CONTEMPORARY APPROACHES IN ARCHITECTURE

The Role of Architecture in the Circular Economy

Editors

Prof. Dr. Rengin BECEREN ÖZTÜRK

Prof. Dr. Arzu ÇAHANTİMUR

20 October 2025

İKSAD Publishing House

Institution of Economic Development and Social Researches

(The Licence Number of Publicator: 2014/31220)

TÜRKİYE TR: +90 342 606 06 75 USA: +1 631 685 0 853

E mail: iksadyayinevi@gmail.com

www.iksadyayinevi.com

It is the responsibility of the author to abide by the publishing ethics rules.

Contemporary Approaches in Architecture: The Role of Architecture in the Circular Economy

ISBN: 978-625-378-348-8

Book and Cover Design:
Sadık AKŞAR

October 20, 2025
Ankara / Türkiye
Size = 16x24 cm

PREFACE

Cultural heritage plays a significant role in driving sustainable urban development. As both an economic and cultural asset, it stimulates economic growth, enhances urban livability, and contributes to environmental adaptability. Moreover, the reuse of abandoned or underutilized heritage buildings and cultural landscapes offers a practical alternative to demolition, bypassing the wasteful processes of destruction and new construction, and thus prolonging the lifespan of cultural assets.

The adaptive reuse of cultural heritage can be instrumental in circularizing the flows of energy, raw materials, and human and cultural capital. In this regard, it plays a vital role in the transition towards a circular economy. Beyond its environmental significance, adaptive reuse also generates substantial economic, social, and cultural benefits. Reusing historic buildings, sites, and landscapes enables diverse communities to attach new meanings and values, strengthening local identity and shared urban memory.

Recent UNESCO policy frameworks reaffirm the central role of culture in sustainability and resilience. The MONDIACULT 2022 Declaration redefines culture as a "global public good" and a fundamental dimension of sustainable development, emphasizing its relevance for climate action, digital transformation, and inclusive governance. Similarly, the Re|Shaping Policies for Creativity Global Report (2022) emphasizes the need for innovative cultural policies and cross-sectoral strategies to integrate culture into sustainable development agendas. Complementing these efforts, the UNESCO Culture|2030 Indicators framework (2019), implemented globally from 2020 onward) provides a robust evidence base for assessing the contribution of culture to the Sustainable Development Goals (SDGs), encouraging data-driven decision-making for cultural heritage management and adaptive reuse.

However, existing regulatory and planning tools are often not flexible enough to allow sustainable and circular transformation processes. Financial resources and funding schemes—largely dependent on public budgets—remain limited worldwide. Therefore, transforming cultural heritage and landscapes from being perceived as a financial burden into becoming a shared resource for collective memory, social inclusion, and sustainable growth has become an urgent necessity.

To achieve this, flexible, transparent, and participatory management tools are required to leverage the transformative potential of cultural heritage and to foster adaptive reuse practices. Cities must adopt governance approaches that embrace complexity, encourage collaboration among diverse stakeholders, and view heritage as a dynamic infrastructure that evolves in response to societal needs and environmental imperatives.

Adopting a circular economy and sustainable development perspective, this book aims to address this critical gap in the field of architecture and the built environment. It introduces innovative economic and environmental models, as well as digital and analytical techniques, that can be effectively employed in the adaptive reuse of historic buildings. By linking theoretical perspectives with practical applications, the book demonstrates how architectural practice can contribute to the transition toward a circular, low-carbon, and culturally resilient future.

The chapters compiled within this volume explore this theme from multiple perspectives. Case studies such as Thermal Heritage in Transition: Kükürtlü Bath, Bursa, Türkiye exemplify the integration of heritage conservation with environmental performance and adaptive reuse. Methodological and technological contributions—including Circular Economy Principles in Preface

Cultural heritage is increasingly recognized as a catalyst for sustainable urban development and a cornerstone of the circular economy. As both an economic and cultural asset, it contributes to economic vitality, enhances urban livability, and supports environmental adaptability. The adaptive reuse of underutilized or abandoned heritage buildings and landscapes offers a compelling alternative to demolition, as it avoids resource-intensive construction processes while extending the lifespan, functionality, and meaning of cultural assets.

This approach resonates with the principles of the circular economy, where flows of energy, materials, and cultural capital are reconfigured to minimize waste and maximize value. Adaptive reuse not only mitigates environmental impacts but also generates significant economic, social, and cultural benefits. By reactivating heritage assets, communities can reconnect with their past, foster inclusive urban narratives, and strengthen their collective identities.

UNESCO’s Culture: Urban Future report (2016) first emphasized that “culture is both an enabler and a driver of sustainable development,” highlighting the transformative potential of heritage in shaping resilient cities. Building upon this foundation, the Policy Document on World Heritage and Sustainable Development (2015) called for heritage-based strategies that integrate environmental, economic, and social dimensions through inclusive governance and adaptive reuse. More recently, the MONDIACULT 2022 Declaration reaffirmed culture as a global public good and a core dimension of sustainability, directly linking it to climate action, digital transformation, and social inclusion. The Re|Shaping Policies for Creativity Global Report (2022) further expanded this perspective by emphasizing the need for innovative cultural policies and cross-sectoral frameworks that integrate culture into sustainable development agendas. Complementing these policy directions, UNESCO's Culture|2030 Indicators Framework (2019–2023) provides evidence-based metrics to evaluate the contribution of culture to the Sustainable Development Goals (SDGs), promoting data-driven and accountable decision-making for cultural heritage management. Together, these instruments reaffirm that adaptive reuse—when grounded in circular and sustainable principles—can serve as a powerful mechanism for resilience, creativity, and inclusive growth.

Despite this growing recognition, regulatory frameworks and planning tools often lack the flexibility to support circular and sustainable transformation processes. Financial constraints—especially the reliance on public funding—further limit the scope of adaptive reuse initiatives. As noted in the European Commission's Horizon 2020 CLIC Project (2020), unlocking the potential of cultural heritage requires "innovative governance models, circular business strategies, and participatory financial mechanisms" that treat heritage not as a cost, but as a regenerative resource.

To reposition cultural heritage as a foundation for circular practices, cities must adopt transparent, adaptive, and engaging tools to manage change while embracing complexity. This calls for a paradigm shift that sees heritage not as static memory, but as dynamic infrastructure for sustainability.

This book, Contemporary Approaches in Architecture: The Role of Architecture in the Circular Economy, responds to this urgent need. It brings together innovative models, methodologies, and case studies that demonstrate how architectural practice can integrate circular economy principles, particularly through the adaptive reuse of historic buildings. The book bridges environmental, economic, and cultural dimensions, offering a forward-looking framework for architects, planners, and policymakers committed to shaping resilient and regenerative cities.

The volume opens with the chapter "Thermal Heritage in Transition: Kükürtlü Bath, Bursa, Türkiye," which exemplifies how the adaptive reuse of historic thermal architecture can balance conservation with technological modernization. Subsequent chapters expand this focus to broader sustainability frameworks, such as "Circular Economy Principles in Building Construction Management: Pathways to Sustainability" and "Adaptive Re-use of Heritage Buildings: A Cornerstone for Circular Economy in the Built Environment."

The book's middle section explores the integration of BIM-based and digital LCA tools, presenting methodological frameworks and case applications, including Life Cycle Assessment of a Cultural Heritage Building in Turkey Based on Digital Modeling: Integration of ArchiCAD and One Click LCA, and The Use of Life Cycle Assessment Tools in the Restoration of Historical Buildings: The Case of OpenLCA.

Further contributions—such as Assessing Sustainability of a Turkish Cultural Heritage Building through Revit Tally-Based Life Cycle Analysis, and Comparative Analysis of Life Cycle Assessment Results Conducted Using Different Software in the Kükürtlü Historical Bath Building—critically evaluate methodological compatibilities and limitations. These analyses are complemented by discussions on integrating LCA and LCC approaches to assess alternative structural systems, as well as explorations of artificial intelligence and textile waste reuse in the context of architectural circularity.

The final chapters, including Circular Economy and Life Cycle Assessment (LCA) Based on Physico-Chemical Effects in Pneumatic (Inflatable) Structured Sports Buildings: Bursa Case Study, expand the discourse to contemporary building technologies and emerging materials, bridging heritage conservation with innovation-driven design.

Through these interdisciplinary contributions, the book positions architecture at the forefront of the circular transition—bridging environmental science, digital technology, cultural heritage management, and economic innovation. By uniting academic rigor with practical applicability, it offers scholars, practitioners, and policymakers a robust framework for rethinking how the built environment can become a regenerative agent within the circular economy paradigm.

This volume was developed within the editorial framework of the Journal of Architectural Sciences and Applications (JASA), which began its publication in 2016. Since 2021, JASA Editorial Board Members have overseen the publication of highly valuable e-books that make meaningful contributions to the architectural discipline. In 2024, in collaboration with IKSAD Publishing House, a series of English-language, peer-reviewed international e-books will be produced to serve the evolving needs of architectural research and practice.

With this volume, we aim to deepen awareness of circular economy principles in architecture, highlight the transformative potential of adaptive reuse, and offer a concrete academic contribution to the field. The call for chapter submissions received a wide range of applications, from which 14 were critically selected through a rigorous peer-review process. We extend our sincere gratitude to all individuals and organizations who contributed to the completion of this book—including the authors, reviewers, IKSAD Publishing House, and Prof. Dr. Atila Gül, the General Coordinator of the Architectural Sciences book series.

We would like to express our sincere gratitude to all chapter authors for their intellectual contributions, dedication, and collaboration throughout the preparation of this volume. We are also indebted to the peer reviewers for their constructive feedback, which greatly enhanced the academic quality of the book. Our appreciation extends to the institutions and research centers that provided support and resources during the editorial process, as well as to the publishing team for their professionalism and patience. Any remaining shortcomings are entirely our own.

EDITORS

Prof. Dr. Rengin BECEREN ÖZTÜRK

Prof. Dr. Arzu ÇAHANTİMUR

OCTOBER, 2025

EDITORS
Prof. Dr. Rengin BECEREN ÖZTÜRK
Prof. Dr. Arzu ÇAHANTİMUR

AUTHORS
The authors were listed in alphabetical order.
Adil YİRMİBEŞ
Arzu ÇAHANTİMUR
Ayşe Begüm KAHYA
Barış Mert KARASU
Bengisu ÖZKILAVUZ
Filiz ŞENKAL SEZER
Göktürk BOSTANCI
Hande Akar
İlayda Şevval ALIŞ
Merve BULUÇ
Neriman Gül ÇELEBİ
Ömer Oğuzhan TURHAN
Rabia Tuğçe İNCE
Rengin BECEREN ÖZTÜRK
Sadık AKŞAR
Tayibe SEYMAN GÜRAY
Ümit ARPACIOĞLU
Yasemin BAL

REVIEWER LIST

The reviewers were listed in alphabetical order.

Ahmet Cüneyt DİRİ	Mimar Sinan Fine Arts University
Ayşe KOPUZ	Tekirdağ Namık Kemal University
Ayşen ÖZTÜRK	Eskişehir Osmangazi University
Belkıs Ece ŞAHİN	Bursa Uludağ University
Didem BARAN ERGÜL	Fenerbahçe University
Didem Güneş YILMAZ	İstanbul Bilgi University
Ender ŞEN	Bursa Technical University
Filiz ŞENKAL SEZER	Bursa Uludağ University
Gökçe TUNA	Yıldız Technical University
Gözde KIRLI ÖZER	Bursa Uludağ University
Miray GÜR	Bursa Uludağ University
Nilüfer TAŞ	Bursa Uludağ University
Pınar ADEM	Yeditepe University
Sebla ARIN ENSARİOĞLU	Bursa Uludağ University
Seden ACUN ÖZGÜNLER	İstanbul Technical University
Sevgen PERKER	Bursa Uludağ University
Sibel POLAT	Bursa Uludağ University
Terane MEHEMMEDOVA BURNAK	Eskişehir Osmangazi University
Tuba SARI	Bursa Technical University
Ümit Turgay ARPACIOĞLU	Mimar Sinan Fine Arts University
Zuhal Şimşek	Bursa Uludağ University

CONTENTS	PAGES

Thermal Heritage in Transition: Kükürtlü Bath, Bursa, Türkiye

Prof. Dr. Arzu ÇAHANTİMUR [1]

[1] Bursa Uludağ University, Faculty of Architecture, Department of Architecture, Nilüfer, Bursa/Türkiye.
ORCID: 0000-0002-5907-1773
E-mail: arzucahan@uludag.edu.tr

Prof. Dr. Rengin BECEREN ÖZTÜRK [2]

[2] Bursa Uludağ University, Faculty of Architecture, Department of Architecture, Nilüfer, Bursa/Türkiye.
ORCID: 0000-0001-6259-3364
E-mail: renginb@uludag.edu.tr

Citation: Çahantimur, A. & Beceren Öztürk, R. (2025). Thermal Heritage in Transition: Kükürtlü Bath, Bursa,Türkiye. Beceren Öztürk, R. & Çahantimur, A. (Eds.). **Contemporary Approaches in Architecture: The Role of Architecture in the Circular Economy.** 2025, Chapter:1, 1-16. ISBN: 978-625-378-348-8. Iksad Publications. DOI: https://doi.org/10.5281/zenodo.17312947

1. Introduction

Bursa, one of the ancient cities of Anatolia, stands out with its multi-layered history extending from the Roman to the Ottoman periods. One of the city's most defining characteristics has always been its rich thermal resources. During the Roman period, baths were not only spaces for hygiene and health but also important centers of social life (Şehitoğlu, 2008). This tradition continued during the Byzantine period; monumental structures such as the *Basilicae Thermae* reflected the culture of health and sociability in the city. In the Ottoman era, baths and thermal buildings became important foci of urban development, while the Çekirge and Kükürtlü districts emerged as prominent centers of treatment, cleanliness, and social interaction (Erer, 2004) (see Fig. 1).

Figure 1. View of the New Thermal Baths, Kara Mustafa Pasha, Kaynarca, and Sulfurous Thermal Baths from the Mudanya Road in 1894.

The Kükürtlü Bath is one of the most tangible examples of this continuity. Its origins date back to the Roman period; its function was expanded during the Byzantine era as a bath complex, and it was reconstructed during the reign of Sultan Murad I. Further extensions were made in the time of Bayezid II and Suleiman the Magnificent, revealing the historical layers of the structure. Archival sources even indicate that Suleiman himself was treated here and, after recovering, ordered the domes to be covered with lead, a fact that demonstrates the building's place not only in health but also in political and social memory (Erer, 2004) (see Fig. 2).

Figure 2. Kükürtlü Kaplıcası (Uludağ University, 2024)

2. Historical Development

By the sixteenth century, the complex had been enlarged in accordance with the classical Ottoman hamam sequence, incorporating the camekân (changing hall), soğukluk (intermediate/warm zone), and sıcaklık (hot room), a layout consistent with the established typology of Ottoman baths (Goodwin, 2003; Erer, 2004). In the nineteenth century, as European balneology advanced, Bursa's thermal facilities underwent modernization. At Kükürtlü, the introduction of sıra banyolar (serial, cell-like bathing units) constituted one of the first applications of this typology in Turkey (Başoğlan, 2010). Contemporary accounts note extensions executed with materials and technical expertise imported from Italy, aligning the complex with the protocols of modern European spa culture. The addition of hotel rooms further recast the site as a combined treatment and accommodation facility (Kılıç, 2011) (see Fig. 3).

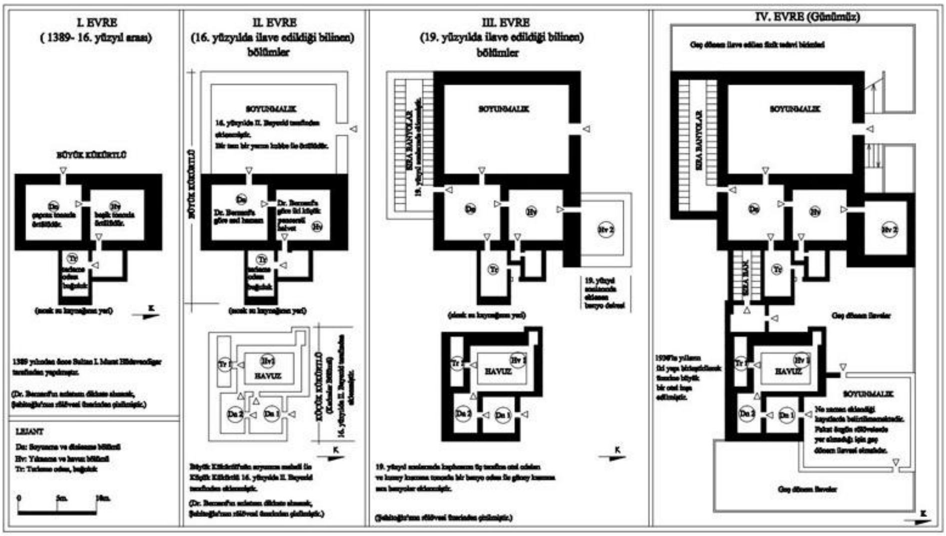

Figure 3. Construction activities of the thermal spring according to periods (Başoğlan, 2010)

During the Republican period, the bath was nationalized in 1978 and incorporated into Uludağ University in 1981, becoming the first university-affiliated thermal treatment center in Turkey (Uludağ University, 2024).

Architecturally, Kükürtlü presents a multi-layered palimpsest formed through successive extensions over time. An initial two-room nucleus expanded into the classical Ottoman arrangement, and in the nineteenth century, it absorbed serial baths and hotel rooms, giving the complex the character of a modern health facility (Erer, 2004). The gardens, fountains, pools, and planted areas enhanced the site's amenity while embedding it within the urban landscape and civic life (Kılıç, 2011) (see Fig. 4). In terms of fabric, cut stone, brick, and timber dominate the historic phases; the domes exhibit traditional Ottoman masonry, whereas nineteenth-century additions register selective Western influences in detailing and program. For the deeper, longue-durée context of bathing culture and typological continuities from Roman and Byzantine precedents to the Ottoman period, see Yegül's foundational synthesis (1992), which helps situate Kükürtlü within a broader Mediterranean tradition.

Figure 4. Garden, pools, and green infrastructure articulating the complex's civic and landscape presence (Kılıç, 2011)

3. Heritage, Adaptation and Sustainability

The Kükürtlü Bath is not only a monument of cultural continuity but also an evolving socio-technical system that has practiced sustainability and circularity long before these were formalized as design doctrines. Its architectural and functional evolution—from a modest dual-chamber structure in the fourteenth century to today's university-affiliated health and rehabilitation center—demonstrates uninterrupted adaptive reuse, material circularity, and life-cycle extension. In this sense, Kükürtlü operates as a "living organism," continually adjusting to shifting social, medical, and environmental expectations while preserving its spatial logic and cultural meaning.

3.1 Life-cycle thinking and material circularity

Circularity in the built environment aims to retain value by minimizing waste, extending the service life of products, and reusing resources (Pomponi & Moncaster, 2017; Geissdoerfer et al., 2017). Read through this lens, seven centuries of incremental adjustments at Kükürtlü illustrate life-cycle thinking by design: rather than demolition and replacement, the complex grew through targeted additions and programmatic integrations that conserved embodied cultural and material capital.

Material choices reinforce this circular logic. Locally sourced cut stone, brick, lime mortar, and timber were selected for availability, durability, and thermal performance. Classic studies demonstrate that material selection and reuse potential significantly influence whole-life energy needs (Thormark, 2006), while high thermal inertia assemblies can reduce operational loads (Cabeza et al., 2014). The domed spaces, built with traditional Ottoman masonry, offer both structural stability and passive thermal regulation. Nineteenth-century sıra banyolar were added without erasing earlier phases, producing a stratified identity. This additive method resonates with what Brambilla et al. (2020) term a "heritage-based circular approach," in which adaptation secures continuity rather than rupture; similarly, Fivet & Brütting (2023) stress material reuse and planned maintenance cycles as primary drivers of sustainability.

Within historic architecture, adaptive reuse extends service life and limits demolition waste (Bullen & Love, 2011; Conejos, Langston, & Smith, 2013). Kükürtlü's transition from imperial bath to modern medical spa exemplifies this "strategic adaptation" (Langston et al., 2008), where new functions—whether the enlarged camekân in the Bayezid II period or nineteenth-century hotel rooms—responded to contemporary health paradigms while retaining the spatial core. Regular, like-for-like maintenance of domes, vaults, and wall surfaces further aligns with Life Cycle Assessment (LCA) thinking; evidence from heritage-LCA studies suggests that conservation-led strategies can materially reduce whole-life carbon when indicators are explicitly tracked (Zanni et al., 2019).

3.2 Energy, water, and regenerative systems

Ottoman bathhouses were early exemplars of energy and water efficiency, leveraging geothermal sources and passive design. At Kükürtlü, geothermal water from Bursa's springs underpins a quasi-closed loop of heat supply, distribution, and recovery (Lund, 2010; Mertoglu et al., 2015). Heated water channelled through ductwork and thermal masses serviced bathing, space conditioning, and atmospheric regulation with minimal exogenous energy.

The spatial hierarchy—soğukluk, ılıklık, sıcaklık—functions as passive thermal zoning, anticipating contemporary low-carbon strategies that privilege zoned conditioning, thermal mass, and buoyancy-driven ventilation. As Lucchi (2022) notes, many historic typologies embed "passive intelligence" that can be paired with modern monitoring to create hybrid systems balancing authenticity and performance. Today's rehabilitation program continues this logic by reusing geothermal energy for hydrotherapy and heating; the ensemble of treatment cabins, small and large thermal pools, and therapeutic baths demonstrates how technological upgrades can be integrated without destabilizing the ecological equilibrium (Erer, 2004; Kılıç, 2011).

Landscape elements act as environmental infrastructure. Gardens, fountains, pools, and planted courtyards mediate microclimate, enhance comfort, and support psychological well-being—values the Florence Charter (1981) recognizes as intrinsic to historic gardens. Recent discourse links such restorative environments to biophilic regeneration, positioning heritage sites as catalysts for urban ecological renewal (Lucchi, 2022; ICOMOS, 2019).

3.3 Social and cultural sustainability

Heritage sustainability is also social: it concerns continuity of use, cultural memory, and community well-being. Historically, Ottoman baths functioned as social condensers, among the few public venues where women participated actively in urban life (Ergin, 2015). These practices of ritual purification, conviviality, and care align with contemporary notions of social sustainability within circular-economy frameworks (Geissdoerfer et al., 2017).

Kükürtlü's ongoing public-health role sustains intangible heritage—not only the built form but also the living practices and shared meanings that recur in place. In Halbwachs' terms, collective memory is reproduced through repeated social action; Smith (2006) similarly frames heritage as an active cultural process rather than a static artifact. The complex's inclusive operation aligns with UN SDG 11 (Sustainable Cities and Communities) (UN, 2015). Under Uludağ University, Kükürtlü has become a hybrid socio-ecological institution, bridging historical identity with clinical research and education. This interdisciplinary model resonates with the New European Bauhaus and the European Green Deal, which invite culture, science, and sustainability to co-produce a built environment oriented toward health, beauty, and ecological responsibility (European Commission, 2021; ICOMOS, 2019).

In sum, Kükürtlü demonstrates how heritage can drive circular transformation. Its long record of material reuse, spatial adaptation, and social continuity embodies the very principles the circular economy seeks to institutionalize—turning a historic monument into a regenerative system with durable social and environmental relevance.

4. Cultural Heritage and Urban Memory

Cultural-heritage buildings are primary vessels of a city's historical memory. Urban memory emerges as a collective experience that is inscribed in space, and its conservation underwrites cultural continuity (Halbwachs, 1992). In this sense, historic structures are not merely stone, brick, and timber; they are carriers of practices, rituals, and values that sustain shared identities (Smith, 2006).

Bursa exemplifies this dynamic with unusual clarity. The thermal-bath tradition, rooted in Roman engagement with natural hot springs, evolved into indispensable social venues in the Ottoman period and, in the Republican era, acquired a new identity as sites of scientific and medical care (Şehitoğlu, 2008; Erer, 2004).

Within this trajectory, Kükürtlü Bath stands out as a powerful conduit between past and present—a place where sultans sought treatment, where local communities socialized, and where contemporary research and rehabilitation now occur. In the city's memory, baths signify not only health but also social solidarity, cultural belonging, and collective well-being. Preserving Kükürtlü therefore safeguards more than an architectural artifact: it protects Bursa's identity and the continuity of the social practices through which that identity is reproduced.

5. Towards a Circular Heritage Model for Bursa

The case of Kükürtlü Bath illustrates how heritage structures can become active participants in a city's circular economy. Instead of treating heritage as static relics, cities can mobilize these assets as living infrastructures that support regeneration—environmentally, socially, and economically. A Circular Heritage Model for Bursa could be developed around three interrelated principles:

- **Material and Energy Circularity:** Implement LCA-based conservation strategies (ISO 14040; CEN/TS 15978), prioritize the reuse of original materials, and introduce reversible interventions. Hybrid retrofitting, which combines geothermal systems and passive thermal methods, can reduce carbon emissions while preserving authenticity (Lucchi, 2022; Brambilla et al., 2020).

- **Socio-Cultural Continuity:** Maintain the bath's role as a public wellness and education center through inclusive design and cultural programming. Integrating social well-being into heritage policy aligns with the New European Bauhaus ethos of "beautiful, sustainable, together."
- **Governance and Knowledge Integration:** Encourage partnerships between municipalities, universities, and private stakeholders for sustainable management of thermal heritage. Through public–academic collaboration, Bursa could position itself as a hub for heritage innovation, linking conservation science and circular design.

These principles converge within the vision of the European Green Deal (European Commission, 2019) and UN SDG 11, framing cultural heritage as both a responsibility and a resource. By adopting such a model, Bursa can transform its historic bath culture into a prototype for regenerative urbanism—where heritage buildings actively contribute to sustainable development goals rather than being passive symbols of the past.

6. Conclusion

Cultural heritage structures mediate between the past and present, shaping social identity through the spatial inscription of memory. Their significance lies not only in aesthetic and architectural merit but also in their capacity to sustain cultural continuity, social memory, and environmental responsibility (Ahunbay, 2009). Each heritage building reveals the historical layers of its city and conveys accumulated knowledge to future generations.

Bursa—first Ottoman capital and long a thermal city—has preserved a bath culture whose roots reach back to Roman and Byzantine engagements with hot springs. Within this lineage, Kükürtlü Bath serves as both evidence of historical continuity and a spatial embodiment of health, cleanliness, and sociability. Its successive adaptations across regimes and centuries mark it as living heritage, able to absorb change while retaining typological and cultural essence.

Kükürtlü's significance is therefore architectural and mnemonic. It is a distinctive cultural landscape: a site of imperial convalescence, everyday social life, and, in the Republican era, Turkey's first university-affiliated thermal health center. Today, conservation and adaptive reuse policies that prioritize reversibility, compatibility, and maintenance-led care can secure this legacy while advancing Sustainable Development Goal 11 on inclusive, resilient, and sustainable cities (UN, 2015).

Protecting and transmitting Kükürtlü to future generations thus means more than restoring a single building. It entails sustaining Bursa's historical memory, reinforcing civic identity, and contributing to the global project of circular heritage—where cultural assets operate as regenerative systems within urban life. Read this way, Kükürtlü is not merely a thermal facility but a strategic node at the intersection of continuity, memory, and sustainability—an enduring example of how the past can illuminate a low-carbon, circular future.

Acknowledgements and Information Note

This article was prepared as part of the requirements of a doctoral-level course. The author would like to express sincere gratitude to the instructors for their valuable guidance, constructive feedback, and continuous support throughout the development of this study.

The study received no financial support or funding from any institution. Ethics committee approval was not required for this study. The article adheres to the standards of national and international research and publication ethics.

Author Contribution and Conflict of Interest Declaration Information

The author is solely responsible for the content and writing of this article. There is no conflict of interest.

References

Ahunbay, Z. (2009). *Tarihi çevre koruma ve restorasyon* [Conservation and restoration of historic environments]. YEM Yayınları.

Başoğlan, Ö. (2010). *Mimari miras yönetimi ve sürdürülebilir turizm: Batı Anadolu tarihi kaplıcaları örneği [Architectural heritage management and sustainable tourism: The case of Western Anatolian thermal baths]* (Doctoral dissertation). Dokuz Eylül Üniversitesi, İzmir.

Bullen, P. A., & Love, P. E. D. (2011). Adaptive reuse of heritage buildings. *Structural Survey, 29*(5), 411–421. https://doi.org/10.1108/02630801111182439

Cabeza, L. F., Rincón, L., Vilariño, V., Pérez, G., & Castell, A. (2014). Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renewable and Sustainable Energy Reviews, 29,* 394–416. https://doi.org/10.1016/j.rser.2013.08.037

CEN. (2011). *EN 15978: Sustainability of construction works—Assessment of environmental performance of buildings—Calculation method*. European Committee for Standardization.

Conejos, S., Langston, C., & Smith, J. (2013). Designing for better building adaptation: A typology of adaptation potential. *Habitat International, 37,* 95–104. https://doi.org/10.1016/j.habitatint.2011.12.002

Erer, İ. (2004). *Türk hamam kültürü ve Bursa kaplıcaları [Turkish bath culture and Bursa's thermal baths]*. Bursa.

European Commission. (2019). *The European Green Deal (COM(2019) 640 final).*

European Commission. (2021). *New European Bauhaus: Beautiful, sustainable, together (COM(2021) 573).*

Halbwachs, M. (1992). *On collective memory* (L. A. Coser, Ed. & Trans.). University of Chicago Press.

ICOMOS Climate Change and Cultural Heritage Working Group. (2019). *The future of our pasts: Engaging cultural heritage in climate action*. ICOMOS.

ISO. (2006). *ISO 14040: Environmental management—Life cycle assessment—Principles and framework*. International Organization for Standardization.

Kılıç, M. (2011). *Bursa kaplıcalarının mimari gelişimi [Architectural development of Bursa's thermal baths]*. Bursa.

Langston, C., Wong, F. K. W., Hui, E. C. M., & Shen, L.-Y. (2008). Strategic assessment of building adaptive reuse opportunities in Hong Kong. *Building and Environment, 43*(10), 1709–1718. https://doi.org/10.1016/j.buildenv.2007.10.017

Lucchi, E. (2022). Integration between photovoltaic systems and cultural heritage. *Energy Policy*, *171*, 113270. https://doi.org/10.1016/j.enpol.2022.113270

Lund, J. W. (2010). Direct utilization of geothermal energy 2010 worldwide review. *Proceedings of the World Geothermal Congress 2010*, 1–23.

Pomponi, F., & Moncaster, A. (2017). Circular economy for the built environment: A research framework. *Journal of Cleaner Production*, *143*, 710–718. https://doi.org/10.1016/j.jclepro.2016.12.070

Şehitoğlu, M. (2008). *Bursa hamamları ve kaplıcaları [Baths and thermal springs of Bursa]*. Bursa.

Smith, L. (2006). *Uses of heritage*. Routledge.

Uludağ University. (2024). *History of Atatürk Rehabilitation Center*. https://uludag.edu.tr

United Nations. (2015). *Transforming our world: The 2030 Agenda for Sustainable Development*. United Nations.

Yegül, F. (1992). *Baths and bathing in classical antiquity*. Cambridge, MA: The MIT Press (with The Architectural History Foundation, New York).

Zanni, M. A., Soetanto, R., & Ruparathna, R. (2019). Balancing heritage conservation and environmental performance in historic buildings: A review of LCA applications. *Sustainable Cities and Society*, *47*, 101516. https://doi.org/10.1016/j.scs.2019.101516

Prof. Dr. Arzu ÇAHANTİMUR
E-mail: arzucahan@uludag.edu.tr
Educational Status: Prof. Dr.
License: Istanbul Technical University, Faculty of Architecture, Department of Architecture, 1990-1994
Degree: Istanbul Technical University, Graduate School of Natural and Applied Sciences, Department of Architecture, 1994-1997
Doctorate: Istanbul Technical University, Graduate School of Natural and Applied Sciences, Department of Architecture, 1999-2007

Prof. Dr. Rengin BECEREN ÖZTÜRK
E-mail: renginb@uludag.edu.tr
Educational Status: Prof. Dr.
License: Anadolu University, Faculty of Architecture and Design, Architecture Department, 1987-1993
Degree: Istanbul Technical University, Graduate School of Natural and Applied Sciences, Department of Architecture, 1995-1998
Doctorate: Istanbul Technical University, Graduate School of Natural and Applied Sciences, Department of Architecture, 1998-2005

Circular Economy Principles in Building Construction Management: Pathways to Sustainability

Asst. Prof. Dr. Tayibe SEYMAN-GÜRAY [1]

[1]Fenerbahce University, Faculty of Architecture and Design, Ataşehir, İstanbul /Türkiye.

ORCID: 0000-0001-5692-9669

E-mail: tayibe.guray@fbu.edu.tr

Citation: Seyman Güray, T. (2025). Circular Economy Principles in Building Construction Management: Pathways to Sustainability. Beceren Örtürk, R. & Çahantimur, A. (Eds.). **Contemporary Approaches in Architecture: The Role of Architecture in the Circular Economy.** 2025, Chapter:2, 17-40. ISBN: 978-625-378-348-8. Iksad Publications. DOI: https://doi.org/10.5281/zenodo.17309929

1. Introduction

The building construction sector is one of the most resource intensive industries worldwide, accounting for approximately 36% of global energy consumption, 37% of energy-related CO_2 emissions, and 40% of raw material use (IEA, 2022; UNEP, 2020). It also generates vast amounts of construction and demolition waste, estimated at nearly one-third of global solid waste, much of which is landfilled rather than reused or recycled (Sheen, 2024; Husgafvel & Sakaguchi, 2021). These figures highlight the sector's central role in resource depletion, environmental degradation, and climate change, underscoring the urgent need to transition from a linear "take–make–dispose" model to a more regenerative, circular economy (CE).

The circular economy has gained increasing attention in construction research as a pathway to minimize waste, extend asset lifespans, and optimize resource use (Chammout & El-Adaway, 2025). Core principles include resource efficiency, design for adaptability and disassembly, material reuse, recycling, and lifecycle thinking (Kumah et al., 2023). Life cycle is an approach that aims to optimize sustainability, efficiency and environmental impacts (Çelebi & Arpacıoğlu, 2025). Resource consumption and environmental emissions, as well as recycling and reuse potential, are important factors affecting the life cycle of a building (Çelebi and Arpacıoğlu, 2023). At the policy level, initiatives such as the European Union Circular Economy Action Plan (European Commission, 2020) and the United Nations Sustainable Development Goals (United Nations, 2015) have positioned the built environment as a priority domain for circular transitions. Yet, despite this momentum, the integration of CE in practice remains fragmented. Much of the literature emphasizes technical aspects such as recycling technologies, modular construction, or material passports (Gondak et al., 2025; Eze et al., 2024), while giving less attention to the managerial processes that determine how circularity is embedded in building projects.

Recent studies have begun to explore CE adoption during early project phases, suggesting that decisions in planning and pre-construction strongly shape lifecycle outcomes (Wijewansha et al., 2021; Katipe Arachchige et al., 2025). For example, incorporating CE requirements into project briefs, procurement strategies, and design coordination can set a trajectory toward more sustainable delivery (Abadi & Sammuneh, 2020). However, these contributions tend to focus on specific subdomains rather than offering a comprehensive framework for embedding CE across all phases of building construction management.

Moreover, existing holistic frameworks often highlight the importance of systemic thinking (Alotaibi et al., 2024; Sheen, 2024) but do not explicitly translate CE principles into construction management processes. The result is a gap between conceptual ambition and managerial practice. Agyekum et al. (2024) further note that professionals across the built environment sector differ in how they prioritize CE principles, revealing inconsistencies that hinder effective implementation. This underlines the need for structured approaches that integrate CE into decision-making, resource allocation, and stakeholder engagement throughout the project lifecycle.

While technical CE strategies such as modular design, design for disassembly, and material recycling have been widely examined in the literature (Kumah et al., 2023; Sheen, 2024), their practical implementation depends fundamentally on management processes, contractual frameworks, and stakeholder coordination (Agyekum et al., 2024; Chammout & El-Adaway, 2025). Without these mechanisms, even the most innovative technical solutions remain fragmented or underutilized. Building construction management therefore provides a critical lens through which CE principles can be operationalized across the building lifecycle**,** ensuring that decisions made in early phases are translated into coherent design, construction, and operational practices (AIA, 2017; ISO, 2008; RIBA, 2020). Positioning construction management at the center of this discussion sharpens the research motivation of this study and ensures stronger alignment with its focus on lifecycle pathways to sustainability.

This study addresses these gaps by adopting a structured literature review and thematic synthesis to explore CE principles in building construction management. The study is guided by the following research questions:

- What are the key circular economy principles relevant to building construction management?
- How can these principles be applied across the different phases of the building construction process?
- What are the major barriers and enablers influencing the adoption of CE in building projects?
- How can building construction management contribute to advancing sustainability through circular practices at the lifecycle level?

The aim of this study is to provide a structured overview of CE in building construction management, clarifying its applications, challenges, and opportunities. The ultimate targets are threefold: to synthesize and categorize CE principles, to demonstrate their relevance across lifecycle phases, and to identify barriers and enablers shaping adoption. By reframing CE as a management-oriented strategy rather than a purely technical concern, this chapter contributes to both scholarship and practice. It argues that building construction management holds a decisive role in operationalizing circularity, enabling the sector to reduce environmental impacts while delivering long term value.

2. Literature Review

2.1. Circular Economy (CE) and Its Applications in the Construction Industry

The construction industry has increasingly been recognized as a critical domain for the transition toward a CE, given its significant contributions to global energy use, greenhouse gas emissions, and raw material consumption (Sheen, 2024; UNEP, 2020). Unlike the linear "take–make–dispose" model, CE emphasizes resource efficiency, waste minimization, and value retention across the lifecycle of materials and assets (European Commission, 2020). Applications in the built environment typically include strategies such as design for adaptability and disassembly, reuse and recycling of materials, modular and prefabricated construction, and the adoption of digital tools to improve traceability (Kumah et al., 2023; Çelebi & Arpacıoğlu, 2024; Gondak et al., 2025).

A substantial body of research demonstrates that CE principles can reduce construction waste, extend asset lifespans, and improve overall sustainability outcomes. For example, Kumah et al. (2023) emphasize design for circularity as a fundamental approach, highlighting strategies for adaptability, modularity, and material recovery. Similarly, Husgafvel and Sakaguchi (2021) show how CE practices in Japan have advanced through adaptive reuse and systemic approaches to waste reduction. Studies focusing on digitalization, such as those by Eze et al. (2024) and Gondak et al. (2025), highlight the role of building information modelling (BIM), internet of things (IoT), and material passports in enabling data-driven management of material flows, thus enhancing transparency and lifecycle accountability.

At the policy and regulatory level, CE in construction has been shaped by international initiatives such as the European Union Circular Economy Action Plan (European Commission, 2020) and the United Nations Sustainable Development Goals (United Nations, 2015), which explicitly identify the built environment as a priority sector for sustainability transformation. These frameworks encourage strategies like extended producer responsibility and lifecycle costing pushing the industry toward more holistic resource management practices (Çelebi & Arpacıoğlu, 2025).

Despite this growing body of work, challenges remain in mainstreaming CE practices in construction. Research often highlights barriers such as high upfront costs, limited client awareness, fragmented supply chains, and the absence of standardized tools for design and material management (Agyekum et al., 2024; Chammout & El-Adaway, 2025). Moreover, much of the literature has concentrated on specific technical aspects, such as recycling technologies or modular systems (Katipe Arachchige et al., 2025; Abadi & Sammuneh, 2020), leaving a gap in understanding how CE can be systematically embedded in broader managerial processes.

2.2. Building Construction Management and Lifecycle Phases

Building construction management is a structured process that organizes and coordinates activities across the entire lifecycle of a project. Rather than being limited to the construction stage alone, it encompasses a sequence of phases that provide continuity from initial project definition to long-term operation. Professional standards developed by organizations such as the American Institute of Architects (AIA), the International Organization for Standardization (ISO), and the Royal Institute of British Architects (RIBA) provide widely recognized frameworks for defining and managing these phases.

The AIA standard documents, including AIA Document A201: General Conditions of the Contract for Construction (AIA, 2014) and the AIA Handbook of Professional Practice (AIA, 2017), outline responsibilities and contractual frameworks for design, construction, and post-construction processes. These documents emphasize the interdependence of planning, contractual arrangements, and execution, highlighting the role of the construction manager as a coordinator of multiple professional inputs.

The ISO 22263:2008 standard complements this perspective by defining project management processes in terms of structured information flows across feasibility analysis, design development, execution, and operation (ISO, 2008). These standard underscores the importance of systematic information management and stakeholder communication throughout the building lifecycle.

Similarly, the RIBA Plan of Work 2020 provides one of the most detailed breakdowns of project stages, beginning with strategic definition and concept design, continuing through technical design and construction, and concluding with handover and in-use phases (RIBA, 2020). Its stage-based structure emphasizes the progressive elaboration of project objectives, technical requirements, and performance targets.

Synthesizing across these professional frameworks, building construction management can be reasonably divided into four overarching phases that provide clarity and consistency for both academic research and professional practice:

Briefing and Planning covering strategic definition, feasibility studies, cost estimation, and project initiation, as emphasized in the *RIBA Plan of Work 2020* and supported by ISO guidelines on feasibility and project initiation (ISO, 2008; RIBA, 2020).

Design encompassing conceptual, schematic, and technical design, as well as coordination among architectural and engineering disciplines, as defined in AIA Document A201 (AIA, 2014), the AIA Handbook of Professional Practice (AIA, 2017), and the RIBA Plan of Work (RIBA, 2020).

Construction involving procurement, on-site management, quality control, and coordination of labor and materials, responsibilities outlined extensively in AIA A201 (AIA, 2014) and supported by ISO standards for execution and information flow (ISO, 2008).

Operation and Maintenance extending from handover through the long-term use, maintenance, and adaptation of the building, as described in the RIBA Plan of Work 2020 (RIBA, 2020) and ISO 22263:2008 (ISO, 2008)

This phase-based understanding provides a systematic lens for analyzing how managerial processes structure the delivery and performance of building projects. It also establishes a foundation for subsequent sections of this chapter, where these phases serve as the reference framework for mapping thematic insights.

2. Material and Method

This study employs a qualitative research design based on a structured literature review and thematic synthesis of academic, industry, and policy sources. The methodological purpose is to construct a framework for embedding CE principles into building construction management processes. This is achieved not through new empirical data, but through a secondary data strategy that consolidates insights from multiple domains into a conceptual model that is academically rigorous and practically applicable.

The source material comprises three categories. First, peer-reviewed academic publications were retrieved from Web of Science and Scopus databases, with a focus on studies published between 2020 and 2025 that address CE in construction, sustainability in building projects, and lifecycle management (e.g., Wijewansha et al., 2021; Katipe Arachchige et al., 2025; Chammout & El-Adaway, 2025; Alotaibi et al., 2024). Second, policy and industry documents such as the European Union Circular Economy Action Plan (European Commission, 2020) and the United Nations Sustainable Development Goals (United Nations, 2015) were reviewed to capture the broader sustainability imperatives shaping CE discourse in the built environment. Third, professional practice standards were considered to structure the lifecycle perspective, particularly the AIA Document A201 and the AIA Handbook of Professional Practice (AIA, 2014; AIA, 2017), ISO 22263:2008 (ISO, 2008), and the RIBA Plan of Work 2020 (RIBA, 2020). These standards provided the basis for classifying project phases according to internationally recognized practice.

From these sources, a set of six CE principles was identified on the basis of recurrence and emphasis across multiple references: design for adaptability and disassembly (Kumah et al., 2023), resource efficiency and waste minimization (Sheen, 2024), material reuse and recycling (Husgafvel & Sakaguchi, 2021), lifecycle costing and risk assessment (Abadi & Sammuneh, 2020), extended stakeholder and producer responsibility (Agyekum et al., 2024), and digital enablement through tools such as BIM, IoT, and material passports (Gondak et al., 2025; Eze et al., 2024).

To operationalize the analysis, these principles were aligned with four phases of building construction management briefing and planning, design, construction, and operation and maintenance defined according to the combined guidance of AIA, ISO, and RIBA frameworks. This ensured that the classification of phases reflects both standardized lifecycle definitions and professionally practiced workflows (Figure 1).

As illustrated in Figure 1, the CE principles were then mapped to the lifecycle phases, producing a conceptual framework that demonstrates how circularity can be embedded across the managerial processes of building projects. This mapping exercise constitutes the analytical core of the study, as it translates broad CE principles into phase-specific practices applicable to building projects.

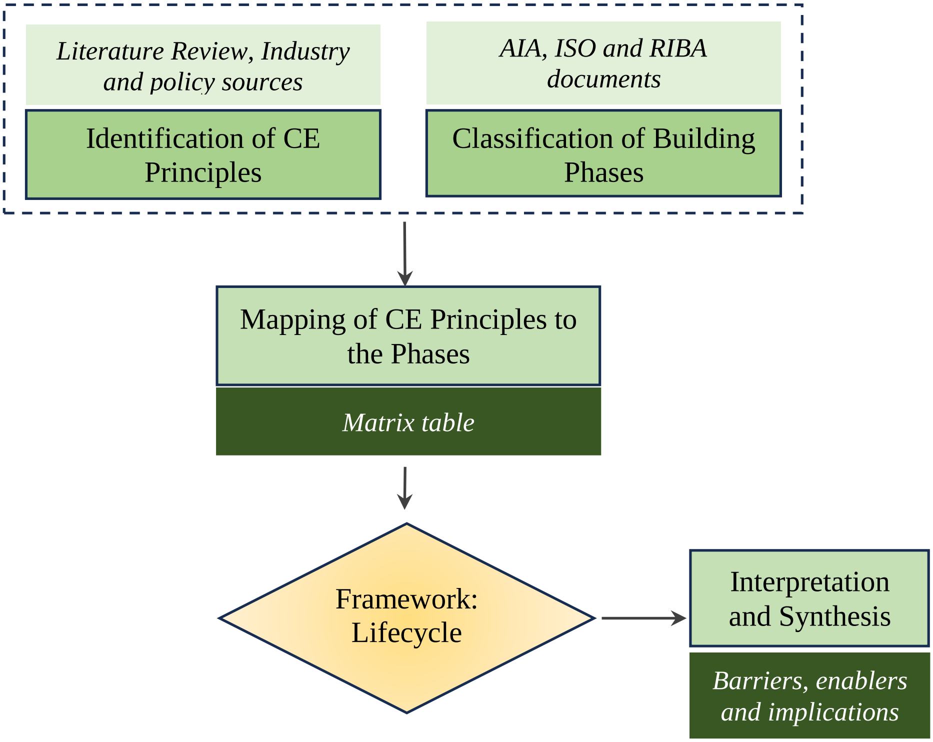

Figure 1. Research methodology flow (Created by the author)

In the final step, possible drivers and enablers were distilled through thematic synthesis of the reviewed literature and linked to the mapped CE principles across phases (Figure 1). These are not presented as empirical findings but as discussion-oriented insights that indicate potential pathways for adoption or obstacles to implementation.

3. Findings and Discussion

3.1. Findings

The analysis resulted in a conceptual framework that maps six CE principles across four key phases of building construction management: briefing and planning, design, construction, and operation and maintenance. This framework (Table 1) illustrates how CE principles can be systematically embedded in the managerial processes that govern the building lifecycle, highlighting that circularity is not solely a matter of technical solutions but also of coordinated decision-making and project management.

Table1. Mapping CE principles into building construction management phases (created by the author).

	Building Construction Phases			
CE Principles	**Briefing & Planning**	**Design**	**Construction**	**Operation & Maintenance**
Design for adaptability & disassembly	Set project goals for adaptability	Architectural / structural design for disassembly	Implement modular/adapt-able methods	Enable adaptability in use/renovations
Resource efficiency & waste minimization	Identify resource efficiency targets	Optimize designs for material efficiency	Minimize waste via site logistics	Maintain efficiency in building operations
Material reuse & recycling	Plan for material recovery at project scope	Specify recyclable /reusable materials	Recover and reuse onsite materials	Recover/recycle during renovations
Lifecycle costing & risk assessment	Integrate lifecycle cost & risk models	Embed lifecycle analysis in design decisions	Track costs vs. lifecycle benefits	Evaluate lifecycle performance
Extended stakeholder & producer responsibility	Assign stakeholder responsibilities in contracts	Facilitate collaboration across design teams	Ensure contractor compliance with CE	Ensure user/owner awareness & responsibility
Digital enablement (BIM, IoT, material passports)	Define digital strategy for circular data	Apply BIM-based circular design tools	Use IoT for real-time resource monitoring	Maintain digital passports for building components

In the briefing and planning phase, the integration of CE is particularly critical as this stage sets the overall direction of the project. Principles such as lifecycle costing and risk assessment ensure that resource efficiency, adaptability, and reuse are embedded into project objectives and procurement strategies from the outset (Abadi & Sammuneh, 2020). Early stakeholder engagement provides an opportunity to align client ambitions with circular practices, although lack of awareness and perceived higher costs remain common obstacles (Wijewansha et al., 2021; Agyekum et al., 2024).

The design phase translates circular ambitions into concrete specifications. At this stage, design for adaptability and disassembly, alongside material reuse and recycling strategies, become operationalized through architectural and engineering decisions (Kumah et al., 2023). The increasing use of digital tools such as BIM, material passports, and modular design systems facilitates the adoption of CE principles by simulating resource flows and future adaptability (Gondak et al., 2025; Eze et al., 2024). Nevertheless, resistance to unfamiliar practices and the absence of standardized tools remain significant barriers.

During the construction phase, CE principles are enacted through procurement, resource management, and on-site practices. Emphasis is placed on minimizing waste, recovering materials, and applying modular and prefabricated systems to reduce inefficiencies (Sheen, 2024). Digital monitoring tools, including IoT-enabled platforms, enhance real-time tracking of resources. Yet, challenges persist due to supply chain immaturity, limited contractual obligations for circular compliance, and cost-driven decision-making (Chammout & El-Adaway, 2025).

Finally, in the operation and maintenance phase, CE practices focus on extending building lifespan and preparing for future adaptability. Preventive maintenance, adaptive reuse, and refurbishment strategies are essential to retaining value over time (Husgafvel & Sakaguchi, 2021). Digital enablement through BIM and material passports supports long-term tracking of components, allowing for more efficient maintenance and eventual recovery of resources (Alotaibi et al., 2024). Despite this potential, weak regulatory enforcement and limited owner incentives remain barriers to consistent adoption.

Overall, the findings emphasize that CE integration is most effective when approached from a lifecycle perspective, with early phases serving as the foundation for long-term success. While design and construction phases allow for operationalization of circular principles, it is the briefing and planning phase that provides the strategic leverage for embedding circular objectives. The operation and maintenance phase, in turn, ensures that these principles are sustained and translated into long-term environmental and economic benefits.

3.2. Discussion

While the framework illustrates opportunities for embedding CE principles across the building lifecycle, the extent of their implementation is shaped by a combination of institutional, managerial, and technical conditions. These factors may act as drivers that facilitate adoption or as barriers that hinder progress, depending on the context in which projects are delivered. To acknowledge the conceptual scope of this study, they are presented as “possible drivers” and “possible enablers” distilled from the literature and professional standards. Table 2 summarizes these dynamics, showing how such conditions influence outcomes at each phase of building construction management.

Table 2. Possible drivers and enablers influencing the integration of CE principles across building construction phases (created by the author)

Phase	Possible Barriers	Possible Enablers
Briefing & Planning	Limited client awareness of CE benefits (Agyekum et al., 2024)	Early stakeholder collaboration (Wijewansha et al., 2021)
	Perceived higher upfront costs	Lifecycle costing and risk assessment (Abadi & Sammuneh, 2020)
	Fragmented roles and unclear responsibilities	Policy drivers (European Commission, 2020)
Design	Lack of familiarity among professionals (Kumah et al., 2023)	Design for adaptability and disassembly (Kumah et al., 2023)
	Limited standardized CE design tools	BIM and material passports (Gondak et al., 2025)
	Resistance to non-conventional methods	Integrating modular and flexible design strategies
Construction	Supply chain immaturity (Chammout & El-Adaway, 2025)	On-site waste reduction and recovery (Sheen, 2024)
	Cost-driven contractor decisions	Digital monitoring (IoT, BIM) (Eze et al., 2024)
	Absence of contractual CE mechanisms	Modular construction practices
Operation & Maintenance	Lack of incentives for owners (Husgafvel & Sakaguchi, 2021)	Adaptive reuse and refurbishment strategies (Husgafvel & Sakaguchi, 2021)
	Weak regulatory enforcement	Preventive maintenance practices
	Limited user awareness	Digital enablement for long-term data accessibility (Alotaibi et al., 2024)

This study's findings are consistent with prior research emphasizing the importance of early project phases in setting trajectories for circularity (Wijewansha et al., 2021; Katipe Arachchige et al., 2025). The identification of briefing and planning as the strategic entry point confirms earlier observations that lifecycle costing, procurement criteria, and stakeholder alignment are decisive in shaping outcomes (Abadi & Sammuneh, 2020). By mapping circular economy principles across all four phases, however, this study contributes a comprehensive lifecycle-oriented perspective that highlights how managerial process structure opportunities for circular adoption.

The findings also align with scholarship that highlights design for adaptability and disassembly as a cornerstone of circularity (Kumah et al., 2023), while adding nuance by illustrating how this principle interacts with digital enablers such as BIM and material passports (Gondak et al., 2025; Eze et al., 2024). In the construction phase, the emphasis on waste reduction and modular approaches resonates with Sheen's (2024) systems analysis of resource flows. Yet, unlike purely technical accounts, this study underscores the managerial mechanisms—contractual frameworks, procurement models, and supply chain coordination—that determine whether such practices are effectively realized. Similarly, in the operation and maintenance phase, the results confirm the importance of adaptive reuse and refurbishment (Husgafvel & Sakaguchi, 2021) but also draw attention to persistent institutional barriers, including limited client incentives and weak regulatory enforcement, which continue to constrain long-term circular practices.

Revisiting the research objectives, the study demonstrates that CE in building construction management is anchored around six recurring principles: adaptability, resource efficiency, material reuse, lifecycle costing, extended responsibility, and digital enablement. These principles are not isolated but interact across all project phases, with briefing and planning emerging as the most critical entry point, since early decisions set trajectories for design, procurement, and long-term performance. The analysis further shows that barriers to adoption are largely systemic and institutional, such as low client awareness, inadequate regulatory support, and immature supply chains, whereas enablers are primarily managerial and technological, including lifecycle costing approaches, modular design strategies, and BIM-based material tracking. By synthesizing these insights into a phase-based framework, the study positions building construction management as the integrative mechanism through which circular practices are operationalized, thereby advancing both sustainability and long-term value creation across the building lifecycle.

Overall, this research supports recent calls for holistic and managerial perspectives on CE in construction (Chammout & El-Adaway, 2025; Alotaibi et al., 2024), while advancing the debate by offering a phase-based conceptual framework grounded in professional standards (AIA, 2017; ISO, 2008; RIBA, 2020). It argues that circularity cannot be achieved by isolated design innovations or recycling technologies alone but requires embedding CE principles systematically into the managerial processes of building projects.

4. Conclusion and Suggestions

This study set out to examine how circular CE principles can be embedded across the phases of building construction management, responding to the urgent environmental and resource challenges faced by the construction sector. By conducting a structured literature review and thematic synthesis, six recurring CE principles were identified adaptability, resource efficiency, material reuse, lifecycle costing, extended responsibility, and digital enablement and mapped across four lifecycle phases defined by professional standards: briefing and planning, design, construction, and operation and maintenance.

The findings demonstrate that CE adoption is not limited to technical innovations but depends critically on managerial processes that structure decision-making, procurement, and lifecycle coordination. Briefing and planning emerged as the most influential stage, where early decisions set the trajectory for project sustainability. Design operationalizes these ambitions through specifications and digital tools, construction enacts them through resource efficiency and on-site practices, and operation and maintenance sustain circularity through adaptive reuse and long-term performance monitoring.

The study makes three main contributions. First, it provides a phase-based framework that clarifies how CE principles can be integrated throughout the building lifecycle. Second, it highlights the barriers and enablers that shape implementation, showing that systemic and institutional challenges must be addressed in parallel with technological and managerial enablers. Third, it positions building construction management as the coordinating mechanism through which circularity can be operationalized, bridging the gap between conceptual ambition and practice.

Like all conceptual research, this study has limitations. The framework was developed based on literature, policy documents, and professional standards, without direct empirical testing. As a result, while it provides a structured theoretical contribution, its practical applicability may vary across different regional, cultural, and regulatory contexts. Furthermore, the reliance on secondary sources may omit emerging practices not yet widely reported in academic or industry literature.

From a practical perspective, the study underscores the importance of early-phase integration of CE objectives, the use of digital tools to enhance traceability, and the need for contractual and policy frameworks that incentivize lifecycle responsibility. For academia, it points to the value of holistic, management-oriented approaches in CE research, complementing existing technical studies.

Future research could extend this framework by testing it empirically in real project contexts, comparing regional differences in CE adoption, and exploring how digital innovations such as digital twins and AI-enabled lifecycle assessment may further support circular practices. Such work would provide the empirical depth needed to refine the framework and support its translation into practice.

Acknowledgements and Information Note

The article complies with national and international research and publication ethics. Ethics Committee approval was not required for the study.

Author Contribution and Conflict of Interest Declaration Information

The article is written by a single author. There is no conflict of interest.

References

Abadi, M. & Sammuneh, M. A. (2020, September). Integrating circular economy and constructability research: An initial development of a lifecycle" circularity" assessment framework and indicators. In *Proceedings 36th Annual ARCOM Conference, 7-8 September 2020, UK, Association of Researchers in Construction Management* (pp. 516-525). ARCOM.

Agyekum, K., Amudjie, J., Pittri, H., Dompey, A. M. A. & Botchway, E. A. (2024). Prioritizing the principles of circular economy among built environment professionals. *Built Environment Project and Asset Management*, *14*(5), 734-750.

AIA (The American Institute of Architects). (2017). *AIA Document A201-2017: General Conditions of the Contract for Construction*. Washington, DC: *The* American Institute of Architects.

AIA (The American Institute of Architects). (2014). *The Architect's Handbook of Professional Practice* (15th ed.). Hoboken, NJ: Wiley.

Alotaibi, S., Martinez-Vazquez, P. & Baniotopoulos, C. (2024). A holistic framework to accelerate implementation of circular economy in Mega-Scale construction projects. *Applied Sciences*, *14*(23), 10958.

Chammout, B. & El-Adaway, I. H. (2025). Circular Economy in Construction: Decision-Making Factors and Future Research Avenues. *Journal of Construction Engineering and Management*, 151(6), 04025059.

Çelebi, N.G. & Arpacıoğlu, Ü. (2023). Evaluation of Life Cycle Energy Efficiency of Buildings. *Livenarch VII-2023: Other Architect/Ure(S),* September 28-30, Trabzon, Türkiye.

Çelebi, N.G. & Arpacıoğlu, Ü. (2024). Structural Frames in the Context of Earthquake and Environmental Impact. Karadağ, A.A. & Ertaş Beşir, Ş. (Eds.). Earthquake Resistant Cities and Disaster Management. 2024, Chapter: 4, 84-107. ISBN: 978-625-367-633-9. Iksad Publications.

Çelebi, N.G. & Arpacıoğlu, Ü. (2025). Life Cycle Assessments (LCA) and Life Cycle Costing (LCC) of Structural Systems. *11th Asia Pacific International Congress on Contemporary Scientific Research*, March 12-15, 2025, Ho Chi Minh, Vietnam.

European Commission. (EU). (2020). *A new Circular Economy Action Plan: For a cleaner and more competitive Europe*. Brussels: European Union. Access Address (25.08.2025): https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0098

Eze, E. C., Sofolahan, O., Ugulu, R. A. & Ameyaw, E. E. (2024). Bolstering circular economy in construction through digitalisation. *Construction Innovation*.

