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Research paper

CIRCULAR ARCHITECTURAL INTERIOR SYSTEMS TRANSFORMATION: MODULARITY, DESIGN FOR DISASSEMBLY AND RECYCLABLE MATERIALS IN THE BUILT ENVIRONMENT

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Abstract

The transition to circular economy within built environments has revived the discussion of strategic pathway for reducing resource extraction, lowering embodied carbon, and fostering resilient local economies. Over the last decades there has been increasing research invested in the area of circular construction, in the scale of buildings. However, relatively little attention has been paid to architectural interior systems. The paper investigates the potential role of circular architectural design practices in Macedonia, based on modularity, design for disassembly and use of recyclables in architectural interior systems. It combines a systematic review of available literature from the field of circular architecture with empirical evidence from case studies of the new circular practice in local context. An engineering-based scenario assessment compares conventional practice into engineering circular scenarios. The results emphasize the potential of modular interior architectural design, reversible connections and recyclable components into improved circular performance of architectural interior systems. Architectural interior systems are itself an ideal testing ground for such changes by being replaced more regularly, due to constantly evolving designs. The case studies show that some elements of circular practice are already developing in the local context through community-based upcycling projects, municipal systems of material recovery, and small modular furniture manufacturers. The paper provides a place-based perspective to circular architecture, and offers recommendations which could be applied in the context of other small and medium-sized transitioning economies.

Key words: *Circular architectural interior design, Design for Disassembly, Modular construction, Recyclable materials, Lifecycle assessment*

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1. INTRODUCTION

The transition shift to a circular economy is defined as one of the most important challenges facing the construction sector today. Circular buildings lower resource consumption, waste generation and embodied carbon in buildings. While the operational performance has been significantly improved in the recent years, the construction materials influence during the building lifecycle have not been effectively addressed. This is very evident for the architectural interior systems which tend to be replaced more frequently and have high material flows which are not recovered at maximum potential. Partition systems, furniture, finishes and technically functional building services are often subject to numerous replacements [1].

Over the last decade, Macedonian construction industry has been characterized by a stable growth, urban regeneration, increase of commercial development and slow adaptation to the European environmental standards [2]. However, there has been still a predominance of the linear model of production and consumption in the building sector. This linear model is resulting in material flow in buildings, material extraction, use in buildings and disposal following intervention for renovation or demolition [3]. Secondary material markets remain limited and design for repair is rarely considered during the project development. Modular construction systems have yet to become part of mainstream professional practice [4]. Design for Disassembly defines function of systems circular organization where building elements can be repaired and rejoined without an enterprise loss. In addition, the materials choice is an essential factor in circular system of construction, as opportunities for modular adaptation, reversible construction and material reuse [5]. This paper investigates how the combination of three strategies: modularity, design for disassembly and recycling, can be applied towards circular architectural practice in North Macedonia [6].

Despite the research on circular construction in the building sector, relatively little empirical evidence is available regarding the implementation of circular architectural interior systems in small and medium-sized economies. There is also lack of understanding as to how modularity, design for disassembly and recyclable materials can be adopted in current architectural practice in the context of the developing market, fragmented recovery infrastructure and emergent policy context. Addressing this knowledge gap, the study aims to answer the following research questions:

- To what level can modular architectural interior systems, design for disassembly, and recyclable materials improve the environmental performance of architectural interior design compared to conventional linear approaches?
- How do existing circular design initiatives in Macedonia contribute to material recovery, product longevity, and resource efficiency within interior systems?

These research questions define the basis of the analytical framework for the study and determine the selection of methods, case studies, engineering scenarios, and evaluation criteria presented in the following sections.

