3D-Printed Termoplastic Pannel	Energy and Seismic Improvement	High (off-site prefabrication and modular assembly)	Not mentioned

(1) Compared to its pre-retrofit (current) condition.
(2) With a solar thermal system.
(3) When choosing the closed balcony solution.

The selected projects illustrate different retrofit strategies and outcomes in the Portuguese context. Almeida et al., (2014) focused on an internal energy retrofit of a single-storey house, where the use of local wood-based materials enabled a 94% reduction in energy consumption. Almeida, Barbosa & Malheiro (2020), applied prefabricated insulated façade panels to a four-storey social housing block; combined with a solar-thermal system, this approach achieved an 86% reduction. Krezlik (2022), explored the addition of balconies to a collective housing scenario, showing that enclosing the new spaces could reduce energy demand by around 50%. More recently, Lopes et al. (2024), proposed modular 3D-printed thermoplastic façade panels for brick-masonry buildings, demonstrating benefits for both energy and seismic performance.

The comparative review presented in Table 1 demonstrates that retrofitting research and practice in Portugal remain largely focused on energy performance, often overlooking broader environmental and social dimensions. Most studies still define sustainability mainly through energy savings, with limited attention to aspects such as circular use of materials, prefabrication, and social aspects. Although recent works, such as Krezlik (2022) and Lopes et al. (2024), begin to address broader dimensions introducing prefabrication, circularity, life cycle thinking, and occupant comfort, as highlighted by Lopes et al. (2024), these concepts remain exceptions rather than the norm. To move towards a more comprehensive approach, retrofit strategies should also value construction circularity, spatial adaptability and liveability as essential measures of success.

5. Implementing Sustainable Retrofitting in Portuguese Housing

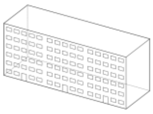
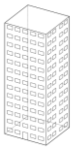
The Portuguese social housing stock was largely developed between the 1960s and 1980s and exhibits a high degree of uniformity in both spatial layouts and structural typologies. This consistency, while reflecting historical approaches to rapid urbanisation, also means that many of these buildings share common pathologies, energy inefficiencies and inadequacy of spatial liveability (Marcelino & Lanzinha, 2018). As a result, they present an opportunity for systematic and replicable retrofitting strategies, making them an ideal focus for exploring the implementation of sustainable interventions in existing housing.

The analysis of the Portuguese social housing stock reveals four dominant typologies that shape retrofitting possibilities. Single units, with typically one or two floors and often attached, represent the simplest form, while low-rise blocks, usually constructed without elevators and featuring linear concrete beam-and-column structures, present more complex challenges. Medium-rise blocks share similar structural systems to low-rise blocks but generally incorporate a service core, whereas tower blocks are characterised by taller reinforced concrete structures and increased vertical complexity (Brandão & Lanzinha, 2021).

Retrofitting interventions for these typologies can be organised according to their focus and scale. Vertical extensions involve adding floors using lightweight systems, allowing an increase in usable space without overloading existing structures (Lopes et al., 2024). Horizontal extensions, such as balconies, winter gardens, or exoskeletons, provide opportunities to expand living areas and improve energy performance (Scuderi, 2016). Façade retrofitting, including external thermal insulation, ventilated façades, and prefabricated envelope solutions, enhances building durability and thermal efficiency, while minimising disruption to occupants (Gomes, 2015). Internal retrofitting interventions, such as layout reorganisation, upgrading service cores, or installing internal insulation, allow improvements in comfort, functionality and space liveability (Almeida et al., 2014).

Altogether, these typologies associated with retrofitting strategies illustrate the potential for replicable interventions across the Portuguese social housing stock, while also acknowledging the need to adapt to specific local, social and legal contexts. Table 2 summarises the alignment of building typologies with different retrofitting possibilities and limitations.

Table 2 - Portuguese housing retrofitting possibilities and limitations.

Building Typology	Structure	Storeys	Retrofitting Possibilities	Limitations
Single Unit 	Brick/ Stone masonry	1 - 2	Façade retrofit; internal retrofit; horizontal extension	Small parcel sizes constrain additions; interventions are individualised, limiting replicability; high dependency on private financing
Low Rise 	Reinforced Concrete and Ceramic vaults	2 - 4	Façade retrofit; internal retrofit; vertical extension; horizontal extension;	Limited structural capacity for additional floors; integration with existing façades; small plots restricting expansions
Medium Rise 	Reinforced Concrete and Ceramic vaults or lightweight concrete or hollow-core slab, service core	5 - 7	Façade retrofit; vertical extension;	Ownership fragmentation; regulatory restrictions on densification; financing difficulties
High Rise 	Reinforced Concrete, service core	8 - 12+	Façade retrofit; internal retrofit; horizontal extension;	Structural limits for vertical extension; high costs of scaffolding; disruption in occupied units; social acceptance of façade changes