Gondak, M. D. O., Hluszko, C., Moretti, V., Zeni, G. L. F. & Francisco, A. C. D. (2025). Guide to digital technologies for circularity in the project lifecycle: perspective of the EN 15643-3: 2012 standard. *Construction Innovation*.

Husgafvel, R. & Sakaguchi, D. (2021). Circular economy development in the construction sector in Japan. *World*, *3*(1), 1-26.

IEA (International Energy Agency). (2022). *World energy outlook 2022*. Paris: IEA. Access Address (25.08.2025): https://www.iea.org/reports/world-energy-outlook-2022

ISO (International Organization for Standardization). (2008). *ISO 22263:2008 Organization of information about construction works: Framework for management of project information*. Geneva: ISO.

Katipe Arachchige, T. V. S., Perera, B. A. K. S., Kavirathna, A. S. & Wijayarathna Mudiyanselage Don, Y. S. (2025). Integration of circular economy principles during the pre-construction stage to enhance the sustainability of MEP works. *Construction Innovation*.

Kumah, V. M. A., Agyekum, K., Botchway, E. A., Pittri, H., Salgin, B., Parisi, L., ... & Atuahene, B. T. (2023, November). Design for Circularity (DFC) in Construction: A Mini-scoping Review of the Strategies. In *International Conference on Infrastructure Development in Africa* (pp. 309-323). Cham: Springer Nature Switzerland.

RIBA (Royal Institute of British Architects). (2020). *RIBA Plan of Work 2020. London*: RIBA Publishing.

Sheen, R. L. (2024, June). Construction Industry and the Circular Economy: A Systems Analysis. In *The International Conference on Net-Zero Civil Infrastructures: Innovations in Materials, Structures,* *and Management Practices (NTZR)* (pp. 1907-1920). Cham: Springer Nature Switzerland.

UNEP (United Nations Environment Programme). (2020). *2020 Global status report for buildings and construction: Towards a zero-emission, efficient and resilient buildings and construction sector*. Nairobi: UNEP. Access Address (23.08.2025): https://globalabc.org/resources/publications/2020-global-status-report-buildings-and-construction

United Nations. (UN). (2015). *Transforming our world: The 2030 Agenda for Sustainable Development (A/RES/70/1)*. New York: United Nations General Assembly. Access Address (21.08.2025): https://sdgs.un.org/2030agenda

Wijewansha, A. S., Tennakoon, G. A., Waidyasekara, K. G. A. S. & Ekanayake, B. J. (2021). Implementation of circular economy principles during pre-construction stage: the case of Sri Lanka. *Built Environment Project and Asset Management*, *11*(4), 750-766.

Assist. Prof. Dr. Tayibe SEYMAN GÜRAY

E-mail: tayibe.guray@fbu.edu.tr

Educational Status: PhD graduate

License: Department of Architecture, Istanbul Technical University.

Master's Degree: Istanbul Technical University, Building Construction Management.

Doctorate: Istanbul Technical University, Construction Sciences-Building Construction Management.

Professional experiences:

Project Manager-SHAYA Türkiye (Starbucks) İstanbul, (2007-2012).

Project Manager -Unitim A.Ş. İstanbul, (2006-2007).

Quality Manager -DİM A.Ş. İstanbul, (2003-2006).

Architect - Doğuş Yapı A.Ş. (2001-2003), İstanbul

Architect - Alp Mimarlar (2000-2001), İstanbul

Academic experiences:

Vice Dean of Architecture and Design Faculty, Fenerbahce University (2025-cont.)

Head of Int. Architecture and Env. Design (Eng) at Architecture and Design Faculty in Fenerbahce University (2023-2025)

Vice Dean of Engineering & Architecture Faculty and Head of Department of Architecture in Beykoz University (2018-2023)

Asst. Prof. Dr. at the Department of Architecture in Altınbaş University (2012-2017)

Adaptive Re-use of Heritage Buildings: A Cornerstone for Circular Economy in the Built Environment

İlayda Şevval ALIŞ [1]

[1] Bursa Uludağ University, Master's Program in Architecture, Graduate School of Natural and Applied Sciences, Nilüfer, Bursa/Türkiye.
ORCID: 0009-0002-9875-3547
E-mail: ilaydaalis02@gmail.com

Prof. Dr. Arzu ÇAHANTİMUR [2]

[2] Bursa Uludağ University, Faculty of Architecture, Department of Architecture, Nilüfer, Bursa/Türkiye.
ORCID: 0000-0002-5907-1773
E-mail:arzucahan@uludag.edu.tr

Citation: Alış, İ. Ş. & Çahantimur, A. (2025). Adaptive Re-use of Heritage Buildings: A Cornerstone for Circular Economy in the Built Environment. Beceren Öztürk, R. & Çahantimur, A. (Eds.). **Contemporary Approaches in Architecture: The Role of Architecture in the Circular Economy**. 2025, Chapter:3, 41-60. ISBN: 978-625-378-348-8. Iksad Publications. DOI: https://doi.org/10.5281/zenodo.17309921

1. Introduction

The construction industry, responsible for over one-third of global waste and nearly 40% of raw material consumption, plays a pivotal role in the transition toward sustainable development (Dabija et al., 2022; Matar et al., 2023; Ossio et al., 2023). As the limitations of the linear "take-make-dispose" model become increasingly evident in the face of environmental degradation and resource scarcity, the circular economy (CE) offers a regenerative alternative — one that aims to close material loops, extend life cycles, and decouple economic growth from environmental harm (Geissdoerfer et al., 2017; Ellen MacArthur Foundation, 2020; Hossain et al., 2020). Within this paradigm shift, the built environment emerges as both a challenge and an opportunity: buildings are long-lived, materially intensive, and culturally embedded assets that hold immense potential for value retention through reuse and regeneration.

Among the various components of the built environment, historic buildings and heritage structures occupy a unique and pressing position. Due to their architectural, cultural, and material richness — and often underutilized state — historic built environments represent ideal candidates for CE-driven interventions (Ranasinghe & Illankoon, 2024; Foster, 2020). The reuse of such buildings avoids the premature demolition of structures with high embodied energy, while also mitigating the environmental cost of new construction. Moreover, historic buildings often benefit from public support and policy attention, especially in Europe where targeted funding and cultural heritage initiatives have promoted the integration of sustainability and conservation goals (Owojori et al., 2021; Gravagnuolo et al., 2019).

In this context, adaptive re-use has emerged as a core strategy for embedding CE principles into existing building stock, particularly within the historic built environment. Adaptive re-use not only conserves resources and reduces carbon emissions but also preserves arhitectural identity and social meaning (Pomponi & Moncaster, 2017; Ollár, 2024). As a design philosophy and operational practise, it extends a building's lifespan by accommodating new functions while minimizing material waste and maximizing embodied energy. Despite increasing attention in research and policy, the alignment between apative re-use and circularity remains fragmented and underexplored in global practice (Hamida et al., 2024; Ranasinghe et al., 2024). Adressing this gap, adaptive re-use can act as a circular economy accelerator, offering tangible pathways for policy innovation, lifecycle extension, and multidimensional sustainability in the built environment.

This chapter explores the intersection of circular economy principles and the historic built environment, with a spesific focus on adaptive reuse as a strategy for resource efficiency and cultural continuity. Following a theoretical overwiev of circular economy frameworks in the construction sector, the discussion highlights the unique potential of heritage buildings to contribute to circularity through reuse, transformation and lifecycle extentions. The core of the chapter presents a comparative analysis of selected adaptive reuse case studies, evaluating their performance in terms of environmental, architectural and functional outcomes.

Methodologically, the chapter adopts a qualitative research approach based on document analysis and comparative criteria drawn from existing literatüre and LCA-informed frameworks. The selected cases represents diverse geographical and typological contexts, allowing for a cross-case synthesis of adaptive reuse practises in heritage settings. The chapter concludes by outlining key insights and strategic recommendations for future implementation of circular economy principles in historic building interventions.

2. Circular Economy in the Built Environment

The Circular Economy (CE) is increasingly recognized as a strategic response to the global ecological crisis. As defined by the European Commission in its Circular Economy Action Plan (2020), CE refers to "a model of production and consumption which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible" Similarly, the Ellen MacArthur Foundation (2013, 2020) describes CE as "an industrial system that is restorative or regenerative by intention and design," aiming to keep products, components, and materials at their highest utility and value at all times.

The urgency for adopting circular economic models extends far beyond the construction sector. Globally, the linear economy — built ont the extract-produce-consume-dispose logic— has led to unprecedented levels of material depletion, biodiversity loss, and greenhouse gas emissions. According to the Global Circularity Gap Report (2023), only 7.2% of the global economy is truly circular, highlighting a vast untapped potential for decoupling economic growth from enviromental harm. The transition to circularity is now central to international sustainability strategies such as the European Green Deal, UN SDG 12 (Responsible Consumption and Production), and climate neutrality targets for 2050.

Within this broader agenda, the built environment has emerged as a critical domain for circular intervention. Encompassing buildings, infrastructure, and urban systems, the sector is responsible for over 35% of total waste in the European Union and consumes more than 40% of all extracted materials (Dabija et al., 2022; Ossio et al., 2023). This unsustainable trajectory demands a fundamental transformation in the way buildings are conceived, used, and decommissioned.

In response, circular economy principles in the built enviroment are operationalized through strategies such as design for adaptability and disassembly, material reuse, lifecycle optimization and extensions of building service life (Matar et al., 2023). Rather than being passive consumers of materials, buildings are increasingly seen as material banks long term repositories of embodied energy, cultural identity and economic value. Their transformation and retention through circular practises can generate environmental, social and economic benefits, aligning local interventions with global sustainability goals.

However, as Ranasinghe and Illankoon (2024) emphasize, there is still a lack of consensus on how CE principles should be systematically applied in practice. Their systematic review identifies three dominant themes in CE for the built environment: (1) policy and planning frameworks for reuse, (2) sustainability attributes for circularity, and (3) decision-making tools. These findings underline the need for a multi-dimensional approach that integrates design, policy, economics and heritage values.

While Matar et al. (2023) point out that CE remains largely conceptual in current parctice, Dabija et al. (2022) call for lifecycle-based frameworks embedded in the earliest design stages. The transition is not technical but deeply institutional and cultural requiring new governance structures, financial models and public engagement strategies.

In summary, the buit environment is both a high-impact sector and a strategic entry point for implementing circularity. The immense volüme of existing buildings — especially in cities — present a major opportunity to embed CE principles not through demolition and replacement, but through adaptive reuse, transformation and regeneration. The following sections explore this potential in depth, particularly within the historic built environment.

3. Adaptive Re-use as a Method for Circular Economy in the Historic Built Environment

The historic built environment—consisting of culturally, architecturally, and socially significant buildings—represents a vital reservoir of material, symbolic, and economic value. These structures often predate modern construction methods and materials, yet they continue to embody long-lasting desing intelligence, skilled craftsmanship, and deep-rooted meanings for communities. Within the framework of a circular economy (CE), which seeks to extend the lifecycle of resources, reduce waste and regenerate value, the adaptive reuse of historic buildings emerges as a highly strategic and multidimensional practice.

Unlike new construction, which typically relies on resource extraction and high embodied carbon inputs, historic buildings already carry substantial investments of materials and energy. Their demolition not only results in waste generation and cultural loss but also negates the opportunity to cınserve embodied carbon and contribute to sustainable development objectives. Adaptive re-use, defined as the process of transforming a building's function while conserving its architectural and historical integrity, aligns with the core goals of CE by maximizing use-value, minimizing demolition and reactivating underused assets. In doing so, it avoids the environmental impacts of new construction while simultaneously preserving cultural heritage.

Multiple studies emphasize that historic buildings are ideally suited for circular strategies due to their construction quality, spatial adaptibility and location within existing urban fabrics. Foster (2020) argues that heritage buildings inherently possess longer lifespans than modern equivalents and are often located in well established neighborhoods, making them valuable assets for sustainable regeneration. Gravagnuolo et al. (2018) further contend that adaptive re-use can support local economic revitalization, reduce land consumption and reinforce place based identity all while maintaining material circularity. Similarly, Saleh et al. (2021) highlight the socio-economic dimensions of adaptive reuse, noting its ability to engage local stakeholders, attract creative industries and support the green transformation of urban centers.

Despite its ptential, adaptive re-use in historic contexts requires careful negotiation between technical upgrades and conservation ethics. Challenges include structural limitations, heritage protection regulations and the need for reversible, non-invasive interventions. Succesful cases often rely on integrated decision making processes involving architects, conservation experts, engineers and community representatives. As De Della Torre et al. (2021) suggest, adaptive reuse shold be approached not as a compromise between preservation and innovation, but as a creative design act that generates new cultural, environmental and social value from existing assets.

To evaluate the contribution of adaptive re-use in hidtoric buildings to circular economy goals, we propose a structured framework synthesizing findings from the current literatüre. This framewerk identifies eight core areas through which historic adaptive re-use can generate circular value. These include resource efficiency, operational energy performance, waste reduction, embodied carbon preservation, cultural value retention, lifecycle extension, economic revitalization, and social cohesion. Each dimension is supported by specific strategies and indicators, as detailed in Table 1 below:

Table 1. Core areas through which historic adaptive re-use can generate circular value (developed by the authors)

Contribution Category	Example Strategies / Indicators	Key References
1. Resource Efficiency	Material reuse, preservation of existing structure, selective demolition	Rodrigues & Freire (2017); Gravagnuolo et al. (2018)
2. Energy Performance & Operational Carbon	Passive design upgrades, HVAC retrofitting, insulation of existing envelopes	Ascione et al. (2015); Saleh et al. (2021)
3. Waste Reduction	Reduction of C&D waste, circular planning for deconstruction	Della Torre et al. (2021); Bullen & Love (2011)
4. Embodied Carbon Preservation	Retention of original structural shell and envelope	Pomponi & Moncaster (2017); Ellen MacArthur Foundation (2020)
5. Cultural Value Retention	Preservation of form, layout, and historic character	Fusco Girard (2019); Gravagnuolo et al. (2018)
6. Extended Building Life Cycle	Flexible new functions, adaptive programming (e.g. school → coworking)	Rodrigues & Freire (2017); Gravagnuolo et al. (2018)
7. Economic Revitalization	Creative industry reuse, tourism-based models, revitalization of abandoned stock	Saleh et al. (2021); Fusco Girard et al. (2018)

8. Social Cohesion & Place Attachment	Participation of community in design, preservation of collective memory, symbolic continuity	Gravagnuolo & Angrisano (2022); Fusco Girard (2019)

This framework highlights the multi-layered contribution of adaptive reuse in historic contexts, extending beyond material flows to encompass cultural continuity, urban regeneration, and stakeholder engagement. In contrast to technocratic approaches that reduce circularity to metrics of reuse and recycling, adaptive reuse in heritage contexts promotes a more integrated and resilient interpretation of CE one that is sensitive to both environmental thresholds and human values.

In the next chapter, the framework is operationalized and applied to selected case studies in Europe and Türkiye. Through a comparative lens, the extent to which real-world projects align with circular-economy strategies is evaluated, and the contextual factors that enable or constrain them are identified.

4. Comparative Analysis of Selected Cases

This section presents a comparative analysis of seven adaptive reuse (AR) projects across Europe and Türkiye, evaluated through a qualitative research approach based on systematic document analysis and comparative criteria derived from existing literature and LCA-informed frameworks. A comparative multiple-case study design was employed, guided by a maximum-variation sampling logic. The cases were selected to represent diverse geographies (Europe and Türkiye), scales (from individual buildings to districts), governance models (public, private, public–private partnership, and community-led), and intervention types. Evaluations were conducted against the eight-dimensional framework outlined in the previous chapter, enabling both within-case and cross-case synthesis. Through this diversity, the contextual conditions shaping the translation of circular economy (CE) principles in heritage-led transformations are revealed. Each case illustrates a unique context, scale, and governance approach, allowing commonalities and differences to be identified across projects. The analysis concludes by deriving key insights and strategic recommendations for the future implementation of CE principles in historic building interventions.

The Ex-Mattatoio complex in Rome, formerly a municipal slaughterhouse, now functions as a university and cultural venue. It’s adaptive reuse demonstrates high performance across all CE criteria. Key arhitectural components were retained to ensure material efficiency, embodied carbon preservation and cultural value. The site was reprogrammed to accomodate contemporary functions while remaining rooted in its industrial heritage. Moreover, the adaptive reuse enable social and aconomic activation in the surrounding area.

Similarly, the Palazzo dell’Innovazione in Salerno repurposed a 19th-century historic building into a modern technology and entrepreneurship hub. While highly efficient in terms of material reuse and lifecycle extension, the project shows slightly weaker social cohesion contributions, likely due to its programmatic orientation toward innovation sectors rather than community-centered functions. Nevertheless, it offers a replicable model for historic structure reactivation through public-private cooperation and GBC Historic Building certification mechanisms.

The Naples Historic Center revitalization, as discussed by Gravagnuolo et al. (2019), provides a city-scale approach to adaptive reuse. Various underused buildings were transformed into spaces for tourism and the creative economy. While not all buildings underwent energy performance upgrades or material audits, the interventions achieved significant outcomes in cultural value retention, local employment, and stakeholder engagement. The case emphasizes CE not only as a material cycle but as a platform for regenerative urban policy.

The Mechelen Circular Hub (Belgium) exemplifies a contemporary reuse model where heritage spaces host circular businesses and social innovation labs. Originally an industrial facility, the building was preserved to house community repair workshops, educational programs, and resource-sharing activities. Though the cultural character of the site is less emphasized, its operational model integrates circularity into everyday urban life. This case demonstrates CE as a lived practice rather than a static retrofit.

A prominent southern European example is Matadero Madrid (Spain), where a former slaughterhouse complex has been adapted into a large-scale cultural hub. It strongly contributes across all CE dimensions. The architectural integrity was preserved through minimal intervention and reversible installations. The site now operates under an adaptive governance model that fosters long-term public engagement, reuse of infrastructure, and mixed funding mechanisms. It represents one of the most comprehensive applications of circular reuse in the heritage sector.

From Türkiye, the Bakırköy Demirciler Sanat Evi in Istanbul stands out as a fine-grained adaptive reuse project in a metropolitan setting. The building, once a blacksmith’s workshop, was transformed into a cultural venue through reversible and low-impact strategies. Despite limited upgrades to energy systems, the project made strong contributions in community-based governance, material retention, and social inclusion. It highlights the relevance of small-scale interventions in local circular ecosystems.

Finally, the Kütahya II. Yakub Çelebi Complex offers a rare example of a monumental religious structure adapted for multifunctional civic use. Without compromising its spiritual role, the complex now hosts a library, archive, and public services. This case illustrates how layered adaptive reuse — respectful of symbolic meanings — can contribute to lifecycle extension, resource conservation, and civic engagement. The success of this project lies in its context-sensitive programming and gradual, participatory transformation. Table 2 summarizes the cases and Table 3 synthesizes each project's contribution across the eight CE categories.

Table 2. Summary of the Selected Adaptive Reuse Projects

Building / Site	Period / Date	Original Function	Architectural Features	Current Use (Post-AR)
Ex-Mattatoio (Rome)	Late 19th century	Industrial slaughterhouse	Large industrial complex, brick façade, wide spans, iron detailing	Cultural, artistic, and educational complex
Palazzo dell'Innovazione (Salerno)	Medieval origin, later additions	Residence / palace	Stone masonry, courtyard layout, multi-period additions	Digital innovation and entrepreneurship hub
Naples Historic Center (Naples)	From Ancient Rome to present	Mixed (religious, civic, residential)	Organic urban fabric, narrow streets, religious buildings, Baroque architecture	Mixed use: tourism, commerce, civic life
Mechelen Circular Hub (Belgium)	Early 20th century	Industrial warehouse	Reinforced concrete structure, spacious interiors, industrial architectural language	Co-working and innovation center

Matadero Madrid (Spain)	Early 20th century	Municipal slaughterhouse	Brick façade, industrial typology, large courtyards	Art, culture, and public events center
Bakırköy Demirciler Art House (Istanbul)	Late 19th century	Guild / workshop	Small-scale hybrid timber–masonry structure	Art house, workshop, cultural events
Yakup Çelebi Complex (Kütahya)	14th century	Religious–civic complex	Early Ottoman külliye typology, stone–brick material, mosque–madrasa–tomb ensemble	Cultural and civic functions (exhibitions, events)

Table 3. Contribution of the projects across the eight CE categories

Case	1. RE	2. EPC	3. WR	4. EC	5. CV	6. LCE	7. ER	8. SC
Ex-Mattatoio (Rome)	✓	✓	✓	✓	✓	✓	✓	✓
Palazzo dell'Innovazione (Salerno)	✓	✓	✓	✓	✓	✓	✓	✓
Naples Historic Center	○	✓	○	○	✓	○	✓	✓
Mechelen Circular Hub (Belgium)	✓	✓	✓	✓	✓	✓	✓	✓
Matadero Madrid (Spain)	✓	✓	✓	✓	✓	✓	✓	✓
Bakırköy Demirciler Sanat Evi (İstanbul)	✓	✓	✓	✓	✓	✓	✓	✓
II. Yakup Çelebi Complex (Kütahya)	✓	✓	✓	✓	✓	✓	✓	✓

Legend: ✔ = Strong contribution | ◯ = Partial or context-specific contribution

This comparative analysis reveals that while most cases deliver robust outcomes in resource efficiency, embodied carbon preservation, and lifecycle extension, contributions to energy performance and economic regeneration are more variable, often depending on the scale, financing model, and policy context. Social and cultural dimensions emerge as critical areas where heritage reuse distinguishes itself from generic CE applications—particularly in fostering symbolic continuity, public value, and multi-generational use.

These cases collectively illustrate how adaptive reuse, when executed thoughtfully, acts as a holistic CE strategy that bridges environmental, cultural, and social sustainability in historic contexts.

5. Conclusion

This chapter has examined how adaptive reuse (AR) of historic buildings can function as an effective strategy for implementing circular economy (CE) principles in the built environment. Through a synthesis of recent literature and comparative case analysis, it has demonstrated that heritage structures are not merely passive recipients of conservation but can actively contribute to sustainability transitions when approached through a circular lens.

The literature review revealed that CE in the construction and heritage sectors is evolving beyond material recovery to include long-term value retention, energy performance, community regeneration, and symbolic continuity. However, adaptive reuse in heritage contexts introduces unique challenges, requiring the integration of cultural, social, and technical criteria. The proposed evaluation framework responded to this complexity by identifying eight interrelated contribution categories: resource efficiency, energy performance, waste reduction, embodied carbon preservation, cultural value retention, life cycle extension, economic revitalization and social cohesion. This multidimensional lens enables more holistic assessments of adaptive reuse beyond the boundaries of environmental metrics alone.

The comparative analysis of seven case studies across Europe and Türkiye confirmed tha framework's relevance and applicability. While all cases demonstrated meaningful alignment with multiple CE dimensions, their contribution profiles varied based on scale, program type, governance structure, and cultural context. For instance, large-scale transformations like Matadero Madrid and Ex-Mattatoio Rome achieved high levels of circularity across all dimensions, integrating long term public use with architectural presevration. Mid-scale projects such as Palazzo dell'Innovazione and Mechelen Circular Hub demonstrated strong material and lifecycle performance, but their social contributions were more context-spesific. Meanwhile, community based or multifunctional reuses — such as Bakırköy Demirciler Sanat Evi and Kütahya II. Yakub Çelebi Complex — highlighted the potential of adaptive reuse to generate symbolic and civic value with relatively modest physical interventions.

Collectively, these cases reinforce the understanding that circularity in heritage reuse is not a one size fits all model. Instead, it is best conceptualized as a spectrum of aligned strategies, in which technical efficiency, cultural meaning, and user engagement intersect. The ability of adaptive reuse to reconcile these often competing dimensions positions it as a unique tool for linking climate action, urban resilience and heritage continuity.

By integrating analytical insights from literature and practice, this chapter has contributed to building a more structured and comparative understanding of how adaptive reuse supports the circular transition in historic contexts. The proposed framework can inform design processes, policy assessments and heritage management strategies. Further research may expand this framework with quantitative life cycle metrics, user experience studies or post-occupancy avaluations to better quantify long term CE outcomes in adaptively reused heritage assets.

As the global construction sector seeks to decarbonize and local governments pursue urban regeneration under sustainability mandates, historic buildings — often viewed as static legacies — can instead become living assets within the circular city. Adaptive reuse, when planned and governed thoughtfully, offers not only environmental dividends but also enduring cultural and social capital.

Acknowledgements and Information Note

This section was developed within the scope of a graduate-level course at Bursa Uludağ University, Faculty of Architecture. The author wishes to sincerely thank the course instructors for their insightful comments, academic support, and valuable guidance throughout the preparation of this work.

Ethics committee approval was not required for this study. The article complies with national and international research and publication ethics standards.

Author Contribution and Conflict of Interest Declaration Information

This section is a double-authored article, and the authors are solely responsible for its content and writing. There are no conflicts of interest.

References

Ascione, F., Bianco, N., De Masi, R. F., de' Rossi, F., & Vanoli, G. P. (2015). Energy refurbishment of existing buildings through the use of phase change materials: Energy savings and environmental impact. *Energy and Buildings*, 87, 142–156. https://doi.org/10.1016/j.enbuild.2014.11.087

Bullen, P. A., & Love, P. E. D. (2011). Adaptive reuse of heritage buildings. Structural Survey, 29(5), 411–421.

Dabija, D. C., Bejan, B. M., & Dinu, V. (2022). A research framework for circular economy in the built environment. *Amfiteatru Economic*, 24(59), 456–470.

Della Torre, S., Cattaneo, G., Lenzi, C., Zanelli, A., & Zanotto, V. (2021). Circular economy strategies for adaptive reuse of heritage buildings. *Sustainability*, 13(13), 4759.

Ellen MacArthur Foundation. (2020). *Completing the picture: How the circular economy tackles climate change*. https://ellenmacarthurfoundation.org/completing-the-picture

Foster, G. (2020). Circular economy strategies for adaptive reuse of cultural heritage buildings to reduce environmental impacts. Resources, *Conservation and Recycling*, 152, 104507. https://doi.org/10.1016/j.resconrec.2019.104507

Gravagnuolo, A., & Angrisano, M. (2022). Evaluating impacts of adaptive reuse of cultural heritage in circular economy perspective: Application to historical districts in Naples. TEMA: Journal of Land Use, *Mobility and Environment*, 15(1), 97–116.

Gravagnuolo, A., Angrisano, M., & Fusco Girard, L. (2019). Circular economy strategies in the heritage conservation sector: A baseline study. *Bollettino del Centro Calza Bini*, 18, 127–146.

Gravagnuolo, A., Saleh, R., Ost, C., & Fusco Girard, L. (2018). Towards an evaluation framework to assess cultural heritage adaptive reuse impacts in the perspective of the circular economy. *INU Edizioni*.

Ossio, F., Aranda Usón, A., & Scarpellini, S. (2023). Circular economy in the built environment: A review of strategies for implementation and assessment. *Journal of Environmental Management*, 325, 116370. https://doi.org/10.1016/j.jenvman.2022.116370

Pomponi, F., & Moncaster, A. (2017). Circular economy for the built environment: A research framework. *Journal of Cleaner Production*, 143, 710–718. https://doi.org/10.1016/j.jclepro.2016.12.055

Ranasinghe, U., & Illankoon, C. (2024). The adaptive reuse of buildings as a circular economy accelerator: A systematic review. *Proceedings of the International Conference on Industrial Engineering and Operations Management*, Sydney, Australia.

Rodrigues, L., & Freire, F. (2017). Integrated life-cycle assessment and energy simulation of buildings: A review. *Renewable and Sustainable Energy Reviews*, 67, 623–639. https://doi.org/10.1016/j.rser.2016.09.058

Saleh, R., Gravagnuolo, A., & Fusco Girard, L. (2021). Adaptive reuse of cultural heritage: Circular economy approach for sustainable future. In Adaptive Reuse of Cultural Heritage (pp. 82–101). *BAcTA Publishing.*

Ilayda Sevval ALIŞ
E-mail: ilaydaalis02@gmail.com
Educational Status: BArch. Candidate
License: Bursa Uludağ University, Faculty of Architecture, Department of Architecture, 2018-2023
Degree: Bursa Uludağ University, Graduate School of Natural and Applied Sciences, Department of Architecture, 2024-in progress

Prof. Dr. Arzu ÇAHANTİMUR
E-mail: arzucahan@uludag.edu.tr
Educational Status: Prof. Dr.
License: Istanbul Technical University, Faculty of Architecture, Department of Architecture, 1990-1994
Degree: Istanbul Technical University, Graduate School of Natural and Applied Sciences, Department of Architecture, 1994-1997
Doctorate: Istanbul Technical University, Graduate School of Natural and Applied Sciences, Department of Architecture, 1999-2007

BIM-Based Life Cycle Assessment: Tools and Integration Approaches

Ömer Oğuzhan TURHAN [1]
[1]Bursa Uludağ University, Faculty of Architecture, Department of Architecture, Nilüfer, Bursa/Türkiye.
ORCID: 0009-0001-5376-6873
E-mail: turhanone@gmail.com

Citation: Turhan, Ö. O. (2025). BIM-Based Life Cycle Assessment: Tools and Integration Approaches. In A. Çahantimur & R. B. Öztürk (Eds.) **Contemporary Approaches in Architecture: The Role of Architecture in the Circular Economy.** 2025, Chapter:4, 61-83. ISBN: 978-625-378-348-8. Iksad Publications.
DOI: https://doi.org/10.5281/zenodo.17309890

1. Introduction

The rapid depletion of our planet's natural resources and the irreversible environmental damage have increased the urgency of sustainability. In this context, developments in the Architecture and Building Design field have accelerated considerably and been integrated into the Life Cycle Assessment (LCA) system.

LCA is a comprehensive method that analyzes the impact of a building during its lifetime. The LCA approach, which started after the Second World War and has come a long way since then, has established a methodological framework, especially with ISO 14040 standards, and has found application in the construction sector (ISO, 2006; Bjørn et al., 2018).

In the early periods, it was limited to a specific area due to the long and complex nature of the LCA processes in the construction sector and the lack of legal legislation. However, with the widespread use of Building Information Modeling (BIM) technology, it has become possible to integrate many data in the design process and provide results. This development has paved the way for BIM-based LCA applications and facilitated the integration of environmental sustainability into design decisions (Soust-Verdaguer et al., 2017).

In this chapter, the historical development and types of LCA will be introduced, and BIM-LCA integration methods, tools used, and their working principles will be discussed. The aim is to reveal how to integrate LCA processes with digital tools in the architecture and construction sector.

2. Methodology and Materials

This study aims to evaluate the applications, databases, software, and integration types for using Building Information Modeling (BIM) with Life Cycle Assessment (LCA), which is essential for sustainable building production. In this study, a qualitative research approach was adopted, and a systematic literature review was used.

A systematic review of international and national academic publications on the topic of BIM–LCA integration was conducted. Sources such as Scopus, Google Scholar, Web of Science, DergiPark, and YÖK Thesis were used for the literature review. To observe academic developments over the years, a search was conducted in the Web of Science (WOS) database using the keywords '*life cycle assessment' OR 'LCA' AND 'building information modelling' OR 'BIM'* for the years 2014 to 2024. The increase during this period is shown in Figure 5. The results indicated that the topic is becoming increasingly important. In this context, recent and comprehensive studies such as Pan & Teng (2021), Wastiels & Decuypere (2019), and Potrč Obrecht et al. (2020) were referenced. Additionally, these studies conducted in Türkiye were reviewed to present the field's current state in the country.

Within the scope of the analysis, software frequently used in the sector, such as Tally, One Click LCA, and OpenLCA, was evaluated. The databases used by this software (e.g., Ecoinvent, GaBi) were analyzed comparatively regarding data accessibility and environmental impact calculation capacity. The evaluation considered aspects such as application integration models and regional data compatibility.

Five main types of integration between BIM and LCA software were analyzed. This analysis examined features such as data transfer formats (e.g., IFC compatibility), direct plug-in connections, and BIM-based data flow capacity. These types are classified based on the theoretical framework developed by Wastiels and Decuypere (2019) and Potrč Obrecht et al. (2020).

The software and databases analyzed are presented in a comparative table according to defined criteria. This table includes information about the scope of use, license type, origin, and ease of integration. This aims to help readers understand the differences between the available tools more easily.

3. Development of Life Cycle Assessment Concept in History

Rapid population growth, industrialization, and wars have significantly increased environmental problems and caused many environmental disasters, and carbon emissions, one of the most important indicators in this regard, have shown a significant increase. The increase in greenhouse gas emissions was a key driver behind developing the LCA methodology, which clearly shows the situation. According to the results of the greenhouse gas inventory of the Turkish Statistical Institute (2023) , the total greenhouse gas emission in 2023 was calculated as 552.2 million tons (Mt) of CO2 equivalent. (Figure 1) Total greenhouse gas emission per capita was 4.1 tons CO2 equivalent in 1990, 6.6 tons of CO2 equivalent in 2022, and 6.5 tons of CO2 equivalent in 2023, showing an almost 3-fold increase in carbon emissions in thirty years and a 2-fold increase in carbon emissions per capita. (Figure 2).

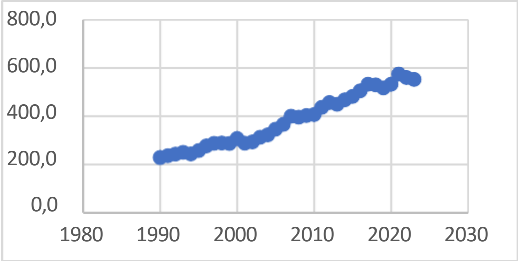

Figure 1. Total greenhouse gas emissions,

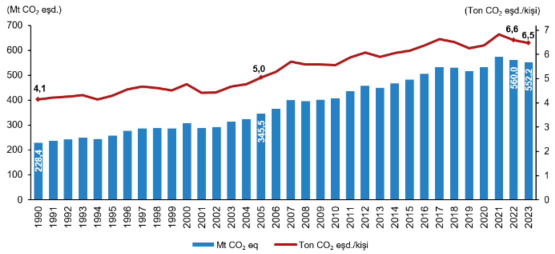

Figure 2. Total and per capita greenhouse gas emissions, 1990–2023 (TÜİK, 2023)

In this framework, the Life Cycle Assessment (LCA) concept emerged in the 1960s with high energy consumption and environmental concerns. Companies initially carried out their processes. Over time, it became more systematic, and ISO 14040 and ISO 14044 standards were established in the 1990s. (ISO, 2006a; ISO, 2006b) (Table 1).

Table 1. Historical Development of LCA (Köşürgeli, 2022; Bjørn et al., 2017)

Development Step	**Year**
Harold Smith publishes the first report focused on LCA.	1963
Coca-Cola commissioned its first study comparing beverage containers	1964
U.S. EPA publishes the first publicly available and peer-reviewed study of the RDD.	1974
In order to harmonize the LCA terminology and methodology The SETAC Code of Practice is published.	1993
GaBi, the first widely used commercial LCA software, was released in its first version	1989
With the first release of another standard commercial LCA software called SimaPro Published	1990

The International Journal of Life Cycle Assessment, the academic journal entirely dedicated to LCA, was born	1996
ISO 14040 was published on the framework and principles of the LCA method.	1997
ISO 14041, which defined the objective and scope of the LCA method, was published.	1998
ISO 14042 standard on life cycle impact assessment is published.	2000
ISO 14043 standard on life cycle interpretation is published.	2000
An ISO 14040-based LCA guideline was created.	2007
TSE has put TS EN ISO 14044 into effect.	2007
ILCD handbook published	2010
EN 15978:2011 Sustainability of Construction Works-Buildings Assessment of Environmental Performance - Calculation Method published	2011
EN 15804:2012 Sustainability in Construction - Environmental Product Declarations-Building Product Category Rules Published	2012
ISO 21930 Sustainability in Building and Construction - Construction Product and Services Environmental Product Declarations standard emerged.	2017
ISO 14071 Critical review processes and competence Published	2024
ISO 14072 Organizational LCA (OLCA) requirements Published	2024
In the Regulation on Zoning of Planned Areas: The phrase "building life cycle analysis to be applied in projects to be determined by the Ministry" has been added and it is recorded by the principles to be determined by the Ministry, by the relevant building information modeling (BIM) standards and digitally in the data infrastructure to be established electronically by the Ministry or the administrations to be authorized by the Ministry, electronically The condition that it is checked, approved, and stored in the environment has been introduced.	2025

3.1 Integration of Life Cycle Assessment into the Construction Sector

The basic backbone of the LCA method has been established within the framework of ISO 14040. The systematics of the established LCA consists of four steps that are feedforward/feedback and iterative (Figure 3) (ISO 14040, 2006a; ISO 14040, 2006b).

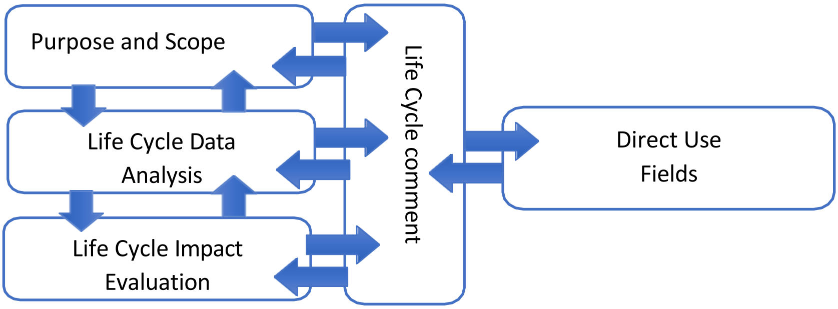

Figure 3. Life Cycle Environment (ISO 14040, 2006)

The life cycle processes of buildings are classified into five groups: production process (A1- A3), application process (A4-A5), use process (B1- B7), end-of-use process (C1- C4), and benefits and burdens beyond the system boundaries (D) (Figure 4) (ISO 21930, 2017; Silvestre et al., 2016).

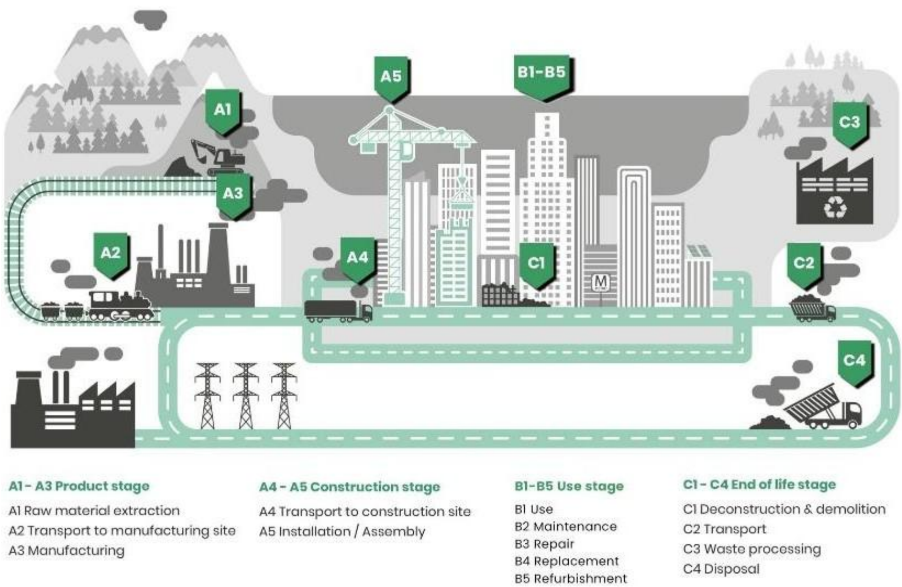

Figure 4. Integration of BIM-LCA in the construction sector (OneClick LCA, n.d.)

The life cycle of buildings is limited within the framework of specific standards with SO 21930, EN 15804, and EN 15978 (Koşurgeli, 2022). These limits can be expressed in 3 stages:

1. **Cradle-to-Gate:** Processes for extracting, transporting, and processing the raw material needed to produce a building.
2. **Cradle-to-Grave**: Processes that start with the extraction of the raw material needed for the production of buildings until the product consumes its life,
3. **Cradle to Cradle**: The process that starts with the extraction of the raw material needed for the production of a building, and then at the end of the useful life of the product, it is included in the reuse and/or recycling processes (Table 2) (Kosurgeli, 2022; Silvestre et al., 2016).

Table 2. Relationship between Process-Based LCA and System Boundaries

Cradle to cradle	**Cradle to grave**	**Cradle to gate**	Product Phase (A1-A3)	A1-raw material extraction and processing
				A2 - transportation to the manufacturer
				A3-production
			Implementation Phase (A4-A5)	A4-transport to the construction site
				A5-building assembly
			Use Phase - information modules on structural components of the building (B1-B5)	B1-use of the dried product or Implementation
				B2-care
				B3-repair
				B4-change
				B5-renovation
			Use Phase - information modules on the operation of the building (B6-B7)	B6-utility energy use
				B7-operating water use
			Post Use Phase (C1- C4)	C1-demolition, dismantling
				C2 - transportation to the waste treatment plant
				C3-recovery and/or recycling
				C4-destruction
			Benefits and Burdens Outside System Limits (D)	D - reuse, recovery, and/or recycling

In order to realize sustainability in buildings, it is necessary to evaluate (1) embodied energy, (2) the energy used and (3) the emissions arising from them. There are three basic methods for this. These are 'Process-Based LCA' (process-based LCA), 'economic input-output based LCA', and 'hybrid LCA'. In this way, LCA can measure the environmental impacts of the whole life cycle.

4. Building Information Modeling: Integration of Life Cycle Assessment

Today, design and production processes have become digitalized, and building information modeling (BIM) has become increasingly important. Although there are many different definitions for BIM, it is a digital project management system that provides a basis for creating, using, storing and sharing the data that may be needed in a common data environment in a digital environment by providing multidisciplinary work within the scope of the project throughout the life cycle of the building (Eastman et al., 2011).

LCA-BIM integration has gained importance with the development of BIM tools. LCA-BIM integration has significantly progressed, especially in the last decade (Table 3) (Safari & AzariJafari, 2021; Duru & Koç, 2021).

Table 3. Historical Development of LCA-BIM Integration (Safari & AzariJafari, 2021)

Year	Description
2012	Technical research on different BIM tools was initiated.
	The calculation process was usually carried out with commercial LCA software or Excel.
	Data flow was linear in BIM-LCA approaches.
2013	A framework for LCA integration with IFC-based BIM was proposed.
	Research focused more on the early stages of design.
2014	First plugin for the BIM tool developed.
2015	Research shifted to a more detailed design phase.
	The green pattern was developed using Revit's library parameterization method.
2016	The model's LOD (Level of Detail) level was a key point in BIM-LCA studies.
2017	IEA EBC Annex 72 project members started to develop guidelines.
	The studies focused more on the connection of parametric tools with BIM.
2018	A BIM-based semi-automated framework has been developed to find the optimal design.
2019	The first new approach to applying LCA was developed throughout the building design process.
	A new approach to mixing LCA databases based on different LOD levels was carried out.
2020	Intensive research on dynamic approaches was carried out.
	LCA was implemented with real-time monitoring throughout the design process.
	Dynamic LCA capabilities are integrated directly into BIM.

There is a growing body of publications on the Integration of Life Cycle Assessment. When the Web of Science (WOS) index is searched by selecting ("life cycle assessment" OR "LCA") AND ("building information modeling" OR "BIM") as keywords, it is seen that the number of publications has increased significantly when the last 10 years of data are examined. The number of publications increased from 6 in 2014 to 100 in 2024 (Figure 5).

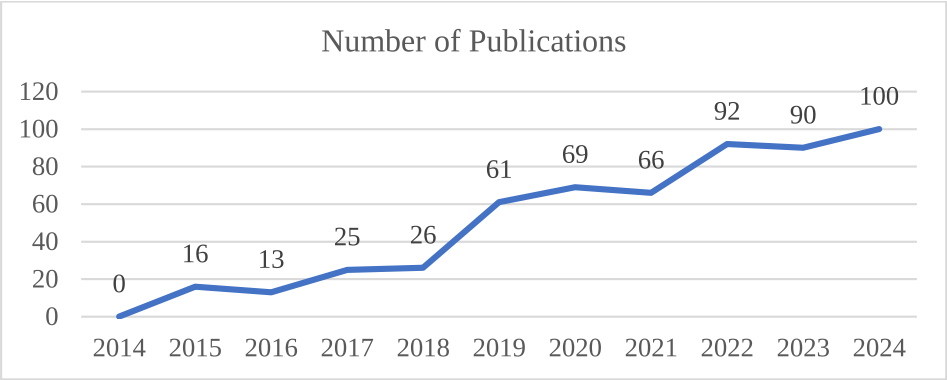

Figure 5. Number of publications (“life cycle assessment" OR "LCA") AND ("building information modeling"OR "BIM")

In this way, complex and lengthy LCA processes have become more standardized. Today, many LCA plugins have been developed for popular BIM tools such as Revit and Archicad. In an LCA study by ISO standards, the need to process a large amount of data and assumptions to create the product's life cycle has created many regional databases (Table 4) (Hollberg & Ruth, 2016).

Table 4. LCA database (Pan & Teng, 2021)

No	Software	Region	Fee Status	Phase	Year
1	AusLCI	Australia	E	Cradleto-gate	-
2	Base Carbone	France	E	Cradle to- grave	-
3	BEDEC	Spain	E	Cradleto-gate	-
4	CLCD	China	E	Cradleto-gate	2009
5	Ecoinvent	Switzerland	H	Cradleto-grave	1990
6	Eco-Profiles	Europe	E	Cradleto-gate	2015
7	EF databases	Europe	H	Cradleto-grave	-
8	ELCD	Europe	E	Cradle to- grave	2006
9	ETH-ESU 96	Switzerland	E	Cradleto-grave	1996
10	GaBi databases	Germany	H	Cradleto-gate	-
11	ICE	UK	E	Cradleto-grave	2005
12	IDEMAT	Netherlands	E	Cradleto-gate	2001
13	INIES	France	E	Cradleto-gate	2004
14	IVAM LCA data	Netherlands	H	Cradle to- grave	2004
15	Milieudatabase	Netherlands	E	Cradleto-gate	-
16	Oekobaudat.de	Germany	E	Cradle to- grave	-
17	U.S. LCI	US	E	Various	2012

In order to bridge the gap between the database and the LCA method, "LCA software tools" have been developed. Thanks to "LCA software tools", "LCA databases", and "LCA plug-ins", a multi-faceted analysis can be performed by reducing the effort and time spent on LCA study (Table 6) (Sevim Koşan & Beyhan, 2024).

"LCA software tools work according to the principle of three predefined application patterns. Level 1: level 1 (product level), level 2 (assembly level/building component group), level 3 (whole building level) (Sevim Koşan & Beyhan, 2024).

Table 5. LCA software tools (Sevim Koşan & Beyhan, 2024)

Software	Level	Origin
SimaPro	Level 1	Netherlands
Sphera (Formerly: GaBi)		Germany
Umberto		
OpenLCA		
EConLCA		Turkey
Envest	Level 2	England
BEES		USA
Athena		Canada
BREAM	Level 3	England
DGNB		Germany
LEED		USA
B.E.S.T		Turkey
Yes-TR		

4.1 Building Information Modeling: Types of Integration between Tools of Life Cycle Assessment

Wastiels & Decuypere, (2019). Integrating Building Information Modeling (BIM) and Life Cycle Assessment (LCA) can be realized through different technical infrastructure and scenarios (Obrecht et al., 2020). The integration approaches defined in the literature can be classified under five main headings according to data transfer methods, workflows, and software infrastructures used:

1. Type -Bill of Quantities (BOQ)-Based Integration: In this approach, data from the BIM model is exported and subsequently analyzed in standalone LCA software such as SimaPro, GaBi, or OpenLCA. According to researchers' observations, this remains the most prevalent scenario in practice. The BOQ is typically managed via Excel (XLS) or CSV files (Figure 6).

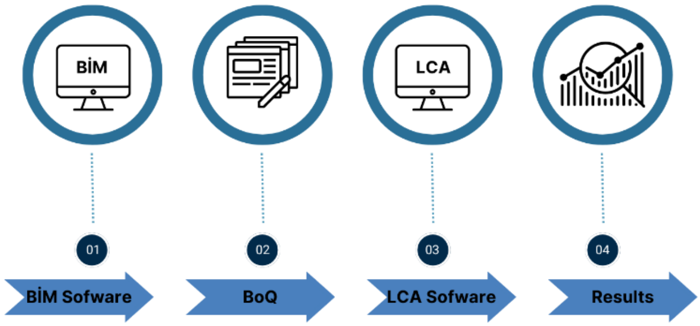

Figure 6. Export-Based Integration (Wastiels & Decuypere, 2019)

2. Type - IFC-Based Integration: In this method, data obtained from the BIM model is exported in IFC (Industry Foundation Classes) format. This open standard ensures data interoperability between software applications and is preferred in multi-disciplinary collaboration projects (Figure 7).

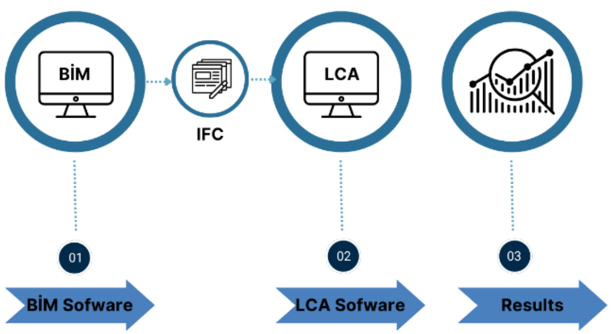

Figure 7. IFC-Based Integration (Wastiels & Decuypere, 2019)

3. Type -Intermediate BIM Layer Integration: This method involves initial data transfer from one BIM environment to another BIM software (e.g., ArchiCAD → Revit). The data is then processed in more detail and optimized for LCA analysis within this intermediate BIM software before being directed to specialized LCA tools. This approach offers advantages in terms of data detailing and model optimization (Figure 8).

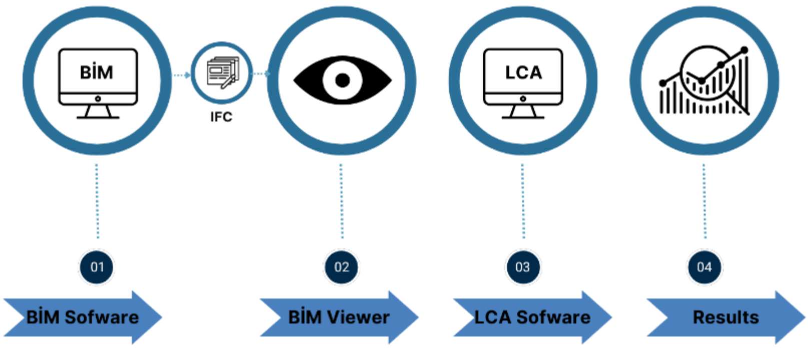

Figure 8. Integration with the Intermediate BIM Layer (Wastiels & Decuypere, 2019)

4. Type -Direct BIM Plugin Integration. This integration method utilizes LCA tools that operate directly within the BIM platform. For example, plugins like Tally or One Click LCA that integrate with Autodesk Revit enable the analysis of environmental impacts, such as carbon footprint, concurrently with the design process. This scenario offers a significant advantage to designers due to its real-time analysis capability (Figure 9).

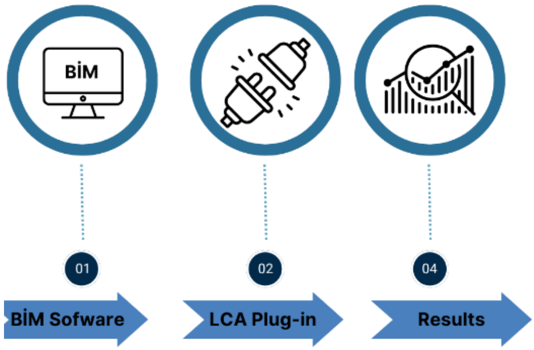

Figure 9. Direct BİM Plugin Usage (Wastiels & Decuypere, 2019)

5. Type Embedding LCA Data into BIM Objects: This approach directly associates environmental performance data (e.g., EPDs – Environmental Product Declarations) with BIM objects. This allows the environmental impacts of each building element to be defined at the model level (Figure 10).

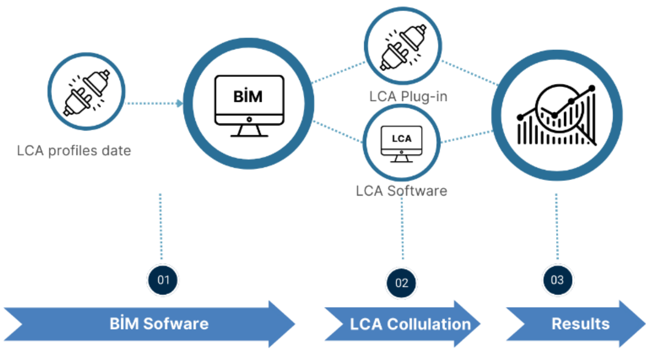

Figure 10. Embedding LCA Data into BIM Objects (Wastiels & Decuypere, 2019)

5. Conclusion and Recommendations

Within the scope of this study, a comprehensive evaluation of the integration of BIM-based Life Cycle Assessment applications has been conducted. The sources examined in the study show that BIM and LCA integration is an important sustainability tool for the construction sector and has high potential to significantly reduce environmental impact in the early stages of design processes.

As a result of the research and analysis conducted, it is believed that regionally used databases for LCA tools can be standardized and modified to be used worldwide, enabling more reliable processes and comparisons.

Among the LCA software examined, Tally, One Click LCA, and open LCA stand out, and these tools have potential for use at different levels of integration in architectural design processes. The impact and effective use of LCA software are influenced by factors such as data access, usage fees, and user interface. In this context, in countries such as Turkey, which lack databases, legal regulations and incentives to adopt these tools will facilitate the development of local databases, increase the reliability of results, and facilitate their use in the sector.

The increasing integration of LCA and BIM has significantly increased the number of studies on this subject in the academic world, and it is anticipated that further action in this area in architectural education will greatly contribute to the construction sector and this integration in the future.

Analyses specific to Türkiye show that BIM- LCA integration is still at an initial stage and has been addressed in a limited number of academic studies. According to the sources reviewed, data insufficiency, the absence of local standards, and low sectoral awareness are considered to be the main obstacles to BIM-LCA integration in Türkiye.

In conclusion, BIM-based LCA applications are becoming increasingly widespread worldwide. It is crucial for Türkiye to develop policies that support this integration in the sector. The initial stages to develop the needed policies can be proposed as follows:

- Local LCA databases should be created through collaboration between academia, the sector, and the public sector;
- Software training and infrastructure support should be increased;
- The use of LCA software should be encouraged in the initial stages of projects.
- The necessary regulatory framework must be established to standardize BIM–LCA integration in Turkey.
- Courses on BIM–LCA should be added to the curricula of relevant university faculties to lay the groundwork for sustainability-focused design.

Such collaboration will contribute significantly to making environmental assessments a standard practice in sustainable building design processes.

Acknowledgements and Information Note

In this section was developed within the scope of a graduate-level course at Bursa Uludağ University, Faculty of Architecture. The author wishes to sincerely thank the course instructors for their insightful comments, academic support, and valuable guidance throughout the preparation of this work.

Ethics committee approval was not required for this study. The article complies with national and international research and publication ethics standards.

Author Contribution and Conflict of Interest Declaration Information

In this section is a single-authored article, and the author is solely responsible for its content and writing. There are no conflicts of interest.

References

Bjørn, A., Laurent, A., Owsianiak, M., & Olsen, S. I. (2018). Goal definition. In M. Z. Hauschild, R. K. Rosenbaum, & S. I. Olsen (Eds.), Life cycle assessment: Theory and practice. *Springer*. https://doi.org/10.1007/978-3-319-56475-3_7

Duru, M. O., & Koç, İ. (2021). *Integration of life cycle assessment (LCA) calculations with building information modeling (BIM) in sustainable building production [Sürdürülebilir yapı üretiminde yaşam döngüsü değerlendirme (LCA) hesaplamalarının yapı bilgi modellemesi (BIM) ile entegrasyonuna yönelik bir araştırma]* (in Turkish). STAR - Journal of Art and Design Research, 2(3), 107–121. https://www.researchgate.net/publication/357407082

Eastman, C. M., Teicholz, P., Sacks, R., & Liston, K. (2011). BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors (2nd ed.). *Hoboken, NJ: John Wiley & Sons.*

Hollberg, A., & Ruth, J. (2016). LCA in architectural design—A parametric approach. *The International Journal of Life Cycle Assessment*, 21(9), 1349–1361https://doi.org/10.1007/s11367-016-1065-1

International Organization for Standardization. (2006a*). Environmental management – Life cycle assessment – Principles and framework* (ISO 14040:2006). ISO.

International Organization for Standardization. (2006b). *Environmental management – Life cycle assessment – Requirements and guidelines* (ISO 14044:2006). ISO.

International Organization for Standardization. (2017). *Sustainability in buildings and civil engineering works – Core rules for environmental product declarations of construction products and services* (ISO 21930:2017). https://www.iso.org/standard/61694.html

Koşurgeli, E. (2022). *Yaşam döngüsü değerlendirmesi bağlamında ürün seçiminde dijital tasarım araçlarının irdelenmesi [Examination of digital design tools in product selection in the context of life cycle assessment]* (Unpublished master's thesis). Yıldız Technical

University, İstanbul, Turkey.

Obrecht, T., Röck, M., Hoxha, E., & Passer, A. (2020). BIM and LCA Integration: A Systematic Literature Review. *Sustainability*. https://doi.org/10.3390/su12145534

One Click LCA. (n.d.). *One Click LCA Help Center*. Retrieved June 12, 2025, from https://oneclicklca.zendesk.com

Pan, W., & Teng, Y. (2021). A systematic investigation into the methodological variables of embodied carbon assessment of buildings. *Renewable and Sustainable Energy Reviews*, 141, 110840. https://doi.org/10.1016/j.rser.2021.110840

Safari, K., & AzariJafari, H. (2021). Challenges and opportunities for integrating BIM and LCA: Methodological choices and framework development. *Sustainable Cities and Society*, 67, 102728. https://doi.org/10.1016/j.scs.2021.102728

Sevim Koşan, N., & Beyhan, F., (2024). A Research on Determination of Database and Software Tool in Life Cycle Assessment (LCA) Method: The Sample of Turkish Building Industry . *7 th International Conference of Contemporary Affairs in Architecture and Urbanism* (ICCAUA-2024) (pp.346-354). Antalya, Turkey

Silvestre, J. D., Pargana, N., de Brito, J., Pinheiro, M. D., & Durão, V. (2016). Insulation cork boards—Environmental life cycle assessment of an organic construction material. *Sustainability*, 8(5), 517. https://doi.org/10.3390/ma9050394

Soust-Verdaguer B, Llatas C, García-Martínez A(2017) Critical review of BIM-based LCA method to buildings. *Energy and Buildings* 136:110–120. https://doi.org/10.1016/j.enbuild.2016.12.009.

Turkish Statistical Institute (TÜİK). (2024, June 6). *Greenhouse gas emission statistics,* 1990–2023. Retrieved from https://data.tuik.gov.tr/Bulten/Index?p=Sera-Gazi-Emisyon-Istatistikleri-1990-2023-53974

Wastiels, L., & Decuypere, R. (2019, August). Identification and comparison of LCA-BIM integration strategies. *In IOP Conference Series: Earth and Environmental Science*, 323(1), 012101. https://doi.org/10.1088/1755-1315/323/1/012101

Ömer Oğuzhan TURHAN
E-mail: turhanone@gmail.com
Educational Status: M.Sc. Candidate
License: Bursa Uludağ University, Faculty of Architecture, Department of Architecture 2017 -2021
Degree: Bursa Uludağ University, Graduate School of Natural and Applied Sciences, Department of Architecture, 2024–Present
Professional Experiences: Manager, Strategic Planning Department, Bursa Uludağ University, 2018–Present.
Member, Sustainability Coordination Office, Bursa Uludağ University, 2023–2025.