2. METHODOLOGY

This research employs a mixed-methods approach, consisting of systematic literature review, an empirical case-study investigation, engineering scenario modelling, and comparative lifecycle assessment [7]. Blending qualitative and quantitative approaches enables this study to examine circular design from engineering and practice-oriented approach [7] [8]. The research was conducted in five sequential stages, each shaping the subsequent stage. The results of the review of literature provided the conceptual framework to examine the engineering principles behind circular designs. This guided the selection of empirical case studies, the construction engineering scenarios and interpretation of environmental performance indicators. The first stage was a systematic review of academic literature, technical guidance documents and European policy concerning circular economy practices in the built environment. Special focus was made to research the modular construction systems, design for disassembly, recyclable and bio-based materials and life cycle assessment. Literature review was based on peer-reviewed journal articles, technical reports, design manuals and policy documents which offered methodological or regulatory background. The second stage drew on empirical evidence from North Macedonia through a multiple case-study technique. Its selection, based on Yin's [9] proposition, was not driven by a statistical representation of construction activity, but on a complete implementation of a circular designs strategy-such as material reuse, modular manufacturing, design for disassembly or municipality material recovery programs. Community-based upcycling schemes, small-scale interior design and furniture manufacturing as modular products, provide material recovery during building refurbishment. They were analyzed using the same analytical framework by material properties, degree of modularity, disassemblarity, maintenance, reuse potential and institutional endorsement. The third stage established an engineering-scenario model to compare architectural interior alternative approaches. Three scenarios of the Case studies were established to represent increasing levels of circular implementation. The scenarios were evaluated using performance indicators commonly reported in circular construction research [10]. Circularity of materials flows was visualized through Sankey-diagrams and comparisons of linear and circular systems represented through engineering graphs distinguishing between modular and traditional interior products. This smart visual presentation enhanced interpretation of the numerical outcomes and exposed the dynamics between interior design choices, material circulation and lifecycle performance [11]. The final stage integrated the engineering findings with empirical case studies and stakeholder consultations with architects, municipal authorities, furniture manufacturers and organizations involved in circular design in order to overcome technical implementation barriers and promote adoption of circular architecture principles [12].

2.1. Case Studies: Circular Architectural Interior Systems in Macedonia

2.1.1. Case Studies Context

The case studies in reveal the context in North Macedonia through which the early adoption of circular architectural design has taken place. Although the country lacks well-established circular construction market like most other European countries, national building sector continues to be structured on traditional linear approaches [13]. The construction sector is comprised of small and medium-sized enterprises, where the wood-processing sector is one of the country's most well-established manufacturing industries. It consists of rapidly growing network of designers, architects, artists, civil and non-governmental organizations that begin to organize and reuse modular production. The cases correspond to the complementary dimensions of the transition: community-based education, public-sector implementation and private-sector innovation. Analyzed together, they provide a broader understanding of technical, institutional and social conditions influencing circular architectural design.

2.1.2. Case Studies of Circular Architectural Interior Systems in Macedonia

Case Study 1: The TUDEC (Through Upcycling to Design of Ecocities) educational program is an example of how community and school workshops can build circular material literacy. TUDEC prototypes small furniture and city fixtures made from upcycled timber, metal drums, and bicycle inner tubes to demonstrate flows of local material [14]. This case study is an example of community upcycling programs run by design collectives in Skopje involved in transforming reclaimed wood, metal, and bio-materials into interior accessories and small furniture. These projects highlight similarities with other worldwide upcycling initiatives to illustrate urban waste flows into circular design practice.

Case Study 2: Municipal pilots in Skopje, reusing modular partition retrofits and reuse programs, presents case study of municipal architectural interior design. These pilots catalogued reclaimed doors, timber panels and modules, reintegrating them into lower-demand public spaces. The pilots illustrate procurement levers and the role of municipal demand in developing reuse markets [15]. This case is a municipality-led circularity pilot in Skopje focusing on material recovery from public buildings. Construction waste such as salvaged wood, metal partitions, glass, and usable interior fittings were documented and partially reintegrated into public buildings. The ecological value of this initiative demonstrates how municipal infrastructure can model circular procurement practices consistent in the EU public procurement guidelines. It represents the volume of materials they reintroduced and the procurement leverage. Local authorities are typically among the largest building clients and their material purchases influence local market circulation.

Case Study 3: Small workshops clusters in Skopje: ModulArt reuses wood offcuts and by-products from industries for their modular furniture kits using reversible fasteners. These kits are designed for local assembly, repairability, and material recovery, demonstrating commercial circular-product pathways. Their objective is local

installation, local rehabilitation and reuse by following commercial circular-product pathways [16]. ModulArt crafts up-cycled modular furniture wood materials form local manufacturers. The modular re-used wood materials are used form local producers. Their modular furniture up-cycled wood joinery and reversible fasteners provide practical examples of design for disassembly adapted to the Macedonian artisan context [17]. Case studies illustrate that transition towards circular architectural interior design is occurring through multiple and interconnected processes rather than through a single policy initiative or technological innovation.