Single-unit houses tend to be more suitable for façade retrofitting interventions, such as external insulation and window replacement, as well as internal reorganisation, since these interventions can be managed at the scale of individual ownership. However, they generally offer limited scalability, and architectural integration may present challenges. Low-rise collective housing (2–4 floors) can often accommodate vertical extensions using lightweight timber or steel modules and internal layout reconfigurations, although such interventions frequently require reinforcement of existing structures and compliance with zoning regulations. Medium Rise (5–7 floors) are generally appropriate for façade retrofitting and horizontal extensions, such as balconies or exoskeleton additions, but ownership fragmentation and potential disruption to residents remain significant barriers. Finally, tower blocks (8+ floors) typically present limited opportunities for vertical expansion due to structural and safety constraints, making façade retrofitting the most viable solution; high intervention costs and fire-safety considerations further limit the feasibility of vertical interventions.

5.1. Framework for Portuguese Housing Retrofitting

Building on the analysis of Portuguese social housing typologies and their associated retrofitting possibilities, it becomes clear that the choice and feasibility of interventions depend not only on technical factors but also on urban context, legal constraints, and ownership conditions (Brandão & Lanzinha, 2021; Durmisevic, 2006). To systematically align these considerations with contemporary sustainability objectives, a structured framework was developed (Figure 2), organised into four sequential stages: Diagnosis, Strategy, Validation and Implementation.

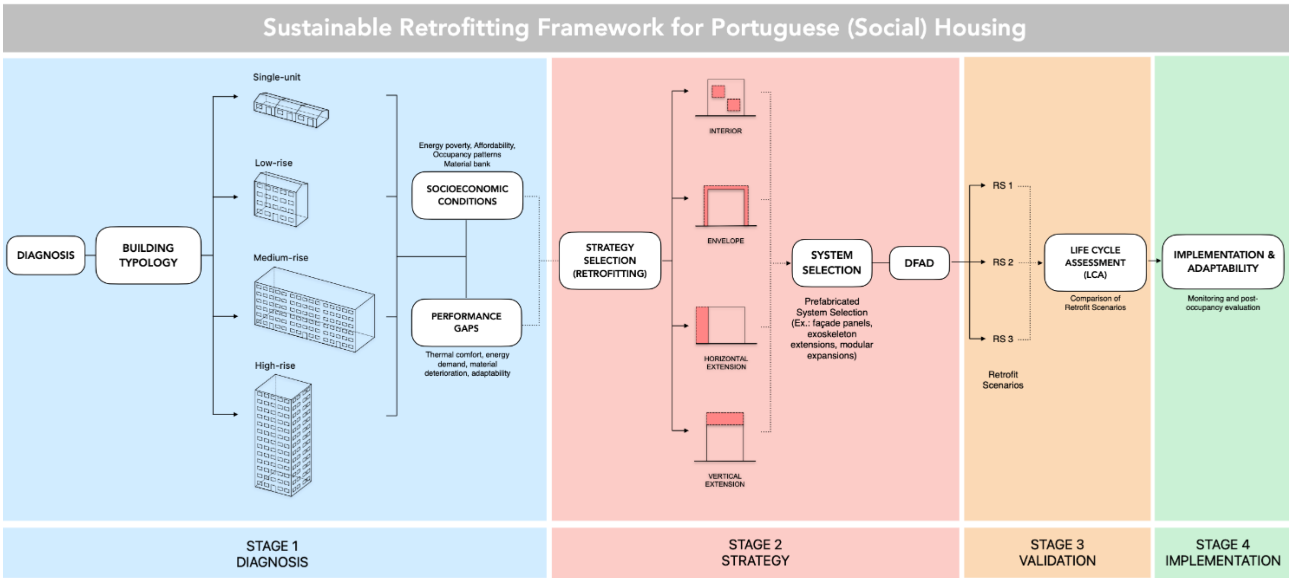


Figure 2. Sustainable Retrofitting Framework for Portuguese Housing

The 'Diagnosis' stage begins with the identification of the building typology—single-unit, low-rise, medium-rise block, or high-rise block—and a detailed assessment of the performance gaps, regarding its physical condition, structural system, and level of degradation. This stage should also consider social and economic aspects, including ownership structure, affordability, and residents' needs, establishing a baseline that captures both technical performance and user requirements. Additionally, the diagnosis identifies building components that can be reused, recycled, or adapted, embedding circular economy principles into the assessment.

Based on the diagnostic outcomes, the 'Strategy' stage selects appropriate retrofitting interventions from four main categories: vertical extensions, horizontal extensions, façade retrofitting, and internal retrofitting. The retrofitting proposal must always consider legal, physical and social constraints. Constructive approaches such as prefabricated and modular systems, can be integrated at this stage and preferably chosen closer to the site, to avoid high costs. Also, DfAD should be considered to enhance the building's lifespan.