Life Cycle Assessment in Architecture: A Bibliographic Mapping and Methodological Trends

Ph.D. Student, Hande AKAR [1]

[1]Bursa Uludag University, Doctoral Program in Architecture, Graduate School of Natural and Applied Sciences, Nilüfer, Bursa/Türkiye.
ORCID: 0000-0001-5905-7720
E-mail: 512412001@ogr.uludag.edu.tr

Citation: Akar, H. (2025). Life Cycle Assessment in Architecture: A Bibliographic Mapping and Methodological Trends. Öztürk, R. B. & Çahantimur, A. (Eds.). **Contemporary Approaches in Architecture: The Role of Architecture in the Circular Economy.** 2025, Chapter:5, 84-112. ISBN: 978-625-378-348-8. Iksad Publications. DOI: https://doi.org/10.5281/zenodo.17309867

1. Introduction

Climate change, rapid depletion of natural resources, and environmental degradation are among the most pressing global issues of our time. Although the built environment sector is at the heart of the transformation toward the 2050 carbon-neutral targets, the construction industry still consumes 32% of global energy and is responsible for 34% of global CO_2 emissions (UNEP & GlobalABC, 2025). Considering the significant environmental impact of the construction sector, architectural practices need to integrate the principles of circular economy and sustainable development. This imperative stems from the projected reduction in CO2 emissions from construction materials on a global scale, estimated to reach up to 38% by the year 2050 (Ellen MacArthur Foundation, 2022). A fundamental scientific tool that enables the systematic evaluation of the environmental impacts of building materials at every stage of their life cycles is life cycle assessment or LCA (European Committee for Standardization, 2011). Life Cycle Assessment (LCA), when employed in conjunction with circular economy strategies, has been demonstrated to reduce waste production and enhance resource efficiency (Benachio et al., 2020). Life Cycle Assessment (LCA) is a comprehensive approach to environmental impact assessment that encompasses a wide range of issues, including ozone depletion, water use, acidification, eutrophication, and carbon emissions (Hauschild, 2019).

Recently, interest in environmental performance assessment tools has increased significantly in the construction sector, particularly following the European Union's adoption of the 2050 carbon neutrality target (European Commission, 2019). The strategic roadmap identifies a series of targets aimed at reducing carbon emissions throughout the building lifecycle and achieving net-zero emissions in all new buildings by 2050 (Toth et al., 2022). Achieving the target of zero operational carbon in new buildings is linked to the climate goals of the European Green Deal.

In collaboration with ARUP and Ellen MacArthur Foundation, developed the Circular Buildings Toolkit – CBT - to help the construction sector align with the EU's carbon neutrality goals (ARUP, 2023). Designed as a practical guide, the CBT integrates circular economy principles throughout the building life cycle and closely aligns with the EU's Level(s) framework for sustainable buildings (Atta, 2023). Notably, the European Commission's four key circularity indicators—material inventories and lifespans, construction and demolition waste, design for adaptability, and design for deconstruction (EC, 2021 are directly reflected in the core strategies of the CBT. This demonstrates the toolkit's role as a bridge between EU policy and implementation on the ground.

As operational energy use in buildings continues to decline due to advances in energy-efficient technologies, material-related (embodied) impacts have become increasingly significant across the building life cycle (Buyle et al., 2013; LETI, 2020; Sturgis et al., 2023). This shift underscores the need for a holistic approach that considers all life cycle stages—particularly material production, construction, and end-of-life scenarios—as key sources of environmental impact. Research suggests that rethinking material processes could eliminate nearly half of a building's carbon footprint (Figure 1) (Nugent et al., 2022). In this context, circular economy strategies such as reuse, recycling, and long-lasting design practices such as repair, remanufacture, modularity offer promising solutions (Geissdoerfer et al., 2017; Ellen MacArthur Foundation, 2019; Adams et al., 2017).

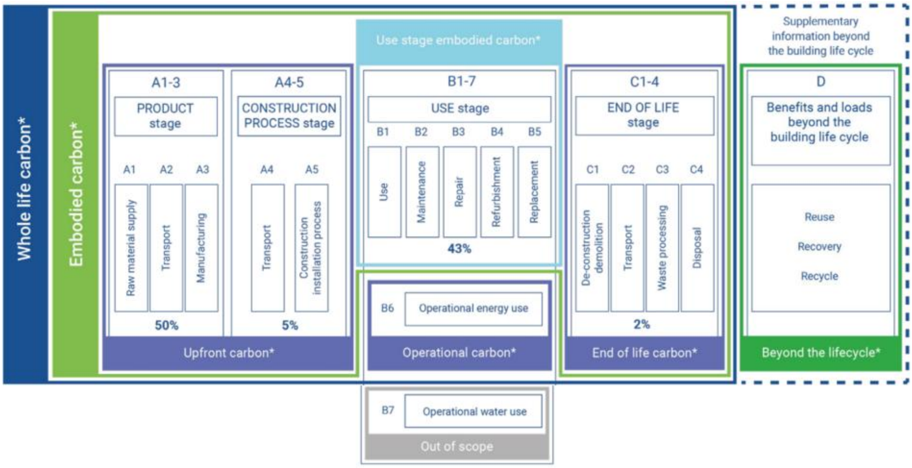

Figure 1. Estimated life cycle emission distribution for residential buildings based on EN 15978 and IStructE data (Nugent et al., 2022)

Life Cycle Assessment (LCA) provides a scientific basis for evaluating the performance of materials throughout their lifecycle, enabling them to obtain resolution of environmental impacts early in the design process (Ortiz et al., 2009; Hollberg and Ruth, 2016). Incorporating digital interfaces, such as BIM-based LCA, further expands this process by embedding sustainability in architectural practice (Esteve et al., 2022). The conceptual and policy framework delineated thus far illustrates the essential function of LCA in architecture. The existing literature is dense and varied, which means that we need to make a complete map of the field and look at its trends in a systematic way. This chapter of the book meets this need by giving not only the theoretical background but also, through a bibliometric approach, a unique look at the scope, trends, and interdisciplinary links of LCA research in architecture.

This book chapter examines approved publications on LCA in architecture using bibliometric procedures based on the Web of Science database. The aim of the study is to analyze the relevant components, chapters, applied methods, and thematic scope of existing research. The chapter seeks to answer the following questions:

– Which disciplines are most active in LCA-related research, and how is architecture positioned among them?

– What countries, institutions, highly cited studies, and research themes are most prominent in this field?

– Over the past 2.5 years, which topics have LCA in building studies focused on?

Overall, the chapter provides a comprehensive overview of current research trends and identifies potential future directions for LCA in architecture, positioning it as a vital tool for advancing sustainability and circular economy goals in the built environment.

2. Material and Method

This study adopts a systematic approach to literature selection, applying a series of filters to narrow down publications related to LCA and examine its disciplinary positioning—particularly within architecture. As shown in Figure 2, the process includes four search stages and two filtering steps, each with specific strategies and exclusion criteria. The bibliometric analysis was conducted in three phases:

1. A general quantitative analysis of LCA-related literature,
2. A quantitative analysis of current literature on building LCA
3. Mapping LCA's position within architecture-related disciplines using VOSviewer,

Although Google Scholar provides broad access, the Web of Science (WoS) database was selected for its advanced filtering capabilities and reliable subject classifications (Gusenbauer, 2019). WoS was preferred over Scopus due to its citation-based journal classification system, which is more accurate and consistent (Wang & Waltman, 2015).

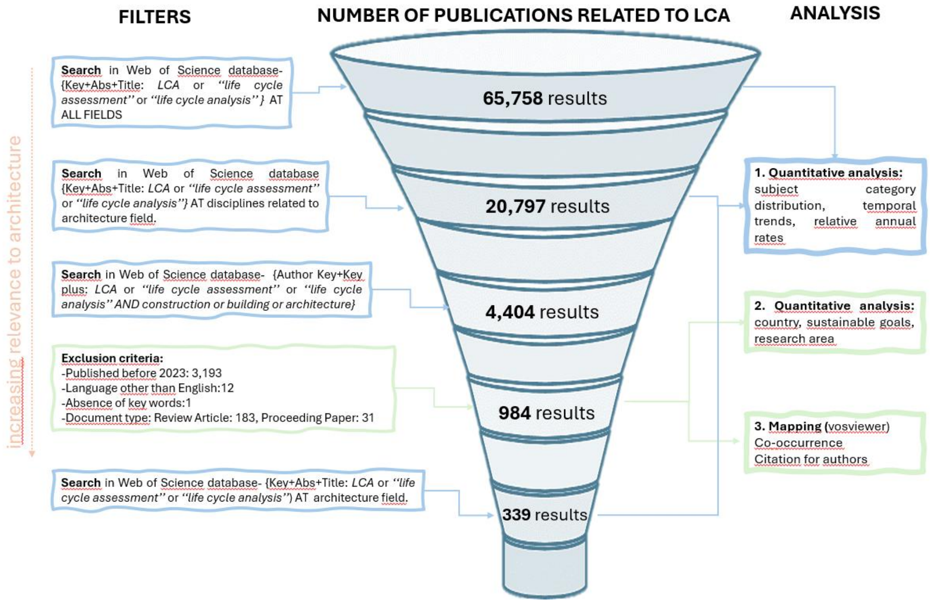

Figure 2. Flow diagram of the literature screening and selection process (Created by the author)

This study employed a three-phase approach to collecting and analyzing bibliometric data. In the first phase, a general overview of LCA-related publications across all subject areas was obtained by scanning all available records that included the term life cycle assessment in their topic fields (n = 65,758). This initial dataset was used to explore the broader disciplinary distribution of LCA-related research. Then, the dataset was refined by identifying the top five research areas most frequently associated with architecture in LCA-related records, narrowing the scope to 20,797 publications. In the final step of this phase, the search was further restricted to publications explicitly categorized under the field of architecture (n = 339). These three sets were analyzed using quantitative methods to compare subject category distributions, temporal publication trends, and relative annual growth rates.

In the second phase, the search strategy was expanded by adding the terms construction, building, or architecture alongside life cycle assessment to retrieve records from all disciplines without applying a specific research area filter. The goal here was to capture all relevant sources related to LCA in the context of buildings and construction, resulting in 4,404 records. To focus on recent research trends, the dataset was filtered to include only publications from 2023 to mid-2025, based on the rationale that the most concrete regulatory steps towards mandatory LCA implementation—such as the 2022 draft of the Construction Products Regulation (CPR) and the wider adoption of the Level(s) Framework after 2020—took place in this period (Nugent et al., 2022; Toth et al., 2022). Publications dated 2022 and earlier (n = 3,193) were excluded for this reason.

After removing non-English publications (n = 12), documents with missing keywords (n = 1), and non-article document types (n = 214), the resulting cleaned dataset of 984 records was analyzed using VOSviewer to ensure the consistency and accuracy of bibliometric data in the third phase. VOSviewer is a widely used and freely accessible software tool that allows for the graphical visualization of bibliometric maps, based on co-occurrence matrices and similarity measures (Van Eck & Waltman, 2010). In the co-occurrence analysis, the Association Strength normalization method was selected, as it balances differences in frequency and improves the thematic clustering of terms.

3. Findings and Discussion

Three main sections comprise the presentation of the results gathered for this book chapter. The quantitative data about the general LCA literature is assessed in the first section, which also presents statistical findings like publication volume, subject distribution, and temporal trends. The second section, focuses specifically on the field of architecture-related disicplines, shows Geographical distribution, representational strength, and SDG priorities in building-scale LCA research. Based on co-occurrence and clustering analyses, the third and final section offers bibliographic maps that show the relational structures found in the literature.

3.1. Quantitative Insights Into LCA Literature

A search using the keywords LCA, “life cycle assessment”, or “life cycle analysis” yielded 65,758 results across 206 Web of Science (WoS) subject categories and 148 research areas. These results were quantitatively analyzed along three dimensions: subject category distribution, temporal trends, and relative annual growth rates. In the next step, additional search terms—building, construction, or architecture—were included to further refine the dataset, and the resulting publications were also subjected to subject category distribution analysis. Furthermore, the analysis includes the relational distribution of the publications in connection with sustainability goals and an examination of the countries to which the publications are affiliated.

3.1.1. Subject category distribution

LCA research is primarily concentrated in disciplines such as environmental sciences, engineering, materials science, energy, agriculture, and chemical engineering (Table 1). The most frequent Web of Science categories include “Environmental Sciences” (35%), “Green & Sustainable Science & Technology” (24%), and “Engineering Environmental” (24%). In contrast, architecture remains notably underrepresented, with only 339 publications (0.5% of the total dataset) directly classified under the “Architecture” category. Similarly, architecture-related fields such as “Regional & Urban Planning” (0.4%) and “Urban Studies” (0.3%) also show limited engagement with LCA.

However, broader domains relevant to the built environment—such as “Construction & Building Technology” (6%), “Civil Engineering” (7%), and “Green & Sustainable Science & Technology” (24%) —demonstrate significantly higher LCA publication volumes. These findings suggest that while architecture has yet to establish a strong presence in LCA research, closely related fields offer considerable interdisciplinary potential for advancing sustainability in the built environment.

Table 1. Top 10 Web of Science Categories for LCA Publications

WoS Category-LCA	Publication Volume-First Phase		WoS Category-Building LCA	Publication Volume-Second Phase	
	Total Pubs.	%		Total Pubs.	%
1.Environmental Sciences	23.297	%35	1.Construction Building Technology	389	%40
2.Green Sustainable Science Technology	15.705	%24	2. Engineering Civil	379	%39
3.Engineering Environmental	15.665	%24	3. Environmental Sciences	305	%31
4.Energy Fuels	10.843	%16	4. Green Sustainable Science Technology	269	%27
5.Environmental Studies	5.296	%8	5. Engineering Environmental	194	%20
6.Engineering Chemical	4.694	%7	6. Environmental Studies	154	%16
7.Engineering Civil	4.354	%7	7. Energy Fuels	143	%15
8.Construction Building Technology	4.020	%6	8. Materials Science Multidisciplinary	72	%7
9.Materials Science Multidisciplinary	3.233	%5	9. Engineering Multidisciplinary	29	%3
10.Chemistry Multidisciplinary	2.285	%3	10. Physics Applied	25	%3
52.Architecture	**339**	**%0,5**			

An analysis of building-scale LCA studies reveals a disciplinary shift compared to the broader LCA literature. While “Environmental Sciences” and “Green & Sustainable Science & Technology” remain significant, “Construction & Building Technology” (40%) and “Civil Engineering” (39%) become the leading categories, indicating a stronger alignment with applied building and engineering domains. Additionally, fields such as “Applied Physics” and “Engineering Multidisciplinary” gain visibility, while categories like “Chemical Engineering” and “Chemistry” drop out of the top ten. However, this does not suggest a reduced focus on material- or energy-related approaches, as such themes are widely addressed under other classifications including “Materials Science” and “Energy & Fuels.” These findings reflect how the thematic and disciplinary emphasis of LCA research varies depending on the scale of analysis.

3.1.2. LCA publication trends and growth rates.

Between 1998 and 2024, there has been a substantial and steady increase in LCA-related publications, rising from 1,479 to 62,366—an approximately 42-fold growth—demonstrating LCA’s expanding interdisciplinary relevance. Similarly, architecture and related disciplines have shown notable growth, with the number of publications increasing from 33 in 1998 to 19,678 in 2024. Although the architecture category remains a smaller subset, it has exhibited significant percentage growth, particularly in recent years (Figure 3).

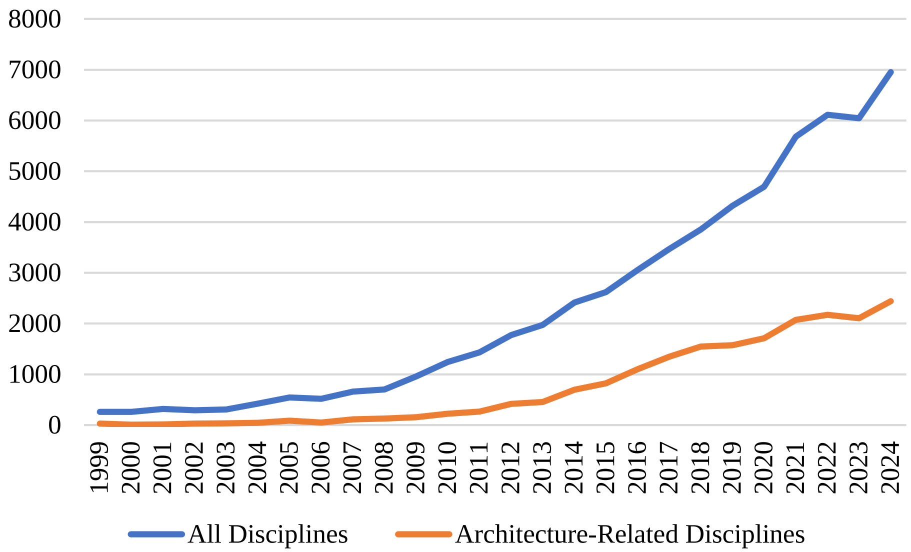

Figure 3. Annual Numbers of LCA Publications: Comparison between All Disciplines and Architecture Related Fields (1998–2024) (Created by the author)

Publications specifically classified under "Architecture" rose from 3 to 335 during the same period. Despite low absolute numbers, percentage-based growth has been pronounced, with notable surges in 2013 and 2019. Annual growth rates across all disciplines range between 12% and 18%, whereas architecture-related fields show more variability, typically between 14% and 35%. Within architecture alone, annual increases can reach up to 60–70% in certain years, indicating a growing and accelerating interest in LCA within the field (Figure 4).

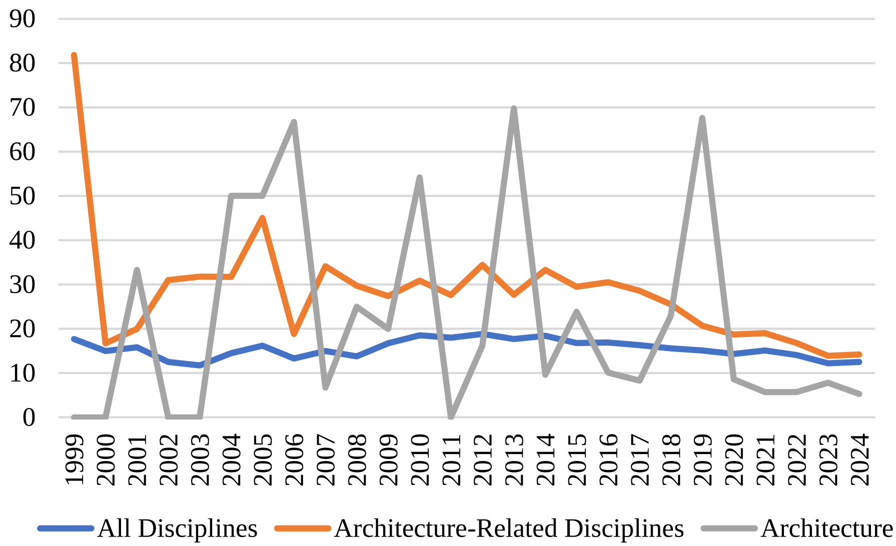

Figure 4. Annual rates of LCA Publications: Comparison between All Disciplines and Architecture Related Fields and Architecture (1998–2024) (Created by the author)

3.2. Geographical Distribution, Representational Strength and SDG Priorities in Building-Scale LCA Research

The country-level distribution of publications reveals that global research output is heavily concentrated in specific geographic regions (Figure 5). China leads by a significant margin, contributing 22.1% of the total publications, followed by Italy (9.1%), Australia (8.7%), the United States (8.5%), and the United Kingdom (7.6%). These figures highlight the dominance of China and the United States in sustainability- and LCA-focused research, underscoring the influence of national policies and institutional investments in these countries. Although individual European countries contribute smaller shares, Italy, the UK, Spain, Germany, and Scandinavian nations collectively form a major academic hub. Turkey's contribution of 2.8% indicates a developing research profile. In contrast, the contribution from countries in the Global South and other developing regions remains notably limited. This uneven distribution points to a lack of inclusive international research collaborations, particularly in underrepresented areas.

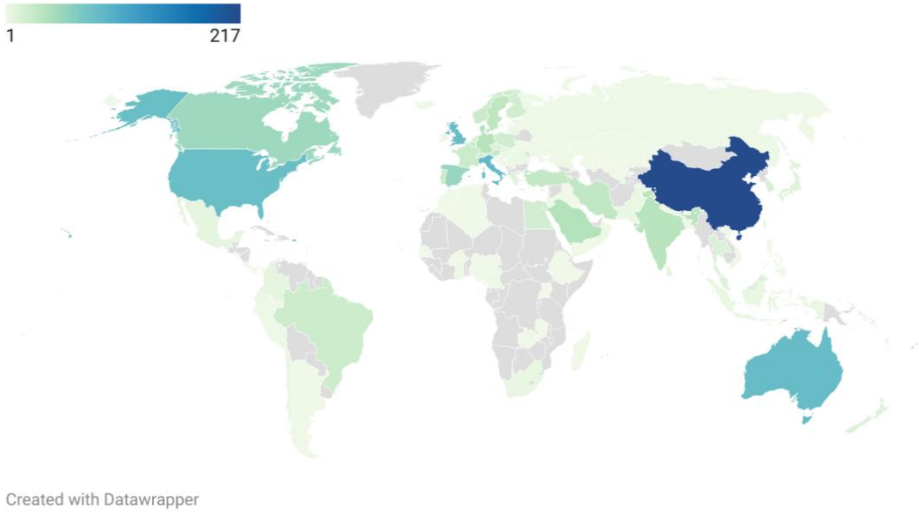

Figure 5. Country-Level Distribution of LCA Publications (Created by the author)

Recent building-scale LCA studies show growing alignment with the UN Sustainable Development Goals (SDGs), particularly SDG 11 (Sustainable

Cities and Communities), which appears in 69.4% of the publications. Other highly associated goals include SDG 7 (Affordable and Clean Energy, 70.9%), SDG 12 (Responsible Consumption and Production, 70.0%), and SDG 13 (Climate Action, 69.5%). These figures highlight a strong emphasis on the pressing need to reduce carbon emissions, use natural resources more responsibly, and improve energy performance in the built environment. While these priorities have long shaped Life Cycle Assessment (LCA) research at the building scale, more recent studies have also begun to reflect a broader understanding of sustainability. In particular, connections to Sustainable Development Goals (SDGs) 6 (Clean Water and Sanitation), 14 (Life Below Water), and 15 (Life on Land) point to a rising interest in evaluating the impacts of buildings on water systems and biodiversity.

3.3. Bibliographic Mapping of the LCA Literature: Keywords, Clusters, and Citations

In this section, a bibliometric analysis is presented that aims to identify current topics of life cycle assessment research in the fields of architecture and construction. The literature map of international publications listed in the Web of Science database was constructed by VOSviewer software. Keyword co-occurrence and citation networks were analyzed to investigate the main concepts, research clusters, and most productive authors of recent times.

The keyword co-occurrence analysis revealed nine different but thematically related clusters. These clusters were classified into the following thematic areas: (i) Low-carbon design & carbon accounting, (ii) Circular economy & sustainable building stock management, (iii) Energy optimization & multi-criteria decision making, (iv) Sustainability assessment tools & metrics, (v) Emission estimation & uncertainty analysis, (vi) Modular & recycled construction Technologies, (vii) Social LCA & adaptive reuse, (iix) Core concepts & general sustainability terminology, (ix) Concrete reuse & life cycle analysis (Figure 6). These clusters demonstrate that LCA research at the building scale is not limited to environmental performance evaluation but is expanding to include diverse methodological directions such as circular economy, energy modeling, social sustainability, and uncertainty analysis. The identified thematic structure provides a systematic understanding of the current trends and topical diversity within the building LCA literature.

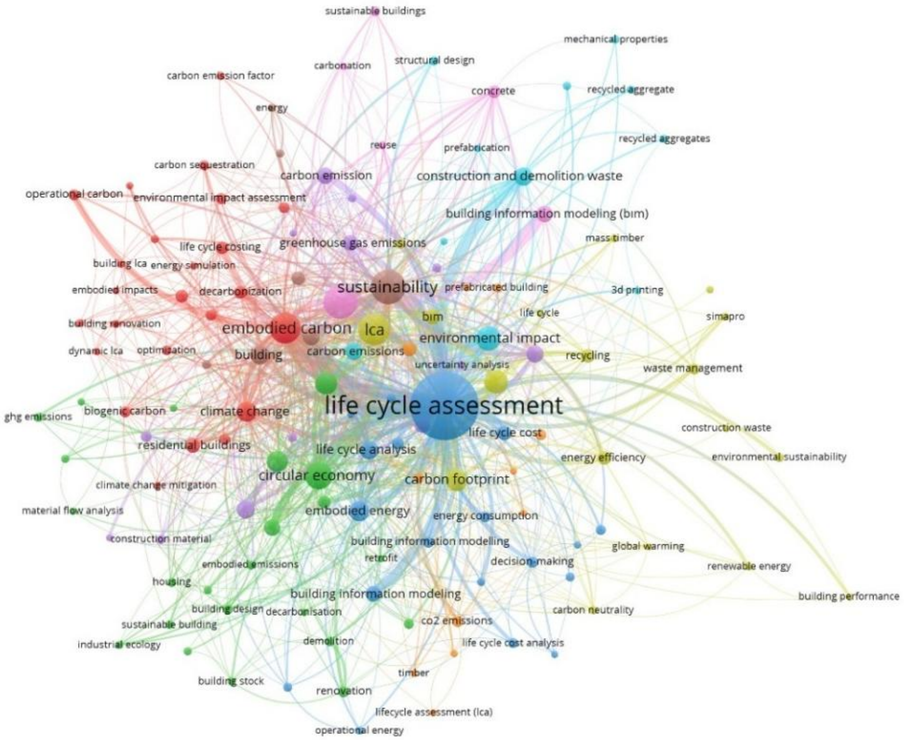

Figure 6. Network visualization (Created by the author using VOSviewer)

Recent developments in building-scale Life Cycle Assessment (LCA) research reveal a rapid diversification and deepening of the field in line with evolving sustainability agendas. Emerging trends can be observed through research topics concentrated within distinct thematic clusters.

Cluster 1: Low-carbon Design & Carbon Accounting

This cluster includes keywords such as biogenic carbon, embodied carbon, carbon sequestration, timber construction, dynamic LCA, operational carbon, thermal insulation, and residential buildings. It reflects a strong focus on carbon mitigation strategies, distinguishing between embodied and operational carbon, with an emphasis on material selection and energy simulation in residential buildings.

Cluster 2: Circular Economy & Sustainable Building Stock Management

This cluster is shaped by terms such as circular economy, building stock, renovation, CDW (construction and demolition waste), geopolymer, urban planning, and material flow analysis. Research here focuses on large-scale building stock transformation, material circularity, and urban-scale planning processes, including end-of-life scenarios.

Cluster 3: Energy Optimization & Multi-Criteria Decision Making

Containing keywords such as decision-making, multi-objective optimization, thermal comfort, energy consumption, building envelope, BIM, and prefabricated construction, this cluster highlights research aimed at enhancing energy efficiency through simulation and supporting the design process with multi-criteria analysis tools.

Cluster 4: Sustainability Assessment Tools & Metrics

This cluster includes carbon footprint, green building, mass timber, LCA, renewable energy, Simapro, and waste management. It reflects a methodological orientation centered on standardized assessment tools, carbon footprint measurement, software applications, and the overall performance of sustainable buildings.

Cluster 5: Emission Estimation & Uncertainty Analysis

With terms like carbon emission, machine learning, uncertainty, Monte Carlo, LCC (life cycle costing), and cement, this cluster focuses on emission quantification through simulation-based approaches and uncertainty analysis, particularly with applications of machine learning and probabilistic modeling.

Cluster 6: Modular & Recycled Construction Technologies

Keywords such as modular construction, recycled aggregate concrete, 3D printing, and mechanical properties define this cluster, which emphasizes emerging material technologies, prefabrication, and the reuse of construction materials in innovative production systems.

Cluster 7: Social LCA & Adaptive Reuse

This cluster includes adaptive reuse, office building, social LCA, material selection, and timber, focusing on socially-oriented LCA approaches, the reuse of existing buildings, and specific material applications such as timber in adaptive reuse scenarios.

Cluster 8: Core Concepts & General Sustainability Terms

This cluster features high-frequency terms such as building, energy, environment, sustainability, and GWP (global warming potential). It represents the foundational vocabulary of the field and functions as the conceptual backbone that connects the other clusters.

Cluster 9: Concrete Reuse & Lifecycle Evaluation

A more narrowly focused cluster, defined by terms such as carbonation, reuse, concrete, and sustainable buildings. It highlights micro-level research on lifecycle performance and reuse strategies for concrete-based construction.

Although the clusters can be distinguished thematically, their boundaries are fluid and often overlap. Low-carbon design strategies (Cluster 1), for instance, are closely connected to circular economy approaches (Cluster 2), since reusing materials also serves as a means of reducing carbon emissions. In a similar way, optimization and decision-making methods (Cluster 3) build on standardized assessment tools (Cluster 4) and help address uncertainties in emission estimations (Cluster 5). The social dimension (Cluster 7) adds ethical and community perspectives to what might otherwise remain technical evaluations, highlighting the interdisciplinary nature of LCA research. Emerging technologies (Clusters 6 and 9) serve as a conduit between material science, engineering, and architectural design. Overall, the clusters show that LCA research is becoming more diverse and has more potential to cross fields, including architecture, engineering, urban planning, computer science, and the social sciences.

To visualize author collaboration and influence networks, a citation analysis was performed using VOSviewer (Figure 7). The resulting map reveals distinct clusters based on citation relationships. Harpa Birgisdottir, Endrit Hoxha, and Christian Grau Sørensen emerge as central figures, reflecting a shared focus on sustainable architecture and life cycle assessment. Another cluster, led by Freia Nygaard Rasmussen and Guomin

Zhang, emphasizes environmentally oriented research with high internal consistency, suggesting domain-specific specialization.

The network also shows a directional flow from foundational works to more recent or topic-specific studies. José Dinis Silvestre acts as a bridging figure, linking disparate clusters and promoting interdisciplinary exchange. A central red cluster, composed of highly cited authors, influences multiple areas and anchors the network. In contrast, blue cluster authors are more inwardly connected, reflecting thematic cohesion but limited external ties. Yellow and purple clusters show minimal inter-cluster connectivity, with occasional single-link bridges indicating emerging collaboration.

These findings underscore both the central contributors shaping the field's theoretical and methodological core, and the growing diversification within architectural LCA research.

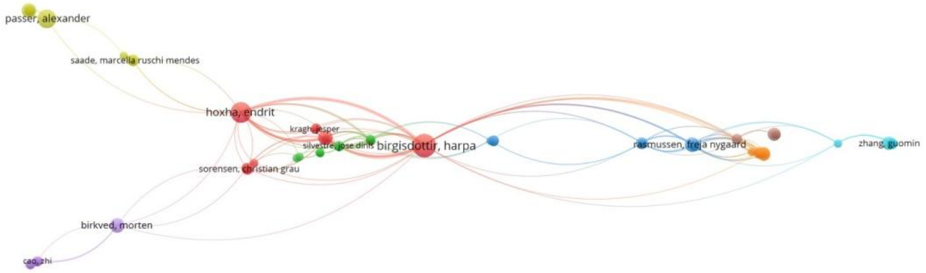

Figure 7. Citations for authors (Created by the author using VOSviewer)

4. Conclusion and Suggestions

The findings reveal that LCA research is largely shaped within the axis of engineering and environmental sciences. However, the discipline of architecture—which is one of the earliest fields where the environmental impacts of the built environment can be identified —occupies a very limited place within this literature. The fact that publications categorized under architecture constitute only 0.5% of the total publications suggests either a methodological adaptation deficiency in this field or that the discipline has not been holistically integrated into LCA. The findings indicate that LCA literature at the building scale is predominantly shaped by application-oriented engineering fields and environmental sustainability. In particular, the publication density in building technologies and civil engineering fields reveals that these studies mostly rely on concrete building projects and focus on performance-oriented outcomes. At the same time, the high proportions in environmental sciences and sustainability categories reflect academic interest in the systematic evaluation of buildings' environmental impacts.

Similarly, a low representation is observed in related fields such as "Regional Urban Planning" (0.4%) and "Urban Studies" (0.3%). This situation may indicate that environmental assessment studies at the urban scale are primarily taken up by other disciplines (such as environmental engineering, energy policy). However, somewhat higher proportions are seen in categories that could be considered directly related to architecture—such as "Construction Building Technology" (6%), "Engineering Civil" (7%), and "Green Sustainable Science Technology" (24%). This suggests that although LCA studies encompass many aspects of the built environment, architecture is approached more from a technical and engineering-heavy perspective rather than from a theoretical or design standpoint. Although architecture is one of the disciplines shaping both the physical and experiential quality of the built environment within the context of LCA it is mostly represented at the level of "sub-disciplines," which complicates the holistic evaluation of design decisions in terms of environmental impacts. LCA, however, is applicable not only to technical areas such as material selection or energy efficiency but also to design parameters such as spatial arrangements, usage scenarios, and user behaviors (Hollberg & Ruth, 2016; Su et al., 2022). Similarly, the lack of LCA use in early design stages is a frequently discussed important issue in the literature (Kumar et. al.,2025). Therefore, there is significant research potential for the architectural discipline: integrating LCA into the early stages of the architectural design process could enable the discipline to contribute more effectively to sustainability goals. Greater recognition of LCA is necessary to fully realize its potential and availability in architectural practice, research, and education in order to facilitate this integration. In this regard, it is imperative that the architectural discipline enhance the LCA methodology by connecting it to distinct dimensions like design choices, user experience, and spatial quality, in addition to material or energy use. This approach contributes to closing the interdisciplinary gap and enhance the visibility of architecture's contribution to environmental sustainability.

Geographical distribution and representational strength in literature emphasizes the need for more inclusive international collaborations in the field of life cycle assessment. The results demonstrate that LCA is becoming one of the key instruments in environmental sustainability and is expanding quickly as an interdisciplinary research topic. The rapid increase in total publications confirms the broad use of LCA applications in response to sustainability requirements and environmental challenges around the world (Poderyte et al., 2025).

Annual growth rates and the expansion of publications by year indicate that LCA in architecture has accelerated at certain points in time. LCA's acceptance as a crucial architectural method was accelerated, in particular, by the growth of digital tools and the implementation of green building standards after 2010. LCA research in the field of architecture is likely to undergo significant expansion and diversification in the forthcoming years, particularly in the context of the ongoing climate crisis and carbon neutrality objectives.

Priorities in sustainable architecture and building research have changed over the last two and a half years, as evidenced by the SDG distribution seen in building LCA literature. According to the results, papers which highly associated with SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) highlight reducing embodied energy use, promoting circular material approaches, and reducing environmental impacts at different life cycle stages. The strong association with SDG 11 (Sustainable Cities and Communities) and SDG 9 (Industry, Innovation and Infrastructure) suggests that LCA is increasingly adopted as a decision-making tool not only at the building scale but also in urban planning and infrastructure development processes. On the other hand, the significant links with SDGs not directly related to the construction sector—such as SDG 14 (Life Below Water) and SDG 15 (Life on Land) —indicate growing awareness of the indirect impacts of building material sourcing and waste management on ecosystems. This suggests that the focus of building life cycle assessment (LCA) research is expanding to include broader environmental issues such as biodiversity and planetary boundaries, as well as energy and emission limits.

Thematic patterns in building-scale life cycle assessment research suggest a shift toward a multidisciplinary framework that extends beyond environmental impact assessment. In addition to environmental metrics, recent papers increasingly focus on social, economic, and technological issues. Social life cycle assessment (LCA) and topics such as adaptive reuse, modular construction, recycled materials, and 3D printing are current methodological trends. Additionally, a shift toward digitally supported and performance-oriented design methodologies is reflected in the use of BIM, multi-criteria decision-making, and energy modeling. In conclusion, this evolving thematic landscape demonstrates how life cycle assessment (LCA) in architecture is e transforming into an integrated sustainability framework that blends technical issues with contextual awareness. The continuous advancement of research in this field will enable earlier and more detailed analysis of environmental impacts, thereby contributing to a significant reduction in the construction sector's carbon footprint.

Acknowledgements and Information Note

In this section was developed within the scope of a docrorate-level course at Bursa Uludağ University, Faculty of Architecture. The author wishes to sincerely thank the course instructors for their insightful comments, academic support, and valuable guidance throughout the preparation of this work.

Additionally, the author of this chapter is supported by the Scientific and Technological Research Council of Türkiye (TÜBİTAK) through the 2244 – Industry PhD Programme (Project No: 123C478), and the support provided by TÜBİTAK is gratefully acknowledged.

Author Contribution and Conflict of Interest Declaration Information

This is a single-author book chapter. There is no conflict of interest.

References

Adams, K. T., Osmani, M., Thorpe, T., & Thornback, J. (2017, February). Circular economy in construction: current awareness, challenges and enablers. In *Proceedings of the institution of civil engineers-waste and resource management* (Vol. 170, No. 1, pp. 15-24). Thomas Telford Ltd.

ARUP (2023). Circular Buildings Toolkit. https://www.arup.com/en-us/services/digital-solutions/circular-buildings-toolkit/

Atta, N. (2023). *Green Approaches in Building Design and Management Practices: Windows of Opportunity Towards Circularity*. Springer Nature.

Benachio, G. L. F., Freitas, M. D. C. D., & Tavares, S. F. (2020). Circular economy in the construction industry: A systematic literature review. *Journal of cleaner production*, *260*, 121046.

Buyle, M., Braet, J., & Audenaert, A. (2013). Life cycle assessment in the construction sector: A review. *Renewable and sustainable energy reviews*, *26*, 379-388.

Ellen MacArthur Foundation. (2021, May 26). *Completing the picture: How the circular economy tackles climate change.* Ellen MacArthur Foundation. https://www.ellenmacarthurfoundation.org/completing-the-picture

Ellen MacArthur Foundation. (2022, March 14). *Reimagining our buildings and spaces for a circular economy*. Ellen MacArthur Foundation. Access Address (12.06.2025): https://www.ellenmacarthurfoundation.org/topics/built-environment/overview

Estève, P., Beckett, C., Pedreschi, R., Bosché, F., Morel, J. C., Charef, R., & Habert, G. (2022, September). Developing an integrated BIM/LCA framework to assess the sustainability of using earthen architecture. In *IOP conference series: earth and environmental science* (Vol. 1078, No. 1, p. 012100). IOP Publishing

European Commission. (2019). *The European Green Deal*. Access Address (02.06.2025): https://ec.europa.eu/commission/presscorner/detail/en/ip_19_6691

European Commission: Directorate-General for Environment. (2021). *Level(s), Putting circularity into practice*. Publications Office of the European Union. Access Address (01.06.2025): https://data.europa.eu/doi/10.2779/19010

European Committee for Standardization. (2011). *EN 15978:2011 Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method*. CEN.

Geissdoerfer, M., Savaget, P., Bocken, N. M., & Hultink, E. J. (2017). The Circular Economy–A new sustainability paradigm?. *Journal of cleaner production, 143*, 757-768.

Gusenbauer, M. (2019). Google Scholar to overshadow them all? Comparing the sizes of 12 academic search engines and bibliographic databases. Scientometrics: *An International Journal for All Quantitative Aspects of the Science of Science, Communication in Science and Science Policy*, 118(1), 177–214. https://doi.org/10.1007/s11192-018-2958-5

Hauschild, M. Z. (2019). Life cycle assessment. In *CIRP encyclopedia of production engineering* (pp. 1034-1043). Springer, Berlin, Heidelberg.

Hollberg, A., & Ruth, J. (2016). LCA in architectural design—a parametric approach. *The International Journal of Life Cycle Assessment, 21*, 943-960.

Kumar, D., Maurya, K. K., Mandal, S. K., Mir, B. A., Nurdiawati, A., & Al-Ghamdi, S. G. (2025). Life Cycle Assessment in the Early Design Phase of Buildings: Strategies, Tools, and Future Directions.

London Energy Transformation Initiative (2020). LETI Climate emergency design guide: How new buildings can meet UK climate change targets. *LETI, London, UK*.

Nugent, A., Owen, C. M., Pallares, L., Richardson, S., & Rowland, M. (2022). World Green Building Council: EU Policy Whole Life Carbon Roadmap. *https://figbc.fi/julkaisu/eu-policy-whole-life-carbon-roadmap.*

Ortiz, O., Castells, F., & Sonnemann, G. (2009). Sustainability in the construction industry: A review of recent developments based on

LCA. *Construction and Building Materials, 23(1),* 28–39. https://doi.org/10.1016/j.conbuildmat.2007.11.012

Poderytė, I., Banaitienė, N., & Banaitis, A. (2025). Life Cycle Sustainability Assessment of Buildings: A Scientometric Analysis. *Buildings*, 15(3), 381.

Sturgis, S., Anderson, J., Astle, P., Bagenal, G. C., Bowles, L., Hamot, L., ... & Papakosta, A. (2023). Whole life carbon assessment for the built environment. *Royal Institution of Chartered Surveyors (RICS): London, UK.*

Su, S., Ju, J., Ding, Y., Yuan, J., & Cui, P. (2022). A comprehensive dynamic life cycle assessment model: considering temporally and spatially dependent variations. *International Journal of Environmental Research and Public Health,* 19(21), 14000.

Toth, Z., Volt, S. S. J., & Steuwer, S. (2022). Roadmap to Climate-Proof Buildings and Construction. How to Embed Whole-Life Carbon in the EPBD. *BPIE (Buildings Performance Institute Europe, Issue January*.

UNEP & GlobalABC (2025). *Not just another brick in the wall: The solutions exist - Scaling them will build on progress and cut emissions fast. Global Status Report for Buildings and Construction 2024/2025*. . Access Address (08.06.2025): https://wedocs.unep.org/20.500.11822/47214.

Van Eck, N. J., & Waltman, L. (2010). Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics: An International Journal for All Quantitative Aspects of the Science of Science, Communication in Science and Science Policy*, *84*(2), 523–538. https://doi.org/10.1007/s11192-009-0146-3

Wang, Q., & Waltman, L. (2015). *Large-Scale Analysis of the Accuracy of the Journal Classification Systems of Web of Science and Scopus*.

Zhang, J., Asutosh, A. T., & Miu, Z. (2024). A study on ecological sustainable cities based on LCA-emergy-carbon footprint and geographic information system (GIS) approach. *Journal of Asian Architecture and Building Engineering*, 1-21. https://doi.org/10.1080/13467581.2024.2407162

Zhang, X., & Zhang, X. (2024). Low-carbon design optimization of reinforced concrete building structures using genetic algorithm. *Journal of Asian Architecture and Building Engineering*, *23*(6), 1888-1902. https://doi.org/10.1080/13467581.2023.2278466

Ph.D. Student, Hande Akar
E-mail: handeakar94@hotmail.com
Educational Status: M.Arch.
License: Bursa Uludag University-Architecture
Degree: MSc in Architecture, Bursa Uludag University
Doctorate: PhD in Architecture, Bursa Uludag University (ongoing)
Professional experiences: Design and user researcher at Çilek Mobilya (ongoing)

Life Cycle Assessment of a Cultural Heritage Building in Türkiye Based on Digital Modeling: Integration of ArchiCAD and One Click LCA

Ph.D. Student, Sadık AKŞAR [1]

[1] Bursa Uludağ University, Graduate School of Natural and Applied Sciences, Department of Architecture, Nilüfer, Bursa/Türkiye.
ORCID: 0000-0003-0583-4197
E-mail: sadikaksar@gmail.com

Prof. Dr. Rengin BECEREN ÖZTÜRK [2]

[2] Bursa Uludağ University, Faculty of Architecture, Department of Architecture, Nilüfer, Bursa/Türkiye.
ORCID: 0000-0001-6259-3364
E-mail: renginb@uludag.edu.tr

Citation: Akşar, S. & Beceren Öztürk, R. (2025). Life Cycle Assessment of a Cultural Heritage Building in Türkiye Based on Digital Modeling: Integration of ArchiCAD and One Click LCA. Beceren Öztürk, R. & Çahantimur, A. (Eds.). **Contemporary Approaches in Architecture: The Role of Architecture in the Circular Economy.** 2025, Chapter:6, 113-156. ISBN: 978-625-378-348-8. Iksad Publications.
DOI: https://doi.org/10.5281/zenodo.17309847

1. Introduction

With the onset of the 21st century, the rapid increase in urbanization and construction activities has led to the excessive consumption of natural resources, a decline in agricultural land, and the transformation of urban green spaces into built environments. These developments have not only caused significant environmental degradation but also posed threats to human health and quality of life. Buildings are largely responsible for the amount of energy consumed and environmental emissions generated in the World (Çelebi & Arpacıoğlu, 2025). In Europe, buildings alone account for approximately 40% of total energy consumption and 32% of CO_2 emissions (TÜİK, 2017), underscoring the urgent need for sustainable strategies in the built environment. In this respect, the construction industry has enormous potential to minimize its carbon footprint and the environmental performance of a building throughout its lifespan is an important issue (Çelebi & Arpacıoğlu, 2023).

Among the most effective tools for addressing these challenges is Life Cycle Assessment (LCA)—a systematic methodology that evaluates the environmental impacts of a product, service, or building throughout its entire life cycle (Tuna Taygun, 2005). While traditionally applied to new constructions, LCA is increasingly being used to assess heritage buildings, whose conservation and adaptive reuse can significantly reduce carbon emissions and material waste. However, the unique materiality, historical layering, and symbolic value of such structures introduce methodological complexities that require nuanced approaches (Vezzoli & Manzini, 2008). In this context, Building Information Modeling (BIM) offers a powerful digital framework for integrating material and spatial data into LCA workflows. BIM-supported LCA enables early-stage environmental impact analysis and supports data-driven decision-making in conservation planning (Potrč Obrecht et al., 2020). Yet, sustainable heritage conservation must go beyond environmental metrics. As Leifeste and Stiefel (2018) argue, it must also encompass cultural continuity, community engagement, and long-term resilience.

This chapter aims to evaluate the environmental performance of a registered heritage building in Bursa, Turkey, through a BIM-integrated LCA approach using ArchiCAD and One Click LCA. The selected case—a historic structure currently serving as a healthcare facility—offers a valuable opportunity to explore how digital tools can inform sustainable conservation strategies. By doing so, the study contributes to the evolving discourse on sustainable heritage, where ecological responsibility, cultural significance, and digital innovation intersect (UN-Habitat, 2021; Life Cycle Initiative, 2024).

2. Conceptual Background

Life Cycle Assessment (LCA) is a systematic and science-based methodology used to evaluate the environmental impacts of a product, process, or system throughout all stages of its life cycle—from raw material extraction to production, use, and end-of-life disposal. Initially developed in the late 1960s and early 1970s as energy-focused analyses (Guinée, 2006; SpringerLink, 2017), LCA has evolved into a multidimensional tool that integrates environmental, economic, and increasingly, social dimensions of sustainability (Finnveden et al., 2009; Nwodo & Anumba, 2019).

The 1980s and 1990s marked a period of methodological expansion, with the introduction of Life Cycle Impact Assessment (LCIA) and Life Cycle Costing (LCC), and the establishment of formal frameworks by organizations like SETAC and ISO (Guinée, 2006; ISO, 2006). The 2000s witnessed the emergence of Social Life Cycle Assessment (S-LCA), culminating in the UNEP/SETAC Guidelines in 2009, which emphasized the inclusion of social and socio-economic impacts in life cycle thinking (UNEP, 2009; Huertas-Valdivia et al., 2020). This process is seen in Figure 1.

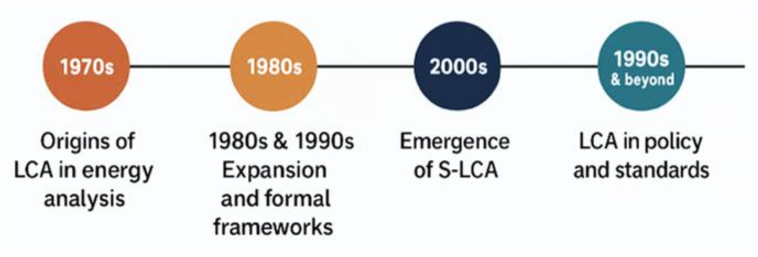

Figure 1. History of LCA in conceptual framework (Prepared by authors)

LCA's policy relevance has grown significantly, particularly within the European Union. The 1992 Ecolabel Regulation and the 2019 European Green Deal positioned LCA as a core tool for sustainable product policy, circular economy strategies, and environmental footprinting (Sala et al., 2021; European Commission, 2024). At the international level, the ISO 14040 and ISO 14044 standards have provided a globally accepted methodological foundation, ensuring consistency and credibility in LCA studies (ISO, 2006).

Methodologically, LCA now includes attributional and consequential approaches, each offering distinct perspectives for system boundaries and decision-making (Finnveden et al., 2009). Hybrid models that combine process-based data with economic input-output analysis further enhance the comprehensiveness of assessments. Despite these advances, challenges remain, such as data quality, methodological inconsistencies, and limited integration with social and policy dimensions (Guinée, 2006; Nwodo & Anumba, 2019; Sala et al., 2021).

As LCA continues to evolve, its integration with digital tools and policy frameworks positions it as a cornerstone of sustainable design and decision-making across sectors, including the conservation of cultural heritage buildings.

2.1. Life Cycle Assessment and Its Application in Buildings

Life Cycle Assessment (LCA) has emerged as a foundational methodology for evaluating the environmental performance of buildings across all stages of their existence—from raw material extraction and manufacturing to use, maintenance, and eventual demolition. As the construction sector continues to grapple with its substantial contribution to global energy consumption and greenhouse gas emissions, LCA offers a structured and science-based approach to support environmentally responsible decision-making in design, construction, and renovation processes (Pérez & Cabeza, 2017; Longo & Cellura, 2019). An LCA study typically comprises four main stages (Figure 2) (ISO, 2006).

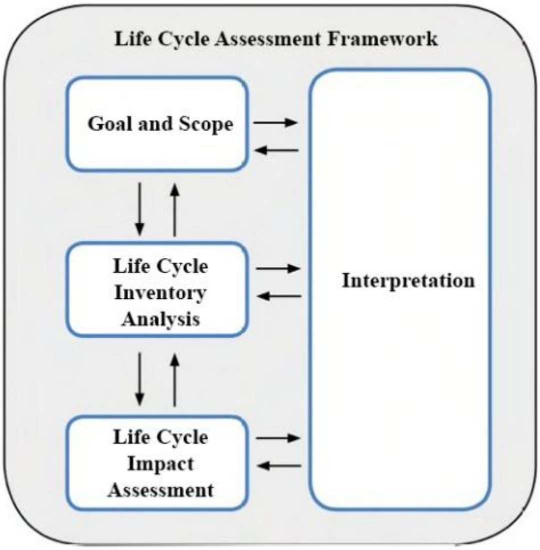

Figure 2. Stages of LCA (ISO, 2006)

The methodological framework of LCA is defined by the ISO 14040 and ISO 14044 standards, which outline four sequential phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation (ISO, 2006). In the first phase, the objectives, system boundaries, and functional unit of the study are established, clarifying the context and purpose of the assessment (Bayraktar, 2010; Tuna Taygun, 2005). The LCI phase involves the systematic collection of data on material and energy inputs as well as emissions and waste outputs (Ortiz et al., 2009). These data are then translated into environmental impact categories—such as global warming potential, acidification, and eutrophication—during the LCIA phase (Finnveden & Potting, 2014; Gültekin & Çelebi, 2016). Finally, the interpretation phase synthesizes the results to provide clear, consistent, and actionable insights aligned with the initial goals of the study (Levent, 2019). This framework is visualized in Figure 3.

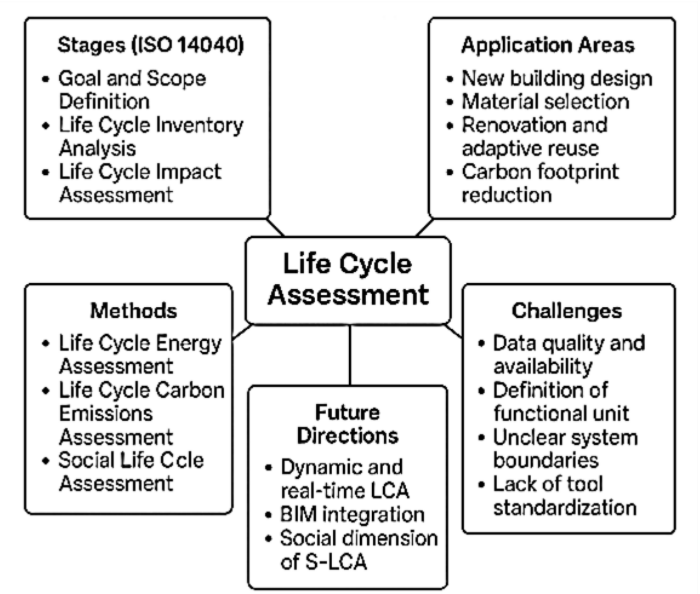

Figure 3. Life cycle assessment and its application in building (Prepared by authors)

In the context of buildings, LCA is widely applied to compare alternative design strategies, assess the environmental performance of construction materials, and guide the development of low-impact components (Singh et al., 2011; Roberts et al., 2020). Specialized variants such as Life Cycle Energy Assessment (LCEA) and Life Cycle Carbon Emissions Assessment (LCCO$_2$A) focus specifically on energy use and carbon emissions, respectively, though they differ in scope and methodological rigor (Chau et al., 2015). However, inconsistencies in defining functional units (e.g., per square meter vs. per building), system boundaries, and data sources often hinder the comparability of LCA studies (Nwodo & Anumba, 2019; Bahramian & Yetilmezsoy, 2020).

Recent advancements in digital technologies have enabled the integration of LCA with Building Information Modeling (BIM), enhancing the accuracy and efficiency of environmental assessments. BIM provides detailed, object-based representations of building components, which can be exported via Industry Foundation Classes (IFC) to LCA software such as One Click LCA, SimaPro, or GaBi (Santos et al., 2019). This integration facilitates real-time feedback during early design stages, allowing architects and engineers to evaluate the environmental implications of design decisions as they are made (Viscuso et al., 2022). Nevertheless, challenges such as semantic data gaps, software interoperability issues, and the absence of standardized workflows continue to limit the widespread adoption of BIM-LCA integration (Bueno & Fabricio, 2018).

Beyond environmental metrics, the social dimension of sustainability has gained increasing attention through the development of Social Life Cycle Assessment (S-LCA). This approach evaluates the social and socio-economic impacts of a product or system across its life cycle, focusing on indicators such as labor rights, community well-being, and stakeholder engagement (UNEP, 2009; Life Cycle Initiative, 2024). In the built environment, S-LCA can be particularly valuable in assessing the social implications of heritage building restoration, including local employment generation, cultural continuity, and participatory design processes. However, S-LCA remains underrepresented in the construction literature, with only a minority of studies addressing all three pillars of sustainability—environmental, economic, and social (Backes & Traverso, 2021).

Another emerging frontier in LCA research is the development of dynamic and real-time assessment models. Traditional LCA assumes static conditions, which may not accurately reflect the temporal and spatial variability inherent in building performance. Dynamic LCA (DLCA) addresses this limitation by incorporating real-time data from IoT sensors, digital twins, and climate-responsive models to capture fluctuations in energy use, occupancy patterns, and environmental conditions (Fnais et al., 2022; Hosamo et al., 2024). These innovations significantly enhance the contextual relevance and precision of LCA, particularly in operational energy monitoring and adaptive maintenance strategies.

Despite its growing applicability, LCA still faces several methodological and practical challenges. High data requirements, subjectivity in impact characterization, and the lack of standardized tools and databases—such as Ecoinvent, ICE, and ATHENA—continue to affect the reliability and comparability of results (Chau et al., 2015; Bahramian & Yetilmezsoy, 2020). Moreover, LCA is often applied too late in the design process, limiting its potential to influence critical decisions. Integrating LCA at the conceptual design stage, alongside tools like BIM and Life Cycle Costing (LCC), can significantly improve the sustainability outcomes of building projects (Roberts et al., 2020; Longo & Cellura, 2019).

In conclusion, Life Cycle Assessment remains an indispensable tool for evaluating and improving the environmental performance of buildings. Its continued evolution—through methodological refinement, digital integration, and the inclusion of social and temporal dimensions—will be essential for advancing sustainable practices in the construction sector.

2.2. Life Cycle Assessment in Historic Buildings

The application of Life Cycle Assessment (LCA) in historic buildings has gained increasing attention as a means to reconcile the goals of cultural heritage preservation with environmental sustainability. Unlike conventional buildings, historic structures present unique challenges and opportunities due to their material composition, construction techniques, and extended service lives. LCA provides a systematic framework to evaluate the environmental impacts of these buildings across all life cycle stages, from material extraction to end-of-life, thereby informing more sustainable conservation and renovation strategies (Serrano et al., 2022; Berg & Fuglseth, 2018).

Recent studies have demonstrated that restoration practices—particularly those that retain original materials and construction methods—can yield environmental impacts that are comparable to or even lower than those of modern renovation approaches focused on energy efficiency (Pachta & Giourou, 2022; Angrisano et al., 2021). For example, bio-based insulation materials used in energy retrofits have been shown to reduce embodied carbon, while maintaining the thermal performance of heritage structures (Angrisano et al., 2021). However, operational energy use remains a critical concern, as historic buildings often exhibit higher energy consumption during the use phase due to outdated systems and limited insulation (Berg & Fuglseth, 2018). A comparative overview of environmental impacts between historic and modern buildings is presented in Table 1.

Table 1. Comparison of the environmental ımpacts of historic and modern buildings (Adapted from Pachta & Giourou, 2022; Berg & Fuglseth, 2018)

Criterion	Historic Buildings	Modern Buildings
Service Life	Long (e.g., 140 years)	Short (e.g., 60 years)
Embodied Environmental Impact	Low (natural materials)	High (industrial materials)
Impact During Use Phase	High	Lower
Fossil Fuel Consumption	Low	High

Despite their advantages, the LCA of historic buildings is constrained by several methodological limitations. One of the most significant challenges is the lack of environmental data for traditional materials and techniques, which are often absent from standard LCA databases such as Ecoinvent or ICE (Franzoni et al., 2020; Nwodo & Anumba, 2019). Additionally, defining appropriate functional units and system boundaries is particularly complex due to the unique architectural and functional characteristics of heritage structures.

Another limitation lies in the static nature of conventional LCA models, which often fail to account for the temporal and spatial variability inherent in long-lived buildings. Dynamic LCA (DLCA) approaches, which incorporate real-time data and changing usage scenarios, offer a promising solution to this issue. These models can better reflect the evolving environmental performance of historic buildings over time, especially in the face of climate change and shifting occupancy patterns (Fnais et al., 2022; Salati et al., 2025).

Moreover, LCA outcomes in heritage contexts are not always directly translatable into policy or design decisions. Cultural values, aesthetic considerations, and stakeholder perceptions often play a decisive role in conservation strategies, introducing a layer of subjectivity that LCA alone cannot capture (Realdania, 2023). Therefore, interdisciplinary collaboration and stakeholder engagement are essential to ensure that LCA findings are meaningfully integrated into heritage conservation practices.

To enhance the robustness of LCA in historic buildings, several strategies have been proposed. These include the development of heritage-specific environmental databases, the integration of Life Cycle Cost Analysis (LCCA) to assess economic sustainability, and the alignment of LCA methodologies with national building codes and conservation guidelines (Hromada et al., 2024; Dong et al., 2021). The combined use of LCA and LCCA, particularly when supported by BIM-based tools, enables a more holistic evaluation of both environmental and financial implications of restoration interventions (McNeil-Ayuk & Jrade, 2024).

In Türkiye, recent research has emphasized the untapped potential of LCA in cultural heritage conservation. Studies highlight the need for localized data, stakeholder participation, and policy frameworks that support the integration of LCA into restoration planning (Başçıl et al., 2024). As the field evolves, dynamic, interdisciplinary, and context-sensitive approaches will be critical to advancing the sustainable preservation of historic buildings.