3. RESULTS

3.1. Engineering Scenario Assessment

The scenario analysis demonstrates significant environmental and material benefits from applying modularity, design-for-disassembly, and use of recyclable materials in circular interior design of the case studies. The examination of the case studies revealed upcycling and maket-based approach which increased public awareness, strengthened repair culture, and expanded aesthetic acceptance of reused materials. Municipal pilots demonstrated institutional capacity, though they require scaling through policy reform. The scenario modelling produced quantitative contrasts among the three scenarios. Material recovery rates rose from an estimated baseline of 10–15% in Scenario C1 with the traditional linear ModulArt case study to 35–45% under partial circularity Scenario C2 with the Municipal pilots in Skopje and exceeded 60% under design for disassembly circularity Scenario C3 with the TUDEC case study in Skopje. Product lifespans increased substantially under circular scenarios. Modular components exhibited lifespan extensions of 40–70% due to ease of repair and remanufacture, while circular systems facilitated multiple reuse cycles. *(Table 1).*

Table 1. Scenario Comparison Model Curves among the three Case Studies in Macedonia

Scenario	Case Study Context	Curve Description	Impact Trajectory
Scenario C1: Linear	Traditional, Linear, non-modular construction, minimal reuse/recycling.	The impact line is high with marginal changes over the lifecycle.	Marginal Improvement
Scenario C2: Partial Circularity	Municipal Pilots in Skopje	The impact line is lower than A and shows a faster descent, especially after the Production stage.	Accelerated Reduction
Scenario C3: Fully Circular	TUDEC or integrated Workshop Cluster model (modularity + design for disassembly + upcycling).	The impact line is the lowest, showing the steepest descent impact at lifecycle assessment	Steepest Descent/Compounded Benefits

The Scenario comparison model curves plots environmental impact index was developed by representing the lifecycle stages for the three scenarios. [18] The curves demonstrate that linear systems Scenario C1 with the ModulArt case study show marginal improvements over time due to minor efficiency, while partial circularity in Scenario C2 at the Municipality pilots case study accelerates the impact reductions through targeted modular upgrades and recycled content. Fully circular systems in Scenario C3 at the TUDEC case study achieves the steepest descent in impact, illustrating compounded benefits from combined strategies of modularity, design for disassembly and recyclability. In the selected case Studies, circularity leads to a faster reduction in environmental impacts, re-usable building components and repeated circularity of materials. The comparison of these scenarios implies that cumulative advantages are secured by adopting various circular principles in a rational design model. Adoption of multiple circular practices by comparison effectively facilitates replication and improvement, which supports the overarching systems approach adopted in this study. *(Figure 1)*

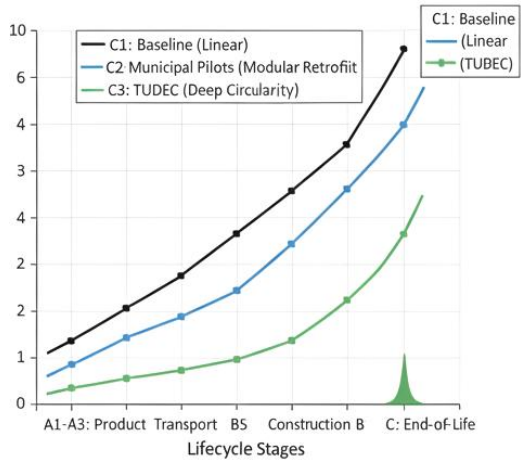


Figure 1. Scenario Comparison Model Curves for selected Skopje Case Studies, North Macedonia

3.2. Sankey Diagram Method

The material flows were investigated with the Sankey-based method analysis, comparing the conventional, linear practice with the proposed circular design scenario. This method illustrates the material flows of wood, metal, plastic and biocomposites within interior architectural systems and compares the two scenarios in terms of potential recovery via reuse, repair, remanufacturing and recycling. The case studies provide practical example of emerging circular practices of selected case studies in Macedonia, where municipal refurbishment projects present potential recovery of architectural components. The repair, upgrading of materials and modular product development represent practical implementation of community and locally owned furniture manufacturing into circular design practice [19]. The circularity of materials: reuse product stream: material flow of wood and metal is directed back into the use phase with modular furniture kits, and recycling stream: material is sent for reprocessing into secondary raw material, residual landfill. The Sankey based analysis

illustrates the impact of more strategic design and recovery actions for a more sustainable resource circulation strategy for interior architectural systems *(Table 2).*

Table 2. Sankey Material Flow Diagram Method

Case Study	Intervention Node in Diagram	Description of Flow
Case Study 1: TUDEC	Non-modular Upcycling Demolition Waste	Informs the initial design phase, promoting the diversion of waste materials (timber and metal drums) and feeding them to upcycling streams.
Case Study 2: Municipal Pilots	Municipal Pilots Modular Reuse	Represents the municipal program where reclaimed doors, timber panels, and modules are reintegrated into public spaces. This interrupts the largest demolition waste flows.
Case Study 3: ModulArt	ModulArt Upcycling	Represents clusters that process smaller fractions like wood offcuts and production residues into new products (modular furniture kits), demonstrating a commercial circular pathway.