The 'Validation' stage focuses on evaluating the selected strategies across four sustainability dimensions: environmental, economic, technical, and social, aiming to help choose the most balanced proposal. This stage implements sustainability assessment tools (LCA), and considers how interventions can be maintained, adjusted over time, and designed to accommodate future needs.

Finally, in the Implementation phase, considers how interventions can be maintained, adjusted over time, and designed to accommodate future needs, through monitoring and post-occupancy assessment.

By these concepts within a single model, this framework provides a practical and replicable tool for guiding sustainable retrofitting in Portuguese social housing, as it aligns building typologies with targeted interventions while ensuring that technical feasibility, occupant needs, and environmental performance are commonly addressed. This framework undergoes qualitative validation in this study, with future work planned to include pilot testing to evaluate its technical and economic feasibility.

6. Discussion

Conventional retrofitting practices in Portugal have largely focused on energy-oriented interventions, such as ETICS and window replacement. While these measures can improve short-term energy performance, they often constrain buildings into rigid configurations with limited adaptability (Brandão & Lanzinha, 2021). In contrast, sustainable retrofitting strategies using prefabricated, dry-assembled, and demountable components enable material recovery, selective replacement, and reuse, extending building lifespan and supporting adaptability (Durmisevic, 2006).

Evidence from European pilot projects highlights that circular retrofits can reduce construction time, minimise occupant disruption, and improve indoor comfort and environmental quality (Nußholz & Bocken, 2023). This is particularly relevant for collective housing, where resident disturbance strongly influences project feasibility. Comparing conventional and circular approaches reveals a tension between short-term economic constraints and long-term environmental and social value, emphasising the role of life-cycle thinking.

PMS further align with LCA objectives by reducing errors, waste, and embodied carbon during controlled off-site production. Challenges remain, including logistics, higher upfront costs, system availability, and regulatory adaptation (Ma et al., 2012). Likewise, DfAD supports reversibility and reduced occupant disruption, but requires detailed documentation of connections and materials, which is not yet standard practice.

LCA has proven effective in comparing retrofit scenarios, showing consistent reductions in greenhouse gas emissions with PMS (Dodoo, Gustavsson, & Sathre, 2014). However, gaps persist in capturing occupant behaviour, regional energy mixes, and long-term adaptability (Röck et al., 2020). Integrating LCA with CD is promising but needs further refinement to fully link material flows, design decisions, and operational performance.

The proposed framework for Portuguese housing retrofitting addresses a critical gap by connecting typologies, intervention strategies, and sustainability parameters in a structured process. While it cannot resolve all practical challenges such as ownership fragmentation or regulatory constraints, it offers a replicable methodology for enhancing collective and social housing while meeting contemporary sustainability goals.

7. Conclusions

This study reviewed contemporary strategies for sustainable retrofitting with a focus on Portuguese collective housing. The analysis confirmed that conventional energy-based retrofits provide short-term efficiency gains but offer little adaptability, whereas sustainable approaches that integrate SR principles — such as CD, PMS and DfAD—deliver long-term benefits through material recovery, waste reduction, and improved social outcomes. Evidence from European pilot projects further demonstrated the feasibility of applying these strategies in occupied buildings, highlighting their environmental and social advantages.

Within the Portuguese context, the comparative assessment of housing typologies revealed both opportunities and constraints. Issues such as fragmented ownership, structural limitations in specific typologies, and regulatory barriers complicate implementation, yet the high degree of 'standardisation' across the housing stock from the 1960s–1980s offers potential for replicable interventions at scale.

The framework proposed in this study contributes a methodological tool that links housing typologies with appropriate retrofit strategies while integrating environmental, technical, economic, and social parameters. By structuring the process into diagnosis, strategy, implementation and validation, the framework provides a practical basis for guiding rehabilitation projects and aligning them with contemporary sustainability goals.

This research deliberately bridges architectural and engineering perspectives, in which architectural analysis provides spatial, typological, and contextual understanding, while engineering-based tools such as DfAD and LCA offer quantitative and technical validation. The integration of design and performance methodologies therefore represents both a methodological contribution and a pathway for advancing interdisciplinary collaboration in SR.

To conclude, the findings reinforce the urgency of adopting SR strategies as a pathway for enhancing the Portuguese housing stock. Future research should further explore the integration of LCA and CD principles into policy and practice, ensuring that retrofitting strategies remain adaptable to current environmental and economic concerns. Crucially, future work should focus on pilot testing to assess the technical and economic feasibility of the proposed sustainable retrofitting framework in practice, combining research-by-design methods with experimental prototyping, LCA and cost analysis, and post-occupancy evaluation. Such testing would enable iterative refinement of the framework in real contexts, validating its capacity to improve not only material and energy performance but also spatial adaptability, liveability, and social value.

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Conflicts of Interest
The authors declare no conflict of interest.

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