2.3. BIM-Based Life Cycle Assessment (LCA) for Historic Buildings: Current Status, Potential, and Limitations

The integration of Building Information Modeling (BIM) with Life Cycle Assessment (LCA) has emerged as a transformative approach in the construction sector, offering significant potential for enhancing sustainability in the conservation and management of historic buildings. BIM-based LCA enables the visualization, quantification, and optimization of environmental impacts across all life cycle stages, from design to demolition, by leveraging digital modeling and structured data environments (Soust-Verdaguer et al., 2017; Mora et al., 2020).

BIM serves as a digital platform that organizes geometric and semantic information about a building, while LCA provides a quantitative framework for assessing environmental impacts. Their integration facilitates more efficient data management, reduces manual input, and supports automated or semi-automated environmental analyses (Potrč Obrecht et al., 2020; Santos et al., 2019). This synergy is particularly valuable in historic buildings, where complex geometries, diverse material compositions, and long service lives pose unique challenges for sustainability assessments.

Recent studies have demonstrated that BIM-LCA integration can support environmental decision-making at both the component and whole-building levels. BIM models allow for the visualization of environmental impact intensities, making LCA results more accessible to designers and stakeholders (Röck et al., 2018). Moreover, the use of BIM plugins and templates has enabled the implementation of LCA during early design phases, thereby enhancing the feedback loop between design and sustainability performance (Chen et al., 2024; Tam et al., 2022).

However, several limitations persist. One of the primary challenges is the lack of semantic richness in BIM models for historic buildings, which often lack standardized object classifications and material definitions (Soust-Verdaguer et al., 2017; Safari & Azarijafari, 2021). Manual data transfer between BIM and LCA tools remains common, particularly in early-stage workflows, due to poor interoperability and the absence of unified data schemas (Potrč Obrecht et al., 2020; Guignone et al., 2023). Additionally, the underrepresentation of traditional materials in LCA databases limits the accuracy of environmental assessments in heritage contexts (Fnais et al., 2022). This framework is visualized in Figure 4.

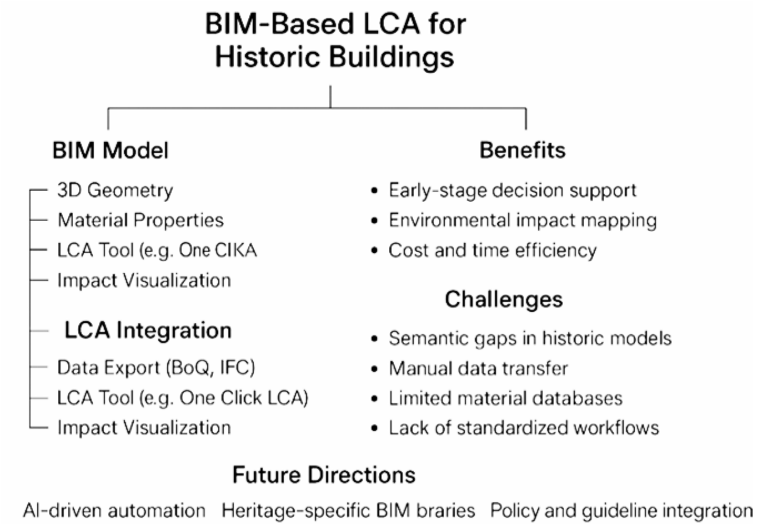

Figure 4. BIM-based LCA for historic buildings (Prepared by authors)

To address these issues, researchers have proposed several strategies. These include the development of heritage-specific BIM object libraries, the adaptation of IFC schemas to accommodate traditional construction elements, and the integration of localized LCA databases (Potrč Obrecht et al., 2020; Mora et al., 2020). Furthermore, the automation of BIM-LCA workflows through AI-driven tools and real-time data integration is gaining traction, offering new possibilities for dynamic and context-sensitive assessments (Espinosa & Tortorella, 2025).

Despite these advancements, the widespread adoption of BIM-based LCA in historic building conservation requires the establishment of standardized methodologies, improved interoperability between platforms, and enhanced training for practitioners. Institutional support and policy alignment are also essential to ensure that digital sustainability assessments are embedded within regulatory frameworks and conservation guidelines (Dong et al., 2021; Atik et al., 2022).

In conclusion, BIM-based LCA holds significant promise for advancing sustainable heritage conservation. While technical and methodological barriers remain, ongoing research and interdisciplinary collaboration are paving the way for more robust, automated, and heritage-sensitive assessment frameworks.

3. Methodology and Materials

This study presents a Life Cycle Assessment (LCA) of a registered historic building located in the Kükürtlü neighborhood of Bursa, Türkiye. Currently functioning as a dermatocosmetology unit, the building was selected due to its representative architectural features and adaptive reuse potential. The methodological framework was structured under three main phases: data collection, digital modeling, and life cycle analysis.

Data Collection; The initial phase involved the acquisition of architectural documentation, including existing plans, sections, and façade drawings, obtained from local public institutions. To supplement these records and verify the current condition of the building, on-site surveys and photographic documentation were conducted. This process enabled the identification of material types, structural components, and architectural features. Particular attention was paid to the documentation of original materials and construction techniques, which are often underrepresented in standard LCA databases (Franzoni et al., 2020; Fnais et al., 2022).

Digital Modeling; Based on the collected data, a three-dimensional digital model of the building was developed using ArchiCAD software. The model included all major structural components such as the load-bearing system, walls, floors, roof, windows, and doors. The foundation system was excluded due to insufficient documentation. ArchiCAD's parametric modeling capabilities allowed for high-fidelity representation of the building's geometry and material properties. The model was exported in Industry Foundation Classes (IFC) format to ensure compatibility with LCA tools, following best practices for BIM-LCA integration (Potrč Obrecht et al., 2020; One Click LCA, 2024).

Life Cycle Assessment (LCA); The LCA was conducted using the One Click LCA platform, selected for its extensive material database, compatibility with BIM workflows, and accessibility through an academic license. The IFC model was imported into the software, where environmental impact calculations were performed. The assessment covered life cycle stages A1–A3 (product stage), A5 (construction), B4–B5 (use phase), and C1–C4 (end-of-life), in accordance with EN 15978 standards. The functional unit was defined as "1 m^2 of gross floor area over a 50-year service life," a common metric in building LCA studies (Soust-Verdaguer et al., 2017).

Limitations and Assumptions

Several limitations were acknowledged in the study. The analysis excluded non-structural elements such as furniture, mechanical systems, and interior finishes due to data unavailability. Additionally, the foundation system was omitted from the model. These exclusions, while necessary, may lead to underestimation of total environmental impacts. Furthermore, the reliance on generic environmental product declarations (EPDs) for traditional materials introduces uncertainty, as many heritage-specific materials are not well represented in existing databases (Franzoni et al., 2020; Realdania, 2023).

Despite these limitations, the study demonstrates the feasibility of applying BIM-integrated LCA to historic buildings. The digital model and LCA outputs provide a replicable framework for evaluating the environmental performance of heritage structures, particularly in the context of sustainable conservation and adaptive reuse. As emphasized in recent literature, such assessments can inform restoration strategies that minimize carbon footprints while preserving cultural value (Başçıl et al., 2024; Serrano et al., 2022). The material and method processes of the study are presented as a process chart in Figure 5.

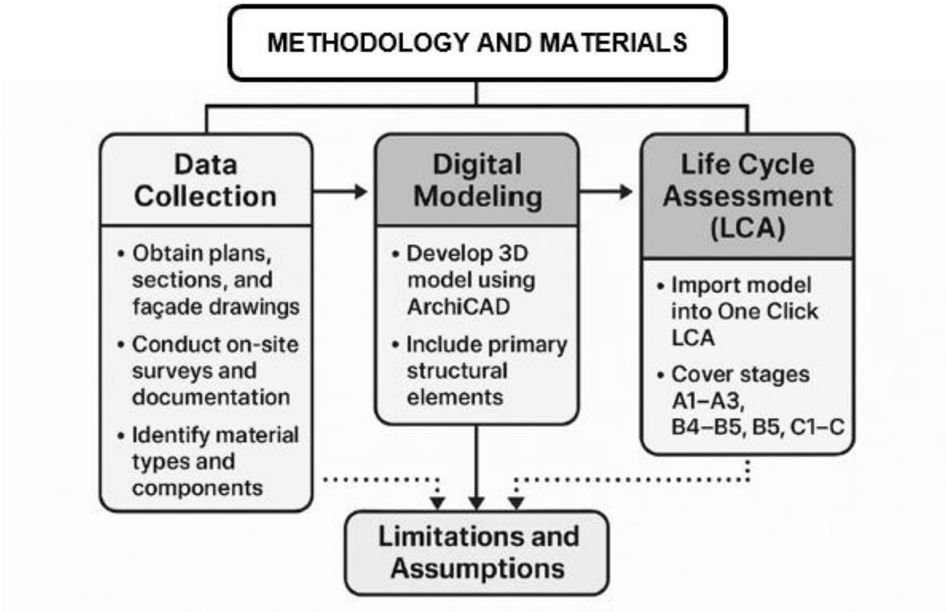

Figure 5. Material and method process of the study (Prepared by author)

3.1. Kükürtlü Uludağ University Dermato-Cosmetology Building

The building analyzed in this study is located in the Kükürtlü neighborhood of Bursa’s Osmangazi district, positioned between Çekirge and Kükürtlü streets (Figure 6).

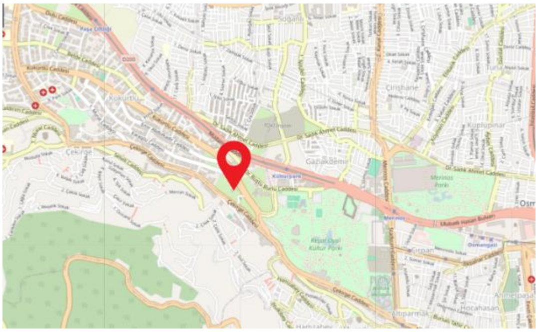

Figure 6. Location of the study area (OpenStreetMap, n.d.)

It lies in close proximity to historically significant thermal health facilities, including the Kükürtlü Thermal Springs and Baths, which date back to the early Ottoman period and were commissioned by Sultan Murad I prior to 1389 (Kültür Portalı, 2024; Termal Rehber, 2024). These facilities, historically known as Büyük and Küçük Kükürtlü Hamams, have long served as centers of hydrotherapy and continue to function today under the Uludağ University Atatürk Hydrotherapy and Rehabilitation Center.

The building currently houses the Dermato-Cosmetology Unit of Uludağ University’s Health Application and Research Center. It is situated within a dense urban fabric characterized by a mix of residential development and health-oriented infrastructure. The Kükürtlü neighborhood lies along Bursa’s westward development axis, a corridor that has experienced rapid urbanization and densification since the mid-20th century, particularly due to industrialization and internal migration (Global Future Cities

Programme, 2023). This axis has become a focal point for health tourism and urban transformation, making the building's location strategically significant.

Historically, the structure was part of a larger thermal complex and has undergone multiple functional transformations. Its proximity to thermal water sources has played a decisive role in its adaptive reuse as a healthcare facility. Today, the building benefits from excellent accessibility, being located near major transportation nodes such as bus stops and the Kültürpark Metro Station, which enhances its usability and integration into the urban system.

The selection of this building for a BIM-based Life Cycle Assessment (LCA) was informed by several factors: its active institutional use, its designation as a registered cultural heritage asset, and the availability of technical documentation. These attributes not only ensured the feasibility of digital modeling and environmental analysis but also positioned the building as a unique case study at the intersection of heritage conservation and sustainable design. Its dual identity—as both a historic structure and a contemporary medical facility—offers a compelling context for evaluating the environmental performance of adaptive reuse strategies through LCA methodology.

3.2. Digital Modeling of the Building

The digital modeling phase of the study was carried out using ArchiCAD, a BIM-based software selected for its parametric modeling capabilities and seamless integration with One Click LCA. Architectural documentation—including plan, section, and elevation drawings—was provided by the relevant department of Uludağ University. While these documents offered a general understanding of the building's morphology, they lacked detailed information on construction techniques and material specifications. To address these gaps, a comprehensive literature review was conducted, supplemented by on-site observations and expert consultations.

Field investigations confirmed that the building features a traditional timber frame (hımış) structural system, infilled with adobe brickwork and finished with double-layer plaster on both interior and exterior façades. These findings were cross-referenced with Sedad Hakkı Eldem's typological classifications in Türk Evi III, a seminal work on traditional Turkish civil architecture. Eldem's systematic approach to Ottoman-era timber construction provided a historically grounded framework for interpreting building's spatial organization and structural logic (Figure 7).

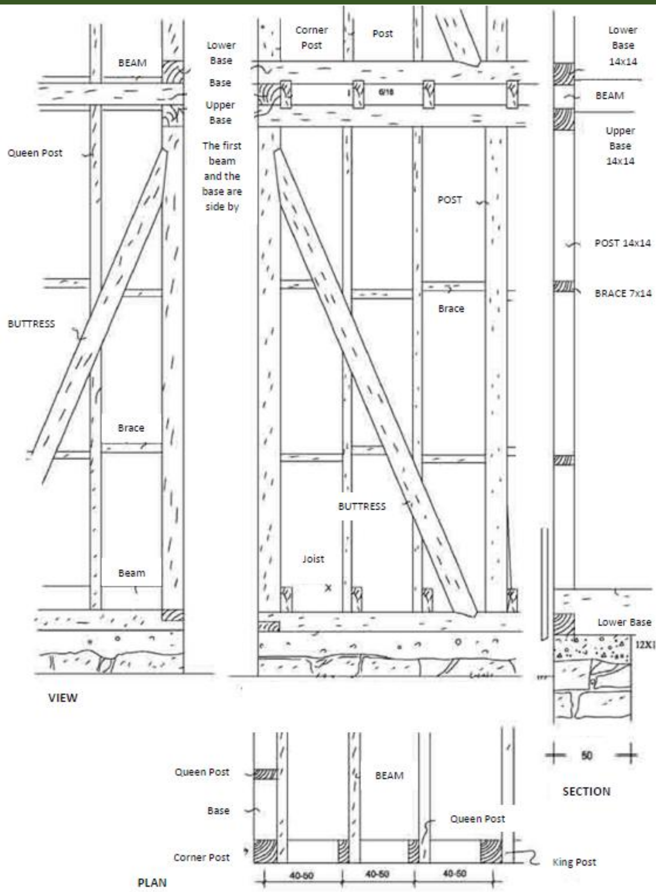

Figure 7. Double-floor timber load-bearing system (Eldem, 1987)

Based on this information, the building was modeled in ArchiCAD with high geometric and semantic accuracy. All major structural components were included in the model: the timber load-bearing frame, infill walls, floors, roof system (including slope and covering), and fenestration elements such as windows and doors. Due to insufficient documentation, the foundation system was excluded from the analysis.

Leveraging the information management advantages of BIM, the model incorporated detailed data on materials, dimensions, and performance parameters. The finalized model was exported in Industry Foundation Classes (IFC) format to ensure interoperability with the One Click LCA platform. This export enabled the integration of geometric and material data into the LCA workflow, facilitating a BIM-based environmental performance analysis.

Figure 8(a) presents the building holistically, showing its volumetric and structural components without infill and cladding layers. Figure 8(b) illustrates the same model with all construction layers included, offering a detailed representation of the building's material composition.

Figure 8. Structural frame view of the building model (a), overall view of the building (b) (Prepared by the author)

3.3. Life Cycle Assessment of the Building

The Life Cycle Assessment (LCA) of the historic building was conducted using the One Click LCA platform, integrated directly with the BIM model developed in ArchiCAD. This integration enabled the automatic transfer of material quantities and classifications from the digital model to the LCA environment via Industry Foundation Classes (IFC) format, streamlining the data exchange process and minimizing manual input (One Click LCA, 2024).

Once imported, the material data were manually reviewed and verified by the researcher. Where necessary, material mappings were adjusted using One Click LCA's extensive environmental product database. Priority was given to datasets specific to Türkiye; in the absence of local data, reliable European sources such as Ecoinvent and ÖKOBAUDAT were utilized to ensure regional relevance and methodological consistency (Circular Ecology, 2024).

The environmental impact assessment was conducted in accordance with the EN 15804+A1 standard, which defines core rules for the environmental performance of construction products. The following life cycle stages were included in the analysis:

- A1–A3: Product stage (raw material supply, transport, manufacturing)
- A5: Construction process stage (installation)
- B4–B5: Use stage (maintenance and repair)
- C1–C4: End-of-life stage (deconstruction, transport, processing, disposal)
- D: Potential benefits and loads from reuse, recovery, and recycling

The assessment focused on key environmental impact categories, including:

- Global Warming Potential (GWP)
- Biogenic Carbon Storage
- Ozone Depletion Potential (ODP)
- Acidification Potential (AP)
- Eutrophication Potential (EP)

Additional indicators related to the use of renewable and non-renewable primary energy, as well as material resource consumption, were also reported. Among these, GWP and ODP were selected as the primary indicators for interpretation, given their relevance to climate change and atmospheric degradation (Ecochain, 2024; Vaayu, 2024).

The results were contextualized based on the building's material composition, structural typology, and operational lifespan. Figure 9 illustrates the technical data derived from the BIM model and the specific life cycle stages addressed in the assessment.

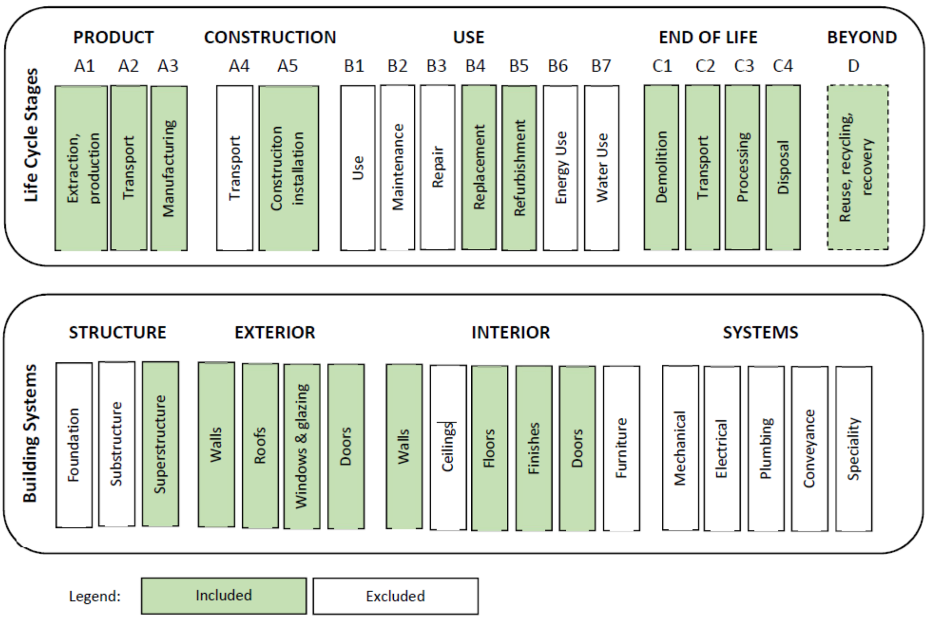

Figure 9. Life cycle stages and scope of assessment across building (Prepared by authors)

The obtained Life Cycle Assessment (LCA) data were calculated in accordance with the EN 15804 +A1 standard. This standard serves as a widely accepted European reference for preparing environmental product declarations of construction materials. Figure 10 presents the proportional distribution of the impact categories resulting from the One Click LCA analysis, displayed as stacked columns according to the LCA phases.

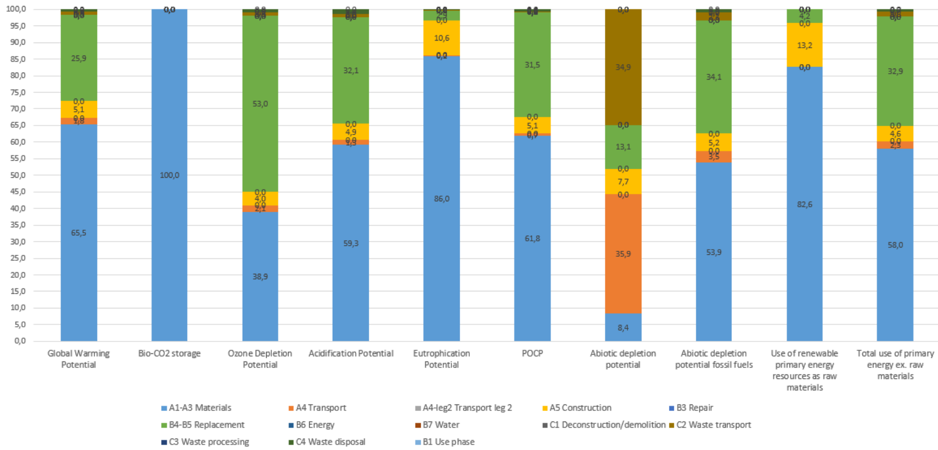

Figure 10. Proportional distribution of environmental ımpact categories across life cycle stages (Edited by the author with One Click LCA data)

This study evaluates the environmental performance of the historic building through two key impact categories: Global Warming Potential (GWP) and Ozone Depletion Potential (ODP). Both indicators were calculated in accordance with the EN 15804 +A1 standard, which provides a harmonized methodology for assessing the environmental impacts of construction products throughout their life cycle. The analysis was conducted using One Click LCA software, integrated with the BIM model developed in ArchiCAD.

The total greenhouse gas emissions associated with the building's life cycle were calculated as approximately 130,310 kg CO_2-equivalent. This value represents the cumulative emissions released into the atmosphere across all life cycle stages and serves as a critical metric for assessing the building's carbon footprint.

As shown in Table 2, the majority of emissions—65.5% (85,302 kg CO_2e)—originated from the product stage (A1–A3), which includes raw material extraction, processing, and manufacturing. The replacement and maintenance stages (B4–B5) accounted for 25.9% (33,811 kg CO_2e), followed by the construction stage (A5) with 5.1% (6,650 kg CO_2e). Transport (A4), waste transport (C2), and disposal (C4) stages contributed marginally, together comprising less than 3.5% of the total.

Table 2. GWP values by life cycle stage

Category	Global warming kg CO_2e
A1-A3 Materials	85301,8
A4 Transport	2379,8
A5 Construction	6649,9
B4-B5 Replacement	33811,4
C2 Waste transport	1147,4
C4 Waste disposal	1019,6

This distribution highlights the dominant role of material production and replacement processes in the building's overall carbon footprint. Accordingly, material selection emerges as a critical factor in reducing embodied emissions, particularly in the context of restoration and adaptive reuse.

A material-specific breakdown of GWP values is presented in Table 3. The analysis reveals that a small number of materials account for a disproportionately large share of emissions. Wood-framed glass doors alone contributed 26.8% (34,668 kg CO_2e), followed by mortar (18.8%), ready-mix concrete (17.4%), and bitumen-based roofing materials (13.2%). These four materials collectively accounted for over 75% of the building's total GWP.

Table 3. GWP values by building material

Category	Global warming kg CO_2e
Wood-framed glass doors	34668,0
Mortar (masonry/bricklaying)	24277,4
Ready-mix concrete for external walls and floors	22451,8
Bitumen and other roofing	17103,0
Sand, soil and gravel	7674,7
Gypsum plaster (interior applications)	6549,9
Brick, common clay brick	6315,0
Plain wood/timber (softwood and hardwood)	6010,3
Wood and wood board doors	4180,3
Other resource types	1079,2

These findings underscore the importance of material-specific sustainability strategies, particularly in the selection of high-impact components such as glazing systems, binders, and roofing materials.

In addition to carbon emissions, the study also assessed the building's Ozone Depletion Potential (ODP), expressed in kg CFC-11-equivalent. The total ODP impact was calculated as approximately 0.02077 kg CFC-11-eq. As shown in Table 4, the B4–B5 stage (replacement and refurbishment) was the largest contributor, accounting for 53% of the total impact. The A1–A3 stage followed with 39%, while construction, transport, and disposal stages contributed less than 8% combined.

Table 4. ODP values by life cycle stage

Category	Ozone Depletion kg CFC11e
A1-A3 Materials	0,008082744
A4 Transport	0,000435175
A5 Construction	0,000824447
B4-B5 Replacement	0,011016023
C2 Waste transport	0,000226492
C4 Waste disposal	0,000183178

The material-based analysis of ODP values, presented in Table 5, reveals that bitumen and other roofing materials were responsible for 74% of the total ozone depletion impact (0.0161 kg CFC-11-eq). Other notable contributors included wood-framed glass doors, ready-mix concrete, and sand-based aggregates, each contributing between 3% and 4%.

Table 5. ODP values by building material

Category	Ozone Depletion kg CFC11e
Bitumen and other roofing	0,016129953
Wood-framed glass doors	0,000927938
Ready-mix concrete for external walls and floors	0,000919109
Sand, soil and gravel	0,00091524
Plain wood/timber (softwood and hardwood)	0,000795407
Brick, common clay brick	0,00068686
Wood and wood board doors	0,000161231
Mortar (masonry/bricklaying)	9,12593E-05
Gypsum plaster (interior applications)	7,79571E-05
Other resource types	6,31054E-05

These results emphasize that ozone depletion impacts are highly concentrated in specific material categories—particularly roofing products—highlighting the need for careful material selection in both initial construction and future maintenance interventions. The findings suggest that substituting high-ODP materials with environmentally preferable alternatives could significantly reduce the building’s long-term environmental burden.

3.4. Evaluation of LCA Results

The Life Cycle Assessment (LCA) results reveal significant environmental disparities among building components when evaluated across two key impact categories: Global Warming Potential (GWP) and Ozone Depletion Potential (ODP). These differences underscore the importance of adopting a multidimensional approach to material selection in both new construction and heritage restoration.

Material-specific GWP analysis identified timber-framed glazed doors, mortar, and ready-mix concrete as the primary contributors to total greenhouse gas emissions. These components exhibit high CO_2-equivalent values due to their energy-intensive production processes and reliance on fossil fuels. Their embodied carbon content significantly influences the building's overall environmental footprint, particularly during the product stage (A1–A3).

In contrast, the ODP assessment presents a distinct environmental profile. Bituminous roofing materials emerged as the most impactful group in terms of ozone layer depletion, accounting for the majority of CFC-11-equivalent emissions. This is primarily attributed to the use of halogenated blowing agents and chemical additives during manufacturing (UNEP, 2021). Other contributors include timber-framed glazed doors, ready-mix concrete, and mineral-based fill materials such as sand and gravel. These findings highlight that ozone depletion is not necessarily correlated with carbon emissions, and that material toxicity and chemical composition must also be considered in environmental evaluations.

When interpreted together, the GWP and ODP results emphasize the necessity of holistic material assessment. Relying solely on a single environmental indicator may obscure trade-offs and lead to suboptimal design decisions. For instance, a material with relatively low embodied carbon may still pose significant risks to atmospheric health due to its ozone-depleting potential. This aligns with recent LCA literature, which stresses the importance of evaluating materials across multiple environmental dimensions (Cabeza et al., 2014).

In this context, the promotion of renewable, low-emission materials—such as sustainably sourced timber—offers a promising pathway, provided that their application is supported by appropriate design strategies and maintenance protocols. Studies have shown that wood-based materials can significantly reduce life cycle emissions when used under controlled conditions (Sathre & O'Connor, 2010). However, even bio-based materials must be critically assessed for their full life cycle impacts, including processing, transportation, and end-of-life scenarios.

Ultimately, these findings reinforce the importance of embedding life cycle thinking into all phases of the building process—from early design and procurement to construction, operation, and eventual deconstruction. Such an approach not only enhances the environmental performance of individual projects but also contributes to broader sustainability goals in the built environment.

4. Conclusion and Recommendations

This study contributes to the growing body of research on sustainability-oriented assessment methods for cultural heritage buildings by applying a BIM-based Life Cycle Assessment (LCA) to a registered historic structure in Türkiye. The case study of the Uludağ University Dermatology and Cosmetology Unit, located in the Kükürtlü neighborhood of Bursa, demonstrates the potential of integrating digital modeling (via ArchiCAD) with environmental performance analysis tools (One Click LCA) to evaluate the life cycle impacts of heritage structures in a systematic and replicable manner.

One of the key findings of the study is the considerable variation in environmental impacts among different material types used in the building. In the Global Warming Potential (GWP) category, components such as timber-framed glazed doors, mortar, and ready-mix concrete were identified as the most carbon-intensive elements. This outcome highlights that even in buildings constructed using traditional techniques, modern material supply chains and manufacturing processes can result in high embodied emissions. Similarly, the Ozone Depletion Potential (ODP) analysis revealed that industrial materials—particularly bituminous roofing products—pose significant environmental burdens due to the use of halogenated compounds and chemical additives. These findings underscore the importance of evaluating multiple environmental indicators beyond carbon emissions when assessing sustainability in the built environment (Cabeza et al., 2014).

The results align with existing literature emphasizing that material selection and maintenance strategies are critical determinants of a building's long-term environmental performance, especially in the context of heritage conservation. In this regard, LCA emerges as a valuable decision-support tool not only for new construction but also for the sustainable management, adaptation, and reuse of existing building stock. The study further reveals that maintenance and refurbishment activities (B4–B5 stages) contribute substantially to environmental impacts—particularly in terms of ODP—reinforcing the need to align restoration practices with sustainability goals.

The BIM-based approach adopted in this study offers significant advantages in overcoming traditional limitations of LCA in heritage contexts. The integration of a detailed digital model with LCA software enabled a more accurate representation of building components and their environmental impacts. This finding is consistent with recent research highlighting the potential of BIM–LCA integration to enhance the precision and efficiency of environmental assessments in the building sector (Potrč Obrecht et al., 2020). However, the study also identified several challenges, including data interoperability issues, the limited availability of localized environmental datasets, and the underrepresentation of traditional materials in existing LCA databases. These limitations affected the precision and generalizability of the results. To address these challenges, the development of heritage-specific environmental datasets and the establishment of BIM–LCA modeling standards that reflect local construction practices are essential. Moreover, enhancing LCA methodologies to account for dynamic variables—such as climate variability, usage scenarios, and temporal degradation—would significantly improve the relevance of sustainability assessments for long-lived heritage structures.

It is also important to acknowledge the scope limitations of this study. Elements such as the foundation system, mechanical infrastructure, and user behavior were excluded from the analysis due to data constraints. As a result, the environmental indicators presented here are limited to the building envelope and structural components. Future research should aim to incorporate these omitted aspects and explore the integration of Life Cycle Cost Analysis (LCCA) to enable a more comprehensive evaluation of environmental, economic, and cultural sustainability.

In conclusion, this study demonstrates the feasibility and value of integrating BIM and LCA methodologies in the sustainability assessment of culturally significant buildings. The use of material-based environmental indicators provides a robust framework for informing restoration and reuse decisions. At the policy level, incorporating LCA findings into conservation regulations could support the institutionalization of sustainable heritage practices, as emphasized by Fouseki and Cassar (2014). In doing so, historic buildings can be redefined not only as cultural monuments of the past but also as environmentally responsible assets for the future.

In conclusion, this study demonstrates the feasibility and value of integrating BIM and LCA methodologies in the sustainability assessment of culturally significant buildings. The use of material-based environmental indicators provides a robust framework for informing restoration and reuse decisions. At the policy level, incorporating LCA findings into conservation regulations could support the institutionalization of sustainable heritage practices, as emphasized by Fouseki and Cassar (2014). In doing so, historic buildings can be redefined not only as cultural monuments of the past but also as environmentally responsible assets for the future.

Looking ahead, cultural heritage buildings hold significant potential to play an active role in sustainable urban transitions by serving as exemplars of low-carbon, resource-efficient, and socially inclusive development. By embedding environmental considerations into conservation practice, heritage structures can contribute not only to the preservation of cultural identity but also to broader climate adaptation and mitigation goals.

Moreover, the integration of multidimensional assessment frameworks such as Social Life Cycle Assessment (S-LCA) and Life Cycle Cost Analysis (LCCA) offers promising avenues for future research. Incorporating these methods alongside environmental LCA would enable more holistic evaluations that address the social, economic, and cultural dimensions of sustainability. Such an approach could guide decision-makers toward restoration strategies that balance environmental performance with community well-being and long-term affordability.

Taken together, these directions underscore the transformative potential of heritage buildings in shaping resilient, sustainable, and culturally vibrant cities of the future.

Acknowledgements and Information Note

In this section was developed within the scope of a docrorate-level course at Bursa Uludağ University, Faculty of Architecture. The author wishes to sincerely thank the course instructors for their insightful comments, academic support, and valuable guidance throughout the preparation of this work.

The study did not receive any financial support or funding from any institution. Ethics committee approval was not required for this study. The article complies with national and international research and publication ethics standards.

Author Contribution and Conflict of Interest Declaration Information

The authors is solely responsible for the content and writing of this article. There is no conflict of interest.

References

Angrisano, M., Fabbrocino, F., Iodice, P., & Girard, L. (2021). The Evaluation of Historic Building Energy Retrofit Projects through the Life Cycle Assessment. *Applied Sciences*. https://doi.org/10.3390/app11157145

Atik, S., Domenech Aparisi, T., & Raslan, R. (2022). The opportunities and challenges of using LCA-based BIM plugins in early-stage building design. *In Proceedings of the 2nd International Civil Engineering and Architecture Conference* (pp. 401–408). https://doi.org/10.1007/978-981-19-4293-8_42

Backes, J. G., & Traverso, M. (2021). Application of life cycle sustainability assessment in the construction sector: A systematic literature review. *Processes*, 9(7), 1248. https://doi.org/10.3390/pr9071248

Bahramian, M., & Yetilmezsoy, K. (2020). Life cycle assessment of the building industry: An overview of two decades of research (1995–2018). *Energy and Buildings*, 219, 109917. https://doi.org/10.1016/j.enbuild.2020.109917

Başçıl, D., Aydemir Karakaş, Ç. E., & Bulut, N. (2024). Potential role of life cycle assessment for cultural heritage conservation practices in Türkiye. *SETSCI Conference Proceedings*, 20, 125–132. https://doi.org/10.36287/setsci.20.16.125

Bayraktar, T. F. (2010). *Türkiye'de yapı malzemesi yaşam döngüsü değerlendirmesi için bir sistem önerisi (PhD Thesis) İstanbul Teknik Üniversitesi, YÖK Tez Merkezi.*

Berg, F., & Fuglseth, M. (2018). Life cycle assessment and historic buildings: energy-efficiency refurbishment versus new construction in Norway. *Journal of Architectural Conservation*, 24, 152 - 167. https://doi.org/10.1080/13556207.2018.1493664

Bueno, C., & Fabricio, M. M. (2018). Comparative analysis between a complete LCA study and results from a BIM-LCA plug-in. *Automation in Construction,* 90, 188-200. https://doi.org/10.1016/j.autcon.2018.02.028

Cabeza, L. F., Rincón, L., Vilariño, V., Pérez, G., & Castell, A. (2014). Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renewable and Sustainable Energy Reviews*, 29, 394–416. https://doi.org/10.1016/j.rser.2013.08.037

Chau, C., Leung, T., & Ng, W. (2015). A review on Life Cycle Assessment, Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on buildings. *Applied Energy*, 143, 395-413. https://doi.org/10.1016/J.APENERGY.2015.01.023

Chen, Z., Chen, L., Zhou, X., Huang, L., Sandanayake, M., & Yap, P. (2024). Recent Technological Advancements in BIM and LCA Integration for Sustainable Construction: A Review. *Sustainability*. https://doi.org/10.3390/su16031340

Circular Ecology. (2024). EN15804 Modules Explained. https://circularecology.com/en15804-modules-explained.html

Çelebi, N.G & Arpacıoğlu, Ü. (2025). Evaluatıon of the relatıonshıp between buıldıng heıght and lıfe cycle envıronmental ımpact of the buıldıng structural system. UMTEB – XVII INTERNATIONAL SCIENTIFIC RESEARCH CONGRESS, May 4-6, 2025 Prague/ Czech.

Çelebi, N.G & Arpacıoğlu, Ü. (2023). Comparatıve analysıs of steel and reınforced concrete structural frames ın terms of envıronmental ımpact. III. International Architectural Sciences and Applications Symposium, September 14-15, 2023, Naples, Italy.

Demirer, G. N. (2011). Yaşam döngüsü analizi, pratik yaşam döngüsü analizi kılavuzu: AB sürecinde işletmeler ve kamu için yaşam döngüsü analizi yöntem ve örnekleri. *Bölgesel Çevre Merkezi* (REC).

Dong, Y., Ng, S., & Liu, P. (2021). A comprehensive analysis towards benchmarking of life cycle assessment of buildings based on systematic review. *Building and Environment*, 204, 108162. https://doi.org/10.1016/J.BUILDENV.2021.108162

Ecochain. (2024). Impact Categories (LCA) – The Complete Overview. https://ecochain.com/blog/impact-categories-lca/

Eldem, S. H. (1987). *Türk Evi III*. Taç Vakfı, İstanbul.

Espinosa, A., & Tortorella, G. (2025). AI & BIM for circular design and life cycle assessment. IAAC Blog. https://blog.iaac.net/ai-bim-for-circular-design-and-life-cycle-assessment/

European Commission. (2024). The European Green Deal. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

Finnveden, G., & Potting, J. (2014). Life cycle assessment. In P. Wexler (Ed.), *Encyclopedia of toxicology* (3rd ed., pp. 74–77). Elsevier.

Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., ... & Suh, S. (2009). Recent developments in life cycle assessment. *Journal of Environmental Management*, 91(1), 1–21. https://doi.org/10.1016/j.jenvman.2009.06.018

Fnais, A., Rezgui, Y., Petri, I., Beach, T., Yeung, J., Ghoroghi, A., & Kubicki, S. (2022). The application of life cycle assessment in buildings: challenges, and directions for future research. *The International Journal of Life Cycle Assessment*, 27, 627 - 654. https://doi.org/10.1007/s11367-022-02058-5

Fouseki, K., & Cassar, M. (2014). Energy efficiency in heritage buildings—Future challenges and research needs. *The Historic Environment: Policy & Practice*, 5(2), 95–100. https://doi.org/10.1179/1756750514Z.00000000061

Franzoni, E., Volpi, L., & Bonoli, A. (2020). Applicability of life cycle assessment methodology to conservation works in historical building: The case of cleaning. *Energy and Buildings*, 214, 109844. https://doi.org/10.1016/j.enbuild.2020.109844

Global Future Cities Programme. (2023). *Bursa City Context Report*. https://www.globalfuturecities.org/republic-turkey/cities/bursa

Guignone, G., Calmon, J., Vieira, D., & Bravo, A. (2023). BIM and LCA integration methodologies: A critical analysis and proposed guidelines. *Journal of Building Engineering*. https://doi.org/10.1016/j.jobe.2023.106780

Guinée, J. B. (2006). Life cycle assessment: Past, present and future. *International Symposium on Life Cycle Assessment and Construction*.

Gültekin, A. B., & Çelebi, G. (2016). Yaşam döngüsü değerlendirme yöntemi kapsamında yapı ürünlerinin çevresel etkilerinin değerlendirilmesine yönelik bir model önerisi. *Düzce Üniversitesi Bilim ve Teknoloji Dergisi*, 3, 1–36.

Hosamo, H., Coelho, G. B. A., & Drissi, S. (2024). Building sustainability through a novel exploration of dynamic LCA uncertainty. *Building and Environment*, 264, 111922. https://doi.org/10.1016/j.buildenv.2024.111922

Hromada, E., Macek, D., Heralova, R. S., Brožová, L., & Střelcová, I. (2024). Integrating Life Cycle Cost Analysis for Sustainable Maintenance of Historic Buildings. *Buildings*, *14*(5), 1479. https://doi.org/10.3390/buildings14051479

Huertas-Valdivia, I., Ferrari, A., Settembre-Blundo, D., & García-Muiña, F. (2020). Social Life-Cycle Assessment: A Review by Bibliometric Analysis. *Sustainability*. https://doi.org/10.3390/su12156211

ISO. (2006). *ISO 14040: Environmental management—Life cycle assessment—Principles and framework & ISO 14044: Environmental management—Life cycle assessment—Requirements and guidelines.* International Organization for Standardization. https://www.iso.org/standard/38498.html

Kültür Portalı. (2024). *Kükürtlü Kaplıcaları*. https://www.kulturportali.gov.tr/turkiye/bursa/gezilecekyer/kukurtlu-kaplicalari

Leifeste, A., & Stiefel, B. L. (2018). Sustainable heritage: Merging environmental conservation and historic preservation. *Routledge*. https://doi.org/10.4324/9781315748948

Levent, Ş. (2019). *Gezilemeyen teras çatılardaki su yalıtımı uygulamalarının üretim ve yapım süreci çevresel etkilerinin değerlendirilmesi*, Master Thesis, İstanbul Technical University, YÖK Tez Merkezi.

Life Cycle Initiative. (2024). *Social Life Cycle Assessment (S-LCA)*. https://www.lifecycleinitiative.org/starting-life-cycle-thinking/life-cycle-approaches/social-lca/

Longo, S., & Cellura, M. (2019). Life-Cycle Assessment of Buildings. *Handbook of Energy Efficiency in Buildings*. https://doi.org/10.1016/B978-0-12-812817-6.00010-3

McNeil-Ayuk, N., & Jrade, A. (2024). A BIM-LCCA integrated model for early-stage decision-making. *Open Journal of Civil Engineering*, 14(3), 277–304. https://doi.org/10.4236/ojce.2024.143015

Mora, D., Bolzonello, E., Cavalliere, C., & Peron, F. (2020). Key Parameters Featuring BIM-LCA Integration in Buildings: A Practical Review of the Current Trends. *Sustainability*. https://doi.org/10.3390/su12177182

Nwodo, M., & Anumba, C. (2019). A review of life cycle assessment of buildings using a systematic approach. *Building and Environment*. https://doi.org/10.1016/J.BUILDENV.2019.106290

One Click LCA. (2024). *Archicad integration guide*. https://help.oneclicklca.com/en/articles/275842-archicad

Ortiz, O., Castells, F., & Sonnemann, G. (2009). Sustainability in the construction industry: A review of recent developments based on LCA. *Construction and Building Materials*, 23(1), 28–39.

Pachta, V., & Giourou, V. (2022). Comparative Life Cycle Assessment of a Historic and a Modern School Building, Located in the City of Naoussa, Greece. *Sustainability*. https://doi.org/10.3390/su14074216

Pérez, G., & Cabeza, L. (2017). Buildings Life Cycle Assessment. *Encyclopedia of Sustainable Technologies*, 275-290. https://doi.org/10.1016/B978-0-12-409548-9.10194-0

Potrč Obrecht, T., Röck, M., Hoxha, E., & Passer, A. (2020). BIM and LCA Integration: A Systematic Literature Review. *Sustainability*, 12(14), 5534. https://doi.org/10.3390/su12145534

Realdania. (2023). *Life Cycle Assessment in Historic Buildings*. https://www.realdania.org/publications/in-english/life-cycle-assessment-in-historic-buildings

Roberts, M., Allen, S., & Coley, D. (2020). Life cycle assessment in the building design process – A systematic literature review. *Building* *and Environment*, 185, 107274. https://doi.org/10.1016/J.BUILDENV.2020.107274

Röck, M., Hollberg, A., Habert, G., & Passer, A. (2018). LCA and BIM: Visualization of environmental potentials in building construction at early design stages. *Building and Environment*. https://doi.org/10.1016/J.BUILDENV.2018.05.006

Safari, K., & Azarijafari, H. (2021). Challenges and opportunities for integrating BIM and LCA: Methodological choices and framework development. *Sustainable Cities and Society*, 67, 102728. https://doi.org/10.1016/J.SCS.2021.102728

Sala, S., Amadei, A., Beylot, A., & Ardente, F. (2021). The evolution of life cycle assessment in European policies over three decades. *The International Journal of Life Cycle Assessment*, 26, 2295 - 2314. https://doi.org/10.1007/s11367-021-01893-2

Salati, M., Costa, A. A., & Silvestre, J. D. (2025). A comprehensive review of dynamic life cycle assessment for buildings. *Sustainability*, 17(1), 159. https://doi.org/10.3390/su17010159

Santos, R., Costa, A., Silvestre, J., & Pyl, L. (2019). Integration of LCA and LCC analysis within a BIM-based environment. *Automation in Construction*. https://doi.org/10.1016/J.AUTCON.2019.02.011

Sathre, R., & O'Connor, J. (2010). A synthesis of research on wood products and greenhouse gas impacts. *FPInnovations*. https://www.woodworks.org/wp-content/uploads/FPI-Greenhouse-Gas.pdf

Serrano, T., Kampmann, T., & Ryberg, M. (2022). Comparative Life-Cycle Assessment of a restoration and renovation of a traditional Danish farmer house. *Building and Environment*. https://doi.org/10.1016/j.buildenv.2022.109174

Singh, A., Berghorn, G., Joshi, S., & Syal, M. (2011). Review of Life-Cycle Assessment Applications in Building Construction. *Journal of Architectural Engineering*, 17, 15-23. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000026

Soust-Verdaguer, B., Llatas, C., & García-Martínez, A. (2017). Critical review of bim-based LCA method to buildings. *Energy and*

Buildings, 136, 110-120. https://doi.org/10.1016/J.ENBUILD.2016.12.009

SpringerLink. (2017). LCA History. In A. Bjørn, M. Owsianiak, C. Molin, & M. Z. Hauschild (Eds.), *Life Cycle Assessment* (pp. 17–30). https://link.springer.com/chapter/10.1007/978-3-319-56475-3_3

Tam, V., Zhou, Y., Illankoon, C., & Le, K. (2022). A critical review on BIM and LCA integration using the ISO 14040 framework. *Building and Environment*. https://doi.org/10.1016/j.buildenv.2022.108865

Termal Rehber. (2024). *Kükürtlü Kaplıca*. https://termalrehber.com/kaplicalar/kukurtlu-kaplica/

Tuna Taygun, G. (2005). *Yapı ürünlerinin yaşam döngüsü değerlendirmesine yönelik bir model*, PhD Thesis, Yıldız Technical University, YÖK Tez Merkezi.

TÜİK. (2017). *Enerji tüketimi ve sera gazı emisyonları istatistikleri*. Türkiye İstatistik Kurumu. https://data.tuik.gov.tr

United Nations Environment Programme (UNEP). (2009). Guidelines for social life cycle assessment of products. *United Nations Environment Programme*. https://www.lifecycleinitiative.org/wp-content/uploads/2012/12/2009%20-%20Guidelines%20for%20sLCA%20-%20EN.pdf

UN-Habitat. (2021). Best practices on social sustainability in historic districts. *United Nations Human Settlements Programme*. https://unhabitat.org/sites/default/files/download-manager-files/Best%20Practices%20on%20Social%20Sustainability%20in%20Historic%20Districts.pdf

United Nations Environment Programme (UNEP). (2021). *Montreal Protocol on Substances that Deplete the Ozone Layer: 2021 Assessment Report*. https://ozone.unep.org

Vaayu. (2024). *LCA Impact Categories: Understanding the Dimensions of Sustainability Assessment*. https://www.vaayu.tech/insights/lca-impact-categories

Vezzoli, C., & Manzini, E. (2008). Design for environmental sustainability. *Springer*. https://doi.org/10.1007/978-1-84800-163-3

Viscuso, S., Monticelli, C., Ahmadnia, A., & Zanelli, A. (2022). Integration of life cycle assessment and life cycle costing within a BIM-based environment. *Frontiers in Sustainability*, 3, 1002257. https://doi.org/10.3389/frsus.2022.1002257

Ph.D. Student, Sadık AKŞAR
E-mail: sadikaksar@gmail.com
Educational Status: PhD Candidate
License: Eskişehir Osmangazi University, Faculty of Engineering and Architecture, Architecture Department, 2014-2019
Degree: Yıldız Technical University, Graduate School of Natural and Applied Sciences, Department of Architecture, 2019-2022
Doctorate: Bursa Uludağ University, Graduate School of Natural and Applied Sciences, Department of Architecture, 2024-in progress

Prof. Dr. Rengin BECEREN ÖZTÜRK
E-mail: renginb@uludag.edu.tr
Educational Status: Prof. Dr.
License: Anadolu University, Faculty of Architecture and Design, Architecture Department, 1987-1993
Degree: İstanbul Technical University, Graduate School of Natural and Applied Sciences, Department of Architecture, 1995-1998
Doctorate: İstanbul Technical University, Graduate School of Natural and Applied Sciences, Department of Architecture, 1998-2005

Applying Life Cycle Assessment Tools in the Restoration of Kükürtlü Hamam: An OpenLCA Case Study

Ayşe Begüm KAHYA

[1]Bursa Uludag University, Faculty of Architecture, Department of Architecture, Bursa/Türkiye.
ORCID: 0009-0003-5280-0800
E-mail: aysebegumkahya@gmail.com

Citation: Kahya, A. B. (2025). Applying Life Cycle Assessment Tools in the Restoration of Kükürtlü Hamam: An OpenLCA Case Study. Beceren Öztürk, R. & Çahantimur, A. (Eds.). **Contemporary Approaches in Architecture: The Role of Architecture in the Circular Economy.** 2025, Chapter:7, 157-186. ISBN: 978-625-378-348-8. Iksad Publications. DOI: https://doi.org/10.5281/zenodo.17316736

1. Introduction

The primary objective of this study is to reveal the environmental impacts of the materials used in the restoration process of the historic Kükürtlü Hamam in the Kükürtlü district of Bursa through the life cycle assessment (LCA) method. The study not only focuses on the restoration of this unique structure, but also aims to develop a systematic approach to how the LCA method can be applied in architectural restoration projects by modeling quantitative data generated through Revit software in the OpenLCA environment. Thus, the research aims to make an important contribution in terms of enabling the numerical evaluation of the environmental performance of traditional building materials and transferring these evaluations to decision-making processes.

The scope of the study is defined by the "cradle to gate" methodological boundaries. Within this framework, all stages from raw material sourcing, processing, production, transportation, and use on site are included in the analysis. However, subsequent stages that may arise during the use of the structure, such as energy consumption, maintenance and repair activities, demolition at the end of its useful life, reuse, or recycling, are not evaluated within the scope of the study. This limitation makes the research more feasible in terms of data accessibility and allows for a clearer and more focused examination of the environmental impacts specific to the restoration process. Therefore, the study is not limited to analyzing the environmental performance of a specific building but also serves as a prototype demonstrating the applicability of the LCA method in the field of restoration.

To ensure that the LCA method yields more functional and reliable results, detailed research was conducted on the processes and materials used. The building has a stone load-bearing system in the basement and a brick infill and timber load-bearing system on the upper floors. Therefore, the analysis was performed on these basic materials.

The study consists of three main sections. In the first section, existing technical drawings were transferred to a three-dimensional digital environment to obtain quantity and material information. Autodesk Revit software was used in this process, and a methodology was proposed to collect the data necessary for LCA.

In the second section, the building's restoration process was modeled within the scope of the life cycle based on the data obtained. At this stage, the analysis process was carried out using OpenLCA software, and explanations were provided about life cycle modeling and the model's subcomponents. This section aims to provide researchers with a practical guide on how to conduct individual LCA studies using OpenLCA.

In the third section, the obtained life cycle data were evaluated and discussed. At this stage, the environmental impacts of the materials were analyzed comparatively, and the reliability and limitations of the outputs provided by the LCA software used were questioned.

Thus, the aim was for users to evaluate the extent to which OpenLCA meets their needs.

2. Literature Review

Today, climatic irregularities and ecological crises have increased; the importance of sustainable environmental policiesthese policies have started to play a decisive role in the evaluation of the environmental impacts of built environments. According to a 2019 global study, the construction sector accounts for 30% of energy-related CO_2 emissions. This ratio clearly reveals that current building production and transformation methods should be made sustainable (Serrano et al., 2022a). It stands out as an effective method to evaluate with a scientific and holistic approach the environmental impacts of buildings (Elnaggar, 2024, p. 2).

Although LCA is widely applied in different sectors, it is especially used in the building sector to assess the environmental impacts of new buildings. However, when, the number of studies in the literature decreases significantly. It comes to the restoration and renovation of historic buildingsIn the study dated of Fahlstedt et al., 2024, it is stated that only 54 academic publications on building renovation were reached in . In a recent literature review based on this study, only 31 relevant studies were found. This number shows that the volume of research is quite insufficient considering the existing historic building stock. The literature study conducted between 2005 and 2022.

Serrano et al. (2022b) emphasise that LCA applications in historic buildings are both few in number and with limited impact categories.

One of the main reasons for this limitation is that existing LCA software and databases are mostly developed for modern buildings. The lack of data on local and traditional materials used in historic buildings limits the applicability of these analyses (Mazzetto, 2024, p. 4). Elnaggar (2024) draws attention to this gap and argues that specialised databases specific to heritage science, including regional environmental, economic and socio-cultural data, should be developed.

In recent years, the relationship between cultural heritage conservation and sustainable environmental policies has become more visible. In 2021, the "Joint Commitment for Climate Action in Cultural Heritage" statement published by the International Institute for the Conservation of Historical and Artistic Works (IIC), the International Centre for the Conservation and Restoration of Cultural Property (ICCROM) and the Conservation Committee of the International Council of Museums (ICOM-CC) emphasises the importance of sustainable practices in this field (Elnaggar, 2024, p.2). However, academic studies in this direction are still limited.

One of the prominent examples in this context is the LCA study carried out by Serrano et al. for the restoration of a farmhouse dating back to the 1800s in Denmark. In this study, restoration and renovation scenarios were compared and it was concluded that restoration performed better in environmental terms. The analysis process was carried out with OpenLCA 1.10.3 software and Ecoinvent database was used. This study constitutes an important example for the sustainable transformation of cultural heritage.

The concept of "green heritage science" put forward by Elnaggar (2024) forms the basis of the paradigm shift in this field. This approach proposes to consider principles such as the use of renewable resources, minimum intervention, reduction of toxic chemicals, energy efficiency and waste minimisation in the socio-economic context. However, the applicability of these principles depends on the development of LCA tools and databases specific to restoration processes.

In conclusion, the application of LCA methodology in the restoration of cultural heritage buildings is still insufficient from both academic and practical perspectives. The elimination of research gaps in this field, the development of analysis tools specific to heritage science and the dissemination of sustainable restoration practices should be among the priority research areas.

LCA stands out as a fundamental method for determining the environmental impacts of both new and existing structures. Huuhka et al. (2023) emphasize that "renovation creates a lower carbon footprint than new construction in most cases" and is therefore a critical strategy in combating climate change (Huuhka, Moisio, Salmio, Köliö & Lahdensivu, 2023). Similarly, Almeida et al. (2015) compared different renovation packages in a low-income area and found that "measures that increase energy efficiency can also offer cost-optimal solutions" (Almeida, Bencresciuto, Ferreira & Rodrigues, 2015). These studies demonstrate that LCA must be evaluated not only in terms of environmental but also economic dimensions.

The balance between energy performance and the preservation of cultural heritage is becoming increasingly important in the renovation of historic buildings. Kertsmik et al. (2024), in their study on a 100-year-old apartment building in Estonia, state that "deep renovation makes it possible to achieve nearly zero energy levels," but that technical restrictions imposed by national heritage boards limit this process (Kertsmik et al., 2024). The literature also states that restoration not only has similar environmental impact levels to renovation, but also preserves cultural heritage value (Serrano et al., 2022a, cited in Kertsmik et al., 2024). These findings emphasize the importance of LCA in the restoration of buildings constructed with traditional material layers.

The studies also focus on the life cycle impacts of building components. Çelebi and Arpacıoğlu (2025) revealed in their analysis of reinforced concrete structural systems that "structural systems are the most dominant building elements in terms of embodied energy and carbon emissions" (Çelebi & Arpacıoğlu, 2025). The same researchers also emphasize the necessity of energy-efficient design with the systematic framework they developed for the life cycle energy efficiency of buildings (Çelebi & Arpacıoğlu, 2023). Furthermore, the international literature states that LCA must integrate not only environmental impacts but also social and economic sustainability dimensions (Huuhka et al., 2023). This perspective indicates that restoration projects must consider the economic and social dimensions of materials such as stone, wood, and brick, in addition to their environmental impacts.

3. Material and Methodology

The Kükürtlü Hamam is located in the Çekirge district of Bursa, known for its thermal springs, on a large area of 23,173 m². Originally built in the 14th century for public use free of charge, the structure was renovated during the reign of Murad I and additions were made during the reign of Bayezid II. The structure, which bears the characteristic features of Ottoman-era bath architecture, was restored in 1983 in accordance with the recommendations of the High Council of Ancient Monuments and Sites and opened as a health facility by Uludağ University in 1985. Today, it both preserves its historical identity and serves as a rehabilitation center (Ay et al., 2004). However, the building's current use has proven insufficient to meet the physical and functional needs that have emerged over time. Therefore, the center is being re-evaluated with the aim of renovating it in line with contemporary conservation approaches. In this process, research is being conducted on how to achieve a more environmentally friendly and sustainable restoration by integrating sustainability principles and life cycle assessment (LCA) into the process. This study was conducted to assess the environmental impacts of historic buildings during restoration processes. Life cycle analysis (LCA) was adopted as the assessment method and the boundaries of the analysis were determined within the framework of the "cradle to gate" approach. This scope includes the stages from the procurement of raw materials to the application of the materials on site. In contrast, subsequent phases such as the utilisation process, maintenance, repair, demolition and recycling are excluded. This limitation allowed to focus only on the restoration process and made the data more manageable.

The study not only provides an assessment specific to the building analysed, but also proposes a methodological model that can be taken as an example for similar site-based projects. The "cradle to gate" approach is one of the scope types used in LCA; alternative delimitations such as "cradle to grave" or "grave to grave" are also available in the literature. In this context, the aim of the study is to provide a conceptual model for researchers to develop similar analysis processes in their own projects.

The analysed building is located in Kükürtlü district of Bursa province and has a floor area of approximately 200 m^2. There are masonry stone walls in the basement floor and timber load-bearing system and brick infill walls in the upper floors. This building system reflects the characteristic features of Ottoman period local architecture. The variety of material layers allowed the environmental impacts of different building components to be analysed separately and comparative assessments could be made.

The main objective of the study is to demonstrate step by step how an assessment process based on life cycle analysis can be carried out in the context of the project. Two main digital tools were used in this process: Autodesk Revit and OpenLCA.

Revit is a BIM (Building Information Modelling) based software, which allows the modelling of multi-layered materials and construction techniques with high accuracy. In this study, Revit was used to extract material quantities, identify building components and create a digital recording environment. The quantity data calculated with the schedule tool were compiled for use in life cycle analysis.

These data were manually transferred to OpenLCA software. OpenLCA is preferred because it is open source, compatible with different databases and offers customisation possibilities to the user. In this project, the ELCD (European Reference Life Cycle Database) database was used because it provides comprehensive data on construction site processes free of charge. In OpenLCA, processes are analysed by first transforming them into product systems and then into projects. The manual definition of processes increased user control and enabled the creation of a tailor-made, unique model. Thanks to the flexible structure of the software, it was possible to work with different databases and the analysis outputs were obtained in detail.

OpenLCA is a free and open-source software used for environmental impact assessments. This software enables the modeling of a product's life cycle, from raw material extraction to post-use disposal, and allows for the quantitative analysis of environmental impacts at each stage. The software allows for the integration of different databases, enabling users to define process flows, customize data sets, and include regional parameters. Furthermore, it is an important tool for comparing different supply chains, determining at which stages the environmental burden of products is concentrated, and supporting more sustainable design decisions. In this respect, OpenLCA enables the effective implementation of life cycle assessment in both academic research and practical applications (Danish, t.y.).

As a result, this study not only presented environmental impact calculations for the restoration of a specific building, but also proposed a holistic and reproducible method of how life cycle analysis can be applied through digital technologies. The integrated use of Revit and OpenLCA made it possible to support sustainability in architectural practices with measurable data, and provided an analytical basis for designers to make decisions that take into account environmental impacts.

In this respect, the study both contributes to the current project and proposes a sustainability-oriented methodological infrastructure for future restoration and design practices.

The method used in this study is a process-based life cycle analysis (LCA) approach that focuses on the generation of practical and measurable data. The method involves quantitatively analysing building components through digital modelling and translating this data into environmental impact calculations through an open-source LCA software.