3.3. Modular vs Non-modular Comparison Chart Method

The engineering assessment of non-modular versus modular architectural interior systems in the case studies in Macedonia, demonstrates tangible implications of circular design strategies. The following chart directly compares the performance of a non-modular construction and modular scenario representing the specific outcomes of the Skopje case studies. The collected data from the circular interior design case studies of municipal retrofits present the modular design columns. The visual chart compares the case studies environmental performance indicators between the non-modular baseline TUDEC and the circular approach modular scenario that integrates the benefits from the Municipal Pilots, and ModulArt workshop activities in the case studies in the city Skopje, North Macedonia *(Figure 2).*

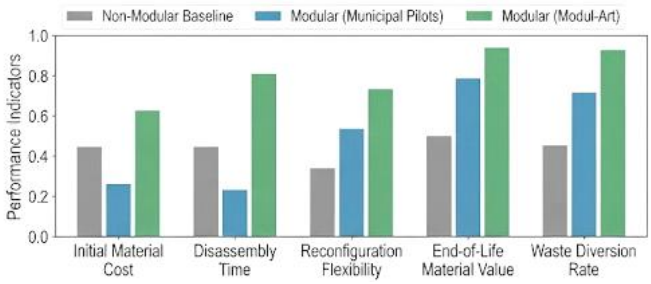


Figure 2. Modular vs Non-Modular Comparison Chart for the selected Skopje Case Studies

The assessed indicators of the circular modular systems in the case studies provided better environmental performance. The maximum savings for the modular systems were reached for embedded carbon and primary energy demand, due to modular reuse design, by increasing its lifetime and reducing replacement measures. The comparison indicates that modular circular interior systems achieve higher material recovery rates than conventional interior assemblies.

4. DISCUSSION

Engineering results demonstrate integrating modularity, design for disassembly, and recyclable materials into architectural interior design practices in the context of an emerging circular economies. The scenario analysis offered a coherent answer for the first research question, by showing how the adoption of modular system solutions, design for disassembly and recyclable materials lead to significant improvements of the environmental performance of architectural interior systems in comparison with traditional linear design [20]. Findings from the case studies of the empirical research, offered answers to the second research question on the critical barriers affecting the development of circular architectural design in Macedonia. These case studies, which include small-scale architectural interior refurbishments, adaptive reuse of commercial spaces, and locally fabricated modular furniture systems, demonstrate that circular practices already exist. The central finding of the municipal pilots in Skopje is that modular architectural interior retrofits significantly increase spatial adaptability while reducing material waste. Offices and public service spaces that adopted demountable partitions were able to reconfigure layouts without demolition of interior systems.

The paper has contribution to the circular construction literature by developing integrated assessments of circular architectural interior systems in diverse Southeast European context [21]. The material flow analysis of the case studies revealed that most interior components in architectural design still enter linear waste streams at the end of their use phase. This finding directly supports the need for policies that promote deconstruction over demolition. Municipal regulations should mandate selective disassembly for interior renovations above a certain scale, and financial support should be provided for the establishment of local material recovery hubs. Policy instruments should explicitly reward modularity and reversibility through tax incentives, or green certification schemes. By linking modularity to environmental performance metrics, these policies would make adaptability a recognized sustainability asset rather than a purely operational choice. In summary, the selected case studies in North Macedonia demonstrate that the policy recommendations articulated here are targeted structural interventions responding directly to observed conditions by reforming procurement systems, stabilizing innovation through public support, restructuring financial mechanisms and reframing architectural education.