The analysis process was carried out in four main stages:

1. **Structural Analysis and Material Determination:** Firstly, the structural system, structural elements and material layers of the building were analysed and the physical and construction properties of each component were determined.
2. **Digital Modelling:** The building was digitally modelled with its layered material system using Autodesk Revit software. This modelling process enabled both visual and numerical data generation.
3. **Quantity and Data Matching:** The quantity data obtained through Revit were classified in accordance with the life cycle analysis and matched with the processes in the ELCD database.
4. **Life Cycle Analysis:** The obtained data were manually transferred to OpenLCA software, where product systems were created and analysed through environmental impact categories. These stages outline the integrated modeling process followed in the research (Figure 1).

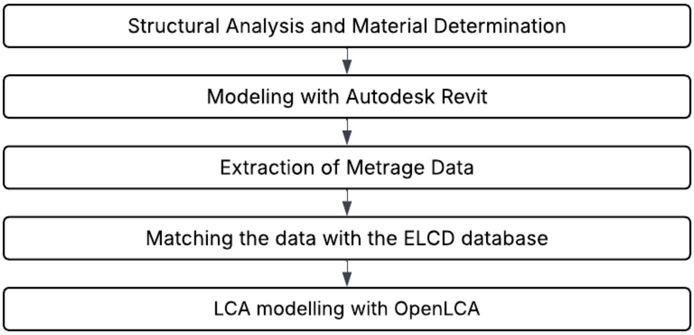

Figure 1. Integrated Modelling Process with OpenLCA (Created by the author)

All these steps are based on practices carried out directly by the researcher. In this respect, the study presents an LCA process that can be applied in both academic and professional contexts, and proposes an exemplary methodological model of how sustainability analyses can be performed with the integration of digital tools.

3.1. Structural Analysis and Material Identification

Before starting the life cycle analysis, a preliminary determination was made as to whether the building components would be included in the scope of the assessment. This step was carried out in order determine .to prepare the ground for the purpose, modelling and analysis processes and to the main components of the building

The analysed building consists of a basement and two upper floors. The basement has a masonry stone carrier system, while the upper floors have a timber frame system and brick infill. walls. Plaster was used on the interior and exterior walls, ceramics were used in wet areas and tiles were used on the roof. This multi-layered building system made it necessary to analyse each material component separately.

Accordingly, the following building layers were categorised in terms of evaluability:

- External and internal walls
- Upholstery
- Ceiling systems
- Carrier system components
- Roof system
- Window and door openings

Surface coating elementsThis list is a preliminary study to determine the building elements to be included in the scope of the analysis. The materials comprising each component were assessed for their compatibility with existing data sets and their potential for environmental impact, and the most basic materials were selected for analysis. Thus, the process is structured with a focused and applicable analysis framework that represents the environmental impacts in the building.

3.2. Modelling and Quantity Surveying Process with Revit Autodesk

In this study, Autodesk Revit software was used for modelling building components in digital environment and obtaining data suitable for life cycle analysis. The main reason for preferring Revit is that it enables the definition of multi- layered building elements together with their sub-components. The coexistence of different construction techniques such as masonry stone in the basement floor and timber structural system and brick infill in the upper floors of the analysed building made this separation necessary.

Revit can model the surface area, volume, storey, material type and other physical properties of each building element with high accuracy and can list these data numerically with the schedule tool. Thus, the data to be used in life cycle analysis are produced directly integrated with the modelling process.

The modelling process was carried out in three basic steps:

1. **Identification of Building Elements:** Exterior and interior walls, floors, structural system elements, ceiling systems and roof components were included in the model.

2. **Inputting Parameters:** For each building element, physical properties such as material type, thickness, density and location were defined.
3. **Layer Decomposition**: Using the "Create Parts" command, multi-layered structural elements were separated into sub-layers and each of them was made independently quantifiable.

In this process, only the basic building elements that would make a meaningful contribution to the environmental impact analysis were included in the model; decorative or negligible details with negligible environmental impact were excluded. Thus, the model is structured as a functional analysis tool rather than a visual representation. The basic commands and functions used in the analysis process are systematically provided (Table 1).

Table 1. Key Features of Revit Enabling Lifecycle Data Modelling

Feature / Command	Description
Layered Structure Definition	It allows modelling of building elements with multi-layer system.
Create Parts	It physically separates the material layers and enables independent quantity take.
Schedule Creation	Automatically lists data such as volume, surface area.
BIM Based Data Structure	Integrates modelling and data management.

At the end of the modelling process, numerical and qualitative data of the structural elements were extracted using Revit's scheduling tool. The "Create Parts" command was used to access the quantity data of the sub-layers so that each layer could be analysed independently. The schedules include ceiling, interior and exterior walls, columns, beam systems, flooring, roof, doors and windows. However, since the data for doors and windows could not be obtained with sufficient accuracy, they were excluded from the scope of the analysis.

In cases where the same material is used in different building elements, the quantities of the identical materials were combined and the table was simplified by calculating the total values. Auxiliary elements and elements with limited environmental impact were also excluded. This simplification was preferred for the empirical nature and methodological integrity of the study.

Although Revit does not directly perform life cycle analysis, it played a fundamental role in the preparation of the quantity data required for the analysis in this study. The obtained data were systematically transferred to be used in OpenLCA software by matching with ELCD database. Thus, Revit is evaluated as a data generation tool that bridges digital modelling and environmental analysis.

3.3. System Modelling and Life Cycle Assessment Creation with OpenLCA

In this chapter, it is explained how the quantity surveying data obtained with Revit is integrated into OpenLCA software and transformed into life cycle analysis; the basic components of the software, database structure and impact assessment methods are introduced. The aim is to demonstrate in a simple and understandable language how OpenLCA can be used as an effective tool in sustainability-oriented projects.

3.3.1. Software Selection and Main Features

In this study, life cycle assessment (LCA) was carried out using OpenLCA, an open source and free software. The reasons for preferring the software are as follows:

- Being open source and free of charge increases its accessibility, especially for academic research and independent projects.
- It offers the opportunity to work with different databases and create user-specific databases.
- It provides transparent and customisable analysis processes thanks to manual data entry and process definition.
- Supports many impact assessment methods such as ReCiPe, ILCD, TRACI.
- It works in compliance with ISO 14040 and ISO 14044 standards, which is important for scientific reliability.
- The outputs can be exported to Excel and other common formats. These features make OpenLCA not only an analysis tool but also a comprehensive modelling and system design platform.

3.3.2. Components and Database Structure of OpenLCA

OpenLCA performs life cycle modelling through four basic components (Table 2) :

Table 2. Main Components of OpenLCA

Component	Description
Flow	Represents material, energy or emissions entering or leaving the system.
Process	Defines activities such as production, transport and repair.
Product System	It is a system model in which processes come together and become analysable.
Project	It is a general analysis structure created by combining more than one product system.

Thanks to this structure, for example, a restoration project can be divided into sub-systems such as stone procurement, transportation and implementation and each of them can be analysed separately. These subsystems can then be combined to calculate the holistic environmental impact of the project.

Databases form the basic building blocks of this modelling process. In this study, the ELCD (European Reference Life Cycle Database) database, which includes free and construction processes, was used. More comprehensive databases such as Ecoinvent were not preferred because they are paid. However, the fact that existing databases do not contain data specific to restoration projects reveals the need for new data production in this field.

Databases such as ELCD can be downloaded from Nexus, the official database platform of OpenLCA. In this study, the analysis was carried out using ELCD data , and the information not included in the database was excluded.

3.3.3. Impact Assessment Methods and Categories

Impact assessment is the stage of life cycle analysis where environmental impacts are measured after the system models are established. This assessment is done through different categories such as carbon footprint, fossil resource consumption, fresh water use.

In this study, ReCiPe impact assessment method was used and the project was analysed in 18 different environmental impact categories. Other methods (ILCD, TRACI, etc.) were not tested in this context. Thanks to the ReCiPe method, it has been determined which processes and materials create more environmental burden in which categories, which allows more sustainable decisions to be made.

3.3.4. Application: Step-by-Step Restoration LCA Modelling

Building a lifecycle analysis model in OpenLCA has been realised by following the following basic steps:

- **Loading and Cleaning Databases:** The modelling process started with the integration of the required databases into OpenLCA. These databases were downloaded from Nexus, the official platform of the software, and loaded into the programme via the "File > Import" command. The loaded databases are organised in a folder structure in the navigation panel (Flows, Processes, Product Systems, Projects, etc.).

  In order to avoid data crowding and improve the accuracy of the analysis, only the data to be used is imported into a new "clean database". This was done by creating an empty database with the "New Database" command and reloading the required data into it.
- **Creation of Flows:** Flows represent the movements of material, energy and emissions in the system. Each process is defined through these flows. If the required flows are not available in the existing database, new flows were created manually by right clicking on the "Flows" folder. These flows were then used as inputs and outputs of the processes.
- **Defining Processes:** Processes represent activities such as production, transport, application. To create a new process, an empty process file was opened by right-clicking on the "Processes" folder, and then the relevant flows were entered in the "Inputs" and "Outputs" tabs. The processes were both adapted from the available data and defined uniquely.

- **Creating Product Systems:** Each process was transformed into an analysable product system with the "Create Product System" command. These systems were used to assess the environmental impact of the individual processes. The product systems are then brought together in the project creation phase.
- **Project Creation and Impact Assessment:** All product systems were added to a new project file created in the "Projects" folder. In the project settings tab, quantities for each product system were entered and ReCiPe 2016 Midpoint (I) was selected as the impact assessment method. With this method, the Project has been analysed in 18 different environmental impact categories.
- **Calculation and Reporting of Results:** The project was analysed with the "Calculate" command and the results were obtained graphically and numerically. The reports were exported with the "Export Report" and "Export to Excel" commands. These outputs revealed the environmental performance of the system in categories such as carbon footprint, fossil resource consumption, freshwater eutrophication.

This process carried out with OpenLCA provided a modular and transparent structure with all steps from database integration to Project analysis. By carefully defining each building block (flow, process, product system, project), the environmental impacts of the restoration project were calculated with high accuracy. This method provides a model that will contribute to making sustainability-oriented decisions in similar projects.

4. Conclusion and Evaluation

This study evaluated the environmental impacts of six main work items involved in the restoration process of a historic building by using life cycle analysis (LCA) method. Digital modelling and quantity extraction were performed with Autodesk Revit; the data obtained were integrated into OpenLCA software and analysed with ReCiPe 2016 Midpoint (I) method. Each work item was assessed in 18 different environmental impact categories and significant differences between the processes were revealed.

According to the results of the analyses, significant differences were observed between the environmental impacts of the work items. The table below summarises the categories where each work item has the highest environmental impact (Table 3).

Table 3. Highest impact categories by work items

Work Item	Highest Impact Categories
Electricity Works	Fine Particulate Matter Formation, Ionising Radiation, Terrestrial Acidification, Terrestrial Ecotoxicity, Water Consumption
Drywall Works	Fossil Resource Scarcity, Freshwater Ecotoxicity, Freshwater Eutrophication, Global Warming, Human Carcinogenic Toxicity, Marine Eutrophication
Tile-brick-ceramic works	Human Non-Carcinogenic Toxicity, Terrestrial Acidification, Marine Ecotoxicity, Ozone Formation (Human Health)
Stone Works	Human Non-Carcinogenic Toxicity, Fossil Resource Scarcity, Freshwater Ecotoxicity
Transport Operations	Ozone Formation (Human Health), Ozone Formation (Terrestrial Ecosystems), Marine Eutrophication, Global Warming
Wood Works	Ozone Formation (Terrestrial Ecosystems), Ozone Formation (Human Health), Fine Particulate Matter Formation (low level)

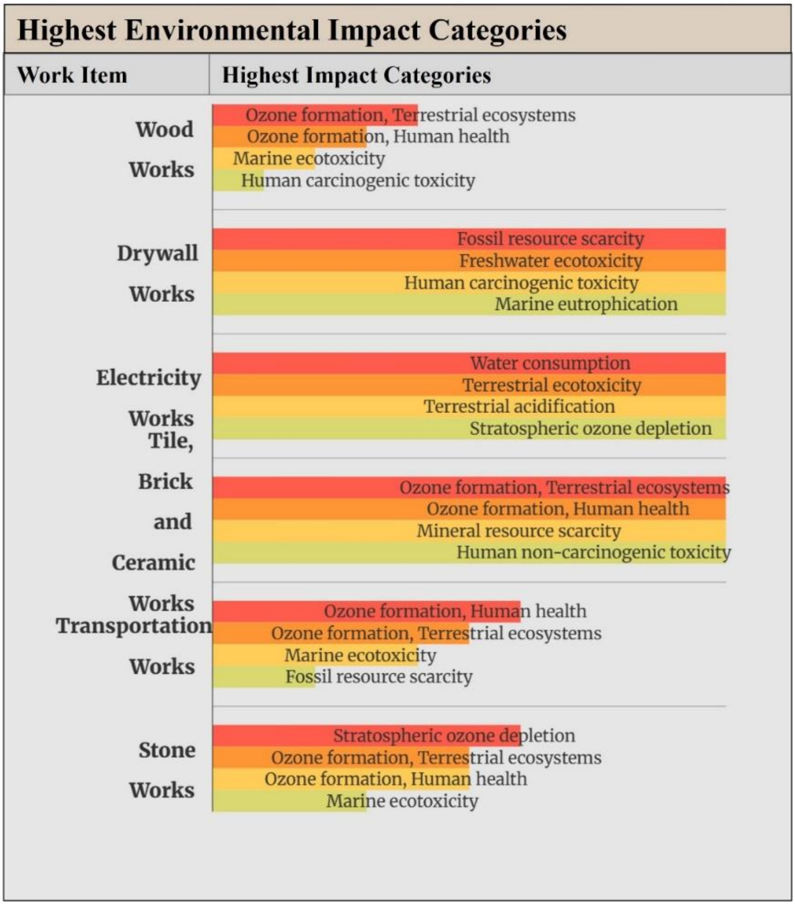

Figure 2. Highest Enviromental Impact Categories (Created by the authors using Autodesk Revit - OpenLCA)

According to these findings, electrical works have the highest environmental impact in all categories, while drywall works have reached critical values especially in terms of water and fossil resource consumption. Tile, brick and ceramic works were characterised by human health impacts such as toxicity and ozone formation. Stone and haulage works were identified as having a moderate environmental burden, while woodworking was identified as the process with the lowest impact (Figure 2).

The life cycle assessment of the restoration process has detailed the environmental impacts of work items across different categories. The analyses show that activities with high energy consumption and material intensity stand out in certain environmental indicators. For example, electrical work has a dominant impact in many categories, while ceramic, brick, and tile work exhibit significant intensity in terms of resource use. In contrast, stone and wood work achieved relatively lower values but made notable contributions in some categories. The numerical findings clearly show which environmental dimensions each work item has a more dominant impact on, and these differences provide a basis for discussions on which steps in the restoration process need to be improved. Thus, the data obtained not only evaluates the current project but also serves as a reference for making more environmentally conscious decisions in similar restoration works.

The highest environmental impact in the global warming (kg CO_2 eq) category was observed in ceramics, brick, and tile work, at 11,735.1 kg CO_2 eq. Electrical work ranked second at 10,788.7 kg CO_2 eq, while drywall work reached 8,247.5 kg CO_2 eq. The lowest impact was recorded in woodworking, at 544.3 kg CO_2 eq. This result shows that energy-intensive work items contribute significantly more to global warming.

In the terrestrial acidification (kg SO_2 eq) category, electrical works showed the highest value at 60.4, followed by ceramic/brick/tile works at 45.2. Stone works remained at a lower level at 10.7. In terms of terrestrial ecotoxicity (kg 1,4-DCB), electrical works stood out with 1,293.7, while ceramic/brick/tile works reached 580.4 and stone works reached 204.5.

This situation reveals that electrical works, in particular, have a strong impact on acidification and toxicity in the ecosystem.

In the fossil resource scarcity category, plasterboard work has the highest value at 2,232.1 kg oil eq. This is followed by electrical work at 1,696.2 kg oil eq and ceramic/brick/tile work at 1,570.8 kg oil eq. In the mineral resource scarcity category, ceramic/brick/tile works stand out by a wide margin with 353.8 kg Cu eq, exhibiting a much higher resource consumption than all other work items.

This study demonstrated how building information modelling (BIM) systems can be integrated into environmental analysis processes by using Revit and OpenLCA together. By combining the detailed data generation capacity of Revit with the multi-layered analysis capabilities of OpenLCA, a powerful system infrastructure has been created that provides both numerical and visual outputs for sustainability-oriented decisions.

This approach fills an important gap by presenting in detail the steps and results of LCA application in restoration projects, which have been little studied in the literature. It also provides researchers and practitioners with a measurable method to compare the environmental impacts of traditional and modern materials.

- **Natural material misconception:** The findings show that materials of natural origin are not always environmentally sustainable. Even local and natural materials can cause high resource consumption in the production and application processes. Therefore, the environmental impact of each input should be analysed separately.
- **Lack of databases:** Existing LCA databases do not adequately cover materials and processes specific to restoration projects. This situation

reveals the necessity of data production specific to local and historical building stock.

- **Accessibility problem:** The high cost of existing databases constitutes an important obstacle to academic research. In order for sustainable architecture practices to become widespread, it is critical to develop open access, comprehensive and local databases.
- **Natural material misconception:** The findings show that materials of natural origin are not always environmentally sustainable. Even local and natural materials can cause high resource consumption in the production and application processes. Therefore, the environmental impact of each input should be analysed separately.
- **Lack of databases:** Existing LCA databases do not adequately cover materials and processes specific to restoration projects. This situation reveals the necessity of data production specific to local and historical building stock.
- **Accessibility problem:** The high cost of existing databases constitutes an important obstacle to academic research. In order for sustainable architecture practices to become widespread, it is critical to develop open access, comprehensive and local databases.

This study has demonstrated the applicability and decision support potential of life cycle analysis in restoration projects. The findings show that restoration should be evaluated not only in terms of aesthetics and culture, but also in terms of environmental sustainability. The data obtained from the analyses revealed that different work items have a concentrated impact on environmental effects in different categories. In particular, it was observed that electrical work has the highest impact in many categories, while other work items stand out in specific environmental indicators. This distribution is supported by graphs that enable a comparative view of the environmental impacts of all work items (Figure 3). This method, developed by using Revit and OpenLCA together, makes an important contribution to increase environmental responsibility and support data- driven decision-making processes in the architecture and building sector.

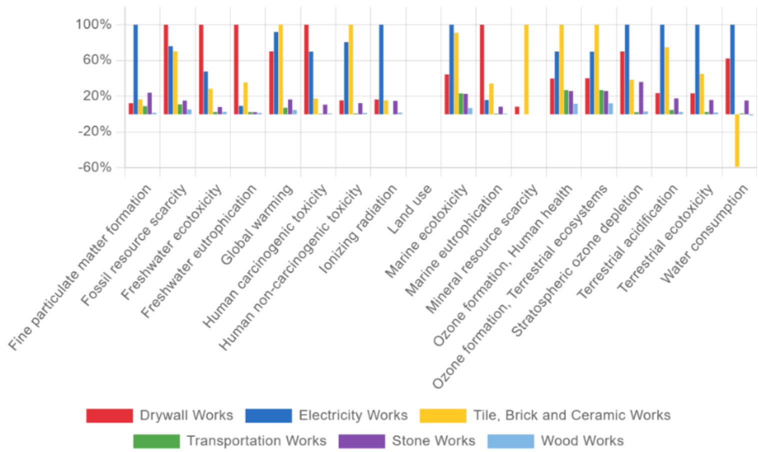

Figure 3. Relative results of construction work items by environmental impact categories (Created by the authors using Autodesk Revit - OpenLCA)

The findings of this study are consistent with the results of similar studies in the literature. As Huuhka et al. (2023) point out, choosing renovation over new construction offers a more environmentally sustainable approach. Similarly, analyses conducted by Almeida et al. (2015) in a low-income residential area have shown that optimization can be achieved in terms of energy efficiency and carbon emissions. Kertsmik et al. (2024) emphasize that deep renovations of historic buildings can achieve near-zero energy levels, highlighting the critical importance of restoration processes in terms of environmental impacts. In this context, the results obtained in this study on mansion restoration are supportive of the findings in the existing literature.

The application of life cycle assessment in historical structures is critical not only in terms of measuring energy and carbon emissions, but also in establishing a balance between the preservation of cultural heritage and environmental sustainability. Determining the environmental impacts of traditional materials (stone, wood, brick) enables more conscious and sustainable decisions to be made during restoration processes. As Çelebi and Arpacıoğlu (2025) emphasize, the embodied energy and carbon load carried by building components throughout their life cycle plays a decisive role in environmental performance. This study demonstrates that environmental impacts in historical building restoration can be comprehensively addressed using an OpenLCA-based approach and provides a guiding framework for developing sustainable conservation strategies.

Acknowledgements and Information Note

In this section was developed within the scope of a graduate-level course at Bursa Uludağ University, Faculty of Architecture. The author wishes to sincerely thank the course instructors for their insightful comments, academic support, and valuable guidance throughout the preparation of this work.

This article has been prepared in accordance with national and international research and publication ethics principles. There is no application that requires Ethics Committee Approval within the scope of the study.

Author Contribution and Conflict of Interest Declaration Information

The entire text of the study was written by the author and then reviewed by the faculty members and necessary scientific and contextual arrangements were made. There is no conflict of interest.

References

Almeida, M., Bencresciuto, A., Ferreira, M., & Rodrigues, A. (2015). Cost-effective energy and carbon emission optimization in building renovation – A case-study in a low income neighbourhood. *Energy Procedia, 78,* 2403–2408. https://doi.org/10.1016/j.egypro.2015.11.203

Ay, A., Ertürk, M. M., Bingöl, Ü., Altan, L., & Yurtkuran, M. (2004). Uludağ Üniversitesi Atatürk Rehabilitasyon Uygulama ve Araştırma Merkezi Kükürtlü Kaplıcalarının son 10 yıllık terapötik etkinlikleri. Romatizma, 19(1), 43–54.

Çelebi, N. G., & Arpacıoğlu, Ü. (2023). *Evaluation of life cycle energy efficiency of buildings. In Ö. İ. Tuluk* (Ed.), Proceedings of the 8th International LivenARCH Congress: Re/De/Generation(s) in Architecture (Vol. 2, pp. 592–602). Karadeniz Technical University, Faculty of Architecture.

Çelebi, N. G., & Arpacıoğlu, Ü. (2025, March). *Life cycle assessments (LCA) and life cycle costing (LCC) of structural systems*. In A. Aksakallı & A. Ada (Eds.), Proceedings of the Asia Pacific 11th International Modern Sciences Congress (pp. 48–53). Liberty Academic Publishers. Ho Chi Minh, Vietnam.

Danish, M. (t.y.). *Life Cycle Assessment*, OpenLCA software, Environmental Assessment [Online kurs]. Udemy. https://www.udemy.com/

Elnaggar, A. (2024). Nine principles of green heritage science: Life cycle assessment as a tool enabling green transformation. *Heritage Science,* 12, 7. https://doi.org/10.1186/s40494-023-01114-z1

Fahlstedt, O., Rasmussen, F. N., Temeljotov-Salaj, A., Huang, L., & Bohne, R. A. (2024). Building renovations and life cycle assessment - A scoping literature review. *Renewable and Sustainable Energy Reviews*, 203, 114774. https://doi.org/10.1016/j.rser.2024.114774

Huuhka, S., Moisio, M., Salmio, E., Köliö, A., & Lahdensivu, J. (2023). Renovate or replace? Consequential replacement LCA framework for buildings. *Buildings and Cities, 4*(1), 212–228. https://doi.org/10.5334/bc.309

Kertsmik, K.-A., Arumägi, E., Hallik, J., & Kalamees, T. (2024). Low carbon emission renovation of historical residential buildings. *Energy Reports, 11*, 3836–3847. https://doi.org/10.1016/j.egyr.2024.03.030

Mazzetto, S. (2024). Comparative life cycle assessment of traditional and modern materials in heritage building restoration: A case study from Ushaiger Village. *Sustainability*, 17(1), 25. https://doi.org/10.3390/su17010025

Serrano, J., Dias, A., Ferreira, J., & Bragança, L. (2022b). Restoration as a sustainable strategy for heritage buildings: Environmental and cultural perspectives. *Journal of Cultural Heritage Management and Sustainable Development*, 12(3), 389–404. https://doi.org/10.1108/JCHMSD-11-2020-0172

Serrano, T., Kampmann, T., & Ryberg, M. W. (2022a). Comparative life-cycle assessment of restoration and renovation of a traditional Danish farmer house. *Building and Environment*, 219, 109174. https://doi.org/10.1016/j.buildenv.2022.109174

Ayşe Begüm KAHYA
E-mail: aysebegumkahya@gmail.com
Educational Status: M.Sc Student
License: Bahcesehir University, Faculty of Architecture and Design, Architecture Department, 2013-2018.
Degree: M.Sc., Bursa Uludag University Graduate School of Building Sciences, Department of Architecture, 2025- in progress.

Assessing Sustainability of a Turkish Cultural Heritage Building through Revit Tally-Based Life Cycle Analysis

Rabia Tuğçe İNCE [1]

[1] Bursa Uludağ University, Graduate School of Natural and Applied Sciences, Department of Architecture, Nilüfer, Bursa/Türkiye.
ORCID: 0009-0000-0526-736X
E-mail: rtugceince@gmail.com

Citation: İnce, R. T. (2025). Assessing Sustainability of a Turkish Cultural Heritage Building through Revit Tally-Based Life Cycle Analysis. Beceren Öztürk, R. & Çahantimur, A. (Eds.). **Contemporary Approaches in Architecture: The Role of Architecture in the Circular Economy.** 2025, Chapter:8, 187-219. ISBN: 978-625-378-348-8. Iksad Publications. DOI: https://doi.org/10.5281/zenodo.17316766

1. Introduction

The intensification of climate change and the degradation of the natural environment have attracted increased attention in recent years. "The sixth assessment report (AR6), published by the IPCC in 2023, showed that anthropogenic greenhouse gas emissions reached 59 GtCO2eq/year in 2019, with the construction sector accounting for 21% of the total" (Ge S. et al., 2025). The cultural heritage protection and restoration field is increasingly considering the contribution of materials and processes used in conservation projects to environmental sustainability. Protecting cultural heritage structures is of great cultural, economic, and ecological importance. Preservation, rather than demolition and reconstruction, is considered sustainable. Therefore, cultural heritage structures require frequent repair and conservation. Prior to conservation and restoration, specific analyses should be conducted to assess their environmental impacts (Franzoni et al., 2018).

As a widely adopted standard methodology for the comparative assessment of construction and building materials, life cycle assessment (LCA) can be usefully applied to conservation materials when specific site-specific issues related to the definition of functional units and reference flows are appropriately addressed (Dal Pozzo A. et al., 2024). As an integrated method for the eco-rehabilitation and adaptive reuse of cultural heritage buildings (CHBs), LCA allows for examining the ecological impacts of existing structures.

The primary effect of LCA is that it considers the entire life cycle of alternatives to be used in pre-restoration renovation, from raw material production, through production and manufacturing, to overuse and waste treatment. LCA provides results that support an ecological approach by identifying the alternative with the lowest potential environmental impact. LCA is often used to measure the function of buildings and the environmental impact of building components. Thus, LCA on historic buildings can be used to determine the most environmentally friendly parameters for transforming existing building stock. Reusing existing building stock avoids producing impact-intensive raw materials, such as concrete, mineral wool, and steel, typically required to construct new buildings (Serrano T. et al., 2022). The databases used for LCA calculations provide important guidance in the resulting analyses. Bibliometric analyses concluded that limited LCA tools are used in building materials research and require further development. Tally software—an LCA tool integrated into Autodesk Revit enables comparison of building materials to evaluate restoration options' environmental impact with rapid research results. The analysis is applied to a historic building in Bursa to inform future restoration projects. The building in focus is the Bursa Kükürtlü Atatürk Hydrotherapy Center Social Facility, currently operating as the Uludağ University SUAM Dermato-Cosmetology Unit. Building Information Modeling (BIM) of the selected historically registered cultural heritage structure—namely the Bursa Kükürtlü Atatürk Hydrotherapy Center Social Facility, currently operating as the Uludağ University SUAM Dermato-Cosmetology Unit—was performed in Revit and used in conjunction with Tally. The LCA examined all building materials in terms of weight, size, type, and processability. The results indicate that the integration of BIM and LCA supports sustainable development goals and offers a robust methodology for enhancing environmental protection and improving decision-making in the construction industry, particularly during the early design phase. By providing a detailed assessment of the environmental performance of materials used in heritage buildings, the study aims to contribute to more sustainable restoration practices and inform future projects.

2. Literature Review

The construction sector has become a key driver of global environmental impacts due to its intensive use of raw materials and energy consumption. Consumption and mass production models constitute the primary source of irreversible ecological problems such as climate change and ozone depletion. At this point, the sustainability of buildings is only possible through technological and methodological advances in production methods. In the building design process, environmental impacts must be assessed for traditional parameters such as function, cost, and safety, as well as for all life cycle stages, including use, disposal, distribution, and raw material acquisition. In this context, Life Cycle Assessment (LCA) has gained an important place in architecture as a tool that systematically analyzes the environmental impacts of buildings and products, from raw material procurement to disposal (Saunders et al., 2013). LCA is used for environmental performance and supports decision-making processes regarding economic sustainability, technical durability, and social impact. Technical components such as material diagrams, lifecycle cost analyses, and functional unit definitions enable the integration of LCA into architectural projects. In recent years, LCA has played a decisive role in ecological architecture strategies in the following areas (Mba et al., 2024):

- Increasing energy efficiency by expanding renewable and passive systems,

- Increasing land use efficiency and green space potential,

- Reducing carbon footprint through compact and integrated designs,

- Developing recycling policies in material selection,

- Supporting sustainable infrastructure with innovative materials.

LCA enables the monitoring of the environmental impacts of the material lifecycle and enables the selection of environmentally friendly materials. In ecological architecture, these analyses contribute to the harmonious integration of buildings with natural ecosystems and social sustainability. LCA analyses conducted in line with Circular Economy (CE) principles (Figure 1.) guide strategies such as adaptability, material reuse, and easy demolition throughout the building's lifespan (Honarvar et al., 2022). The reuse of historic buildings, in particular, contributes to preserving cultural heritage and reducing environmental impacts associated with the material production of new buildings. Giving new functions to historic areas through adaptive reuse offers environmental, social, and cultural benefits. Carbon planning aims to reduce carbon emissions through renewable energy integration and efficient transportation systems. In this regard, integrating solar panels, wind turbines, and passive systems into building design promotes low-carbon lifestyles and contributes to sustainable energy policies (Mba et al., 2024; Pizzol, 2015).

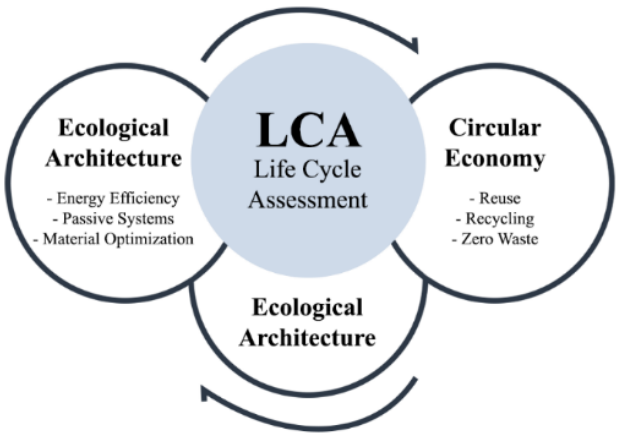

Figure 1. Interactions between LCA, Ecological Architecture and Circular Economy (Edited by the author)

Consequently, the integration of the LCA method with circular economy principles enables the implementation of resource reduction, recycling, and reuse strategies at the building scale. Factors such as material quality assessments, preservation of technical and economic durability, long-term product use, and waste reduction contribute to an integrated design process with an understanding of environmental responsibility. For example, while hardwood flooring and low-CO_2-emission tiles offer environmental advantages, local recycling potential is a determining factor in material selection (Honavar et al., 2022).

Life cycle assessment initiatives address nine planetary boundaries: climate change, ocean acidification, stratospheric ozone depletion, the nitrogen cycle, the phosphorus cycle, global freshwater use, land use change, biodiversity loss, atmospheric aerosol load, and chemical pollution. Global initiatives such as the European Green Deal, which include absolute sustainability and climate targets, are being introduced to ensure global human and economic well-being. Key themes include transitioning to a circular economy, zero pollution, transforming agriculture and rural areas, access to clean and reliable energy, sustainable transportation, and protecting Europe's natural capital. Governments prioritize life cycle assessments and develop targeted policies to minimize environmental impacts. All these initiatives are expected to contribute not only to economic and environmental sustainability but also to innovation (Kalıpçıoğlu, 2025).

2.1. Applications of LCA in Historic Buildings and Their Influence on Restoration Decision-Making

Cultural heritage, as a set of values that embody a society's historical memory and identity, is a responsibility that must be passed on to future generations. This transfer process should be ensured through physical protection and by integrating cultural continuity with sustainable development principles. Actors within management mechanisms are expected to address this responsibility within the social responsibility framework and environmental awareness. The preservation of cultural heritage is closely related to the restoration of the structures and works of art that constitute it and the environmental impacts of the materials and techniques used in this process. Heritage and sustainability are approached as an integrated perspective that blends past values with future potential (Serrano et al., 2022). In this context, systems such as life cycle management (LCM) aim to assess environmental, social, and economic sustainability together. Life cycle assessment (LCA) is the most common and reliable method for this quantitative assessment.

With increasing environmental awareness, the ISO 14000 series of standards has been developed to measure the environmental impact of buildings. Modules such as Environmental Labels and Declarations, Ecodesign, and Life Cycle Assessment within these standards provide tools for determining the environmental performance of products (Lee & Inaba, 2004). Commonly used LCA standards in analysis include ISO 14040-14044, ISO 21930:2017, ISO 21931:2010, EN 15804:2012, and EN 15978:2011. These standards reference the "cradle-to-grave" system and consider all life stages of building components. The LCA approach contributes to the development of the concept of "Cultural Heritage Life Cycle Management" (CH-LCM) by combining it with complementary methods such as life cycle costing (LCC) and social life cycle assessment (S-LCA) to measure the sustainability of restoration processes (Settembre-Blundo et al., 2014).

CH-LCM is recognized in the literature as an innovative approach that aims to integrate the economic and social impacts of cultural heritage conservation through LCA. However, existing studies indicate a lack of empirical data on applying LCA in cultural heritage projects and the need for more comprehensive methodologies (Fregonara et al., 2015). In restoration decisions for historic buildings, LCA allows for comparing multiple alternatives regarding their environmental impacts. Evaluating the materials and techniques used in the original construction of buildings is particularly important for cultural preservation principles. However, energy efficiency improvements achieved through restoration may be limited compared to standard solutions recommended by contemporary building codes, increasing the importance of the multidimensional data provided by LCA in intervention decisions.

LCA provides a scientific basis for the sustainable transformation of historic buildings by analyzing past, present, and future building use scenarios. For example, an LCA analysis of restoration work in Uncastillo, a Spanish village in the Cinco Villas region of the province of Zaragoza (Aragon Autonomous Community), with a complex socio-economic system, showed an environmental impact of 321 Pt, with 81% attributed to the restoration of the palace, 16.5% to the restoration of the tower, and 2.4% to the layout of the access to the monumental complex. The data show the impacts of three restoration processes. The most significant impact for all studies, the negative impact on human health, was found to be 49.8%, primarily related to transporting building materials and stone from the extraction sites to the restoration site in Uncastillo, contributing to climate change (Settembre-Blundo et al., 2018).

2.2. Integration of LCA with BIM-Based Building Modeling

Building Information Modeling (BIM) is a fundamental tool for digitalization in design and project management processes. BIM models provide decision-makers with speed and accuracy, particularly in material management, energy efficiency, and environmental impact analysis. In the context of sustainability, integrating BIM with Life Cycle Assessment (LCA) tools allows for assessing the environmental impacts of construction projects at the early stages of design (Serrano-Baena et al., 2023). The combined use of BIM and LCA produces comprehensive data for topics such as estimating carbon emissions, comparing the environmental impacts of different building materials, and developing waste management strategies. This allows for environmentally sensitive decisions to be made throughout the project process and supports sustainability standards. BIM-based design variations provide users with a comprehensive decision support system, ranging from energy consumption estimations to environmental impact analyses (Naijara et al., 2017).

3. Methodology and Material

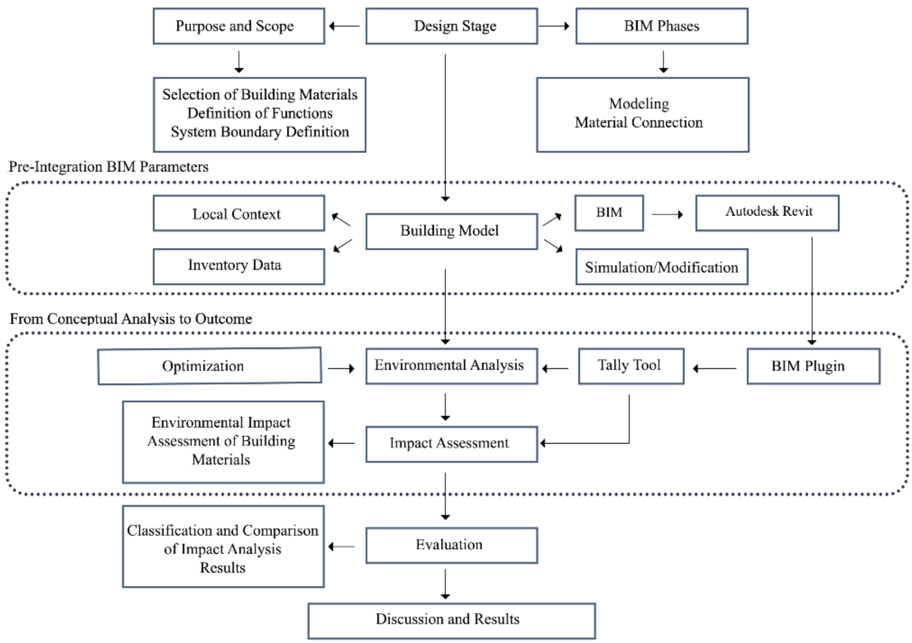

Figure 2. LCA Study Methodology (Edited by the author using the Naijara et al. (2017))

The methodology used in this study is based on the integrated work of Autodesk Revit and Tally software. The application methodology using the Tally tool is structured around the following steps:

1. Purpose and Scope Definition: The study's environmental objectives and modeling boundaries are determined.

2. BIM Phases: Building planning and three-dimensional modeling are performed in the Autodesk Revit environment.
3. Material Inventory: Local location data, material types, and quantities are integrated into the model.
4. LCA Application: The environmental impacts of selected building materials are assessed using Tally software.
5. Data Analysis and Optimization: Model data is analyzed to compare the environmental performance of design alternatives.
6. Discussion and Results: Differences between alternatives are presented, and environmental recommendations for the design are developed.

This methodology is a structured decision analysis system that supports sustainable decision-making, particularly during the early design phase. Figure 2 visualizes the BIM-LCA integration process within the context of the Tally application. The BIM-integrated LCA application represents a transition to new modeling strategies prioritizing environmental sensitivity in the design process (Figure 3).

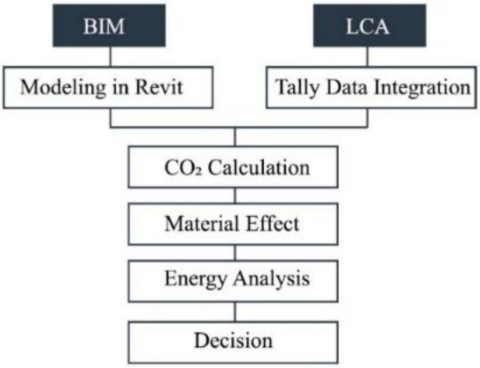

Figure 3. BIM-Based Lifecycle Assessment Methodology (Created by the author)

The modeling process with Autodesk Revit, data analysis outputs from the Tally tool, and decision support stages are visually presented. Assessing environmental impacts at an early design stage provides critical contributions to sustainability. Source: Edited by the author.

4. Integration of Digital Modeling and Life Cycle Assessment (LCA) in Historic Buildings Case Study: Bursa Kükürtlü Atatürk Hydrotherapy Center

This section explores the integration of digital modeling, Building Information Modeling (BIM), and Life Cycle Assessment (LCA) methodologies in the context of cultural heritage preservation, using the the Kükürtlü Atatürk Hydrotherapy Center Social Facilities Building in Bursa as a case study. To evaluate both the structural integrity and environmental impact of the historic building, a digital model was developed using Autodesk Revit, followed by a material-based LCA conducted via the Tally plugin on the same platform.

The objective of this integration is to generate sustainability-oriented data to inform preservation strategies, assess the ecological footprint of restoration materials, and illustrate the role of digital tools in enhancing heritage-sensitive architectural practices. The selected building, currently functioning as the Dermato-Cosmetology Unit within Uludağ University's Health Application and Research Center (SUAM), offers a compelling case due to its architectural features and conservation potential.

Environmental and structural data were sourced from official architectural documentation, including plans, sections, and elevations provided by public institutions. Complementary visual data were obtained through a technical site visit conducted by a field expert, with on-site photographs supporting the digital modeling process. Based on this comprehensive dataset, a three-dimensional BIM model was constructed and subsequently integrated into Tally for LCA, enabling a systematic evaluation of the environmental impacts associated with the building's material composition.

Situated at the intersection of Çekirge and Kükürtlü Streets in central Bursa, the hydrotherapy center is part of a historically significant thermal complex affiliated with Bursa Uludağ University. The complex reflects a layered architectural history: the initial structure was commissioned by Sultan Murad I Hüdavendigâr during the Early Ottoman period, with subsequent additions by Sultan Bayezid II and later by Suleiman the Magnificent (Türkiye Kültür Portalı, 2025).

Environmental and structural data were sourced from official architectural documentation, including plans, sections, and elevations provided by public institutions. Complementary visual data were obtained through a technical site visit conducted by a field expert, with on-site photographs supporting the digital modeling process. Based on this comprehensive dataset, a three-dimensional BIM model was constructed and subsequently integrated into Tally for LCA, enabling a systematic evaluation of the environmental impacts associated with the building's material composition. Situated at the intersection of Çekirge and Kükürtlü Streets in central Bursa, the hydrotherapy center is part of a historically significant thermal complex affiliated with Bursa Uludağ University. The complex reflects a layered architectural history: the initial structure was commissioned by Sultan Murad I Hüdavendigâr during the Early Ottoman period, with subsequent additions by Sultan Bayezid II and later by Suleiman the Magnificent.

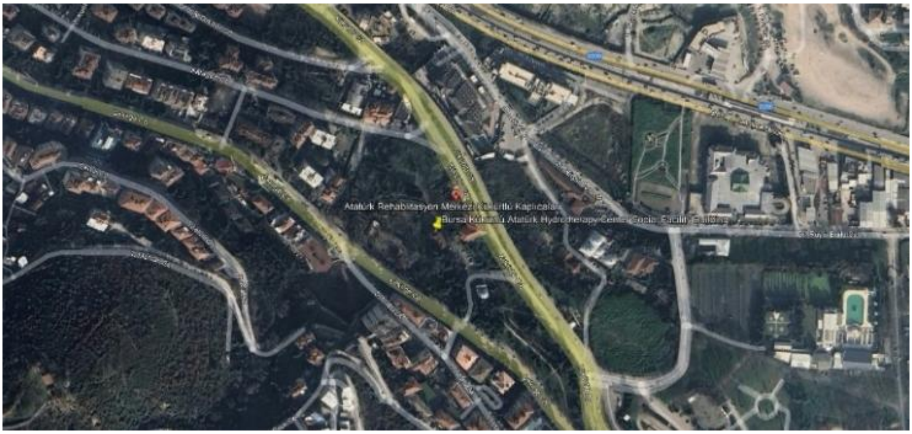

Figure 4. Location of Bursa Kükürtlü Atatürk Hydrotherapy Center Social Facility Building (Google Earth, 2025)

Currently, the thermal spring complex operates as the Atatürk Rehabilitation and Research Center under Bursa Uludağ University. Within this complex, the Social Facilities Building serves dual functions: it houses both the Dermato-Cosmetology Polyclinic and the SUAM Dermato-Cosmetology Unit of the university. Architecturally, the Social Facilities Building and its entrance structures—located opposite one another—are constructed primarily of wood and date back to the Republican era. The structural system is based on traditional timber framing, with chamfered-edge blended brick used as infill material. During restoration interventions, reinforced concrete elements were introduced, and straw-based hydraulic binders were identified in the original infill composition. Distinctive features include diagonally placed wooden beams on the short façades, and projecting balcony and bay window structures formed by outward-extending timber beams. These are supported by traditional wooden buttresses known locally as Eli Böğüründe. Figure 5 illustrates the balcony design and timber load-bearing details.

The roof system incorporates U-shaped and L-shaped iron profiles that interconnect all structural components. Timber materials were selected from insect-resistant and highly durable hardwood species, notably pine. In alignment with Ottoman architectural traditions, the original rain gutter system was replaced by wide eaves, although modern gutters were subsequently added. Interior ceiling surfaces were finished with mortar-based cladding.

The total gross building volume was calculated as 203.7 m³, providing a compact yet structurally rich example of early Republican-era architectural adaptation within a heritage context.

Figure 5. The North Facade of the Building (a). The South Facade of the Building with the Details (b). (Source: The Author's Archieve)

Based on the comprehensive dataset—including architectural documentation, site observations, and material specifications—a Building Information Model (BIM) was developed to facilitate Life Cycle Assessment (LCA). This model incorporated environmental data layers to evaluate material-specific carbon emissions, energy consumption, and reuse potential. Through integration with the Tally application, the process enabled a rapid and holistic assessment of the building's environmental performance.

The BIM-LCA synergy provided a robust framework for generating sustainability-oriented insights, supporting environmentally responsible decision-making throughout the restoration process. By quantifying the ecological impacts of material choices, the methodology contributes to the development of conservation strategies that align with both heritage preservation and climate-conscious architectural practice.

4.1. Life Cycle Assessment (LCA) with the Tally Tool

Tally is an analysis tool integrated with the Autodesk Revit environment, developed to perform Life Cycle Assessments (LCA) tool is embedded within the Autodesk Revit environment, designed to evaluate the environmental impacts of buildings through a comprehensive *cradle-to-grave* methodology. It enables the assessment of architectural, structural, and finishing systems by quantifying their ecological footprint across all life cycle stages—from material extraction to end-of-life disposal (Phillips et al., 2020).

Tally supports. Both comparative analyses of individual building designs and multi-parameter analyses evaluations, thereby generating sustainability-oriented data to inform design decisions. The tool is highly. Customizable, allowing users to define parameters such as building typology (e.g., office, school, residential), functional requirements (regulatory standards, energy performance),occupancy models, spatial efficiency, and projected service life.

To ensure methodological rigor, the modeler must establish functional equivalence among reference buildings and clearly define the scope of the assessment, encompassing construction, operational phases, and end-of-life scenarios. Tally's analytical framework is underpinned by the GaBi LCA database, which integrates material specifications, installation processes, and environmental impact metrics. This infrastructure enables detailed calculations of material production, maintenance, replacement cycles, and usage patterns. Additionally, users may opt to include construction-related impacts—such as on-site energy, water, and fuel consumption—as well as operational energy use, thereby enhancing the granularity of the analysis. Figure 7 presents the LCA workflow within the Tally-Revit integration, highlighting key input parameters, analytical stages linked to the GaBi database, and output indicators such as carbon footprint and embodied energy.

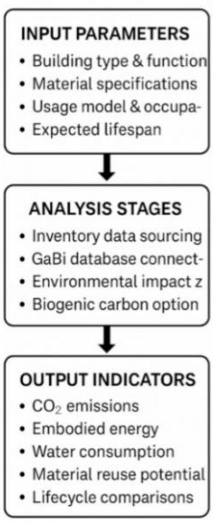

Figure 7. Tally-Based Life Cycle Assessment Process: Input Parameters – Analysis Stages – Output Indicators (Created by the author)

Tally allows modelers to define advanced parameters such as biogenic carbon flow—carbon emissions and sequestration originating from biological sources like trees and algae, excluding fossil-based inputs. This capability enables a nuanced evaluation of the environmental characteristics of building materials, enhancing the precision of sustainability-driven design decisions.

The tool incorporates a comprehensive inventory of architectural components, including hardware, insulation materials, adhesives, coatings, and finishing elements. This holistic approach ensures that the environmental impact assessment encompasses all material layers and systems within the building envelope.

Moreover, Tally is compatible with the Environmental Product Declaration (EPD) framework. While EPD data typically covers only the Product stages (A1–A3), Tally extends the analysis across the entire building life cycle, offering a more complete and consistent basis for environmental comparisons. This functionality supports robust evaluations of design alternatives and ensures methodological consistency across reference models (see Table 1).

Table 1. Life Cycle Assessment (LCA) Modules and Impact Indicators Based on EN 15978 (Created by the authors using Autodesk Revit-Tally)

Module	Description
A1–A3 (Product Stage)	Raw material extraction, transport, processing, and product manufacturing. Infrastructure (e.g. machines, buildings) excluded. Represents cradle-to-gate approach.
A4 (Transport)	Delivery of 1 kg of material from manufacturer to site. Includes transport types: barge, container ship (27500 DWT), train (1000t), truck (45,000 lb).
A5 (Construction Installation)	Optional. Site energy and water consumption during installation. The modeler must input values.
B2–B5 (Maintenance & Replacement)	Material replacement based on service life. Covers re-production and transport of substituted components.
B6 (Operational Energy Use)	Optional. Site electricity and thermal energy use during operation.
C2–C4 (End-of-Life)	Material recovery, incineration, and landfill. Includes transport from site, treatment, and disposal rates. Material-specific scenarios (e.g. 55% concrete recycled).
D (Benefits Beyond System Boundary)	Energy recovery and secondary material reuse. Modelling includes burden-shifting across life cycles

Table 2. Impact equivalents are calculated in relation to regional ecosystems and expressed as weighted damage potential (e.g. kg CO_2eq.). (Created by the authors using Autodesk Revit-Tally)

Indicator	Unit	Description
Global Warming Potential (GWP)	kg CO_2eq	Climate impact from greenhouse gases (CO_2, CH_4).
Acidification Potential (AP)	kg SO_2eq	Effect of emissions lowering pH in water/soil.
Eutrophication Potential (EP)	kg Neq	Excessive nitrogen/phosphorus affecting aquatic ecosystems.
Ozone Depletion Potential (ODP)	kg CFC-11eq	Substances reducing stratospheric ozone layer.
Photochemical Ozone Creation (Smog) Potential (SFP)	kg O_3eq	Ground-level ozone from VOCs and NO_x under sunlight.
Primary Energy Demand (PED)	MJ	Total energy required—split into renewable/non-renewable.
Non-renewable Energy Use	MJ	Contribution from fossil-based sources (e.g. oil, gas).

Workflow (including Table 1.-2.) of Life Cycle Assessment (LCA) using the Tally application integrated into Autodesk Revit. The diagram illustrates the key stages of the LCA process—from input parameters such as building type and material specifications to analytical procedures using GaBi databases, culminating in environmental output indicators like CO_2 emissions, energy demand, and smog formation potential. This workflow enables comprehensive assessment of design alternatives, supports sustainable material selection, and facilitates data-driven decision-making in historical restoration projects.

5. Evalution and Disscussion

In this study, a post-restoration life cycle assessment (LCA) was conducted for the Bursa Kükürtlü Atatürk Hydrotherapy Center Social Facility Building. The building, digitally modeled in Autodesk Revit, was analyzed within the "cradle-to-grave" system boundaries using the Tally LCA tool. A complete classification of the selected materials and processes was performed, including the biogenic carbon impact, and an average service life of 60 years was considered.

Material selection was based on products that provided the closest equivalent to the existing structure in composition and properties. For example:

- Interior walls: Laminated Strand Lumber (LSL), US, CA iEPD
- Ceilings: Mineral Wool, Knauf DDP-EPD, and Softwood Lumber I, US, CA iEPD

Building components included in the inventory include ceilings, curtain wall studs/panels, doors, floors, roofs, stairs, railings, structure, walls, and windows. Based on the 60-year analysis results:

- A1–A3 Production Stage: A negative impact of –28,412 kg CO_2eq was reported thanks to biogenic carbon sequestering materials.
- C2–C4 Disposal Stage: The highest carbon emissions occur at 162,585 kg CO_2eq in this stage.
- Module D Recycling: A positive impact of 7,010 kg CO_2eq indicates that carbon emissions from recycling may occur.
- Total Primary Energy Consumption: The most intensive process occurred in the A1–A3 stages, recorded at 5,000,765 MJ.
- Energy Savings in Module D: A reduction of –705,013 MJ was identified, indicating the potential for contribution to the energy cycle through recycling.

These results demonstrate that choosing biobased materials in building design creates a carbon sink effect and that disposal processes are among the most critical stages in sustainability (Figure 8.). Furthermore, given the high environmental impact of recycling scenarios, material selection in restoration decisions should be based on structural and environmental performance.

Environmental Impact Totals	Product Stage [A1-A3]	Construction Stage [A4]	Use Stage [B2-B5]	End of Life Stage [C2-C4]	Module D [D]
Global Warming (kg CO_2eq)	-28.412	7.172	2.392	162.585	7.010
Acidification (kg SO_2eq)	655,9	33,23	10,52	531,7	-130
Eutrophication (kg Neq)	68,83	2,706	0,7812	111,2	-4,71
Smog Formation (kg O_3eq)	13.662	1.098	275,7	2.706	-1.435
Ozone Depletion (kg CFC-11eq)	0,001211	2,456E-010	2,669E-009	3,667E-007	-2,130E-005
Primary Energy (MJ)	5.000.765	104.301	53.413	251.412	-705.013
Non renewable Energy (MJ)	3.161.759	101.805	48.211	235.426	-422.594
Renewable Energy (MJ)	1.839.751	2.522	5.160	16.144	-282.680
Environmental Impacts / Area					
Global Warming (kg CO_2eq/m^2)	-139	35,21	11,74	798,2	34,41
Acidification (kg SO_2eq/m^2)	3,220	0,1632	0,05165	2,610	-0,6378
Eutrophication (kg Neq/m^2)	0,3379	0,01328	0,003835	0,5459	-0,02313
Smog Formation (kg O_3eq/m^2)	67,07	5,391	1,353	13,28	-7,04
Ozone Depletion (kg CFC-11eq/m^2)	5,944E-006	1,206E-012	1,310E-011	1,800E-009	-1,046E-007
Primary Energy (MJ/m^2)	24.550	512,0	262,2	1.234	-3.461
Non renewable Energy (MJ/m^2)	15.522	499,8	236,7	1.156	-2.075
Renewable Energy (MJ/m^2)	9.032	12,38	25,33	79,25	-1.388

Figure 8. Summary of LCA Analysis of a Selected Cultural Heritage Building over 60 years (Created by the authors using Autodesk Revit-Tally)

The results of the analysis show that environmental impacts are concentrated in different modules throughout the building's lifespan. In particular, 91% of total carbon emissions occur in the C2–C4 (disposal) phase. Acidification potential (AP) and eutrophication potential (EP) values were also high in the C2–C4 phase. These impacts stem from emissions released during waste transportation and disposal. Furthermore, the highest smog formation (O_3eq) value was reported during the use phase (275.7 kg O_3eq), indicating that operational energy consumption contributes to ozone depletion. Some negative values in energy and emissions indicate the environmental benefits arising from the reuse and recycling of building materials. Recovery systems were observed to contribute to a carbon-neutral approach through Module D. The environmental contribution rate was determined to be 4%. The impact of the use phase (B2–B5) on global warming is 4%, while the impact of transportation (A4) processes is 1%. Dismountable systems, recyclable material selection, and low-carbon disposal scenarios should be prioritized during the design phase (Figure 9.).

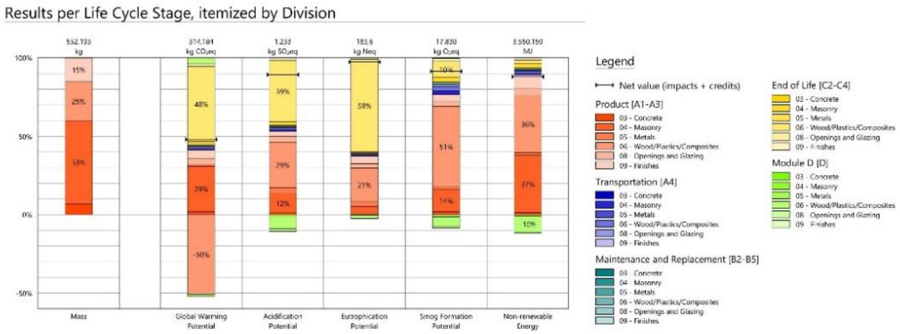

Figure 9. Life Cycle Stage of a Selected Cultural Heritage Building (Created by the authors using Autodesk Revit-Tally)

They also demonstrate that the highest carbon emissions from cultural heritage structures occur during the end-of-life disposal phase (C2–C4). During this phase, environmental impacts significantly increase due to material dismantling, transportation, and final disposal. The -16% negative value observed in the Product Phase (A1–A3) can be explained by the CO_2 absorption of bio-based materials such as wood. This absorption was evaluated as providing environmental credits for the material in the LCA analysis. Within the scope of Module D:

• The 4% negative carbon contribution demonstrates that recycling and reuse provide environmental benefits beyond system boundaries.

• The 11% decrease in Acidification Potential (AP) indicates the positive environmental impact of the material recovery process following disposal.

• The 89% energy dependence in the Product Phase reflects the intensive production process relying on fossil resources.

• Module D's 12% negative energy contribution demonstrates the impact of recycled materials in reducing fossil energy use in new product production.

. The environmental credit earned by Module D demonstrates the vital importance of design decisions such as recyclability and disassembly in sustainable restoration strategies.

Considering the findings, the results in Chart 3 indicate that masonry elements play a dominant role in environmental impacts (Figure 11.). These elements contribute to a 67% impact on the Global Warming Potential (GWP). The wood, plastic, and composite materials used in the building have a 69% acidification potential, an 81% eutrophication potential, and a 63% smog potential. The majority of the building's carbon footprint comes from the masonry.

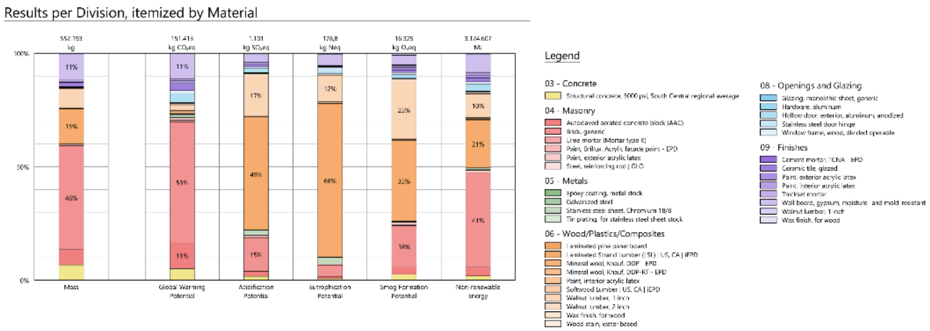

Figure 10. Material Analysis of a Selected Cultural Heritage Building (Created by the authors using Autodesk Revit-Tally)

The analysis of Figure 11. reveals the impact of building components in terms of global warming potential (GWP) based on family groups according to Revit categories. Walls, the most dominant component in terms of mass and volume, account for 54% of the total GWP. Roof systems follow with 23%. This distribution confirms that blended walls are the largest component of the building by volume and contribute the most to the carbon footprint.

A similar distribution is observed in terms of non-renewable energy use; walls account for 51%, and roof systems for 21%. Wooden floors and ceramic-tiled flooring components have a significant impact on smog potential and energy consumption. Ceramic flooring, in particular, despite its low mass, leads to negative impacts on the ecosystem due to its high energy consumption during the production process.

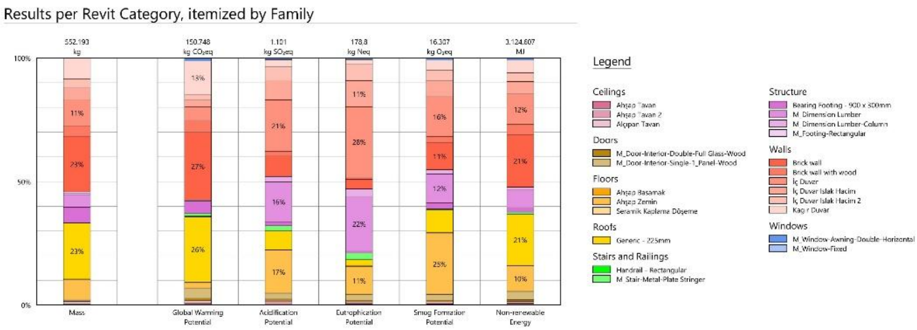

Figure 11. Analysis of a Selected Cultural Heritage Building Specified by Revit Family Categories (Created by the authors using Autodesk Revit-Tally)

In light of these data, the wall system stands out as the first structural component to be considered in the design of the evaluated cultural heritage building in terms of carbon cycle and environmental impacts. Considering the material volume, production type, energy consumption and emission values, redefinition of wall elements and optimization with the use of local and low-carbon materials are recommended in sustainable architecture decisions.

6. Conclusion and Suggestions

Production processes must be more closely aligned with new sustainability regulations focused on reducing environmental impact for economies and industrial systems to achieve their decarbonization goals. Life cycle assessment (LCA) methods support this transformation in the construction industry. Based on the ISO 14040 standard, the LCA framework provides a scientific framework for integrating sustainability criteria into design.

Restoring historic buildings stands out among environmentally friendly options due to its potential to reduce natural resource consumption and virgin material production. LCA analyses allow these savings to be measured, and strategies that strengthen sustainability in restoration decisions can be developed.

The LCA results obtained from the example building examined in this study demonstrated how building services can be improved in specific ecosystems through material analysis through Revit–Tally integration. Because the environmental footprint affects the usage process and all stages, such as production, distribution, and disposal, the analysis revealed the need for an environmentally conscious redesign of building components. To reduce the building's carbon footprint, recommendations such as:

- Alternative wall systems,
- Low-emission material selections,
- Use of products with EPD (Environmental Product Declaration) is presented (Table 3.).

Table 3. The evaluation and discussion resulted in explanations of the findings and suggestions for improvement

Observation	Explanation	Improvement Suggestion
Carbon absorption rates of wood/composite materials	As wood is bio-based, it stores CO_2.	The use of wood in structural and cladding materials can be increased.
Concrete and brick play a dominant role in energy impacts.	Intensive fossil energy is consumed during the production process.	Low-carbon concrete can be preferred, and local production can be supported.
Metals contribute to acidification and smog formation.	Mining and refining processes have significant effects.	Recycled metal use and modular design for reuse can be promoted.
Module D (recovery) provides significant environmental benefits.	There are energy and emission savings.	Design details can be adjusted to include highly recyclable materials and composite elements.
91% of GWP occurs during stages C2–C4.	Disposal processes contribute significantly to carbon emissions.	Design for disassembly and reuse should be adopted, and carbon-neutral disposal methods should be considered.
Negative impacts occur during stages A1–A3.	The use of bio-based materials is effective.	More use of sustainable materials such as wood should be encouraged.
The contribution of Module D is significant.	Recovery systems provide environmental benefits.	Recovery and recycling strategies should be incorporated into the design phase.
Energy and smog impacts are prominent during the production stage.	Industrial production has high environmental impact.	Local, low-carbon, and ecological production methods should be targeted.

In particular, it is recommended that the procurement and processing of wood materials be reevaluated, and that local and low-process alternatives be preferred for cladding and infill materials due to their energy density. Passive design principles, high insulation requirements, material optimization, and reuse strategies are among the study's key findings. LCA evaluates environmental parameters such as energy consumption, greenhouse gas emissions, acidification, eutrophication, water use, and waste generation, enabling the design of existing buildings and future ones based on more sustainable criteria. This holistic approach has revealed significant opportunities to reduce environmental impacts at every stage of a building's lifecycle.

Acknowledgements and Information Note

In this section was developed within the scope of a graduate-level course at Bursa Uludağ University, Faculty of Architecture. The author wishes to sincerely thank the course instructors for their insightful comments, academic support, and valuable guidance throughout the preparation of this work.

The article adheres to national and international standards of research and publication ethics. Ethics Committee approval was not required for the scope and nature of this study.

Author Contribution and Conflict of Interest Declaration Information

The author affirms sole responsibility for the research design, data analysis, and manuscript preparation. No potential conflicts of interest are declared with respect to the research, authorship, or publication of this article.

References

Dal Pozzo, A., Masi, G., Sassoni, E., & Tugnoli, A. (2024). Life cycle assessment of stone consolidants for conservation of cultural heritage. *Building and Environment,* 249, 111153. https://doi.org/10.1016/j.buildenv.2023.111153

Franzoni, E., Volpi, L., Bonoli, A., & Spinelli, R. (2018). The environmental impact of cleaning materials and technologies in heritage buildings conservation. . *Energy & Buildings,* 165, 92–105. https://doi.org/10.1016/j.enbuild.2018.01.051

Fregonara, E. & Coscia, C. (2019). Multi Criteria analyses, Life Cycle approaches and Delphi Method: a methodological proposal to assess design scenarios. *Journal valori e valutazioni,* No. 23. Access Address (18.07.2025): https://siev.org/wp-content/uploads/2020/02/23_13-_-FREGONARA-COSCIA_eng.pdf

Ge, S., O'Ceallaigh, C., & J. McGetrick, P. (2025). A review of best international life cycle assessment (LCA) practices in wood construction: Challenges for Ireland. *Cleaner Environmental Systems*, 16, 100260. https://doi.org/10.1016/j.cesys.2025.100260

Google Earth. (2025). *Kükürtlü, Bursa, Türkiye* [Uydu görüntüsü]. Access Address (29.05.2025): Google. https://earth.google.com

Honarvar, S. M. H., Golabchi, M., Ledari, M. B. (2022). Building circularity as a measure of sustainability in the old and modern architecture: A case study of architecture development in the hot and dry climate. *Energy and Buildings*, 275, 112469. https://doi.org/10.1016/j.enbuild.2022.112469

Kalıpçıoğlu C. (2025). *Avrupa Birliği Mevzuatında Yaşam Döngüsü Değerlendirmesi Yaklaşımının Rolü*. Access address (10.07.2025): https://escarus.com/avrupa-birligi-mevzuatinda-yasam-dongusu-degerlendirmesi-yaklasiminin-rolu/

Lee, K. M., & Inaba, A. (2004). Life Cycle Assessment Best Practices of ISO 14040 Series.

Mba, E. J., Okeke, F. O., Igwe, A. E., Ozigbo, C. A., Oforji, P. I., & Ozigbo, I. W. (2024)**.** Evolving trends and challenges in sustainable architectural design; a practice perspective. *Heliyon*, 10, 20, e39400. https://doi.org/10.1016/j.heliyon.2024.e39400

Naijara, M Figueiredob, K., Palumboc, M., & Haddadb, A. (2017). Integration of BIM and LCA: Evaluating the environmental impacts of building materials at an early stage of designing a typical office building. *Journal of Building Engineering* 14, 115–126. https://doi.org/10.1016/j.jobe.2017.10.005

Phillips, R., Troup, L., Fannon, D., & Eckelman, M. J. (2020). Triple bottom line sustainability assessment of window-to-wall ratio in US office buildings. *Building and Environment*, 182, 107057. https://doi.org/10.1016/j.buildenv.2020.107057

Pizzol, M. (2018 Life Cycle Assessment and the Resilienceof Product Systems. *Journal of Industrial Ecology*, 19, 2. https://doi.org/10.1111/jiec.12254

Saunders, C. L., Landis, A. E., Mecca, L. P., Jones, A. K., Schaefer, L. A., & Bilec M. M. (2013). Analyzing the Practice of Life CycleAssessment Focus on the Building Sector. *Journal of Industrial Ecology*, 17, 5. https://doi.org/10.1111/jiec.12028

Serrano, T., Kampmann, T. & Ryberg, M. W. (2022). Comparative Life-Cycle Assessment of restoration and renovation of a traditional Danish farmer house. *Building and Environment,* 219, 109174. https://doi.org/10.1016/j.buildenv.2022.109174

Serrano-Baena, M. M., Ruiz-Díaz, C., Boronat, P. G., & Mercader-Moyano P. (2023). Optimising LCA in complex buildings with MLCAQ: A BIM-based methodology for automated multi-criteria materials selection. *Energy and Buildings,* 294, 113219. https://doi.org/10.1016/j.enbuild.2023.113219

Settembre Blundo, D., Ferrari, A. M., Fernandéz del Hoyo, A., Riccardi, M. P., & García-Muiña F. E. (2018). Improving sustainable cultural heritage restoration work through life cycle assessment based model. *Journal of Cultural Heritage*, 32, 221–231. https://doi.org/10.1016/j.culher.2018.01.008

Settembre-Blundo, D.; Ferrari, A.M.; Pini, M.; Riccardi, M.P.; Garcıá, J.F.; Del Hoyo, A.P.F. (2014). The Life Cycle Approach as anInnovative Methodology for the Recovery and Restoration of

Cultural Heritage. *J. Cult. Herit. Manag. Sustain. Dev*., 4, 133–148. DOI: 10.1108/JCHMSD-05-2012-0016.

Türkiye Kültür Portalı. (2025). Kükürtlü Kaplıcaları – Bursa.Access Address (16.06.2025): https://www.kulturportali.gov.tr/turkiye/bursa/gezilecekyer/kukurtlu-kaplicalari

Rabia Tuğçe İNCE
E-mail: rtugceince@gmail.com
Educational Status: Master Student
License: Yeditepe University, Faculty of Architecture, Department of Architecture, 2015-2020
Degree: Bursa Uludağ University, Graduate School of Natural and Applied Sciences, Department of Architecture, 2024-Present

Comparative Analysis of Life Cycle Assessment Result Conducted Using Different Software in the Kükürtlü Historical Bath Building

Göktürk Bostancı [1]

[1]Bursa Uludağ University, Master's Program in Architecture, Graduate School of Natural and Applied Sciences, Nilüfer, Bursa/Türkiye.

ORCID: 0009-0009-7983-3008

E-mail: gokturk.96@hotmail.com

Citation: Bostancı, G. (2025). Comparative Analysis of Life Cycle Assessment Result Conducted Using Different Software in the Kükürtlü Historical Bath Building. In A. Çahantimur & R. B. Öztürk (Eds.) **Contemporary Approaches in Architecture: The Role of Architecture in the Circular Economy.** 2025, Chapter:9, 220-237. ISBN: 978-625-378-348-8. Iksad Publications. DOI: https://doi.org/10.5281/zenodo.17316794

1. Introduction

Global environmental challenges are no longer distant concerns, they directly influence how we design and build. Buildings aren’t just static structures; they actively contribute to greenhouse gas emissions, energy usage, and resource depletion across every stage of their existence, from extraction to eventual demolition. That’s why sustainability is no longer an optional goal but an essential principle in construction processes (Dixit et al., 2010; Cabeza et al., 2014).

Life Cycle Assessment (LCA) plays a key role about this issue. It's not just a technical method, it’s a design approach. LCA provides a way to evaluate a building’s environmental performance from start to finish, grounded in data and informed by sustainable design values (ISO 14040, 2006).

In practical terms, architects use LCA to explore choices around materials, energy efficiency, and emissions (Ortiz et al., 2009). Despite its advantages, the use of LCA can be particularly challenging for new users. The amount of data, time, and expertise needed often turns it into a complex puzzle. This is where Building Information Modeling (BIM) steps in. With BIM’s detailed, 3D digital models, it becomes easier to integrate LCA software and streamline the evaluation process (Eastman et al., 2011).

Yet even with advanced tools, results can vary wildly depending on the databases and algorithms used. Different systems mean different outcomes, which is why choosing the right software isn’t just a technical decision but a strategic one (Moncaster & Song, 2012).

For this study, we focused on a historical bathhouse in the Kükürtlü Neighborhood of Bursa, Türkiye. An architectural gem rich in cultural heritage and restoration potential. After documenting the building in detail, we digitally reconstructed it in ArchiCAD and ran environmental impact assessments using three tools:

1. One Click LCA
2. OpenLCA
3. Revit Tally

The interactions, advantages, and disadvantages among the examined programs were first compared internally, and then each platform measured critical indicators like Global Warming Potential (GWP), biogenic carbon capture, Ozone Depletion Potential (ODP), Acidification Potential (AP), and Eutrophication Potential (EP). Comparing the results shed light on how software methods influence outcomes and emphasized the need for thoughtful tool selection when applying sustainability principles to historical architecture.

Figure 1, presents a conceptual flowchart detailing the integration process between Building Information Modeling (BIM) and Life Cycle Assessment (LCA) frameworks. The modeling workflow initiates within ArchiCAD, with subsequent data migration and evaluation carried out using three distinct LCA software platforms;

One Click LCA, OpenLCA, and Revit Tally. Each path highlights the variance in system boundaries, impact categories assessed, and data sources (e.g., Ecoinvent vs. proprietary databases), allowing for comparative interpretation of Global Warming Potential (GWP), biogenic carbon, Ozone Depletion Potential (ODP), Acidification (AP), and

Eutrophication (EP) values.

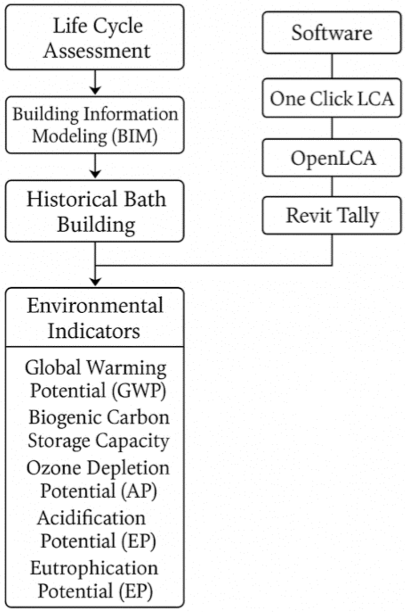

Figure 1. Comparative Analysis of Life Cycle Assessment Result Conducted Using Different Softwares in the Kukurtlu Historical Bath Building (Prepared by author)

2. Method and Materials

This study adopts a comparative Life Cycle Assessment (LCA) methodology to evaluate the environmental performance of a culturally significant historic bath structure in Kükürtlü Neighborhood, Osmangazi district, Bursa, Türkiye. The primary aim is to explore how different LCA software—each applying distinct databases, system boundaries, and calculation logics—impact the interpretation of environmental indicators. Such an approach is vital for heritage-sensitive sustainable design, where material-specific assessment and restoration constraints significantly shape sustainability outcomes.

The method consists of four main stages:

1. Data Collection and Fieldwork
2. Digital Modeling of the Structure
3. Life Cycle Assessments via Three Software Tools
4. Comparative Evaluation of Output Metrics

This staged structure aligns with ISO 14040 and 14044 standards on life cycle methodology (ISO, 2006) and ensures robust analytical comparison based on reproducible processes.

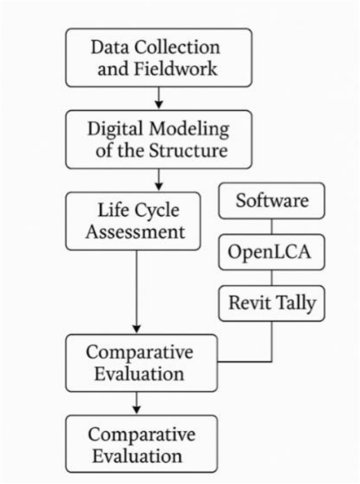

Figure 2. Workflow Diagram of BIM-LCA Integration and Analysis Steps (Prepared by author)

This diagram summarizes the procedural flow: from data acquisition and BIM-based modeling in ArchiCAD, through LCA execution using three software platforms (One Click LCA, OpenLCA, Revit Tally), to comparative synthesis. Arrows indicate data transfer direction and the variation points across tools in databases and impact categories (Figure 2).

Data Collection and Fieldwork; In the initial phase, site surveys were conducted to document the physical structure of the historical bath, focusing on material compositions, architectural elements, and conservation status. Archival sources and restoration project documentation were consulted to supplement the on-site data. These inputs ensured a comprehensive basis for digital modeling and environmental data interpretation.

Digital Modeling of the Structure; Using ArchiCAD, a BIM-based 3D model of the bath structure was created. The model incorporated:

- Detailed geometry (walls, domes, HVAC systems),
- Material specifications (local stone, wood, insulation layers),
- Usage zones and building functions.

This BIM model enabled accurate quantity take-offs and material definitions essential for automated or manual LCA data input.

Life Cycle Assessments via Three Software Tools; Environmental performance was analyzed using three software tools. Each software interacts differently with BIM inputs and environmental databases, which affects the final LCA outputs.

Designed for architects and engineers, this software automates BIM data extraction and computes environmental impacts through an intuitive interface. It uses pre-built templates and extensive databases, enabling quick comparisons across multiple materials and building elements.

Open LCA

As an open-source platform, OpenLCA allows users to construct custom processes, modify system boundaries, and plug in specific material datasets. It is particularly advantageous for localized material evaluation and academic transparency.

Revit Tally

Revit Tally integrates directly into the Revit environment and uses the GaBi database to assess lifecycle phases—manufacturing, operation, and end-of-life. It offers detailed numerical outputs and stage-specific impact analysis, making it ideal for full building lifecycle assessment.

After individual analyses, environmental impact results—such as Global Warming Potential (GWP), biogenic carbon content, Acidification Potential (AP), and Eutrophication Potential (EP)—were compared. Differences were attributed to:

- Data granularity (automated vs. manual entry),
- Database content and regional specificity,
- Software assumptions and boundaries.

Table 1. Comparative Summary of LCA Software Used in the Study

Feature	Revit Tally	One Click LCA	OpenLCA
BIM Integration	Native Revit plugin	Direct from ArchiCAD	Manual import via Excel
Database Used	GaBi	Proprietary + Ecoinvent	Ecoinvent, ELCD
Impact Categories	Full life cycle coverage	10+ incl. GWP, ODP, etc.	Customizable
Flexibility	Moderate (preset schemas)	High (automatic inputs)	Very high (manual control)
Ideal Use Context	Deep stage-based outputs	Rapid analysis, industry	Academic, detailed control
Source Example	Simonen et al., 2017	Soust-Verdaguer et al., 2017	Wernet et al., 2016; Bach et al., 2020

These comparisons were visualized in bar graphs and comparative matrices, emphasizing the strategic importance of software selection in heritage-focused sustainability assessment.

3. Results and Findings

Efforts to enhance sustainability in the construction sector have accelerated the adoption of Life Cycle Assessment (LCA) methodologies. In this study, three widely used LCA software tools—Revit Tally, One Click LCA, and OpenLCA—were comparatively analyzed to assess their methodological frameworks, database structures, and implications for environmental performance evaluation.

Revit Tally, as a plug-in integrated with Autodesk Revit, can perform in-model real-time analyses. Its advantage is working synchronously with design; however, using only a US-based dataset may create limitations for local adaptation (Dalla Mora et al., 2018). One Click LCA, on the other hand, is a web-based tool supporting multiple data inputs such as Revit, IFC, gbXML. One Click LCA's integration withn quality control tools and certification systems provides a strong solution for professional applications (One Click LCA, 2023).

Although OpenLCA does not have integrated BIM integration, its detailed and modular structure offers a transparent modelling process, making it preferred especially in academic studies (Ciroth, 2020).

In terms of databases and calculation methodology, Tally is based on the Athena dataset and provides layer-based analysis; it enables simple and fast modelling but has limited data transparency. One Click LCA uses local EPD-based data, includes scenario analysis and a material comparison tool. OpenLCA can work with a wide variety of databases such as Ecoinvent and ELCD; its data source transparency and customization options are quite high.

According to Dalla Mora et al. (2018), database differences between Tally and One Click LCA lead to significant result differences. A master's thesis from the University of Toronto further supports this observation. According to that research, One Click LCA produced a 50% lower carbon result compared to Tally when analysed with the same data. This finding shows that the software used cannot be directly compared with each other in terms of data sources and calculation methods.

In terms of certification compliance, One Click LCA produces automatically compatible reports with systems such as LEED, BREEAM, DGNB. Tally works compatible with LEED and can integrate with EC3. Although OpenLCA does not provide direct integration, customized reports can produce outputs suitable for certification.

Table 2. Comparative Matrix of LCA Software Programs Based on Certification Compatibility

Criterion	Revit Tally	One Click LCA	OpenLCA
Certification Compliance	LEED v4/v4.1, EC3	LEED, BREEAM, DGNB, HQE, LEVEL(s)	Customised reports
User Friendliness	Medium (requires BIM experience)	High (guided interface)	Low (technical knowledge)
Transparency	Medium	Medium (QC controlled)	High (source visible)
License Model	Commercial plug-in	Subscription	Open source
Online/Offline	Offline (within Revit)	Online (cloud-based)	Offline (desktop)
Local Data	Limited	Rich (including Turkiye)	User can add data

3.1. Use of One Click LCA in Kükürtlü Historical Bath

Using One Click LCA software, the environmental impacts of building components such as wooden-framed glass doors, mortars, and bituminous roof coverings were examined in detail. The software analysed the impacts of these building elements throughout the process from production to post-use. According to One Click LCA analysis results, wooden-framed glass doors and bituminous roof coverings have high global warming potential. Especially in the production stage of these building components, high energy consumption and carbon emissions occur.

Although the use of wood materials provides an advantage as a renewable resource, high emissions occur during their processing stages. Additionally, it was determined that bituminous materials used in roof coverings have high environmental impacts in their production and usage processes

3.2. Use of OpenLCA in Kükürtlü Historical Bath

In the analysis conducted with OpenLCA software, quantity data obtained using Autodesk Revit program were transferred to the ELCD database. The environmental impacts of basic building materials such as stone, brick, and wood used in the building were evaluated in detail. In the analyses, the environmental impacts of building materials used in the restoration process were comparatively evaluated in detail. According to the analysis results, it was determined that the production and supply processes of local materials such as brick and stone have low environmental impacts, while environmental load increases during the processing of wooden materials. The analysis reveals the impact of material selection and building components on the environment during the restoration process

3.3. Use of Revit Tally in Kükürtlü Historical Bath

In the analyses conducted with Revit Tally, reinforced concrete structural elements, wooden floor coverings, ceramic coverings, roof systems, and interior finishing elements in the building were evaluated in detail. The software revealed the environmental impacts of building elements in detail at different stages (production, use, disposal). According to the analysis results, a global warming potential of 179,159 kg CO_2-equivalent, an acidification potential of 1,231 kg SO_2-equivalent, and a eutrophication potential of 183.5 kg N-equivalent were determined throughout the building. The environmental impacts of reinforced concrete structural elements, especially concrete and steel production processes, were found to be quite high. While the environmental impacts of wooden floors and ceramic coverings remained relatively low, significant environmental loads were determined during the end-of-life disposal processes of the building.

3.4. Comparative Analysis of Software Applications and Scales of Use (Case of the Kükürtlü Bath Building)

Within the scope of the environmental assessments conducted for the historical Kükürtlü Bath, three Life Cycle Assessment (LCA) software tools—One Click LCA, OpenLCA, and Revit Tally—were employed to generate results across varying scales and levels of analytical detail.

- One Click LCA proved particularly effective in analyzing environmental impacts of individual building components, such as doors, mortars, and roof systems. Its capacity for rapid data processing and automated scenario analyses makes it highly suitable for design-stage evaluations and component-level optimizations. The platform excels in quantifying impacts during both production and end-of-life phases, offering insights into short-term sustainability strategies.

• OpenLCA, by contrast, emerged as a robust tool for academic and research-oriented applications, particularly where localized and restoration-specific materials are central to the analysis. Its manual data entry functionality and flexible database integration (e.g., ELCD, Ecoinvent) allow for customized modelling and detailed interpretation of heritage-sensitive construction materials. This makes OpenLCA ideal for projects emphasizing material provenance, process transparency, and scholarly replicability.

• Revit Tally demonstrated high competence in addressing whole-building life cycle assessments, providing detailed environmental outputs across production, use, and disposal stages. Its integration with BIM workflows supports synchronous modeling and facilitates data-rich reporting for large-scale restoration and professional architectural projects. Tally's numerical precision across multiple indicators contributes to its effectiveness in comprehensive sustainability planning.

Comparative evaluations of One Click LCA, OpenLCA, and Revit Tally within the Kükürtlü Historical Bath Building demonstrate that each tool's distinctive features—ranging from data structures to certification alignment—significantly influence the interpretation of environmental impacts. These findings underscore the necessity of strategic tool selection in sustainability-oriented architectural research, particularly when addressing heritage-sensitive projects. Based on the data in this study, the final section presents key conclusions and recommendations.

4. Conclusion

According to this study, the choice of LCA software is not merely a technical preference but also a variable that will directly influence the outcomes of the analysis. The comparative evaluation of One Click LCA, OpenLCA, and Revit Tally revealed that:

- Software architecture and database transparency influence the reliability of impact assessments.
- Flexible modeling environments are required to integrate locally sourced materials and restoration-specific elements.
- Certification compatibility and reporting precision play a central role in aligning analytical outcomes with regulatory frameworks.

In the Kükürtlü Historical Bath case study, each tool offered different advantages:

- One Click LCA provided rapid and design-integrated insights by enabling automated extraction of material data from the ArchiCAD model, which allowed for quick evaluation of components such as doors, mortars, and roof coverings.
- OpenLCA allowed customized analysis of restoration materials, particularly through the integration of local datasets (e.g., stone and brick) and the flexibility to define system boundaries in line with heritage-specific restoration practices.
- Revit Tally enabled detailed life cycle reports for the entire building, generating precise numerical outputs across different

phases (production, use, and disposal), which were valuable for assessing large-scale structural elements like reinforced concrete.

For future projects involving historic structures it is recommended to:

- Align software capabilities with project-specific goals and data availability,
- Prioritize platforms that offer transparent modeling procedures, especially for academic or research-based work,
- Employ regionally adapted databases to enhance the accuracy of local environmental evaluations.

By advancing the methodological integration of BIM and LCA, this study contributes to the discourse on sustainability oriented architectural decision making and empowers practitioners to make contextually aware choices.

Acknowledgements and Information Note

In this section was developed within the scope of a graduate-level course at Bursa Uludağ University, Faculty of Architecture. The author wishes to sincerely thank the course instructors for their insightful comments, academic support, and valuable guidance throughout the preparation of this work.

The study did not receive any financial support or funding from any institution. Ethics committee approval was not required for this study. The article complies with national and international research and publication ethics standards.

Author Contribution and Conflict of Interest Declaration Information

The author is solely responsible for the content and writing of this article. There is no conflict of interest.

References

Cabeza, L. F., Rincón, L., Vilariño, V., Pérez, G., & Castell, A. (2014). Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renewable and Sustainable Energy Reviews*, 29, 394–416. https://doi.org/10.1016/j.rser.2013.08.037

Ciroth, A. (2020). OpenLCA- Life Cycle Assessment Software. *GreenDelta*.

Dalla Mora, T., et al. (2018). Comparative Analysis of BIM-based LCA Tools for Building Design. *Journal of Cleaner Production*, 196, 321-334.

Dixit, M. K., Fernández-Solís, J. L., Lavy, S., & Culp, C. H. (2010). Identification of parameters for embodied energy measurement: A literature review. *Energy and Buildings*, 42(8), 1238–1247. https://doi.org/10.1016/j.enbuild.2010.02.016

Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2011). BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors (2nd ed.). *Wiley*.

International Organization for Standardization. (2006). ISO 14040: Environmental management — Life cycle assessment — Principles and framework. Access Address (20/06/2025): https://www.iso.org/standard/37456.html

Moncaster, A. M., & Song, J. Y. (2012). A comparative review of existing data and methodologies for calculating embodied energy and carbon of buildings. *International Journal of Sustainable Building Technology and Urban Development*, 3(1), 26–36. https://doi.org/10.1080/2093761X.2012.67391

One Click LCA. (2023). *Product Overview and Technical Documentation*. Retrieved from https://www.oneclicklca.com

Ortiz, O., Castells, F., & Sonnemann, G. (2009). Sustainability in the construction industry: A review of recent developments based on LCA. *Construction and Building Materials*, 23(1), 28–39. https://doi.org/10.1016/j.conbuildmat.2007.11.012

Soust-Verdaguer, B., Llatas, C., & García-Martínez, A. (2017). Critical review of BIM-based LCA method to buildings. *Energy and Buildings*, 136, 110–120. https://doi.org/10.1016/j.enbuild.2016.12.009

Göktürk BOSTANCI
E-mail: gokturk.96@hotmail.com
Educational Status: Master's Student
License: Istanbul Kültür University, Faculty of Architecture, 2014-2018.
Degree: Bursa Uludağ University, Graduate School of Natural and Applied Sciences, Department of Architecture, 2024-in progress.

Integration of the Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) for an Evaluation of Alternative Structural Systems

Neriman Gül ÇELEBİ [1]

[1] Mimar Sinan Fine Arts University, Graduate School, Department of Architecture, 34427, Istanbul/Türkiye.
ORCID: 0000-0003-0478-0449
E-mail: ngcelebi@gmail.com

Prof. Dr. Ümit ARPACIOĞLU [2]

[2] Mimar Sinan Fine Arts University, Faculty of Architecture, Department of Architecture, 34427, Istanbul/Türkiye.
ORCID: 0000-0001-8858-7499
E-mail: umit.arpacioglu@msgsu.edu.tr

Citation: Çelebi, N. G. & Arpacıoğlu, Ü. (2025). Integration of the Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) for an Evaluation of Alternative Structural Systems. Beceren Örtürk, R. & Çahantimur, A. (Eds.). **Contemporary Approaches in Architecture: The Role of Architecture in the Circular Economy.** 2025, Chapter:10, 238-260. ISBN: 978-625-378-348-8. Iksad Publications.
DOI: https://doi.org/10.5281/zenodo.17316804

1. Introduction

The construction industry accounts for 40% of carbon emissions and 36% of global energy consumption, and this rate is increasing. In addition, a significant part of the built environment consists of buildings. In this direction, the construction sector has great potential and importance in minimizing its carbon footprint and maximizing its environmental performance. In this respect, the focus of this study is energy and carbon emissions. Compared to other building elements, structural systems constitute the largest percentage of a building (Stek et al., 2011). The structural systems' environmental impacts throughout their lifespan are of great importance. Life Cycle Assessment (LCA) is an important tool used for environmental management. The energy consumed by a building element or material throughout its lifespan and its impact on the environment can be analyzed or measured by the Life Cycle Assessment (LCA) methodology. It measures and analyzes the product or system's environmental impacts in an integrated and systematic manner throughout its lifespan. Sustainability, environmental impact, and efficiency optimization are the main aims of the life cycle approach.

Life cycle costing (LCC) also adopts and uses the LCA approach and systematics from an economic viewpoint (Hasik et al., 2019). It provides the quantification and identification of building lifecycle costs. LCC aims to optimize building lifecycle costs. Life cycle cost analysis is a widely used method to investigate the most cost-effective solution or product design (Marszal & Heiselberg, 2011). LCC systematic is described in four stages in the ISO 15686-5 (2017) standard as construction, operation, maintenance, and end-of-life. Life cycle costing can be a decision method and tool to select the best structural alternative from an environmental perspective. LCA is about protecting the environment, and LCC is about cost control and optimization. The LCA and LCC integration can provide a comparison and selection between different structural elements, focusing on economic costs with environmental impacts (Dejaco et al., 2020).

In the study by Islam et al. (2015) noted that the life cycle assessment and costing results depend on many factors. These factors include the assumptions identified in the study, system boundaries, the choice of construction techniques, the building typology, and the study's scope. It also underlines that cost and environmental impacts are determined based on the buildings' life cycle stages.

A study conducted by Nässén et al. (2012) compared the net current costs, total material, carbon, and energy costs of two alternative buildings: timber and reinforced concrete. The study did not consider labor, construction, maintenance, and demolition costs. The data obtained indicated that the material cost difference between the two buildings was small. Therefore, the study noted that the cost-effectiveness of timber buildings is uncertain.

In Kim et al.'s study (2013), two structural frames, reinforced concrete and steel, were compared in terms of environmental performance and construction costs, in the direction of the LCA and LCC systems. The study focused particularly on the construction phase. The findings showed that reinforced concrete structural frames had 26% less CO_2 emissions and 29% less energy consumption than steel structural frames. It has been stated that a large portion of the emissions are caused by the steel production process. The study also showed that the reinforced concrete framed building's total cost was approximately 9.8% lower than the steel framed building.

Balasbaneh & Ramli (2020) provide a comparative life cycle assessment of steel and concrete prefabricated buildings in Malaysia. The structures were assessed according to five environmental impact categories using SimaPro 8 software. These impact categories are non-renewable energy, greenhouse gas emissions, respiratory inorganics, mineral/raw material extraction, and land use. The findings show that the emissions of steel structures are higher than concrete structures only in the greenhouse gas category, while the emissions of concrete structures are higher in other environmental categories. The study also analyzes these two types of structures in terms of life cycle cost effectiveness. Although the construction phase cost of the steel prefabricated structure is higher, the overall life cycle cost of the concrete prefabricated structure is higher.

The number of integrated studies in the field of LCA and LCC is increasing significantly in the literature. However, studies including comprehensive evaluation approaches are limited. Therefore, the development of comprehensive methodological approaches has great importance. The study aims to make a comparison of different structural systems in terms of environmental impact and economic costs, and to support the decision-making process in the early design phase. A system framework for evaluating alternative structural systems is explained. This LCA and LCC integration approach provides a framework for considering all environmental (LCA) and economic (LCC) impacts in decision-making processes. It aims to analyze and evaluate alternative structural systems, focusing on environmental impacts and costs.

2. Material and Method

In the study, a comprehensive literature review covering LCA and LCC approaches, LCA and LCC integration, analysis and evaluation methods, and basic parameters is conducted, the scope and systems of LCA and LCC are explored, and the framework for life cycle assessment and life cycle cost systems for structural systems is defined. The basic modules and sub-parameters that constitute the system are explained. In line with the defined framework, two structural system alternatives, steel and reinforced concrete, are analyzed using GaBi thinkstep LCA software. The GaBi is an LCA software developed to contribute to sustainability and reduce environmental emissions (e.g., carbon emissions). It analyzes the whole life cycle of a product and contributes to environmentally friendly decisions (Sphera, n.d.). It also provides life cycle cost analysis, and in this study, the life cycle cost analyses are also performed with GaBi.

GaBi is a key tool for analyzing building components, with its flexible and powerful structure, and is a focal point of academic research. It has a large dataset, and the software provides the ability to produce a product or material. Its basic components are plan, process, and flow. Modeling based on these components can be managed by the user, and scenario analysis can be performed. It also provides results for multiple impact assessment methods such as Environmental Footprint, ReCiPe, and Traci. In this respect, GaBi is chosen as the analysis tool in this study. Reinforced concrete and steel structural systems are modeled using GaBi software, and a comparative assessment of alternative structural systems is conducted using data obtained from LCA and LCC simulations. The findings obtained within the scope of environmental impact and life cycle cost integration are evaluated and explained.

3. Findings and Discussion

In this section, firstly, the life cycle assessment (LCA) and life cycle costing (LCC) system boundary are defined, and the parameters within the scope of the system boundary are explained. Alternative structural systems, including reinforced concrete and steel systems, are analyzed in the GaBi LCA software in line with the defined system framework, and evaluations are explained in light of the obtained data.

3.1. Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) Systematics for Structural Systems

Life Cycle Assessment (LCA) can be described as an integrated system that evaluates all flows, including inputs and outputs, throughout the life of a product system and provides the calculation of its potential environmental impacts (Zuo et al., 2017). Variables evaluated include resource use as well as various emissions to land, air, and water. The LCA method considers different possibilities and scenarios to minimize resource and energy consumption and reduce the environmental footprint of building materials (Oladazimi et al., 2020). Resource consumption and greenhouse gas emissions are fundamental measures of environmental impact. Energy, an especially important resource, is a widely used indicator of the environmental impact of buildings. The building energy consumption throughout its life cycle is described as embodied and operational energy. Studies highlight the importance of both embodied and operational energy throughout the buildings' lifespan (Fay & Treloar, 2003).

The definition and general method of life cycle assessment are described in the ISO 14044:2006 (2006) LCA guidelines and requirements standard. According to the standard, the purpose and scope must first be defined. The product, system, or process, the purpose of the study, system boundaries, the functional unit, impact categories, impact assessment methods, assumptions, limitations, etc., must be defined and explained. Life Cycle Inventory (LCI) Analysis should be performed. LCI includes collecting data on raw materials, energy consumption, emissions, waste, etc., to measure the inputs and outputs of each lifecycle stage. The inventory analysis stage includes all inputs and processes that create products and services are collected. Life Cycle Impact Assessment (LCIA) should be described. LCIA is the assessment of potential environmental impacts. This phase includes selecting impact categories and category indicators and assigning inventory data to the selected impact categories. The potential human health and environmental impacts of raw material and energy use data collected in the inventory analysis are determined. Finally, the interpretation stage means analyzing the results based on LCI and LCIA, explaining the main conclusions, limitations, and possible recommendations.

Life cycle systematics, system framework, modules, and sub-parameters are defined in the international standard EN 15978:2011 (2011). The standard includes four main stages and a module on achievements (Table 1).

Table 1. Life Cycle Assessment (LCA) System Boundary Defined in EN 15978:2011

Production Stage	Construction Stage	Use Stage	End-of-Life Stage	Benefits and Loads Beyond the System
A1: Raw Materials Supply	A4: Construction-installation	B1: Use	C1: Deconstruction, demolition	Reuse
A2: Transport	A5: Transport	B2: Manufacturing	C2: Transport	Recovery
A3: Manufacturing		B3: Repair	C3: Waste process for reuse	Recycling Potential
		B4: Replacement	C4: Disposal	
		B5: Refurbishment		
		B6: Operational energy use		
		B7: Operational water use		

Energy in the life cycle is defined as operational and embodied energy. From a building design perspective, building components and materials have embodied energy and greenhouse gas emissions, such as carbon, in the phases of their life cycle. The embodied energy is inherent in the formation of building materials. The life cycle embodied energy means the sum of the initial, recurring, and deconstruction energy. Primary energy sources, the conversion efficiency of building material production processes, and the type of material are the primary factors determining embodied energy (Koç et al., 2022). Embodied energy represents the energy demand for manufacturing, transportation, material production, repair and maintenance, and all end-of-life activities. Operational energy (usage) is described as the energy consumed for heating and cooling, air conditioning, lighting, and equipment of a building to ensure comfort conditions in the interior (Azari & Abbasabadi, 2018).

Carbon emissions to the environment throughout the life of a building are evaluated operationally and embodied. The definitions of carbon forms and the relationships between them are the same as for embodied and operational energy properties. In life cycle systematics and life cycle impact assessment methods, and life cycle software, carbon emissions are considered as global warming potential (GWP). As seen in Table 1, energy consumption and environmental emissions (especially carbon) occur for each life cycle stage and subparameter in the life cycle system boundary. Resources such as water and energy flow throughout the buildings' life cycle and are categorized into operational and embodied flows (Helal et al., 2020).

In this study, the usage phase (B1-B7) is not handled at the life cycle system boundary, because international standards define the structural system life as one hundred years. In the life cycle perspective, a building's life is generally considered as fifty (50) years. Additionally, repair, demolition, or reuse of a structural system requires seismic or static performance calculations and analysis. The IEA (International Energy Agency) states in Annex 57 that scenarios should be planned for reuse, maintenance, and repair (B1-B7: use phase) of structural systems (IEA Annex 57, 2016). At the same time, the structural systems do not directly affect operational energy. In this study, LCA and LCC system frameworks consist of the production, the construction, the end-of-life, and the recovery modules. The Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) systematics frameworks are shown in Figure 1.

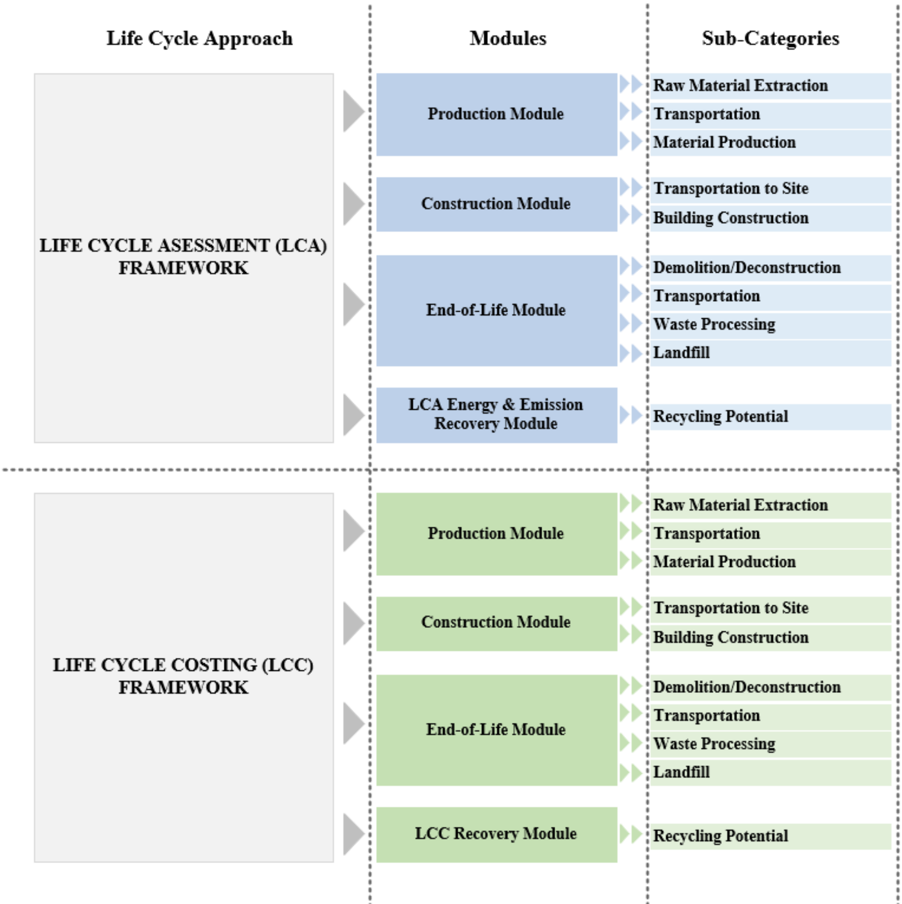

Figure 1. Life Cycle Assessment and Life Cycle Costing System Boundary (Created by the authors)

The framework and parameters defined for the life cycle assessment of structural systems are the same as the life cycle cost framework and parameters. Raw material extraction, material production, and transportation factors are sub-categories of the production module. Transportation to the site and building construction are sub-categories of the construction module. The end-of-life module includes demolition/deconstruction, transportation to the waste recycling centers and the landfills, waste processing, and landfilling. LCA energy and emission recovery module and LCC recovery module are related to the recycling potential. Processing recyclable materials in the building's end-of-life stages is a prominent factor for mores efficient use of natural resources and reduction of waste production. In the study, energy consumption (embodied) and carbon emissions are analyzed for each module. Using different LCA and LCC scopes will not only make data collection or analysis more complex but will also prevent the results from being representative of the same system (França et al., 2021). In order to make an evaluation in line with environmental and economic factors, it is important to determine and integrate the system framework of LCA and LCC.

3.2. Alternative Structural Systems' Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) Analyses

In line with the LCA and LCC systematics defined in the study, life cycle environmental impact and cost analyses of two load-bearing systems, reinforced concrete and steel, are explained in this section. Structural frames, cores, and floors are determined and evaluated as structural system components. The buildings have a central core and grid system plan typology. The buildings' floor areas are 600 m^2, and their heights are 24 m. The location of reinforced concrete-framed and steel-framed residential buildings is at earthquake ground motion level 1. By the Turkish Earthquake Code 2018, the building importance coefficient (residential) is defined as 1, and the local soil class is defined as solid or strong. The reinforced concrete column size is 70x70 cm, the beam is 70x60 cm, and the flooring height is 25 cm. The steel column type is HEB 450, the beam is IPE 750, and the composite flooring height is 18cm. For the comparative analysis of two different structural systems, these structures must be located under the same conditions. In this respect, the buildings' structural systems with equivalent strength in the same plan plane are analyzed in the study. Information on reinforced concrete and steel-framed buildings is shown in Table 2.

Table 2. Reinforced Concrete and Steel Structural Systems' Properties

Parameter	R.C. Framed Building	Steel Framed Building
Building type	Residential Building	Residential Building
Study period	50 years	50 years
Gross area	600 m^2	600 m^2
Building story and total height	8-story and 24m	8-story and 24m
Structural frame type	R.C. Frame	Steel Frame
Structural materials	Concrete, rebar	Structural steel, bolt
Building core	Reinforced Concrete	Steel
Core materials	Concrete, rebar	Steel, bolt
Flooring type	R.C. flooring	Composite flooring
Flooring materials	Concrete, rebar	Concrete, rebar, steel sheet
Concrete amount (t)	4726 tons	2000 tons
Rebar amount (t)	98 tons	33,9 tons
Structural Steel (t)	-	260 tons
Bolt connection amount (t)	-	0,5 tons
Steel sheet amount (t)	-	38, 4 tons

After the dimensions and material quantities of the structural systems are defined, they are modeled in GaBi software, and LCA and LCC simulations are performed. In the study, in the light of comprehensive research, GaBi thinkStep software, which is at the focus of academic studies and provides the analysis of building components with its flexible and powerful design, is selected as the LCA analysis tool. Plan, process (materials & process), and flows are the basic parameters regarding the operation principle of the software. A plan is a visual diagram created to model the lifecycle of a product or process. It is one of the fundamental constituents of LCA and represents all processes of a product in the form of a flowchart. Process symbolises a specific stage in the life cycle of a material or product. Inputs and outputs define it. Flows represent the movement of matter or energy between processes.

Figure 2 shows the reinforced concrete structural system modeling at the GaBi interface, and Figure 3 shows the steel structural system modeling. Models are created in line with the life cycle assessment and cost frameworks defined for structural systems. In the study, transport effects are considered equally for steel and reinforced concrete framed structures, and distances are defined as 100 km. For the reinforced concrete structure system, the concrete is considered non-recyclable and transported to landfills, and the rebar is considered fully recyclable and transported to the recycling site. For the steel structure system, concrete is considered non-recyclable and is transported to landfills. Other materials, including structural steel, rebar, connection elements (bolts), and steel sheet, are considered recyclable and transported to the recycling centers.

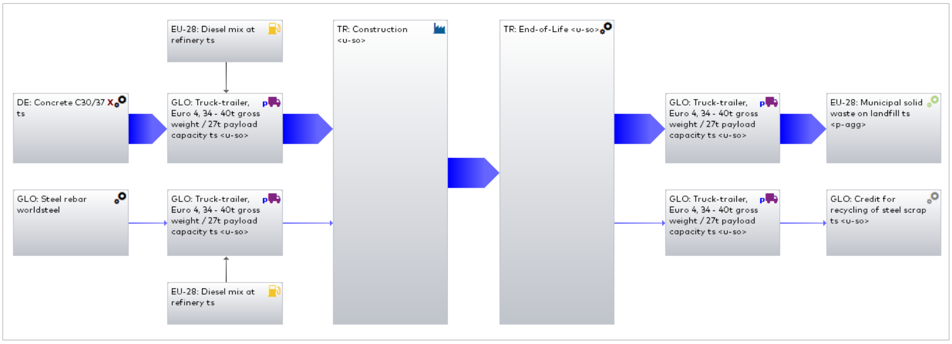

Figure 2. Reinforced Concrete Structural System Modeling in GaBi Software (Created by the authors)

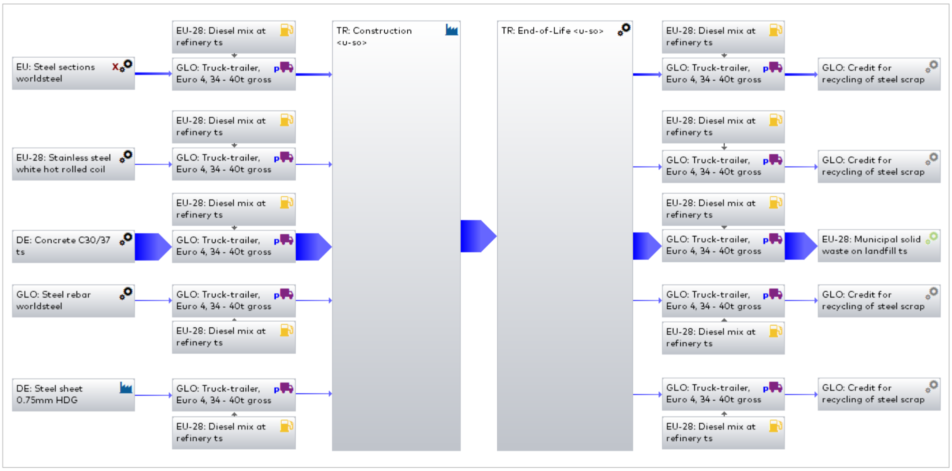

Figure 3. Steel Structural System Modeling in GaBi Software (Created by the authors)

The embodied energy, global warming potential (embodied carbon), and cost data obtained for reinforced concrete and steel structural systems in the light of the simulation are shown in Table 3.

Table 3. Alternative Structural Systems' LCA and LCC Results

Life Cycle Approach	Indicator	R.C. Framed Building	Steel Framed Building
LCA	Embodied Energy (Mj)	8,15E006 Mj	8,58E006 Mj
	Global Warming Potential (GWP) (kgCO2-eq)	5,13E006 kgCO2-eq	2,65E006 kgCO2-eq
LCC	Total Life Cycle Cost (£)	7,87E005 £	1,18E006 £

The total amount of embodied energy throughout the life cycle of the reinforced concrete structure system is 8.15E006 Mj (Megajoule). 8.15E006 Mj represents $8.15x10^6$ Mj. The total global warming potential or amount of embodied carbon of the reinforced concrete structural frame is $5.13x10^6$ kgCO2-eq (kilograms carbon equivalent). The life cycle cost of a reinforced concrete structural system is £$7.87x10^5$ (Euro). The total embodied energy over the life cycle of the steel structural system is 8.58 x 10^6 Mj. The total global warming potential or embodied carbon of the steel structural frame is $2.65x10^6$ kgCO2-eq (kilogram carbon equivalent). The reinforced concrete structural system's life cycle cost is $1.18x10^6$ £ (Euro). The amount of embodied energy in the reinforced concrete structure system is less than that of the steel structure system, but the difference is not high. In terms of carbon emissions, the steel structural system has performed better than reinforced concrete. In steel material production, energy consumption in the melting process accounts for a large proportion of the whole life cycle energy consumption, and directly affects the steel's life cycle energy performance. Cement production in concrete production causes high carbon emissions. The findings in the study are consistent with this information.

When examining lifecycle costs, the steel structure's life cycle cost is higher than the reinforced concrete structure. Life cycle cost is a parameter that needs to be optimized, so it is difficult to define limit values for cost. For an integrated approach of LCA and LCC in a life cycle management perspective, the cost factor can be evaluated as a decision factor in cases where alternative load-bearing systems are under equivalent environmental performance or in light of internationally defined environmental targets such as the RIBA (Royal Institute of British Architects) Sustainable Outcomes Guide (RIBA, 2019). In addition, considering the effects of carbon emissions on the environment and the goals of being carbon neutral, it can be said that the steel structure system is more environmentally friendly. Life cycle costing (LCC) adopts the best performance principle, not the lowest life cycle cost. In this respect, if equivalent results are achieved in terms of environmental performance, the economically dominant alternative can be evaluated.

In addition to the findings, it is difficult to state which of the steel or reinforced concrete structural systems is more environmentally friendly. Although steel has obvious advantages, such as its recycling property, there are many studies in the literature that show higher environmental performance of reinforced concrete. It can be said that the main reasons for this situation are the context of the study, study boundaries, and the parameters evaluated. In particular, the impact of parameters such as the primary energy source and local context on the results should be specified. In the direction of local context, transportation distances may not be the same for alternative structural systems constructed in the same location. Material production, recycling, or waste disposal distances may vary depending on the location of the buildings. Transportation is a major source of carbon emissions in the construction industry (Moussavi Nadoushani & Akbarnezhad, 2015). In this case, transportation and distance factors will impact energy, carbon, and cost outcomes. In this respect, the acceptances and limits in studies should be clearly stated. Further analysis studies are needed in the field of LCA, LCC, and their integration.

4. Conclusion and Suggestions

Sustainable development is aimed at meeting and protecting the needs and aspirations of present and future generations. Environmental and economic parameters are important components of sustainable development. Life Cycle Assessment (LCA) is about protecting the environment; Life Cycle Costing (LCC) is about cost control and optimization.

This study investigates the lifecycle energy, carbon, and cost performance of steel and reinforced concrete structural systems with equivalent performance in the same plan plane. The data obtained indicate that the reinforced concrete structural system has a higher embodied carbon value than steel, while the steel structural system has a higher embodied energy and cost value than reinforced concrete. However, the difference in global warming potential (carbon emissions) is significant. It can be argued that the steel structural system has an advantage in terms of environmental performance. Because lifecycle cost is a parameter that needs to be optimized, the obtained data should be evaluated in light of environmental performance. It can be evaluated as a determining factor in the case of equivalent environmental performance or in line with environmental limit values.

There are many parameters to be managed in life cycle energy and cost integration; however, having common system boundaries for the two approaches is a significant advantage in terms of integration. The integrated approach developed in this study clearly specifies all parameters within the LCA system, providing the reduction, evaluation, and comparison of environmental and economic impacts. Designers or decision-makers can analyze the impact of each parameter on the results.

LCA and LCC provide information on the environmental and economic dimensions of sustainability, providing a basis for determining environmentally strong strategies. In this respect, integration of the life cycle environmental performance and life cycle cost is of great importance. Especially in terms of an effective application area, it's important to support the environmental factor with cost considerations. However, adopting a best-cost approach is necessary rather than the lowest-cost.

Life cycle costing (LCC) is a cost approach focused on environmental impact. In addition to emphasizing the importance of cost, LCC supports the selection of optimum costs in line with high environmental performance. Reducing energy consumption, resource efficiency, and reducing the carbon footprint are also of great importance for the circular economy. In conclusion, it should be stated that the LCA and LCC integration approach should adopt an evaluation system focused on environmental performance. The evaluation approach described in this study can be improved in the direction of mathematical limit values. For example, an integrated cost assessment system can be defined by accepting environmental limit values defined in light of international scientific data.

Acknowledgements and Information Note

This study is produced within the scope of the project titled "Development of a Decision Support Model for Structure Selection in the Context of Earthquake and Environmental Impact (24/ÖAP/06)" supported by the Scientific Research Projects Coordination Unit of Mimar Sinan Fine Arts University, led by Prof. Dr. Ümit ARPACIOĞLU. We would like to thank the MSFAU Scientific Research Projects Coordination Unit for their contributions to the study.

The article complies with national and international research and publication ethics.

Ethics Committee approval was not required for the study.

Author Contribution and Conflict of Interest Declaration Information

All authors contributed equally to the article. There is no conflict of interest.

References

Azari, R. & Abbasabadi, N. (2018). Embodied energy of buildings: A review of data, methods, challenges, and research trends. *Energy and Buildings,* 168, 225–235. DOI: https://doi.org/10.1016/J.ENBUILD.2018.03.003

Balasbaneh, A. T. & Ramli, M. Z. (2020). A comparative life cycle assessment (LCA) of concrete and steel-prefabricated prefinished volumetric construction structures in Malaysia. *Environmental Science and Pollution Research,* 27(34), 43186–43201. DOI: https://doi.org/10.1007/S11356-020-10141-3/METRICS

Dejaco, M. C., Mazzucchelli, E. S., Pittau, F., Boninu, L., Röck, M., Moretti, N. & Passer, A. (2020). Combining LCA and LCC in the early-design stage: a preliminary study for residential buildings technologies. *IOP Conference Series: Earth and Environmental Science,* 588(4), 042004. DOI: https://doi.org/10.1088/1755-1315/588/4/042004

EN 15978:2011. (2011). Sustainability of Construction Works— Assessment of Environmental Performance of Buildings— Calculation Method. European Committee for Standardization (CEN), Brussels.

Fay, R. & Treloar, G. (2003). Life Cycle Energy Analysis— A measure of the environmental impact of buildings. The Environment Design Guide.

França, W. T., Barros, M. V., Salvador, R., de Francisco, A. C., Moreira, M. T. & Piekarski, C. M. (2021). Integrating life cycle assessment and life cycle cost: a review of environmental-economic studies. *The International Journal of Life Cycle Assessment* 2021 26:2, 26(2), 244–274. DOI: https://doi.org/10.1007/S11367-020-01857-Y

Hasik, V., Ororbia, M., Warn, G. P. & Bilec, M. M. (2019). Whole building life cycle environmental impacts and costs: A sensitivity study of design and service decisions. *Building and Environment,* 163, 106316. DOI: https://doi.org/10.1016/J.BUILDENV.2019.106316

Helal, J., Stephan, A. & Crawford, R. H. (2020). The influence of structural design methods on the embodied greenhouse gas emissions of structural systems for tall buildings. *Structures*, *24*, 650–665. DOI: https://doi.org/10.1016/J.ISTRUC.2020.01.026

IEA, ANNEX 57. (2016). Evaluation of Embodied Energy and CO2eq for Building Construction (Annex 57). Access Address (01.01.2025): https://www.iea-ebc.org/projects/project?AnnexID=57

Islam, H., Jollands, M. & Setunge, S. (2015). Life cycle assessment and life cycle cost implication of residential buildings—A review. *Renewable and Sustainable Energy Reviews*, 42, 129–140. DOI: https://doi.org/10.1016/J.RSER.2014.10.006

ISO 15686-5. (2017). Buildings and constructed assets—Service life planning—Part 5: Life-Cycle Costing.

ISO 14044:2006. (2006). Environmental management—Life cycle assessment—Requirements and guidelines.

Kim, S., Moon, J. H., Shin, Y., Kim, G. H. & Seo, D. S. (2013). Life comparative analysis of energy consumption and CO2 emissions of different building structural frame types. *The Scientific World Journal*, *2013.* DOI: https://doi.org/10.1155/2013/175702

Koç, İ., Duru, M. O. & Dinçer, S. G. (2022). Yapılarda Gömülü ve Kullanım Enerjisi Kavramlarının Yaşam Döngüsü Değerlendirmesi (YDD) Metodolojisiyle İrdelenmesi. *Bāb Journal of FSMVU Faculty of Architecture and Design*, 3(1), 55–69.