5. CONCLUSION

The study explores the potential of the circular modular architectural interior design, design for disassembly and recyclable materials towards the transition to a circular built environment in Macedonia. Towards this aim, a systematic review of existing literature, engineering scenario modelling and empirical case studies were employed. The study demonstrated that architectural interior design is a technically possible as well as pragmatic method for a circular economy in developing countries. The engineering assessment presents the utilization of a modular design solution with Design for disassembly and recyclable materials could significantly enhance environmental

performance through material recovery, prolonging product lifetime and embodied carbon reduction, with these largely delivered via means of maximum material value retention with reuse, repair and adaptation, rather than mainly end-of-life recycling. Although the investigated case studies confirm that circular design solutions are technically achievable, their wider adoption is constrained by fragmented regulations, procurement systems focused on initial cost, limited recovery infrastructure and underdeveloped secondary-material markets. These findings reinforce the view that circular construction should be understood as a socio-technical transition requiring coordinated change across policy, industry and professional practice. The research highlights that with the appropriate policy and professional guidance, North Macedonia has the capacity to change architectural interiors from large-volume consumers of resources into a resource-efficient built environment, by developing larger paradigm change necessary to enable a transition to a sustainable, resilient and resource-efficient built environment.

LITERATURE

[1] Adams, K., Osmani, M., Thorpe, T., Thornback, J. (2017). Circular economy in construction: Current awareness, challenges and enablers. Proceedings of the ICE - Waste and Resource Management, 170(1), 15–24. https://doi.org/10.1680/jwarm.16.00011

[2] Mangaroska, V. (2024). Circular Built Environment as International Concept of Sustainable Innovation. ZELENA GRADNJA 2024, 169. https://doi.org/10.5937/greenb24022m

[3] Durmiševic, E. (2018). Reversible building design. In Designing for the circular economy . Routledge, pp. 344-359. https://doi.org/10.4324/9781315113067-32

[4] Blismas, N., Wakefield, R. (2009). Drivers, constraints and the future of offsite manufacture in Australia. Construction Innovation, 9(1), 72–83. https://doi.org/10.1108/14714170910931552

[5] European Environment Agency. (2021). Circular economy and the built environment. European Environment Agency

[6] Mangaroska, V. (2024). Advanced sustainable interior design concept as methodological approach in the process of architectural design. Sci.(IJTNS), 4(1), 55-72. https://doi.org/10.69648/poqs2692

[7] Mangaroska, V. (2021). Incorporation of Cultural Functions in Architectural Adaptation from Traditional Historic Buildings into Art Galleries in Skopje, N. Macedonia. IBU International Journal of Technical and Natural Sciences, 2, 1-9.

[8] Yin ,R. (2018). Case Study Research and Applications. Sage. https://doi.org/10.4135/9781506326139.n99

[9] Molenveld, K. et al (2020). Flexible laminates within the circular economy (, Ed.). Wageningen https://doi.org/10.18174/519019

[10] Mangaroska, V., et al (2024). Smart buildings as architectural international technological concept. Zbornik radova sa Nacionalne konferencije sa međunarodnim učešćem–Zelena Gradnja 2024, (Green building), 175-180. https://doi.org/10.5937/greenb24023m

[11] Mangaroska, P. S. V. (2021). Complexity and composition in contemporary architectural parametric design. IBU International Journal of Technical and Natural Sciences, 2(2), 1-13.

[12] Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study. Research Policy, 31(8–9), 1257–1274.

[13] https://ecologic.mk/tudec/ (21.06.2025)

[14] Re-Cycle and Re-Use of Construct and Demolition Waste, Municipality City Skopje, Macedonia

[15] https://modulart.mk/ (21.06.2025)

[16] Mangaroska, V. (2025). Semiotic Theory of the Modern Computer Architectural Terminology of Today. In Reimagining Intelligent Computer-Assisted Language Education (pp. 359-380). IGI Global Scientific Publishing. https://doi.org/10.4018/979-8-3693-4310-4.ch013

[17] Cheshire, D. (2019). Design for disassembly and reuse. Building Revolutions, 65–79. https://doi.org/10.4324/9780429346712-10

[18] Mangaroska, F. Prof. D. V., Mangaroska, L., Mangaroski, F. Prof. D. K. (2025). Strategy for Sustainable Urban Development of the Cultural Route in Skopje, Republic of North Macedonia. Proceedings Volume 2, 707–716. https://doi.org/10.62683/sinarg2025.100

[19] United Nations Environment Programme. (2020). Sustainability and circularity in the built environment. UNEP

[20] European Commission. (2020). A new Circular Economy Action Plan: For a cleaner and more competitive Europe. European Union

[21] Sung, K., Cooper, T., Kettley, S. (2019). Developing Interventions for Scaling Up UK Upcycling. Energies, 12(14), 2778. https://doi.org/10.3390/en12142778