Marszal, A. J. & Heiselberg, P. (2011). Life cycle cost analysis of a multi-storey residential Net Zero Energy Building in Denmark. *Energy*, 36(9), 5600–5609. DOI: https://doi.org/10.1016/J.ENERGY.2011.07.010

Moussavi Nadoushani, Z. S. & Akbarnezhad, A. (2015). Effects of structural system on the life cycle carbon footprint of buildings. *Energy and Buildings*, *102*, 337–346. DOI: https://doi.org/10.1016/J.ENBUILD.2015.05.044

Nässén, J., Hedenus, F., Karlsson, S. & Holmberg, J. (2012). Concrete vs. wood in buildings – An energy system approach. *Building and Environment*, 51, 361–369. DOI: https://doi.org/10.1016/J.BUILDENV.2011.11.011

Oladazimi, A., Mansour, S. & Hosseinijou, S. A. (2020). Comparative Life Cycle Assessment of Steel and Concrete Construction Frames: A Case Study of Two Residential Buildings in Iran. *Buildings 2020*, Vol. 10, Page 54, 10(3). DOI: https://doi.org/10.3390/BUILDINGS10030054

RIBA. (2019). RIBA Sustainable Outcomes Guide. Access Address (01.01.2025): https://www.architecture.com/

Sphera. (n.d.). Life Cycle Assessment (LCA) Software. Access Address (01.01.2025): https://sphera.com/product-stewardship/life-cycle-assessment-software-and-data/?nab=1

Stek, E., Delong, D., McDonnell, T. & Rodriguez, J. (2011). Life Cycle Assessment Using ATHENA Impact Estimator for Buildings: A Case Study. *Structures Congress 2011-Proceedings of the 2011 Structures Congress*, 483–494. DOI: https://doi.org/10.1061/41171(401)42

Zuo, J., Pullen, S., Rameezdeen, R., Bennetts, H., Wang, Y., Mao, G., Zhou, Z., Du, H. & Duan, H. (2017). Green building evaluation from a life-cycle perspective in Australia: A critical review. *Renewable and Sustainable Energy Reviews*, 70, 358–368. DOI: https://doi.org/10.1016/J.RSER.2016.11.251

Ph. D. Student, Neriman Gül ÇELEBİ
E-mail: ngcelebi@gmail.com
Educational Status
License: Okan University, Faculty of Engineering and Architecture, Department of Architecture, 2016.
Degree: Istanbul Technical University, Graduate School, Department of Architecture, 2021.
Doctorate: Mimar Sinan Fine Arts University, Graduate School, Department of Architecture, (2022-Continues).
Professional experiences: Lecturer (part-time), Istanbul Commerce University, (07.2022-09.2022, 02.2023-07.2023).
Lecturer, Istanbul Nişantaşı University, (02.2024-09.2024).
Lecturer (part-time), Istanbul Sabahattin Zaim University, (09.2023-01.2024, 09.2024-01.2025).
Lecturer (part-time), Altınbaş University, (02.2025-……).

Prof. Dr. Ümit ARPACIOĞLU
E-mail: umit.arpacioglu@msgsu.edu.tr
Educational Status
License: Mimar Sinan Fine Arts University, Faculty of Architecture, Department of Architecture, 2001.
Degree: Mimar Sinan Fine Arts University, Institute of Natural and Applied Sciences, Department of Architecture, 2005.
Doctorate: Mimar Sinan Fine Arts University, Institute of Natural and Applied Sciences, Department of Architecture, 2010.
Professional experiences: Res. Assist., Mimar Sinan Fine Arts University, (2001-2014)
Assoc. Prof. Dr., Mimar Sinan Fine Arts University, (2018-2025)
Prof. Dr., Mimar Sinan Fine Arts University, (2025-…)

Integration of Architecture and Artificial Intelligence within the Context of Life Cycle Assessment: A Bibliometric Exploration of Research Landscapes

M.Sc. Adil YİRMİBEŞ [1]

[1] Bursa Uludağ University, Faculty of Architecture, Department of Architecture, Görükle Campus, Bursa/Türkiye.
ORCID: 0000-0002-4755-6888
E-mail: adilyirmibes@uludag.edu.tr

M.Sc. Barış Mert KARASU [2]

[2] Bursa Uludağ University, Faculty of Architecture, Department of Architecture, Görükle Campus, Bursa/Türkiye.
ORCID: 0000-0002-0743-208X
E-mail: bmertkarasu@uludag.edu.tr

Citation: Yirmibes, A. & Karasu, B.M. (2025). Integration of Architecture and Artificial Intelligence within the Context of Life Cycle Assessment: A Bibliometric Exploration of Research Landscapes. Beceren Öztürk, R. & Çahantimur, A. (Eds.). **Contemporary Approaches in Architecture: The Role of Architecture in the Circular Economy.** 2025, Chapter:11, 261-308. ISBN: 978-625-378-348-8. Iksad Publications.
DOI: https://doi.org/10.5281/zenodo.17316813

1. Introduction

The rise in global temperature records in the 21st century was exemplified by the extreme heatwave experienced in the United Kingdom in July 2022; the Met Office issued a ‘red’ warning, the highest level, the health infrastructure implemented extraordinary protocols, and the government declared a ‘national emergency’. Scientific findings increasingly confirm that climate change is the primary driving force behind the increasing frequency and intensity of meteorological extremes (Arnell, 2022). Construction and architectural activities contribute critically to the global carbon footprint; current data shows that this sector accounts for 34% of global energy consumption and 37% of energy-related CO_2 emissions (Namaki et al., 2024). In this context, life cycle assessment (LCA) enables the identification of potential areas for improvement and possible disadvantages by analyzing the environmental impacts of buildings throughout their lifecycle, from design to end-of-life. LCA is the process of systematically analyzing the resources used, outputs produced, and potential environmental impacts of a product system throughout its life cycle. This process encompasses interconnected and sequential stages, starting from the extraction of raw materials from natural resources and ending with the final disposal of the product (Fnais et al., 2022; Moutik et al., 2023; Yardımcı et al., 2024). LCA provides a methodological framework for determining the scope, defining the evaluation objectives, conducting inventory analysis, assessing impacts, and finally interpreting these processes in a systematic way (Guinee, 2002). Governments in various countries are systematically supporting the adoption of LCA methodology by implementing policy tools and regulatory frameworks and continuing their efforts in this (Guinée et al., 2010).

The architecture and construction sector is responsible for approximately 40% of global carbon emissions (UNEP, 2022), making sustainable design solutions an urgent priority. Artificial Intelligence (AI) is used to describe artificial systems that gain data analysis, pattern recognition, and decision-making capabilities through algorithms that mimic human intelligence (Russell & Norvig, 2022). In this context, AI technologies play a critical role in reducing the carbon footprint by offering innovative solutions to sustainability issues in the architecture and construction sector. In recent years, AI has taken on a promising role in this field, with generative design algorithms that optimize material usage (Castro Pena et al., 2021), AI-based energy simulations that reduce operational carbon (Ahmad et al., 2024), and approaches that test the effectiveness of machine learning (ML) techniques in predicting real-world carbon emissions (Al Nuaimi et al., 2025). However, despite this potential at the intersection of AI and architecture, research has remained fragmented due to interdisciplinary disconnects, lack of data standardization (Tian et al., 2021), and limitations in building-scale applications (Bass et al., 2022). Methodological frameworks and biometric analyses that address LCA and AI together are particularly limited. The LCA method and the software that implements it are important tools for developing strategies to reduce the environmental impacts of human activities (Basbagill et al., 2013; Malmqvist et al., 2011; Namaki et al., 2024; Soust-Verdaguer et al., 2016; Yardımcı et al., 2024). Researchers have obtained valuable results by conducting bibliometric and scientometric analyses in the field of LCA research and development

(Fnais et al., 2022; Ghoroghi et al., 2022; Guinée et al., 2010; Isah et al., 2024; Martinez et al., 2019; Moutik et al., 2023; Teng et al., 2022; Yılmaz & Seyis, 2021). Since the beginning of the 21st century, LCA has gained importance as an interdisciplinary research field with the development of methodological standards at the international level and the spread of sustainability-focused policies (Moutik et al., 2023). The most current interdisciplinary research fields are AI and ML-supported systems (Ghoroghi et al., 2022). The architecture field is responsible for approximately 40% of global carbon emissions. However, the number of LCA studies in the architecture field is quite limited compared to the fields of "environmental studies" and "environmental sciences" (Figure 1).

The study is focused on academic research in the fields of "LCA and AI" and "LCA and Architecture," aiming to reveal academic trends in these areas. The main research objective of the study is to share how research in the field of LCA has developed over time in the subheadings of architecture and AI, which themes have come to the forefront, and what gaps and opportunities have emerged for future research. The research question for the study is defined as "What is the current state of AI and ML-based LCA studies in the field of architecture?" The study focuses on the following topics to answer this question:

Traditional LCA methods are insufficient to meet the dynamic and multidimensional data management needs of architectural studies I. Traditional LCA methods are insufficient to meet the dynamic and multidimensional data management needs of architectural studies (Moutik et al., 2023), (Figures 1–2). It is emphasized that the literature at the intersection of LCA and architecture is open to research compared to other academic fields that produce LCA-related studies (Figures 1–2). It is emphasized that the literature at the intersection of LCA and architecture is open to research compared to other academic fields that produce LCA-related studies.

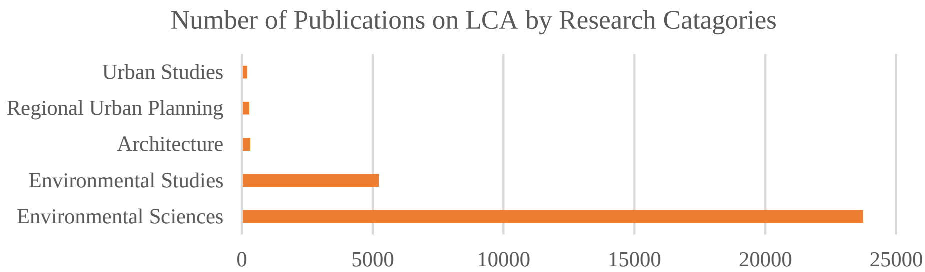

Figure 1. WoS-based Life Cycle Assessment (LCA) studies graph (created by the author(s))

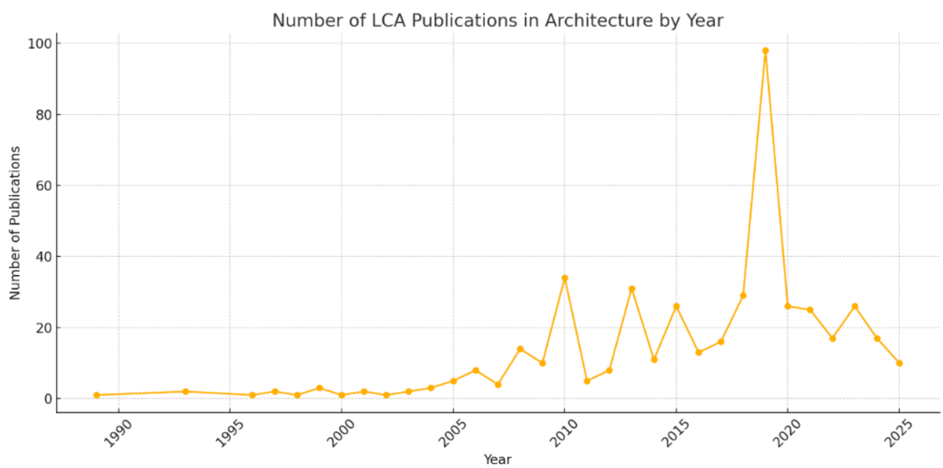

Figure 2. Graph of Life Cycle Assessment (LCA) studies in the field of architecture sourced from WoS (created by the author(s))

The integration of current research topics in LCA and AI into the field of architecture is weak (Figure 3). Therefore, the adaptability of AI and ML methods used in other research areas to the field of architecture under the general heading of LCA is being questioned.

LCA focuses on increasing the diversity of research areas in response to the literature gap caused by the limited research conducted at the intersection of AI and architecture.

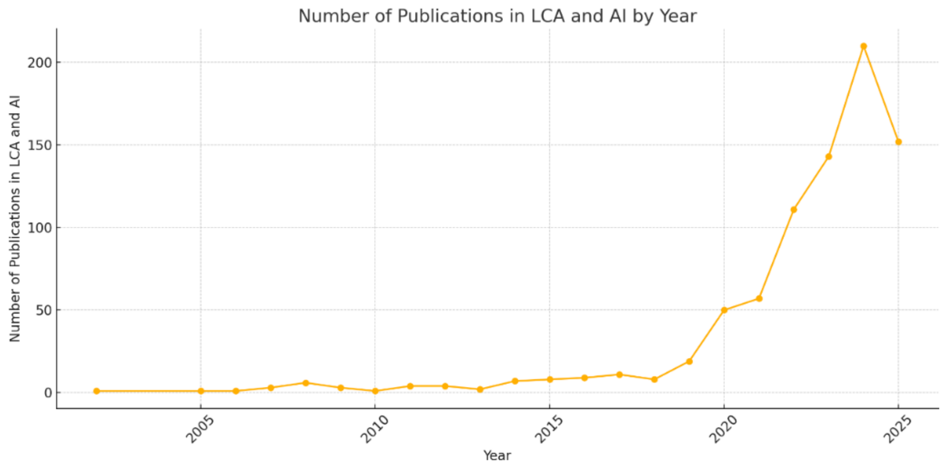

Figure 3. WoS-based Life Cycle Assessment (LCA) and Artificial Intelligence (AI) studies graph (created by the author(s))

Within the scope of the study, filtering options in the WoS database were used to distinguish studies in the field of architecture. Bibliometric data was collected under the main headings of "LCA and AI" and "LCA and Architecture" with the help of filtering. Bibliometric analysis was performed using the publication year, publication title, and keywords for each publication from the raw bibliometric data obtained. The discovery of AI and Architecture studies conducted in the LCA field, which was determined as the research objective, was conducted using keywords. During the research process, it was determined that there are limited LCA studies conducted at the intersection of architecture and AI in the literature, and that there is no comprehensive review to fill this gap. This bibliometric framework aims to identify current research areas in LCA within the field of architecture while outlining potential new research areas for future AI-supported LCA studies.

2. Materıals and Methodology

The "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" (PRISMA) procedure was adopted to conduct a systematic review of the research (Page et al., 2021). The current PRISMA procedure was reorganized to suit the purpose of the study. For this purpose, [1] databases related to the LCA research field, which is the main title of the study, were examined. [2] Search queries were developed to access LCA and AI studies and LCA and architecture studies, which were determined as the main research areas of the study. [3] Incomplete bibliometric data obtained through search queries were identified, complete data were reorganized, and publications with incomplete data were excluded from the study. [4] The co-occurrence of the two research areas was determined through bibliometric analysis. [5] The research areas were explored through bibliometric analysis, and sub-research areas were clustered according to frequency of use within the framework of LCA-AI and LCA-Architecture co-occurrence. [6] Publications with the highest number of citations were selected for the common sub-areas, taking into account content suitability. [7] The integration of research areas was achieved by utilizing the commonalities and differences between LCA-AI and LCA-Architecture identified through bibliometric analysis. The publications examined in the study were reported using the revised PRISMA procedure. The workflow diagram of the study is shown in Figure 4.

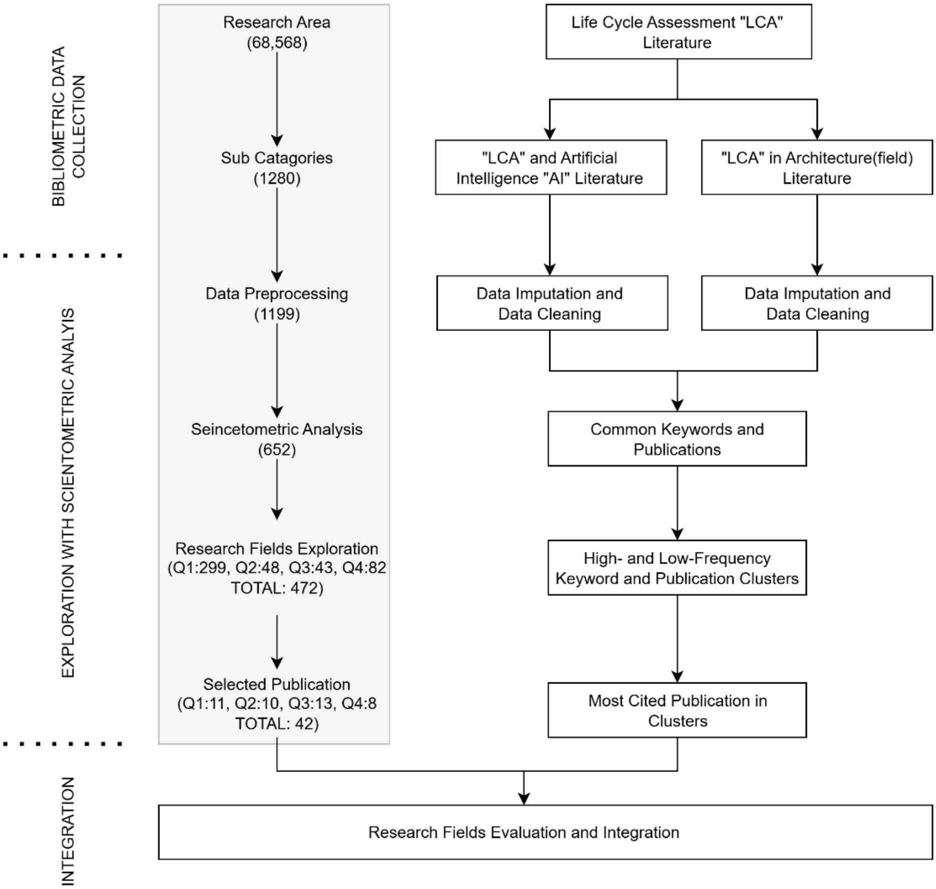

Figure 4. Workflow diagram of the study (created by the author(s))

2.1. Target Literature Source of the Research

In the first stage mentioned in the workflow, a preliminary review was conducted to understand the current state of scientific orientation in the study and to identify gaps in the literature. The research identified the status of studies produced in the LCA literature in different databases (Table 1). In addition, it was revealed in which scientific fields studies on the LCA theme were conducted (see Figure 1). The situation in the AI and Architecture categories, which were determined as the field of study, was observed. The annual distributions of publications on the LCA-

Architecture theme and publications at the intersection of LCA-AI are shown (see Figures 2 and 3). A research strategy was determined through a preliminary review, and the scope and limitations of the study were defined. Using the quantitative data obtained from the preliminary review, the database to be used, the time periods to be researched, and the identification and organization of keywords used to extract the data were established.

Bibliometric studies conducted in the field of LCA were observed in determining the database to be used in the study. In current bibliometric and scientometric studies, it is seen that researchers use Proquest, Scopus, and WoS data combined (Moutik et al., 2023; Teng et al., 2022; Yılmaz & Seyis, 2021). Combining databases to identify trends in a field of study can broaden the scope of the research but may also lead to inaccuracies in the information produced. At the same time, data obtained from multiple databases does not provide a broader perspective in revealing trends in a field (Echchakoui, 2020). The absence of field filtering in the Scopus database raises the problem of not being able to access research-specific data when examining a topic such as LCA, which is not focused on architecture. It also carries the risk of expanding the scope of the study (Table-1) beyond the focus of architecture. For these reasons, the WoS database was used to obtain data from studies in the literature within the scope of the study. From the WoS database, it is possible to access information such as author, publication title, publication type, source, language, publication location, scientific field category, total number of citations, keywords, and publication abstracts.

Table 1. Number of academic studies unfiltered under the LCA heading in the WoS and Scopus databases

Database	Search Terms	Number of Publications
Web of Sience (Wos)	"life cycle assessment" OR "LCA" (All Fields)	68,568
Scopus	"life cycle assessment" OR "LCA"	107,189

The study was prepared under the heading of LCA to identify common topics in the fields of architecture and AI and to ensure the integration of existing research areas. For this reason, the number of studies in the field of AI was examined. It is observed that studies in the AI field have been rapidly increasing in recent years (Figure 5). At the same time, AI studies in the field of architecture show a similar trend (Figure 6). No time constraint was imposed on the data collected for the bibliometric analysis, which aims to include current discussions under the AI heading and to discover different fields as a result of the research.

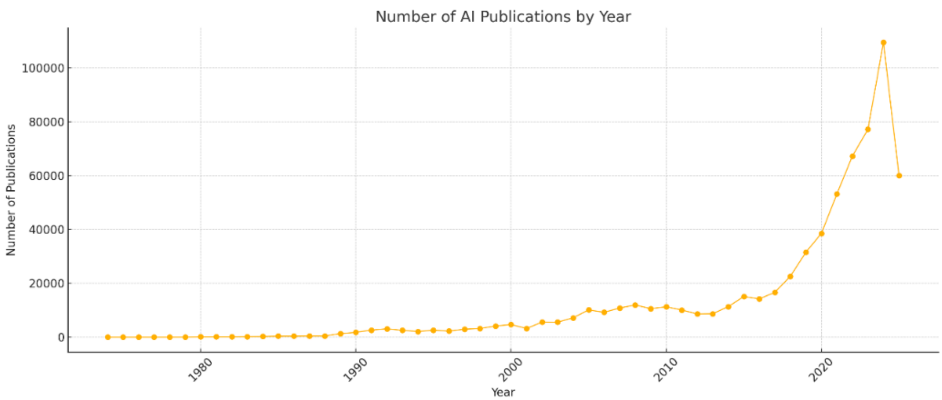

Figure 5. WoS-based Artificial Intelligence (AI) studies graph (created by the author(s))

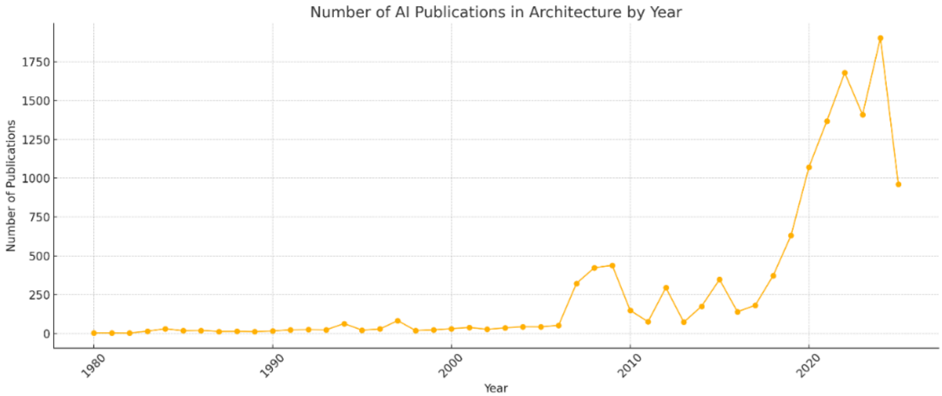

Figure 6. WoS-based graph of Artificial Intelligence (AI) studies in the field of Architecture (created by the author(s))

Search terms related to research areas have been determined for the second stage of the workflow. When examining the database, it is important to write search terms that will cover the literature completely in order for the bibliometric analysis to be performed correctly. In particular, in studies using keywords for trend analysis and research area discovery, missing data affects the accuracy of the study. For this reason, the term "LCA," which is used as an abbreviation for "Life Cycle Assessment" studies, has been added to the search terms to broaden the scope of the research. The search query has been expanded to include abstracts by searching for terms in the "all fields" category. The WoS architecture category has been added to narrow down the search for studies in the field of architecture with LCA. The literature in the field of AI is not limited to the AI heading alone. It is known that the AI heading in studies in this field also covers the fields of ML and deep learning (DL) (Goodfellow et al., 2016; Kühl et al., 2020; Russell & Norvig, 2022) (Figure 7). When examining studies within the scope of AI using LCA, the inclusion of subfields within the AI field brings the scope of the study into line with the AI literature. Search queries and publication numbers in the WoS database are shown in Table 2. A total of 1,325 publications were accessed in the fields of study. The query resulted in 874 articles in the fields of LCA and AI. The query used for the search on LCA and architecture resulted in 451 articles.

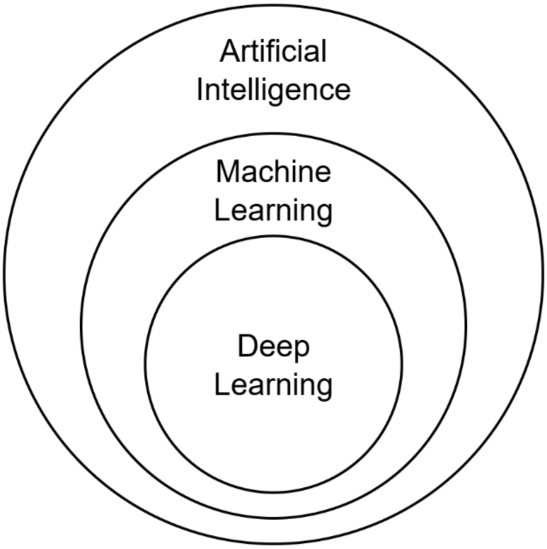

Figure 7. AI, ML, and DL Venn Diagram (Adapted from Goodfellow, 2016.)

Table 2. Search queries used in research fields in the WoS database and number of academic studies

Reasearch Field	Search Terms	Number of Publications
LCA & AI	("life cycle assessment" OR "LCA" (all fields)) AND ("artificial intelligence" OR "machine learning" OR "deep learning"(all fields))	874
LCA & Architecture	("life cycle assessment" OR "LCA" (all fields)) AND "architecture (Web of Science Categories)"	451

2.2. Method: Exploration of Research Areas Using Biometric Analysis

The systematic examination and evaluation of developments in a scientific field is a common research approach today (Hou et al., 2015). With this widespread use, it has become inevitable to observe the trajectories of scientific research in order to identify the current state of the literature and future trends (Lim et al., 2024). Bibliometric and scientometric analyses, which are quantitative approaches, are effective and efficient methods for understanding knowledge accumulation and analyzing scientific research (Donthu et al., 2021; Lim & Kumar, 2024; Lim et al., 2024; Mukherjee et al., 2022; Zupic & Čater, 2015). These analysis methods serve as an important methodological tool in the scientific research process, fulfilling the following functions:

(1) Formulation and delimitation of the research problem,

(2) Systematic identification of theoretical foundations,

(3) Identification of new research areas in the literature using quantitative data,

(4) Identification of gaps in the existing literature,

(5) Mapping of methodological trends and key findings in previous studies,

(6) preventing repetitive or inefficient research orientations (Linnenluecke et al., 2020).

In the third stage of the study, two separate queries were made in the WOS database in the LCA-AI and LCA-Architecture fields to access the number of publications on LCA studies in the fields of architecture and AI (see Table 2). The data obtained as a result of the query was exported as a tab-separated value (tsv) file. The study continued with a total of 1,325 publications in the bibliometric data. The data was processed using the Python language and OpenRefine software. OpenRefine is an open-source software frequently used for bibliometric data organization and data cleaning (Ahmi, 2023). It is particularly used to make scattered and inconsistent data meaningful. This program makes it possible to find, correct, format, and convert errors in data sets to different formats. It is used to prepare data for analysis through various functions such as text manipulation, data matching, repetition, and clustering (Miller, 2022).

With the OpenRefine software, spelling mistakes in author names and keywords were corrected. Then, the two datasets were cleaned up using Python. Duplicate publications were removed from the 1,325 publications, reducing the number of publications to 1,315. Since subcategories will be determined using keywords in the study, publications with keywords were included in the study. Keywords are found in the [DE] and [ID] fields in the WoS database. The [DE] field was prioritized during the review. If the [DE] field was empty in the relevant publication, the keywords in the [ID] field were used. If there was no information in either heading, the relevant publication was excluded from the scope of the study. The data were processed using Python (Table 3). The number of publications containing the keyword was determined to be 1,199. The study continued with these 1,199 publications.

Table 3. 1315 unique publications with keyword titles filled and empty publication rows

Keyword Columns	Filled	Empty
DE (Keywords)	1075	240
ID (Keyword Plus)	943	372
Total	1199	116

In the fourth stage of the study, work was carried out on the data set obtained and organized from WoS. In this stage, work was carried out on the organized keyword heading in the bibliographic data in the LCA-AI and LCA-Architecture fields. Keywords found in both data sets were examined for bibliometric analysis. A total of 53 common keywords were identified that were used in both LCA-AI and LCA-Architecture headings. Search queries were scanned under the LCA heading. Therefore, the terms “LCA” and “life cycle assessment” appear together in many publications. However, the study was conducted to determine which subheadings under the LCA heading had commonalities. For this reason, the keywords “life cycle assessment” and “LCA,” which were common to both search queries, were excluded during the discovery of common keywords. The frequency of other keywords in the LCA-AI and LCA-Architecture datasets was determined within the common keyword set. The identified frequency values were assigned to these keywords. Scaling operations were performed to balance the distribution in the newly created dataset.

During data scaling operations, logarithmic transformations are preferred to balance the distribution of data, especially in cases where positive values are concentrated. In this study, Log1p Min-Max Normalization, which is a combination of logarithmic transformation and min-max normalization, was used (Kuhn & Johnson, 2013). Following normalization, keywords with a value of zero were excluded from the study. As a result of the analysis, the number of common keywords was reduced to 48. The number of publications in the dataset was updated based on the common keywords. The study continued with 652 publications containing the 48 keywords.

In the fifth stage of the study, 48 common keywords were clustered according to their frequency of occurrence in the research fields. Log1p Min-Max normalized data was used for this process. The frequency of occurrence of keywords in the LCA-AI and LCA-Architecture fields and the average values of the data were plotted on the x and y coordinates. The scatter plot and the average values of the data are shown in Figure 8. The areas above and below the average values in the graph are colored differently. Thus, the LCA-AI and LCA-Architecture fields are divided into four regions according to the frequency of occurrence of common keywords. These regions are named Q1, Q2, Q3, and Q4. The Q1 region is represented by green dots and consists of 12 keywords. It contains keywords that are more effective in both AI and Architecture fields. The Q2 region is represented by blue dots and consists of 13 keywords. It contains keywords that are strong in Architecture but weakly represented in AI. The Q3 region is represented by red dots and consists of 14 keywords. It contains keywords that are less frequently used in both AI and Architecture fields. The Q4 region is represented by yellow dots and consists of keywords. It contains keywords that are strong in the field of AI but weak in the field of architecture. The clusters, consisting of a total of 48 keywords, are listed in Table 4 in order and sorted according to the frequency of keywords within each cluster. Publications containing keywords specific to each region have been listed for the discovery and integration of research areas. The number of publications to be examined in the research area has been reduced to 472. The number of publications containing only keywords from the Q1, Q2, Q3, and Q4 clusters is shown in Table 5.

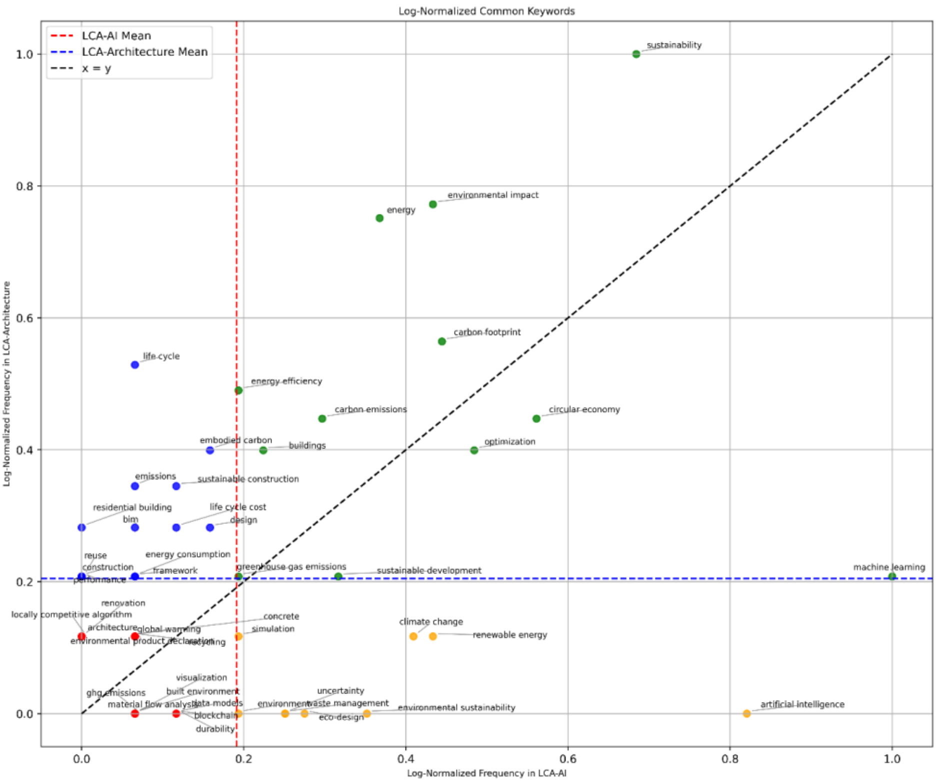

Figure 8. Scatter plot created to identify clusters related to the frequencies of keywords common to studies in the fields of LCA-Architecture and LCA-AI (created by the author(s)).

Table 4. Keyword clusters and frequencies common to studies conducted in the fields of LCA-AI and LCA-Architecture

Quadrants (Q)	Keywords	Mean Frequency	AI-Freq	Arch. Freq.
Q1	sustainability	0,842146	0,684293	1
Q1	machine learning	0,603964	1	0,207929
Q1	environmental impact	0,602778	0,433345	0,772212
Q1	energy	0,559482	0,367632	0,751333
Q1	carbon footprint	0,504386	0,44449	0,564283
Q1	circular economy	0,504179	0,561174	0,447184
Q1	optimization	0,441778	0,484316	0,399241
Q1	carbon emissions	0,371985	0,296786	0,447184
Q1	energy efficiency	0,341806	0,193542	0,49007
Q1	buildings	0,311642	0,224044	0,399241
Q1	sustainable development	0,262295	0,316661	0,207929
Q1	greenhouse gas emissions	0,200735	0,193542	0,207929
Q2	life cycle	0,297289327	0,06571307	0,52886557
Q2	embodied carbon	0,278785647	0,15833045	0,39924084

Q2	sustainable construction	0,23078588	0,116684098	0,34488766
Q2	design	0,22023599	0,15833045	0,28214152
Q2	emissions	0,20530037	0,06571307	0,34488766
Q2	life cycle cost	0,199412812	0,116684098	0,28214152
Q2	bim	0,173927301	0,06571307	0,28214152
Q2	residential building	0,141070763	0	0,28214152
Q2	energy consumption	0,136820837	0,06571307	0,20792859
Q2	framework	0,136820837	0,06571307	0,20792859
Q2	construction	0,103964299	0	0,20792859
Q2	performance	0,103964299	0	0,20792859
Q2	reuse	0,103964299	0	0,20792859
Q3	concrete	0,091406	0,065713	0,117099
Q3	environmental product declaration	0,091406	0,065713	0,117099
Q3	global warming	0,091406	0,065713	0,117099
Q3	recycling	0,091406	0,065713	0,117099
Q3	locally competitive algorithm	0,05855	0	0,117099
Q3	architecture	0,05855	0	0,117099
Q3	renovation	0,05855	0	0,117099
Q3	durability	0,058342	0,116684	0
Q3	data models	0,058342	0,116684	0
Q3	blockchain	0,058342	0,116684	0
Q3	built environment	0,032857	0,065713	0
Q3	ghg emissions	0,032857	0,065713	0
Q3	material flow analysis	0,032857	0,065713	0
Q3	visualization	0,032857	0,065713	0
Q4	artificial intelligence	0,410331	0,820662	0
Q4	renewable energy	0,275222	0,433345	0,117099
Q4	climate change	0,263189	0,409278	0,117099
Q4	environmental sustainability	0,175936	0,351872	0
Q4	simulation	0,155321	0,193542	0,117099
Q4	eco-design	0,137507	0,275015	0
Q4	uncertainty	0,125474	0,250948	0
Q4	waste management	0,125474	0,250948	0
Q4	environment	0,096771	0,193542	0

Table 5. All publications representing all keywords for each of the clusters created

Quadrant (Q)	Number of Publication
Q1 - Both High (AI & Arch)	299
Q2 - Arch High, AI Low	48
Q3 - Both Low	43
Q4 - AI High, Arch Low	82
Total	472

The sixth stage of the study was based on 472 publications. One publication summary and content check was performed for each cluster to select all keywords included in the keyword lists formed for each cluster. During the selection process, a search was conducted from the publication with the highest number of citations to the one with the lowest number of citations. When publications representing all the keywords of a cluster were found, the search for that cluster was concluded. The number of publications representing each region and each keyword is shown in Table 6. During the search, some publications related to certain keywords could not be accessed. One of these was the publication related to the keyword "locally competitive algorithm" in the Q3 cluster, and the other was the publication related to the keyword "emissions" in the Q2 cluster. The integration of studies in the LCA-AI and LCA-Architecture fields was limited to 42 publications.

Table 6. Minimum number of publications representing all keywords for each cluster created

Quadrant (Q)	Number of Publication
Q1 - Both High (AI & Arch)	11
Q2 - Arch High, AI Low	10
Q3 - Both Low	13
Q4 - AI High, Arch Low	8
Total	42

3. Findings and Discussion

In the seventh and final stage of the study, a list of publications was compiled that included each keyword at least once and received the most citations. The lists contain the title of the study, the source information, the keywords used in the study, and information about which keyword is represented in the list. The contents of the listed studies were examined under the LCA heading to determine which niche themes were studied in the fields of AI and Architecture. The clusters and the publications within the clusters were examined in order.

3.1.Q1 Both High (AI & ARCH) Cluster

A group of keywords frequently used in the fields of LCA-AI and LCA-Architecture was examined (see Table 4), and the publications in which the keywords appeared were listed in a table (Table 7). The identified publications were examined systematically.

Table 7. Q1 Studies using high-frequency keywords in the subheadings of Architecture and AI

Authors and Year of Publication	Title	Method	Journal	Matched Keywords
Sharma et al., (2020)	A systematic literature review on machine learning applications for sustainable agriculture supply chain performance	Systematic literature review (SLR)	Computers & Operations Research	machine learning; sustainability
Zhao et al.., (2023)	A bibliometric review of green building research 2000-2016	Bibliometric and co-citation analysis	Architectural Science Review	energy
Y. Li et al., (2023)	Review of biochar production via crop residue pyrolysis: Development and perspectives	LCA- and machine learning-based review of biochar production	Bioresource Technology	sustainable development
Luccioni et al., (2022)	Estimating the Carbon Footprint of BLOOM, a 176B Parameter Language Model	Using LCA techniques to investigate the carbon footprint of a LLM's	Journal of Machine Learning Research	carbon footprint
Xayachak et al., (2022)	Pyrolysis for plastic waste management: An engineering perspective	AI-assisted optimization and LCA-based review	Journal of Environmental Chemical Engineering	circular economy
Ghoroghi et al., (2022)	Advances in application of machine learning to life cycle assessment: a literature review	Using machine learning techniques (ANN, SVM, RF) to review and enhance LCA	International Journal of Life Cycle Assessment	optimization
Dai et al., (2023)	Multiscale Location Attention Network for Building and Water Segmentation of Remote Sensing Image	Multiscale location attention network (MSLANet)	IEEE Transactions on Geoscience and Remote Sensing	buildings
Feng et al., (2019)	Assessing environmental performance in early building design stage:	Integration of parametric design and	Sustainable Cities and Society	environmental impact

	An integrated parametric design and machine learning method	machine learning.		
Jung et al. (2023)	Is Additive Manufacturing an Environmentally and Economically Preferred Alternative for Mass Production?	LCA-based comparative review	Environmental Science & Technology	greenhouse gas emissions
P. Li et al., (2023)	A probabilistic life-cycle assessment of carbon emission from magnesium phosphate cementitious material with uncertainty analysis	LCA with Monte Carlo simulation	Journal of Cleaner Production	carbon emissions
Bashroush (2018)	A Comprehensive Reasoning Framework for Hardware Refresh in Data Centers	LCA-based framework for hardware refresh.	IEEE Transactions on Sustainable Computing	energy efficiency

LCA-AI integration is emerging as a rapidly developing approach in sustainability-focused interdisciplinary studies. This integration supports both environmental and economic decision-making processes in various sectors, particularly sustainable construction (Ghoroghi et al., 2022), agriculture (Sharma et al., 2020), and production systems (Jung et al., 2023). Ghoroghi & Colleagues (2022) noted that LCA and ML techniques offer high potential in areas such as carbon footprint estimation, material selection, and energy modeling in building and infrastructure systems. Similarly, P. Li et al. (2023) emphasized that this integration could influence early design decisions in the context of architecture. These findings align with the work of Feng et al. (2019), who noted that methodological diversity and data gaps complicate the integration of LCA into the design process (Feng et al., 2019).

Xayachak et al. (2022) emphasize that ML algorithms complement the weaknesses of LCA, such as uncertainty analysis, data gap estimation, and process modeling; Y. Li et al. (2023) show that ML-supported LCA applications have a wide range of applications in sustainable construction, especially through automated decision support systems. Among the studies expanding the infrastructure of AI-supported LCA systems, Luccioni et al. (2022) evaluated the carbon footprint of large language models throughout their entire life cycle and applied LCA in digital systems. This approach parallels the work of Bashroush (2018), which addressed the environmental impacts of hardware renewal strategies in data centers. Bashroush presented a decision support model that evaluates hardware lifespan, energy consumption during the usage phase, and embedded emissions together, demonstrating how LCA can be integrated into time-based decision-making processes.

In this context, the use of parametric design tools, BIM, and AI-supported optimization algorithms appears inevitable for the direct integration of LCA into design in the field of architecture (P. Li et al., 2023). Indeed, Dai et al. (2023) have shown that an ML model that performs building segmentation from remote sensing data has potential for spatial environmental impact analyses. Thus, data-driven architectural LCA systems can address both AI and physical environment analysis in a holistic manner. Finally, Zhao et al. (2019) conducted a bibliometric analysis of the evolution of green building literature and found that LCA is closely related to topics such as energy, water, and material use.

3.2.Q2 Arch High, AI Low Cluster

A group of keywords that are frequently used in the field of LCA-Architecture and rarely used in the field of LCA-AI was examined (see Table 4), and the publications in which the keywords appeared were listed in a table (Table 8). The identified publications were examined systematically.

Table 8. Q2 Studies using words with high frequency in the architecture subheading and low frequency in the AI subheading

Authors and Year of Publication	Title	Method	Journal	Matched Keywords
Rizo-Maestre et al., (2020)	UAV plus BIM: Incorporation of Photogrammetric Techniques in Architectural Projects with Building Information Modeling Versus Classical Work Processes	Photogrammetry (UAV) and BIM integration	Remote Sensing	bim; sustainable construction
Schwartz et al., (2021)	A decision support tool for building design: An integrated generative design, optimisation and life cycle performance approach	Generative design, NSGA-II optimisation, and LCA	International Journal of Architectural Computing	life cycle
Budig et al., (2021)	Computational screening-LCA tools for early design stages	Computational screening LCA for early design	International Journal of Architectural Computing	embodied carbon
Durao et al., (2019)	Economic valuation of life cycle environmental impacts of construction products - A critical analysis	LCA and monetisation methods for environmental impacts	Sustainable Built Environment D-A-Ch Conference 2019 (Sbe19 Graz)	design
Jia et al., (2024)	Sustainable valorisation of food waste into engineered biochars for CO2 capture towards a circular economy	LCA and machine learning-assisted biochar synthesis analysis	Green Chemistry	performance
Pushkar & Verbitsky (2016)	Environmental damage from wall technologies for residential buildings in Israel	LCA (SimaPro, ReCiPe) and EnergyPlus simulation	Journal of Green Building	residential building
Chinara & Rath (2008)	Mobility Based Clustering Algorithm and the Energy Consumption Model of Dynamic Nodes in Mobile Ad Hoc Network	Mobility-based clustering algorithm and energy consumption model	ICIT 2008	energy consumption
Lismont & Allacker (2019)	Turning the existing building stock into a resource mine:	Clustering algorithm and artificial neural network-based	Sustainable Built Environment D-	construction; framework

	proposal for a new method to develop building stock models	building stock modelling	A-CH Conference 2019 (Sbe19 Graz)	
Glick & Guggemos (2010)	Life-Cycle Assessment and Life-Cycle Cost as Collaborative Tools in Residential Heating System Selection	Hybrid LCA (EIO-LCA and process-based LCA)	Journal of Green Building	life cycle cost
Hoxha & Fivet (2018)	Environmental Benefits when Reusing Load-Bearing Components in Office Buildings: A Case Study	LCA for assessing reuse of building components	Smart and Healthy Within The Two-Degree Limit (Plea 2018), Vol 1	reuse

A literature review conducted at the intersection of LCA-AI and LCA-architecture shows that a wide variety of methods have been developed to optimize the environmental impacts of early design decisions. Budig et al. (2020) evaluated the effects of structural variants on GWP using a parametric "shoebox" approach, providing a visual and computational workflow that enables LCA integration in the early stages of design. This approach forms an important foundation for generative design and AI-based decision systems, as it enables the systematic search of architectural variants. Similarly, Schwartz et al. (2021) developed a decision support tool that integrates parametric generative design, multi-criteria genetic optimization, and LCA data, enabling the early identification of design scenarios shaped by environmental performance. Jia et al. (2024) take this framework a step further by proposing a time- and user-behavior-sensitive environmental impact analysis method that integrates dynamic data from AI-supported digital twins in smart buildings into LCA calculations.

On the other hand, the environmental impact of building components extends beyond the use phase to include production and reuse scenarios. Hoxha & Fivet (2018) found that the reuse of load-bearing building components could reduce GWP by 39% over three cycles, but emphasized that the LCA methodologies (Cut-off, EOL, PAS2050) used to calculate this contribution could lead to significant deviations in the results. In this context, the AI-supported building stock modeling method developed by Lismont & Allacker (2019) combines AI methods such as GIS, ANN, and kNN with LCA to estimate reuse potential at the city scale, providing decision-makers with scenario-based tools. Pushkar & Verbitsky (2016), on the other hand, argued that material-based decisions should be evaluated in conjunction with energy systems by separating the environmental impacts of the OE and P&C stages according to the energy source (natural gas/PV).

Finally, UAV + BIM integration, supported by AI's visual data collection and modeling power, is also transforming LCA applications in architecture. Rizo-Maestre et al. (2020) have shown that this system offers significant advantages over traditional methods in terms of time, cost, and accuracy in early design and can provide high-precision topographic data for LCA. All these studies reveal that AI is not merely a computational tool but also a catalyst that integrates LCA into architectural practice.

3.3. Q3 Both Low Cluster

A group of rarely used keywords in the fields of LCA-AI and LCA-Architecture was examined (see Table 4), and the publications in which the keywords appeared were listed in a table (Table 9). The identified publications were examined systematically.

Table 9. Q3 Studies using low-frequency words in the subheadings of Architecture and AI

Authors and Year of Publication	Title	Method	Journal	Matched Keywords
Shahjalal (2023)	Fiber-reinforced recycled aggregate concrete with crumb rubber: A state-of-the-art review	Systematic literature review	Construction and Building Materials	concrete
Liu et al., (2020)	Visualized analysis of knowledge development in green building based on bibliographic data mining	Bibliometric and co-citation analysis	Journal of Supercomputing	visualization
Alshamrani (2022)	Integrated LCA-LCC assessment model of offsite, onsite, and conventional construction systems	Integrated LCA-LCC assessment model	Journal of Asian Architecture and Building Engineering	global warming
Keller et al., (2024)	Predicting environmental concentrations of nanomaterials for exposure assessment - a review	Material flow analysis (MFA) and Environmental Fate Models (EFM)	Nanoimpact	material flow analysis
Tajuddeen et al., (2023)	Regression Models for Predicting the Global Warming Potential of Thermal Insulation Materials	Regression models (MLR, SVR, LASSO, XGBoost)	Buildings	environmental product declaration
Hardaway et al., (2025)	Electric vehicle adoption and planning: The increasing importance of the built environment	Supervised machine learning	Journal of Transport Geography	built environment
Arvizu-Montes & Martinez-Echevarria (2025)	Vegetable Fibers in Cement Composites: A Bibliometric Analysis, Current Status, and Future Outlooks	Bibliometric analysis and scientometric mapping	Materials	durability

In recent years, the integration of LCA and artificial intelligence methods in the development of sustainability-focused systems in the construction industry has become more important. In this context, Keller et al. (2024) demonstrate that the use of LCA and machine learning methods in building envelope design is a powerful tool for environmental and performance optimization. On the other hand, Shahjalal et al. (2023) highlight the potential of BIM–LCA integration to provide environmental feedback in early design decisions. In particular, the rapid and automatic analysis of LCA outputs using artificial intelligence-based modeling enables the calculation of environmental impacts from the earliest stages of design.

The challenges encountered in the development of BIM-based LCA systems (data incompatibility, semantic deficiencies, limited automation) have necessitated the support of digital data management with more sophisticated models (Shahjalal et al., 2023). In this context, the NFT-based model protection approach developed by Mouris & Tsoutsos (2024) enables IP protection in digital architectural production processes while supporting the verification and life cycle tracking of CAD models, thereby strengthening the sustainability of LCA in the digital environment. Similarly, the ECNet model developed by Wang et al. (2024) provides infrastructure for AI-supported LCA applications in areas such as energy and leak detection in building systems, due to its ability to process local and cross-layered information in time series data.

On the other hand, studies by Alshamrani (2022) and Karamoozian et al. (2023), which evaluate the sustainability of building systems, show that when LCA is combined with life cycle cost (LCC) and multi-criteria decision-making models, environmental, economic, and technical parameters can be managed in a balanced manner in the selection of building systems. Such models can be integrated into both AI-based weighted decision mechanisms and city-scale sustainable architecture strategies. Cooper & Fava (2009), on the other hand, point out that traditional LCA models not supported by building physics are limited, and therefore emphasize the necessity of integrating dynamic energy performance data into LCA.

Similar trends are observed in studies conducted on building materials. Arvizu-Montes & Martinez-Echevarria (2025) bibliometrically demonstrate the environmental advantages of vegetable fibers and suggest that the carbon storage potential of these materials can be optimized using ML methods based on LCA assessments. Monticelli & Zanelli (2018), on the other hand, evaluate the material performance and environmental impacts of structural membranes using LCA principles and argue that numerical criteria should be integrated into the design. The widespread adoption of such eco-friendly materials is directly related to the removal of barriers to circular economy applications, as discussed by Tajuddeen et al. (2023). LCA-supported circular material passports and AI-enabled automation systems offer data-driven transformation in architecture regarding material reuse and resource traceability.

On a broader scale, the bibliometric analysis conducted by Liu et al. (2020) highlights the importance of interdisciplinary integrated approaches by showing how LCA has taken shape in the field of green buildings around themes such as building envelopes, assessment tools, and user experience. Hardaway et al. (2025), on the other hand, analyze the impact of the built environment on electric vehicle adaptation using AI-supported models, showing how LCA can be repositioned within the relationship between transportation, energy, and buildings in infrastructure planning. Finally, the threshold-value analysis methodology developed by Vuarnoz (2021) offers an LCA-AI-supported framework that contextually evaluates the environmental and economic benefits of energy storage systems.

When all these studies are evaluated together, it becomes clear that there is a developing “integration area” between LCA, AI, and architecture disciplines. This integration spans a wide area, from early decision support systems in the architectural design process to the validation of digital production approaches, real-time analyses, and material-based circular strategies. In the future, it is anticipated that LCA will not only serve as an evaluation tool but also become an integral part of intelligent systems that generate decisions.

3.4. Q4 AI High, Arch Low Cluster

A group of keywords frequently used in the field of LCA-AI but rarely used in the field of LCA-Architecture was examined (see Table 4), and the publications in which the keywords appeared were listed in a table (Table 10). The identified publications were examined systematically.

Table 10. Q4 Studies using words with low frequency in the architecture subheading and high frequency in the AI subheading

Authors and Year of Publication	Title	Method	Journal	Matched Keywords
Jha et al., (2017)	Renewable energy: Present research and future scope of Artificial Intelligence	Literature review, AI applications analysis	Journal of Cleaner Production	artificial intelligence; renewable energy
Gan et al., (2020)	Simulation optimisation towards energy efficient green buildings: Current status and future trends	Simulation- and optimisation-based review	Environmental Science & Policy	climate change
French & Geldermann (2005)	The varied contexts of environmental decision problems and their implications for decision support	Decision analysis and multi-criteria methods	Energy Reports	uncertainty
Soudagar et al., (2024)	Optimizing IC engine efficiency: A comprehensive review on biodiesel, nanofluid, and the role of artificial intelligence and machine learning	Comprehensive literature review	Buildings	environmental sustainability
López-Andrés et al., (2018)	Environmental impact assessment of chicken meat production via an integrated methodology based on LCA, simulation and genetic algorithms	LCA, process simulation, Monte Carlo, and genetic algorithms	Journal of Cleaner Production journal	simulation
Apeh et al., (2022)	Contributions of Solar Photovoltaic Systems to Environmental and Socioeconomic Aspects of National Development-A Review	Literature review and comparative analysis	Results in Engineering	environment
Dostatni et al., (2023)	Environmental analysis of a product manufactured with the use of an additive technology-AI-based vs. traditional approaches	Artificial neural networks (ANN) and LCA	Clean Technologies and Environmental Policy	eco-design
Hajabdollahi Ouderji et al., (2023)	Integration of anaerobic digestion with heat Pump: Machine learning-based technical and environmental assessment	Machine learning (GPR) and LCA	Bioresource Technology	waste management

Soudagar et al. (2024) revealed that large-scale AI models cause significant carbon emissions and energy consumption during the training phase, indicating the need for specific LCA methodologies for these systems. Gan et al. (2020) demonstrated that AI methods are effectively used to fill data gaps, reduce uncertainties, and generate scenarios in the inventory and impact assessment stages of LCA. Dostatni et al. (2023) compared an AI-supported artificial neural network model with the traditional LCA software SimaPro. They emphasized that, compared to traditional LCA approaches, artificial intelligence can make successful predictions even with small sample sets and offers more flexible scenario modeling. French & Geldermann (2005) emphasized the use of artificial intelligence as a decision support tool in LCA analyses, especially those based on parametric inputs. The data-driven flexibility offered by AI provides a significant advantage in multi-actor decision scenarios. On the other hand, Ouderji et al. (2023) achieved successful results in predicting environmental technologies such as biogas production using AI and optimized the carbon footprint of alternative energy systems. This technical approach was adapted to the building scale by López-Andrés et al. (2018) in the context of waste management; LCA scenarios developed for demolition waste in Madrid clearly demonstrated the environmental benefits of material-based recycling strategies. Jha et al. (2017) analyzed the factors affecting green building technologies and stated that sustainability in the construction sector should be evaluated not only at the technical level but also at the institutional and social levels. Apeh et al. (2022) and French & Geldermann (2005) emphasized the environmental and economic advantages of renewable energy technologies. They noted that decision support systems play a guiding role in this regard.

3.5. LCA-AI and LCA-Architecture Fields Integration

Keywords and related publications in the fields of LCA-AI and LCA-Architecture were examined. When looking at common themes and intersections, Decision Support Systems, Data-Driven Approaches, and Environmental Sustainability are seen to be at the forefront.

- Decision Support Systems: The aim is to integrate LCA into the design process in both areas through decision support systems. AI-supported LCA models offer advantages such as reducing uncertainty, scenario creation, and forecasting in both the early design stages of architecture and the production-consumption chain.
- Data-Driven Approaches: Data scarcity is a common limitation in both architecture and AI-based LCA applications. At this point, data generation and integration methods such as remote sensing, BIM, digital twins, and photogrammetry offer solutions in both fields.
- Environmental Sustainability: Approaches that combine architectural-specific environmental assessment topics such as building envelope, material selection, and energy management with AI's data analytics power are increasingly coming to the forefront.

The areas that stand out in the publications examined in the LCA-AI literature are automation and uncertainty management, carbon footprint and digital systems, and energy and alternative systems.

- Automation and Uncertainty Management: AI algorithms are effectively used to reduce uncertainties in traditional LCA processes, estimate missing data, and generate scenarios (Gan et al., 2020; Xayachak et al., 2022).
- Carbon Footprint and Digital Systems: Measuring the environmental impacts of digital systems such as large language models (e.g., GPT-3) and data centers has necessitated the development of specialized LCA methodologies for AI (Luccioni et al., 2022; Soudagar et al., 2024).
- Energy and Alternative Systems: AI models play a critical role in optimizing environmental impacts in the LCA assessment of biogas, waste management, and renewable energy systems (Ouderji et al., 2023).

The areas that stand out in the publications examined in LCA-Architecture literature are: LCA in Early Design, Material and System Circularity, and Digital Environment Integration.

- LCA in Early Design: LCA is integrated into architectural projects while they are still in the concept phase, based on parameters such as building material selection, structural systems, and energy scenarios (Budig et al., 2020; Schwartz et al., 2021).
- Material and System Circularity: Topics such as reuse potential, circular economy applications, and GIS-supported modeling of the building stock point to LCA's spatial-scale assessments in architecture (Hoxha & Fivet, 2018; Lismont & Allacker, 2019).
- Digital Environment Integration: The integration of BIM, digital twins, and remote sensing data with LCA enables architectural

decisions to become responsive to time, user behavior, and environmental variables (Jia et al., 2024; Rizo-Maestre et al., 2020).

The research found that there is a lack of interdisciplinary case studies testing the direct applicability of models developed under LCA-AI in architectural contexts. This situation limits the benefits that could be gained from combining the two methods. Additionally, the fact that AI-supported LCA tools are not integrated with intuitive and user-friendly interfaces specific to the architecture discipline hinders the widespread adoption of practical applications. Studies that optimize environmental parameters such as carbon storage and recycling using artificial intelligence are quite limited. The combination of sociological and technical variables such as user behavior, social acceptance, and political approaches has not been integrated into LCA systems. These areas are not sufficiently represented in the literature.

3.6. Limitations and Future Research

This study has some limitations, including the research method and the selected data source. The study is limited to sources found in the WoS database and selected fields. The study was conducted within the framework of co-occurrence-based bibliometric research. Authors, publication locations, and countries were not the focus of the study. As a result of this choice, there is a possibility that some sources found in other databases, such as Scopus and Google Scholar, may have been missed by the study. These limitations tend to affect the results. Although the search terms used in the study were an effective tool in achieving the study's objective, there is a possibility that publications focusing on more specific keywords may have been overlooked. In future studies, identifying interchangeable terminology to define the current state of research in the fields of LCA and architecture and expanding the scope of the research may increase the sensitivity of the study to some extent. Furthermore, the approaches used in the research can be utilised alongside studies in the field of architecture.

4. Conclusion

This literature review study utilized bibliometric and scientometric methods such as thematic evolution and co-occurrence to reveal the themes that LCA studies in the field of architecture focus on. The findings reveal that the studies concentrate on the themes of sustainability, energy, and carbon footprint, and that studies using these themes have high citation rates. It was observed that approaches such as AI and ML, which have recently begun to emerge in LCA research, were addressed within a limited framework. This situation highlights that future studies should focus on the possibility of simultaneously addressing variables that human intelligence struggles to identify, using these methods together to protect humans and nature. This study represents a significant effort to uncover the critical characteristics of LCA in the field of architecture and to guide the direction of future studies. The study also points to the potential of future studies.

The fields of LCA-AI and LCA-Architecture are increasingly converging, integrating in areas such as data-driven decision-making, sustainability criteria, and performance optimization. However, there is a noticeable lack of user-friendly AI-LCA tools suitable for intuitive design processes in architecture; on the other hand, AI literature still has limited application scenarios specific to architectural contexts. Therefore, the development of AI-supported LCA systems that are integrated into design processes and work with user behavior and contextual data will make important contributions to both literatures.

Acknowledgements and Information Note

The authors declare that there are no conflicts of interest associated with this publication. The study was conducted independently, without any commercial or financial relationships that could be construed as a potential conflict. It fully complies with national and international research and publication ethics, and ethics committee approval was not required for this type of study.

Author Contribution and Conflict of Interest Declaration Information

All authors contributed equally to the article. The authors declare that there are no conflicts of interest associated with this publication. The research was conducted independently and does not involve any commercial or financial relationships that could be construed as a potential conflict.

References

Ahmad, A., Bande, L., Ahmed, W., Young, K & Jha, M. (2024). AI application in architecture in UAE: Application of an advanced optimized shading structure as a retrofit strategy of a midrise residential building façade in downtown Abu Dhabi. *Energy and Buildings*, *325* (September), 114995. https://doi.org/10.1016/j.enbuild.2024.114995

Ahmi, A. (2023). OpenRefine: An approachable tool for cleaning and harmonizing bibliographical data. *IP Conference Proceedings*.

Al Nuaimi, H. S., Acquaye, A & Mayyas, A. (2025). Machine learning applications for carbon emission estimation. *Resources, Conservation and Recycling Advances*, *27*(June), 200263. https://doi.org/10.1016/j.rcradv.2025.200263

Alshamrani, O. S. (2022). Integrated LCA-LCC assessment model of offsite, onsite, and conventional construction systems. *Journal of Asian Architecture and Building Engineering*, *21*(5), 2058–2080. https://doi.org/10.1080/13467581.2021.1942001

Apeh, O. O., Meyer, E. L & Overen, O. K. (2022). Contributions of Solar Photovoltaic Systems to Environmental and Socioeconomic Aspects of National Development—A Review. *Energies*, *15*(16). https://doi.org/10.3390/en15165963

Arnell, N. W. (2022). The implications of climate change for emergency planning. *International Journal of Disaster Risk Reduction*, *83*(August), 103425. https://doi.org/10.1016/j.ijdrr.2022.103425

Arvizu-Montes, A & Martinez-Echevarria, M. J. (2025). Vegetable Fibers in Cement Composites: A Bibliometric Analysis, Current Status, and Future Outlooks. *Materials*, *18*(2). https://doi.org/10.3390/ma18020333

Basbagill, J., Flager, F., Lepech, M & Fischer, M. (2013). Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts. *Building and Environment*, *60*, 81–92. https://doi.org/10.1016/j.buildenv.2012.11.009

Bashroush, R. (2018). A Comprehensive Reasoning Framework for

Hardware Refresh in Data Centers. *IEEE Transactions on Sustainable Computing*, *3*(4), 209–220. https://doi.org/10.1109/TSUSC.2018.2795465

Bass, B., New, J., Clinton, N., Adams, M., Copeland, B & Amoo, C. (2022). How close are urban scale building simulations to measured data? Examining bias derived from building metadata in urban building energy modeling. *Applied Energy*, *327*(June), 120049. https://doi.org/10.1016/j.apenergy.2022.120049

Budig, M., Heckmann, O., Hudert, M., Ng, A. Q. B., Xuereb Conti, Z & Lork, C. J. H. (2021). Computational screening-LCA tools for early design stages. *International Journal of Architectural Computing*, *19*(1), 6–22. https://doi.org/10.1177/1478077120947996

Castro Pena, M. L., Carballal, A., Rodríguez-Fernández, N., Santos, I & Romero, J. (2021). Artificial intelligence applied to conceptual design. A review of its use in architecture. *Automation in Construction*, *124*. https://doi.org/10.1016/j.autcon.2021.103550

Chinara, S & Rath, S. K. (2008). Mobility based clustering algorithm and the energy consumption model of dynamic nodes in mobile ad hoc network. *Proceedings - 11th International Conference on Information Technology, ICIT 2008*, 171–176. https://doi.org/10.1109/ICIT.2008.54

Cooper, J., Häkkinen, T., Vares, S., Jahn, J & Pulakka, S. (2009). Combining building renovation and ground source heat pump installations for the reduction of greenhouse gas emissions: A case study in Vaasa Finland. *Journal of Green Building*, *4*(1), 146–168. https://doi.org/10.3992/jgb.4.1.146

Dai, X., Xia, M., Weng, L., Hu, K., Lin, H & Qian, M. (2023). Multiscale Location Attention Network for Building and Water Segmentation of Remote Sensing Image. *IEEE Transactions on Geoscience and Remote Sensing*, *61*, 1–19. https://doi.org/10.1109/TGRS.2023.3276703

Donthu, N., Kumar, S., Mukherjee, D., Pandey, N & Lim, W. M. (2021). How to conduct a bibliometric analysis: An overview and guidelines. *Journal of Business Research*, *133*(March), 285–296.

https://doi.org/10.1016/j.jbusres.2021.04.070

Dostatni, E., Dudkowiak, A., Rojek, I & Mikołajewski, D. (2023). Environmental analysis of a product manufactured with the use of an additive technology – AI-based vs. traditional approaches. *Bulletin of the Polish Academy of Sciences Technical Sciences*, *71*(1), 144478–144478. https://doi.org/10.24425/bpasts.2023.144478

Durao, V., Silvestre, J. D., Mateus, R & De Brito, J. (2019). Economic valuation of life cycle environmental impacts of construction products - A critical analysis. *IOP Conference Series: Earth and Environmental Science*, *323*(1). https://doi.org/10.1088/1755-1315/323/1/012147

Echchakoui, S. (2020). Why and how to merge Scopus and Web of Science during bibliometric analysis: the case of sales force literature from 1912 to 2019. *Journal of Marketing Analytics*, *8*(3), 165–184. https://doi.org/10.1057/s41270-020-00081-9

Feng, K., Lu, W & Wang, Y. (2019). Assessing environmental performance in early building design stage: An integrated parametric design and machine learning method. *Sustainable Cities and Society*, *50*(September 2018), 101596. https://doi.org/10.1016/j.scs.2019.101596

Fnais, A., Rezgui, Y Petri, I., Beach, T., Yeung, J., Ghoroghi, A., & Kubicki, S. (2022). The application of life cycle assessment in buildings: challenges, and directions for future research. *International Journal of Life Cycle Assessment*, *27*(5), 627–654. https://doi.org/10.1007/s11367-022-02058-5

French, S & Geldermann, J. (2005). The varied contexts of environmental decision problems and their implications for decision support. *Environmental Science and Policy*, *8*(4), 378–391. https://doi.org/10.1016/j.envsci.2005.04.008

Gan, V. J. L., Lo, I. M. C., Ma, J., Tse, K. T., Cheng, J. C. P & Chan, C. M. (2020). Simulation optimisation towards energy efficient green buildings: Current status and future trends. *Journal of Cleaner Production*, *254*, 120012. https://doi.org/10.1016/j.jclepro.2020.120012

Ghoroghi, A., Rezgui, Y., Petri, I & Beach, T. (2022). Advances in application of machine learning to life cycle assessment: a literature review. *International Journal of Life Cycle Assessment*, *27*(3), 433–456. https://doi.org/10.1007/s11367-022-02030-3

Glick, S., Ap, L & Guggemos, A. (2010). Life-cycle assessment and life-cycle cost as collaborative tools in residential heating system selection. *Journal of Green Building*, *5*(3), 107–115. https://doi.org/10.3992/jgb.5.3.107

Goodfellow, I., Bengio, Y., Courville, A & Bengio, Y. (2016). *Deep Learning* (Vol. 1, Issue 2). MIT press. https://doi.org/10.1007/978-3-030-95041-5_6

Guinee, J. B. (2002). Handbook on Life Cycle Assessment Operational Guide to the ISO Standards. *International Journal of Life Cycle Assessment*, *7*(5), 311–313. https://doi.org/10.1016/s0195-9255(02)00101-4

Guinée, J. B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T & Rydberg, T. (2010). Life Cycle Assessment: Past, Present, and Future. *Environmental Science & Technology*, *45*(1), 90–96.

Hajabdollahi Ouderji, Z., Gupta, R., Mckeown, A., Yu, Z., Smith, C., Sloan, W & You, S. (2023). Integration of anaerobic digestion with heat Pump: Machine learning-based technical and environmental assessment. *Bioresource Technology*, *369*(December 2022), 128485. https://doi.org/10.1016/j.biortech.2022.128485

Hardaway, K., Genc, U., Cai, H & Nateghi, R. (2025). Electric vehicle adoption and planning: The increasing importance of the built environment. *Journal of Transport Geography*, *123*(November 2024), 104115. https://doi.org/10.1016/j.jtrangeo.2025.104115

Hou, Q., Mao, G., Zhao, L., Du, H & Zuo, J. (2015). Mapping the scientific research on life cycle assessment: a bibliometric analysis. *International Journal of Life Cycle Assessment*, *20*(4), 541–555. https://doi.org/10.1007/s11367-015-0846-2

Hoxha, E & Fivet, C. (2018). Environmental benefits when reusing load-bearing components in office buildings: A case study. *PLEA 2018 -*

Smart and Healthy within the Two-Degree Limit: Proceedings of the 34th International Conference on Passive and Low Energy Architecture, *1*, 38–43.

Isah, M. E., Zhang, Z., Matsubae, K & Itsubo, N. (2024). Bibliometric analysis and visualisation of research on life cycle assessment in Africa (1992–2022). *International Journal of Life Cycle Assessment*, *29*(7), 1339–1351. https://doi.org/10.1007/s11367-024-02313-x

Jha, S. K., Bilalovic, J., Jha, A., Patel, N & Zhang, H. (2017). Renewable energy: Present research and future scope of Artificial Intelligence. *Renewable and Sustainable Energy Reviews*, *77*(May 2016), 297–317. https://doi.org/10.1016/j.rser.2017.04.018

Jia, W., Li, S., Wang, J., Lee, J. T. E., Lin, C. S. K., Mašek, O., Zhang, H & Yuan, X. (2024). Sustainable valorisation of food waste into engineered biochars for CO2 capture towards a circular economy. *Green Chemistry*, *26*(4), 1790–1805. https://doi.org/10.1039/d3gc04138g

Jung, S., Kara, L. B., Nie, Z., Simpson, T. W & Whitefoot, K. S. (2023). Is Additive Manufacturing an Environmentally and Economically Preferred Alternative for Mass Production? *Environmental Science and Technology*, *57*(16), 6373–6386. https://doi.org/10.1021/acs.est.2c04927

Karamoozian, M & Hong, Z. (2023). Using a decision-making tool to select the optimal industrial housing construction system in Tehran. *Journal of Asian Architecture and Building Engineering*, *22*(4), 2189–2208. https://doi.org/10.1080/13467581.2022.2145205

Keller, A. A., Zheng, Y., Praetorius, A., Quik, J. T. K & Nowack, B. (2024). Predicting environmental concentrations of nanomaterials for exposure assessment - a review. *NanoImpact*, *33*(December 2023), 100496. https://doi.org/10.1016/j.impact.2024.100496

Kühl, N., Goutier, M., Hirt, R & Satzger, G. (2020). Machine learning in artificial intelligence: Towards a common understanding. *ArXiv*, 5236–5245. https://doi.org/10.24251/hicss.2019.630

Kuhn, M & Johnson, K. (2013). Applied Predictive Modeling with Applications in R. In *Springer* (Vol. 26).

http://appliedpredictivemodeling.com/s/Applied_Predictive_Modeling_in_R.pdf

Li, P., Chen, B & Cui, Q. (2023). A probabilistic life-cycle assessment of carbon emission from magnesium phosphate cementitious material with uncertainty analysis. *Journal of Cleaner Production*, *427*(July), 139164. https://doi.org/10.1016/j.jclepro.2023.139164

Li, Y., Gupta, R., Zhang, Q & You, S. (2023). Review of biochar production via crop residue pyrolysis: Development and perspectives. *Bioresource Technology*, *369*(September 2022), 128423. https://doi.org/10.1016/j.biortech.2022.128423

Lim, W. M & Kumar, S. (2024). Guidelines for interpreting the results of bibliometric analysis: A sensemaking approach. *Global Business and Organizational Excellence*, *43*(2), 17–26. https://doi.org/10.1002/joe.22229

Lim, W. M., Kumar, S & Donthu, N. (2024). How to combine and clean bibliometric data and use bibliometric tools synergistically: Guidelines using metaverse research. *Journal of Business Research*, *182*(June), 114760. https://doi.org/10.1016/j.jbusres.2024.114760

Linnenluecke, M. K., Marrone, M & Singh, A. K. (2020). Conducting systematic literature reviews and bibliometric analyses. *Australian Journal of Management*, *45*(2), 175–194. https://doi.org/10.1177/0312896219877678

Lismont, A & Allacker, K. (2019). Turning the existing building stock into a resource mine: Proposal for a new method to develop building stock models. *IOP Conference Series: Earth and Environmental Science*, *323*(1). https://doi.org/10.1088/1755-1315/323/1/012070

Liu, X., Wang, M & Fu, H. (2020). Visualized analysis of knowledge development in green building based on bibliographic data mining. *Journal of Supercomputing*, *76*(5), 3266–3282. https://doi.org/10.1007/s11227-018-2543-y

López-Andrés, J. J., Aguilar-Lasserre, A. A., Morales-Mendoza, L. F., Azzaro-Pantel, C., Pérez-Gallardo, J. R & Rico-Contreras, J. O. (2018). Environmental impact assessment of chicken meat production via an integrated methodology based on LCA, simulation and genetic algorithms. *Journal of Cleaner Production*, *174*, 477–491. https://doi.org/10.1016/j.jclepro.2017.10.307

Malmqvist, T., Glaumann, M., Scarpellini, S., Zabalza, I., Aranda, A., Llera, E & Díaz, S. (2011). Life cycle assessment in buildings: The ENSLIC simplified method and guidelines. *Energy*, *36*(4), 1900–1907. https://doi.org/10.1016/j.energy.2010.03.026

Martinez, S., Delgado, M. del M., Martinez Marin, R & Alvarez, S. (2019). Science mapping on the Environmental Footprint: A scientometric analysis-based review. *Ecological Indicators*, *106*(July), 105543. https://doi.org/10.1016/j.ecolind.2019.105543

Miller, M. (2022). *Geospatial data and software reviews OpenRefine: An approachable open tool to clean research data*. *170*, 2–8. https://github.com/OpenRefine/OpenRefine#credits

Monticelli, C & Zanelli, A. (2018). Structural membranes in architecture: An eco-efficient solution for the future? *Techne*, *16*, 235–246. https://doi.org/10.13128/Techne-23041

Mouris, D & Tsoutsos, N. G. (2024). NFTs for 3D Models: Sustaining Ownership in Industry 4.0. *IEEE Consumer Electronics Magazine*, *13*(5), 13–22. https://doi.org/10.1109/MCE.2022.3164221

Moutik, B., Summerscales, J., Graham-Jones, J & Pemberton, R. (2023). Life Cycle Assessment Research Trends and Implications: A Bibliometric Analysis. *Sustainability (Switzerland)*, *15*(18). https://doi.org/10.3390/su151813408

Mukherjee, D., Lim, W. M., Kumar, S & Donthu, N. (2022). Guidelines for advancing theory and practice through bibliometric research. *Journal of Business Research*, *148*(May), 101–115. https://doi.org/10.1016/j.jbusres.2022.04.042

Namaki, P., Vegesna, B. S., Bigdellou, S., Chen, R & Chen, Q. (2024). An Integrated Building Information Modeling and Life-Cycle Assessment Approach to Facilitate Design Decisions on Sustainable Building Projects in Canada. *Sustainability (Switzerland)* , *16*(11). https://doi.org/10.3390/su16114718

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T.

C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *The BMJ*, *372*. https://doi.org/10.1136/bmj.n71

Pushkar, S & Verbitsky, O. (2016). ENVIRONMENTAL DAMAGE FROM WALL TECHNOLOGIES FOR RESIDENTIAL BUILDINGS IN ISRAEL. *Journal of Green Building*, *11*(4), 154–162.

Rizo-Maestre, C., González-Avilés, Á., Galiano-Garrigós, A., Andújar-Montoya, M. D & Puchol-García, J. A. (2020). UAV + BIM: Incorporation of photogrammetric techniques in architectural projects with building information modeling versus classical work processes. *Remote Sensing*, *12*(14), 1–18. https://doi.org/10.3390/rs12142329

Russell, S & Norvig, P. (2022). Artificial Intelligence : A Modern Approach, 4/E. In *Pearson Series in Artifical Intelligence*.

Schwartz, Y., Raslan, R., Korolija, I & Mumovic, D. (2021). A decision support tool for building design: An integrated generative design, optimisation and life cycle performance approach. *International Journal of Architectural Computing*, *19*(3), 401–430. https://doi.org/10.1177/1478077121999802

Shahjalal, M., Islam, K., Batool, F., Tiznobaik, M., Zahid Hossain, F. M., Sakil Ahmed, K., Alam, M. S & Ahsan, R. (2023). Fiber-reinforced recycled aggregate concrete with crumb rubber: A state-of-the-art review. *Construction and Building Materials*, *404*(July), 133233. https://doi.org/10.1016/j.conbuildmat.2023.133233

Sharma, R., Kamble, S. S., Gunasekaran, A., Kumar, V & Kumar, A. (2020). A systematic literature review on machine learning applications for sustainable agriculture supply chain performance. *Computers and Operations Research*, *119*, 104926. https://doi.org/10.1016/j.cor.2020.104926

Soudagar, M. E. M., Shelare, S., Marghade, D., Belkhode, P., Nur-E-Alam, M., Kiong, T. S., Ramesh, S., Rajabi, A., Venu, H., Yunus

Khan, T. M., Mujtaba, M. A., Shahapurkar, K., Kalam, M. A & Fattah, I. M. R. (2024). Optimizing IC engine efficiency: A comprehensive review on biodiesel, nanofluid, and the role of artificial intelligence and machine learning. *Energy Conversion and Management*, *307*(February), 118337. https://doi.org/10.1016/j.enconman.2024.118337

Soust-Verdaguer, B., Llatas, C & García-Martínez, A. (2016). Simplification in life cycle assessment of single-family houses: A review of recent developments. *Building and Environment*, *103*, 215–227. https://doi.org/10.1016/j.buildenv.2016.04.014

Tajuddeen, I., Sajjadian, S. M & Jafari, M. (2023). Regression Models for Predicting the Global Warming Potential of Thermal Insulation Materials. *Buildings*, *13*(1). https://doi.org/10.3390/buildings13010171

Teng, Y., Xu, J., Pan, W & Zhang, Y. (2022). A systematic review of the integration of building information modeling into life cycle assessment. *Building and Environment*, *221*(May), 109260. https://doi.org/10.1016/j.buildenv.2022.109260

Tian, Z., Zhang, X., Wei, S., Du, S & Shi, X. (2021). A review of data-driven building performance analysis and design on big on-site building performance data. *Journal of Building Engineering*, *41*(January), 102706. https://doi.org/10.1016/j.jobe.2021.102706

UNEP. (2022). United Nations Environment Programme. In *Global status report for buildings and construction*. https://doi.org/10.1007/978-3-031-25984-5_302264

Vuarnoz, D. (2021). Assessing the required life-cycle characteristics of electricity storage for ensuring sustainability in buildings. *Architectural Science Review*, *64*(1–2), 28–36. https://doi.org/10.1080/00038628.2020.1772193

Wang, X., Wang, T., Bi, H., Jiang, C., Yan, W., Li, P & Li, J. (2024). ECNet: Network Based on Encoder With Local Convolutional Attention and Cross Layer Information Fusion for Natural Gas Pipeline Leakage Detection. *IEEE Sensors Journal*, *24*(7), 11886–11894. https://doi.org/10.1109/JSEN.2024.3365740

Xayachak, T., Haque, N., Parthasarathy, R., King, S., Emami, N., Lau, D & Pramanik, B. K. (2022). Pyrolysis for plastic waste management: An engineering perspective. *Journal of Environmental Chemical Engineering*, *10*(6), 108865. https://doi.org/10.1016/j.jece.2022.108865

Yardımcı, Y., Colak Demirel, B. B & Ertosun Yıldız, M. (2024). Climatic Influences on the Environmental Performances of Residential Buildings: A Comparative Case Study in Turkey. *Buildings*, *14*(12), 1–18. https://doi.org/10.3390/buildings14124015

Yılmaz, Y & Seyis, S. (2021). Mapping the scientific research of the life cycle assessment in the construction industry: A scientometric analysis. *Building and Environment*, *204*(March), 108086. https://doi.org/10.1016/j.buildenv.2021.108086

Zupic, I & Čater, T. (2015). Bibliometric Methods in Management and Organization. *Organizational Research Methods*, *18*(3), 429–472. https://doi.org/10.1177/1094428114562629

Res. Asst. Adil YİRMİBEŞ
E-mail: adilyirmibes@uludag.edu.tr
Educational Status: M.Sc.
License: Mimar Sinan Fine Art University, Faculty of Architecture, Department of Architecture, 2012-2016
Degree: Bursa Uludağ University, Master’s Program in Architecture Graduate School of Natural and Applied Sciences, Department of Architecture, 2018-2022
Doctorate: Bursa Uludağ University, Ph. D. Program in Architecture, Graduate School of Natural and Applied Sciences, Nilüfer, Bursa/Türkiye., 2022-in progress
Professional experiences: Research Assistant at Bursa Uludağ University, Faculty of Architecture, Department of Architecture

Res. Asst. Barış Mert KARASU
E-mail: bmertkarasu@uludag.edu.tr
Educational Status: M.Sc.
License: Eskişehir Osmangazi University, Faculty of Engineering and Architecture, Department of Architecture, 2012-2017
Degree: Bursa Uludağ University, Master’s Program in Architecture Graduate School of Natural and Applied Sciences, Department of Architecture, 2019-2022
Bursa Uludağ University, Ph. D. Program in Architecture, Graduate School of Natural and Applied Sciences, Nilüfer, Bursa/Türkiye., 2022-in progress
Professional experiences: Research Assistant at Bursa Uludağ University, Faculty of Architecture, Department of Architecture

An Overview on the Life Cycle Assessment of Building Materials Produced from Textile Waste

Merve BULUÇ [1]

[1]Bursa Uludağ University, Graduate School of Natural and Applied Sciences, Department of Architecture, Görükle Campus, Bursa/Türkiye.
ORCID: 0009-0006-9202-0894
E-mail: 502312004@ogr.uludag.edu.tr

Citation: Buluç, M. (2025). An Overview on the Life Cycle Assessment of Building Materials Produced from Textile Waste. Beceren Öztürk, R., & Çahantimur, A. (Eds.). **Contemporary Approaches in Architecture: The Role of Architecture in the Circular Economy.** 2025, Chapter: 12, 309-344. ISBN: 978-625-378-348-8. Iksad Publications. DOI: https://doi.org/10.5281/zenodo.17316834

1. Introduction

Life Cycle Assessment (LCA) is a methodology that is utilized to identify, report and manage the environmental impacts that occur in the stages of the cycle, commencing with the acquisition of raw materials used in the product produced by the first manufacturer or in the service provided, including all production, transportation, use by the end consumer and disposal of wastes when their useful life is completed (Tok, 2015). The formal analytical scheme proposed by Harry E. TEASLEY, Jr., later referred to as LCA, was developed in 1969. Following a comprehensive study, he developed a visual study with the aim of measuring the energy and materials utilized in the life cycle of a packaging product, from the extraction of raw materials to its eventual disposal and the environmental consequences of these processes. He aimed to determine that the use of materials is related to energy resources and to know the effects of various packages to be used. REPA (Resource and Environmental Profile Analysis) is a historical term that has been used since 1970 for environmental life cycle studies. The REPA/LCA method was established between 1970 and 1974, simultaneously creating a modern approach to impact assessment. In accordance with customer requests, all projects were executed in private until 1974 and were not published. The term 'LCA' was first used in the USA in 1990 (Hunt & Franklin, 1996). Since the beginning of the 1990s, the concept of 'Cradle to Grave' has been utilised in the evaluation of materials and products. In 1992, at the United Nations World Summit Meeting, it was reported that the 'Cradle to Grave' concept should also be utilised in environmental management. In 1993, "The LCA

Sourcebook: A European Guide to Life Cycle Assessment" was published (Tok, 2015).

The LCA tool is utilised to evaluate a product or service from the extraction of raw materials to the conclusion of its useful life, that is defined as from cradle to grave. It was built on ISO 14040, a set of environmental management standards by the International Standards Organization. The LCA model is categorized into four phases (Sulochani, Jayasinghe, Fernando, Nilmini & Priyadarshana, 2023):

1. Goal and scope definition
2. Lifecycle Inventory (LCI) analysis
3. Lifecycle impact assessment (LCIA)
4. Interpretation" (Sulochani et al., 2023, p. 443)

In Life Cycle Assessment, two distinct model are employed depending on the stages determined by researchers (Rana, Karunamoorthy, Parveen & Fangueiro, 2015):

1. In the "cradle-to-grave" (Rana et al., 2015, p. 200) model, the entire life cycle of a product or service is analysed.
2. In the "cradle-to-gate or cradle-to-factory gate" (Rana et al., 2015, p. 200) model, the stage or stages within a specified process throughout the entire life cycle of a product or service are analysed.

The environmental parameters generally employed in Life Cycle Assessment can be listed as follows (Rana et al., 2015) "Agricultural land occupation, Climate change, Freshwater ecotoxicity, Freshwater eutrophication, Human toxicity, Ozone layer depletion, Terrestrial acidification, Terrestrial ecotoxicity" (Rana et al., 2015, p. 201).

The LCA method has been subject to significant improvements in terms of its reliability and has gained international acceptance due to the collaborative endeavours of "ISO and SETAC (The Society of Environmental Toxicology and Chemistry)" (Tok, 2015, p. 15). The standards specified by the "TS EN ISO 14040, EN ISO 14041, EN ISO 14042, EN ISO 14043, and EN ISO 14044" (Tok, 2015, p. 16) provide comprehensive descriptions of the Life Cycle Assessment (LCA). The "TS EN ISO 14041" and "TS EN ISO 14042" standards have been repealed (Tok, 2015, p. 16). The following standards are currently in force: "TS EN ISO 14040" (Tok, 2015, p. 16) for the principles and framework of LCA, and "TS EN ISO 14044" (Tok, 2015, p. 16) for the requirements and guidelines of Life Cycle Assessment. The Principles and Framework describe the environmental management techniques in which the possible environmental impacts are evaluated within the framework of this cycle, from the acquisition of raw materials of the products to their use and recycling or disposal processes at the end of their life cycle. The Requirements and Guidelines define the purpose and scope of LCA, and describe the processes and conditions for conducting, interpreting, and reporting analyses (Tok, 2015).

1.1. LCA Method in the Construction Sector

As with any product, a structure in the construction industry is a system that can be evaluated throughout its life cycle, including the procurement of raw materials, the conversion of these raw materials into construction products, the construction process, the use of the structure, and the demolition phase. The LCA method is a scientific approach that evaluates various scenarios and possibilities for minimising energy and resource consumption, and thereby reducing the environmental footprint of the materials used in the structure (Çelebi & Arpacıoğlu, 2024). The LCA method is addressed in the literature in four stages (Çelebi & Arpacıoğlu, 2023):

“1) Process analysis

2) Process-based hybrid analysis

3) Input-output analysis

4) Input-output hybrid analysis” (Çelebi & Arpacıoğlu, 2023, p. 448)

A building consumes energy in two ways (Çelebi & Arpacıoğlu, 2023):

“1) Operational energy

2) Embodied energy” (Çelebi & Arpacıoğlu, 2023, p. 448):

Operational energy can be defined as the energy utilized for the purpose of maintaining comfort conditions within a building, including heating, cooling, ventilation, hot water supply, lighting, and equipment. Embodied energy can be defined as the energy necessary for the extraction of raw materials and their conversion into building products, the construction process, the utilization of the building, and its demolition. In consideration of the energy consumption necessitated by the construction industry, efforts to reduce greenhouse gas emissions at the national level are of paramount importance (Çelebi & Arpacıoğlu, 2023). As illustrated in Figure 1, the life cycle for a building encompasses a series of stages (Adapted from Simonen, 2014).

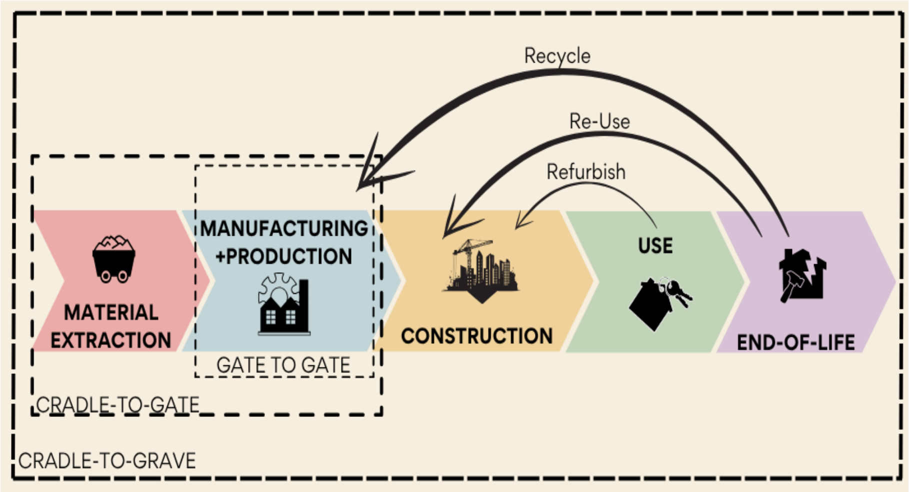

Figure 1. "*Life Cycle Stages of a Building*" (Adapted from Simonen, 2014)

1.2. LCA Method in the Textile Sector

The textile and clothing industry, a major economic sector, is also the industry that causes the most pollution, with its negative environmental impacts ranking it after the food, transportation, and construction sectors. The negative environmental impact of this industry can be explained under five main categories, depending on the raw materials used and the production stages (Resta & Dotti, 2015):

-The amount of energy consumed in the process from the production of primary materials to the sale

-The amount of water consumed in the extraction of raw materials, chemical processes in production, and cleaning

-The chemicals used and the amount of water they leave behind

-The amount of solid waste generated from the packaging of the final product to its disposal

-The amount of CO_2 generated during the transportation process and other processes

The life cycle of products manufactured in the textile industry is shown in Figure 2 (Adapted from Eryuruk, 2015). Any textile product has various inputs and outputs throughout its life cycle. Factors that enable the product to exist, such as raw materials or water, are defined as inputs, while emissions into the air, water, or land during the raw material or product's production phase are defined as outputs (Eryuruk, 2015).

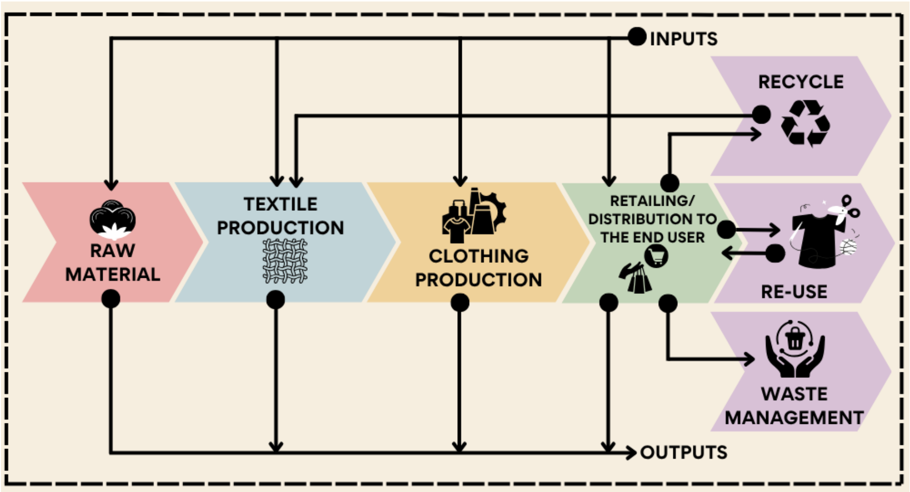

Figure 2. The life cycle of any product in the textile industry (Adapted from Eryuruk, 2015)

Despite being an important economic sector, the textile industry contributes significantly to ecosystem pollution and necessitates prioritising waste management practices such as recycling, reuse, and reduction to mitigate its harmful environmental impacts.

Textile waste is a potential source for building materials (Buluç, Beceren Öztürk & Çahantimur, 2024). insulation materials produced from cotton waste by turning it into felt for use on roofs, insulation material for hot water pipe insulation produced from cotton and jute waste, clay bricks mixed with cotton and textile ash, gypsum board made from ethylene-vinyl acetate material produced during the cutting of boards used in the footwear industry, felt made from textile waste for vertical gardens, and acoustic wall coverings produced from recycled denim fibres are examples of building materials produced from textile waste, as demonstrated in the study of Buluç et al. (2024).

2. Material and Method

A comprehensive literature review was conducted using the Scopus database to provide a general assessment of the LCA evaluation of building materials produced from textile waste. A simple search was performed in the Scopus database on 27th July 2025 using the search terms "textile waste" AND "life cycle assessment" AND "life cycle" in the “Article title, Abstract, Keywords” search field. This resulted in a comprehensive search on textile waste and LCA studies, which yielded 63 studies published between 2011 and 27/07/2025. As a result of this research conducted in the starting year was determined as 2011 because the Scopus database indexes relevant studies from that year onwards. Therefore, 2011 represents the earliest point at which comprehensive and systematic coverage of the field becomes available. In the context of the retrieved publications, the keyword field was narrowed down to target publications covering the relationship between textile waste, construction, building materials, and LCA. For this reason, the following terms were entered in the Keyword section: Building Materials, Circular Economy, Composite, Composites, Construction Industry, Environmental Impact Assessment, Environmental Life Cycle Assessment, Insulation Materials, Lca, Life Cycle, Life Cycle Analysis, Life Cycle Assessment, Life Cycle Assessment (lca), Life-cycle Assessment, Recycling, Recycling Process, Reuse, Sustainability, Textile Waste, and Thermal Insulation. Consequently, a total of 62 studies published between 2011, and 27th July 2025 were identified. The application of filters enabled the effective segregation of publications related to architecture and construction from those in other fields. Consequently, the list that had been saved with a .csv extension was opened in Excel format. In the Excel form, the search brick, building, cement, ceramic, construction, facade, façade, finishing material, insulation, Insulation, and wall were searched for in the Abstract and Author Keyword columns of the Excel form, and the results were examined. This was done to distinguish construction materials produced from textile waste from other studies. A review of research studies identified 10 publications that focused on the analysis of construction materials produced from textile waste using the LCA method.

3. Findings and Discussion: Life Cycle Assessment of Textile Waste-Based Building Materials

In this section, the 10 studies identified through bibliometric analysis are reviewed in relation to keywords, raw materials, products, standards, methods, system boundaries, comparative products, impact categories, and the overall results within the scope of Life Cycle Assessment (LCA).

This study by Augello, Carcassi, Pittau, Malighetti & De Angelis (2022) was evaluated within the scope of LCA. The summary of the study's results and the findings presented in Table 1 are provided below:

Table 1. Findings of The Study Presented by Augello et al. (2022).

The study under examination		**"Closing the loop of textile: Circular building renovation with novel recycled insulations from wasted clothes" (Augello et al., 2022, p. 203)**
	Headings examined	**Findings**
1	Keywords	"Circular economy, life cycle assessment, sustainability, textile wastes, thermal conductivity, transient plane source method" (Augello et al., 2022, p. 203)
2	Raw materials	"Cotton waste" (Augello et al., 2022, p. 205)
3	Samples	"Loose fibres (Cotton_1), thermal treatment (Cotton/BICO%5 and Cotton/BICO %25)" (Augello et al., 2022, p. 205)
4	Standards	ISO 14067:2018 (Augello et al., 2022)
5	Methods	Ecoinvent 3.8 database and SimaPro software
6	System boundaries	The Cradle-to-Gate model: This model encompasses the process from textile waste collection to product production (Augello et al., 2022).
7	Alternatives compared	"Cotton/BICO %95/%5, Cotton/BICO %75/%25, EPS, Rockwool, Glasswool, and Woodfibre" (Augello et al., 2022, p. 207)
8	Categories of impact	"Global warming potential, carbon footprint" (Augello et al., 2022, p. 206)

This study presents the main results of the RECYdress project, which aimed to develop new thermal insulation materials to combat high emission values in the construction and textile sectors. The study shows that textile waste can be used for thermal insulation, but that the binding agents, density, number of components, and production method contained within it should be considered, as these affect thermal conductivity (Augello et al., 2022).

The increase in the number of components in textile-based products has a negative impact on the carbon footprint. In the Cotton/BICO 95/5 product, the global warming potential value is negative due to the low number of bi-component fibres, while the amount of CO2 stored is positive (Augello et al., 2022).

This study by Komaei, Mosaddegh, Hemmati & Fahimifar (2025) was evaluated within the scope of LCA. The summary of the study's results and the findings presented in Table 2 are provided below:

Table 2. Findings of The Study Presented by Komaei et al. (2025).

The study under examination		**“Stabilization of rammed earth with waste materials for sustainable construction under rainfall Conditions: With consideration of life cycle assessment (LCA)” (Komaei et al., 2025, p. 1)**
	Headings examined	**Findings**
1	Keywords	“Alkali-activated materials, Life cycle assessment, Low-carbon technology, Rammed earth, Sustainable construction, Waste utilization” (Komaei et al., 2025, p. 1)
2	Raw materials	“Soil, ordinary portland cement, granulated blast furnace slag, potassium hydroxide and carpet waste fibres” (Komaei et al., 2025, p. 2, p. 11, p. 3)
3	Samples	“Compacted unstabilised soil, compacted fibre-reinforced soil, compacted soil composed of alkali-activated materials, and compacted fibre-reinforced soil composed of alkali-activated materials” (Komaei et al., 2025, p. 2)
4	Standards	ISO 14040 and ISO 14044 (Komaei et al., 2025)
5	Methods	ReCiPe 2016 Midpoint (H) method, OpenLCA software, and the Ecoinvent v3.8 database (Komaei et al., 2025)
6	System boundaries	The extraction of raw materials, processing of raw materials, production of raw materials, and transportation of raw materials (Komaei et al., 2025)
7	Alternatives compared	“Soil stabilised with ordinary Portland cement and soil stabilised with alkali-activated materials” (Komaei et al., 2025, p. 15)
8	Categories of impact	“Climate change, primary energy demand, ozone layer depletion, terrestrial acidification, marine eutrophication, human toxicity, particulate matter formation, photochemical oxidant formation, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, metal depletion” (Komaei et al., 2025, p. 2)

This study investigated the potential of waste carpet fibres and alkali-activated materials to increase the performance and durability of compressed soil walls. The study aimed to decrease the environmental footprint of the construction industry. Using waste carpet fibres supports the circular economy in both the textile and construction industries. Compressed soil created using a combination of carpet waste fibres and alkali-activated materials exhibited an increase in unconfined compressive strength compared to unstabilised soil. In addition, it has proven its durability in long-term use by demonstrating properties such as improved moisture resistance, superior tensile strength and durability, and reduced brittleness. Using carpet waste improves mechanical properties and supports the circular economy in construction by reusing waste materials. The utilisation of compressed soil, comprising alkaline active ingredients, has been demonstrated to exert a substantial influence on the reduction of greenhouse gas emissions and energy consumption (Komaei et al., 2025). The utilisation of carpet waste fibres and alkaline active substances in the construction of durable building materials for compacted soil structures has the potential to reduce carbon footprints (Komaei et al., 2025).

This study by Violano & Cannaviello (2023) was evaluated within the scope of LCA. The summary of the study's results and the findings presented in Table 3 are provided below:

Table 3. Findings of The Study Presented by Violano & Cannaviello, (2023).

The study under examination		**"Stabilization of rammed earth with waste materials for sustainable construction under rainfall Conditions: With consideration of life cycle assessment (LCA)" (Violano & Cannaviello, 2023, p. 1)**
	Headings examined	**Findings**
1	Keywords	"Carbon footprint, circular model, embodied carbon, life cycle assessment, textile waste, thermal insulation, whole life carbon" (Violano & Cannaviello, 2023, p. 1)
2	Raw materials	"Recycle textile waste" (Violano & Cannaviello, 2023, p. 1)
3	Samples	"Insulation material that is entirely composed of textile waste" (Violano & Cannaviello, 2023, p. 1)
4	Standards	ISO 14044 (Violano & Cannaviello, 2023)
5	Methods	The methodology based on EN 15804 (Violano & Cannaviello, 2023)
6	System boundaries	The Cradle-to-Gate model: "Raw material supply, transport, manufacturing, carbon footprint of thermal insulation, transport to the site, construction process or installation process, using, management, recycling or reuse, and disposal" (Violano & Cannaviello, 2023, p. 18)
7	Alternatives compared	"Traditional-EPS, nature-based-cork, and innovative-insulation from textile waste" (Violano & Cannaviello, 2023, p. 19)
8	Categories of impact	"Carbon footprint" (Violano & Cannaviello, 2023, p.7)

This study concluded that traditional EPS is considered to have a negative environmental impact due to its production from non-renewable resources and high energy consumption, but its widespread processing is considered to have a positive environmental impact during the transportation phase. Although EPS that cannot be reused after dismantling is completely recyclable, the recycling process requires intensive use of water and energy (Violano & Cannaviello, 2023).

This study by Salah, Vololonirina & Godik (2022) was evaluated within the scope of LCA. The summary of the study's results and the findings presented in Table 4 are provided below:

Table 4. Findings of The Study Presented by Salah et al. (2022).

The study under examination		**"Development of fibrous materials applied in timber-framed construction using recycled fibers from textile waste" (Salah et al., 2022, p. 1)**
	Headings examined	**Findings**
1	Keywords	"Nonwoven, Rain-screen, Recycled fibers, Textile waste, Timber-frame construction, Vapor barrier" (Salah et al., 2022, p. 1)
2	Raw materials	"Textile waste containing 13.4% wool, 25.4% cotton, 7.3% polyester, 47% acrylic, 0.5% viscose, and 6.4% polyamide" (Salah et al., 2022, p. 2) with increased resistance thanks to "high-strength polyester or two-component fibres" (Salah et al., 2022, p. 2)
3	Samples	LCA samples are not specified because the LCA method was not performed in detail.
4	Standards	LCA standards are not specified because the LCA method was not performed in detail.
5	Methods	LCA methods are not specified because the LCA method was not performed in detail.
6	System boundaries	The Cradle-to-Gate model: the system boundary was used to guide future LCA studies in this study. "Waste collection, transportation, selection of fibres, nonwoven fabric production stages, nonwoven fabric lamination, packaging, distribution, use phase, end of life" (Salah et al., 2022, p. 11) stages can be used as boundaries for potential future LCA studies (Salah et al., 2022)
7	Alternatives compared	Since the LCA method was not carried out in detail, no product comparison based on LCA has been specified.
8	Categories of impact	LCA impact categories are not specified because the LCA method was not performed in detail.

In this study, Salah et al. (2022) found that nonwoven fabrics produced from recycled textile waste had the potential to serve as an alternative to rain screens and vapour barriers made from petrochemicals in timber frame buildings. These fabrics met the standards for use as vapour barriers and rain screens when laminated with membranes and treated with chemical water repellents (Salah et al., 2022).

The study emphasises the necessity of conducting an LCA as imperative to ascertain the actual impacts of such innovative materials throughout their entire life cycle. The initial step in this study was to define the cradle-to-grave system boundary to produce nonwoven fabric. The inputs in fabric production were classified, the processes to be applied were listed, and the outputs that could be obtained at the end of production were defined at the technical centre scale (Salah et al., 2022).

This study by Ventura, Álvarez, Gonzalez-Lopez, Claramunt & Ardanuy (2022) was evaluated within the scope of LCA. The summary of the study's results and the findings presented in Table 5 are provided below:

Table 5. Findings of The Study Presented by Ventura et al. (2022).

The study under examination		"Cement composite plates reinforced with nonwoven fabrics from technical textile waste fibres: Mechanical and environmental assessment" (Ventura et al., 2022, p. 1)
	Headings examined	**Findings**
1	Keywords	"Composite, Fibre reinforcement, Textile waste, Life cycle assessment, Mechanical properties, Portland cement" (Ventura et al., 2022, p. 1)
2	Raw materials	"Portland cement, technical textile waste (TTW) fibres that are obtained from the shredding of firefighters' protective shirts, and fashion textile wastes (FTW)" (Ventura et al., 2022, p. 1)
3	Samples	Nonwoven fabric, portland cement composite plates that contain technical textile waste (TTW-4L), portland cement composite plates that contain fashion textile waste (FTW-4L) (Ventura et al., 2022)
4	Standards	ISO 14040 (ISO/TC 207, 2006a) and ISO 14044 (ISO/TC 207, 2006b) (Ventura et al., 2022)
5	Methods	SimaPro 9.1.0.11" software, the ReCiPe 2016 v1.1 midpoint hierarchy version approach, and Ecoinvent v3.6 databased (Ventura et al., 2022)
6	System boundaries	The Cradle-to-Gate model: Shredding of TTWs and FTWs, conversion of TTWs and FTWs into fibres, conversion of fibres produced from waste into non-woven fabrics, and production of the final composite panel that is based on Portland cement and nonwoven fabric (Ventura et al., 2022)
7	Alternatives compared	"Ceramic tiles, natural stone plates, fibre cement facing tiles, FTW-4L composite plate, and TTW-4L composite plate" (Ventura et al., 2022, p. 9)
8	Categories of impact	"Global warming, stratospheric ozone depletion, ionizing radiation, ozone formation, human health, fine particulate matter formation, terrestrial ecosystems, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, land use, mineral resource scarcity, fossil resource scarcity, water consumption" (Ventura et al., 2022, p. 9)

This study concluded that composite panels produced from technical textile waste have a similar environmental impact to fibre cement cladding tiles. On the other hand, composite panels produced from fashion textile waste have a negative environmental impact compared to fibre cement cladding tiles. Additionally, these new composites have been found to have a more positive impact on the environment than traditional ceramic tiles and natural stone panels (Ventura et al., 2022).

This study by Sulochani, Jayasinghe, Fernando, Nilmini & Priyadarshana (2023) was evaluated within the scope of LCA. The summary of the study's results and the findings presented in Table 6 are provided below:

Table 6. Findings of The Study Presented by Sulochani et al. (2023).

The study under examination		**"Life Cycle Assessment (LCA) of a Textile Waste Thermoplastic Composite Material for Wall Partitioning Applications" (Sulochani et al., 2023, p. 441)**
	Headings examined	**Findings**
1	Keywords	"GHG, Global Warming Potential, LCA, Textile waste, Thermoplastic composite, Wall partitioning material" (Sulochani et al., 2023, p. 442)
2	Raw materials	"Polyester textile waste, pre-consumer polyester textile waste, thermoplastic packaging waste (Polypropylene, Linear low-density polyethylene, Low-density polyethylene), and water" (Sulochani et al., 2023, p. 441)
3	Samples	"7.5 wt% waste polyester textile fiber reinforced thermoplastic composite" (Sulochani et al., 2023, p. 444)
4	Standards	ISO 14040 (Sulochani et al., 2023)
5	Methods	GaBi (V8.7.1.3) software and database, Ecoinvent 3.8" database, Global data set (GLO) (Sulochani et al., 2023)
6	System boundaries	Mechanical shredding of textile waste, processing of shredded textile and packaging waste, and production of the final composite panel product (Sulochani et al., 2023)
7	Alternatives compared	"Thermoplastic composites containing polyester textile waste and thermoplastic packaging waste, and gypsum panels produced using unprocessed raw materials" (Sulochani et al., 2023, p. 444)
8	Categories of impact	"Global warming potential" (Sulochani et al., 2023, p. 444)

This study concluded that, in terms of global warming potential, thermoplastic composite panels made entirely from waste materials and reinforced with 7.5% polyester textile fibres from waste are a more sustainable option than plasterboard panels for partition walls (Sulochani et al., 2023).

This study by Islam & Bhat (2019) is a review article providing a general overview. It presents research on acoustic and thermal insulation materials produced from textile waste (Islam & Bhat, 2019). This study by Islam &

Bhat (2019) was evaluated within the scope of LCA. The summary of the study's results and the findings presented in Table 7 are provided below:

Table 7. Findings of The Study Presented by Islam & Bhat (2019).

The study under examination		**"Environmentally-friendly thermal and acoustic insulation materials from recycled textiles" (Islam & Bhat, 2019, p. 1)**
	Headings examined	**Findings**
1	Keywords	"Acoustic insulation, Composites, Recycling, Sustainability, Textile waste, Thermal insulation materials" (Islam & Bhat, 2019, p. 1)
2	Raw materials	Polyester, nylon, acrylic, cotton, elastane, polypropylene, and polyamide (Islam & Bhat, 2019)
3	Samples	In studies examined in chapter 5 by Islam & Bhat (2019), textile products made from cotton, polyester, nylon, acrylic, and elastane are samples used within the scope of LCA.
4	Standards	ISO14040 (2006) and ISO14044 (2006) (Islam & Bhat, 2019) Standards ISO14040 (2006) and ISO14044 (2006) are mentioned in Section 5 for a comprehensive LCA analysis to be used by Islam & Bhat (2019).
5	Methods	Although the fifth section does not specify a method or software, Figure 2 presents the carbon footprint of the Swedish apparel industry over one year. This data originates from Roos et al. (2015, 2016), who modelled it using GaBi v6.0 and SimaPro v8.0 software with data from the Ecoinvent database (Islam & Bhat, 2019)
6	System boundaries	This study adopts a 'Cradle-to-Gate' system boundary, while some reviewed works also extend the analysis to product design and development. For instance, Islam et al. (2019) included electricity generation, raw material extraction, material production, clothing collection, processing, product distribution, and final waste disposal within the defined system boundaries (Islam & Bhat, 2019)
7	Alternatives compared	The studies examined in Chapter 5 by Islam & Bhat (2019) mention that textile products made from cotton, polyester, nylon, acrylic, and elastane were compared within the scope of LCA.
8	Categories of impact	Islam & Bhat (2019) refer to the study conducted by Roos et al. (2016), in which the carbon footprint was measured in Chapter 5.

This study concluded that the utilisation of recycled textiles will reduce environmental impacts (Islam & Bhat, 2019).

This study by Islam, Bhat & Mani (2024) was evaluated within the scope of LCA. The summary of the study's results and the findings presented in Table 8 are provided below:

Table 8. Findings of The Study Presented by Islam et al. (2024).

The study under examination		**"Life cycle assessment of thermal insulation materials produced from waste textiles" (Islam et al., 2024, p. 1071)**
	Headings examined	**Findings**
1	Keywords	"Greenhouse gas emissions, Nonwoven, Recycling, Textile wastes, Thermal insulation" (Islam et al., 2024, p. 1072)
2	Raw materials	Recycle cotton fibres, recycle nylon fibres, and polylactic acid fibres (Islam et al., 2024)
3	Samples	"N1: Thermal insulation panels from 100% recycled cotton fibres (control) N2: Thermal insulation panels from 90% recycled cotton fibres/10% PLA (thermoplastic binder polylactic acid fibres) N3: Thermal insulation panels from 42.5% recycled cotton fibres/42.5% recycled nylon fibres/15% PLA (thermoplastic binder polylactic acid fibres" (Islam et al., 2024, p. 1074)
4	Standards	ISO14040 and ISO14044 (Islam et al., 2024)
5	Methods	TRACI 2 V. 3.03 assessment method (Islam et al., 2024)
6	System boundaries	The Cradle-to-Gate model: Collection of waste textiles, fabric shredding, the extraction of PLA fibres from raw materials, fiber web formation, needle punching, and heat and pres/heat setting/insulation panel (Islam et al., 2024)
7	Alternatives compared	"N1: Thermal insulation panels from 100% recycled cotton fibres (control) N2: Thermal insulation panels from 90% recycled cotton fibres/10% PLA (thermoplastic binder polylactic acid fibres) N3: Thermal insulation panels from 42.5% recycled cotton fibres/42.5% recycled nylon fibres/15% PLA (thermoplastic binder polylactic acid fibres" (Islam et al., 2024)
8	Categories of impact	"Global warming, acidification, carcinogenics, noncarcinogenics, respiratory effects, eutrophication, ozone depletion, ecotoxicity, and smog" (Islam et al., 2024, p. 1079)

At this study concluded that samples containing 100% recycled cotton fibres (N1) and 90% recycled cotton fibres/10% PLA (N2) have been discovered to have a lower environmental impact than samples containing

42.5% recycled cotton fibres, 42.5% recycled nylon fibres, and 15% PLA (N3) particularly regarding thermal bonding and other production processes (Islam et al., 2024).

This study by Karmakar, Majumdar & Butola (2025) was evaluated within the scope of LCA. The summary of the study's results and the findings presented in Table 9 are provided below:

Table 9. Findings of The Study Presented by Karmakar et al. (2025).

The study under examination		**"A sustainable recycling process and its life cycle assessment for valorising post-consumer textile materials for thermal insulation applications" (Karmakar et al., 2025, p.749)**
	Headings examined	**Findings**
1	Keywords	"Circular economy, denim waste, life cycle assessment (LCA), nonwovens, post-consumer waste, sustainability, thermal insulation" (Karmakar et al., 2025, p.749)
2	Raw materials	The recycled cotton denim fibre (r-denim), and hollow PET fibres (Karmakar et al., 2025)
3	Samples	"R-denim/PET (40/60) fibres" (Karmakar et al., 2025, p.759)
4	Standards	ISO14040 and ISO14044 (Karmakar et al., 2025)
5	Methods	SimaPro software and CML-IA baseline V3.05/World 2000 characterization method (Karmakar et al., 2025)
6	System boundaries	The "Cradle-to-Gate" model: The definition of this boundary encompasses the production of raw materials and the fibre manufacturing stage and is based on a functional unit of 1 tonne (Karmakar et al., 2025).
7	Alternatives compared	R-denim/PET (40/60) fibres, and virgin PET fibres (Karmakar et al., 2025)
8	Categories of impact	"Marine aquatic ecotoxicity, abiotic depletion (fossil fuels), global warming, human toxicity, acidification, eutrophication, and ODP (ozone layer depletion)" (Karmakar et al., 2025, p.760)

This study concluded that the LCA of thermal insulation materials derived from post-consumer cotton denim waste that was first mechanically recycled and then mixed with hollow polyester fibres reduced the impact values in the specified categories, except for human toxicity (Karmakar et al., 2025).

This study by Moazzem, Wang, Daver & Crossin (2021) was evaluated within the scope of LCA. The summary of the study's results and the findings presented in Table 10 are provided below.

Table 10. Findings of The Study Presented by Moazzem et al. (2021).

The study under examination		**"Environmental impact of discarded apparel landfilling and recycling" (Moazzem et al., 2021, p.1)**
	Headings examined	**Findings**
1	Keywords	"Discarded apparel, environmental benefit, fibre material recycling, landfill, life cycle assessment, textile waste management" (Moazzem et al., 2021, p.1)
2	Raw materials	"%64,4 natural textile fibres, and %35,6 synthetic textile fibres" (Moazzem et al., 2021, p.3)
3	Samples	"Post-consumer household discarded apparel waste" (Moazzem et al., 2021, p.2)
4	Standards	ISO14040:2006 and ISO14044:2006 (Moazzem et al, 2021).
5	Methods	OpenLCA software (Moazzem et al, 2021).
6	System boundaries	The scenarios were analysed based on 1 tonne of clothing waste. The landfill scenario evaluates the environmental impact of non-recyclable clothing, including collection, transport, storage, landfill emissions, and energy recovery credits. In contrast, the recycling scenario examines four alternatives for recyclable garments, covering transport, recycling processes, process losses, and the substitution of equivalent products (Moazzem et al., 2021).
7	Alternatives compared	"Landfill of discarded apparel (baseline system), the recycling of cotton fibre (Mechanical recycling), the recycling of insulation material (Mechanical recycling), the recycling of PET raw material (Chemical recycling), and the recycling of industrial cleaning wipes (Mechanical recycling)" (Moazzem et al., 2021, p.4).
8	Categories of impact	Climate change potential, water depletion, agricultural land occupation, and acidification potential (Moazzem et al, 2021).

This study concluded that the conversion process of recycled clothing provides environmental benefits that offset the impact of similar products and landfill processes (Moazzem et al, 2021).

The results of the ten studies analysed in the present study have been presented in charts. In order to make the results of the graphing work more comprehensible, a cradle-to-grave approach that addresses different stages in each study, and the software, database, and standards with different versions and details, has been addressed without taking these details into account. Figure 3 presents the number of studies in which each of the identified keywords was employed, providing an overview of their relative prominence.

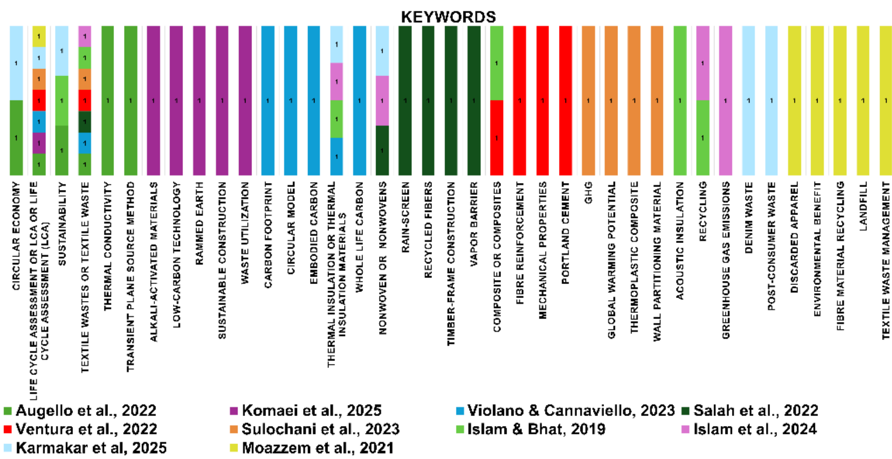

Figure 3. The chart of keywords used in articles (Created by author)

According to the chart results, in seven out of ten studies, ‘Life cycle assessment or LCA or Life cycle assessment (LCA)’ and ‘Textile waste or Textile waste’ were the most frequently used keywords, while in four studies, at least one of the keywords “thermal insulation” or “thermal insulation materials” was determined to have been used. (Figure 3).

Figure 4 shows the number of studies utilizing each raw material, highlighting their relative significance in the literature.

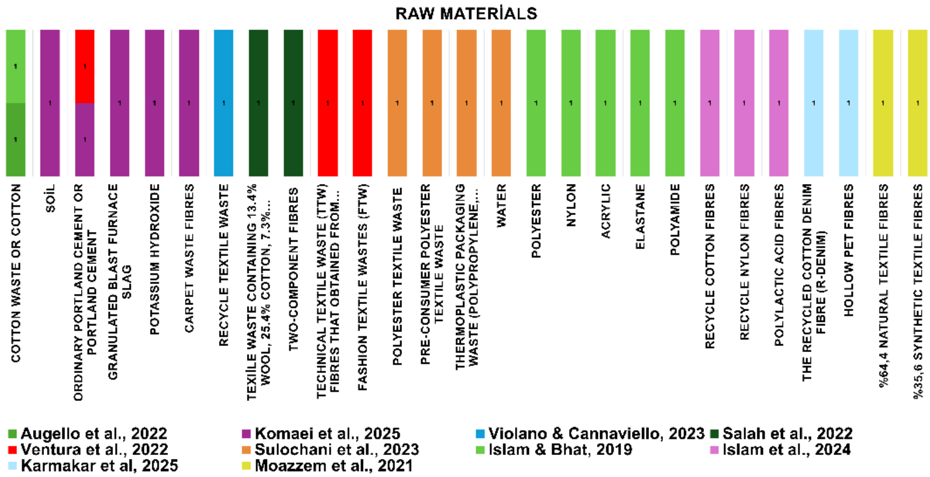

Figure 4. The chart of raw materials used in studies (Created by author)

According to the chart results, in two of the ten studies, 'Cotton waste or Cotton' and, similarly, in two of the ten studies, 'Ordinary Portland cement or Portland cement' were identified as the most frequently used raw materials. In addition, an analysis of other raw materials revealed a frequent utilisation of cotton-based materials (Figure 4).

Figure 5 shows the number of studies utilizing each sample type, providing insight into their prevalence within the literature.

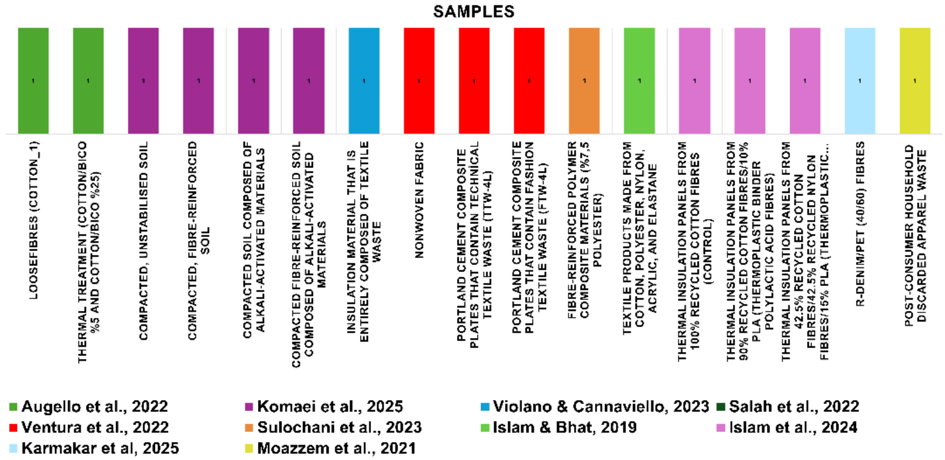

Figure 5. The chart of samples used in studies (Created by author)

As shown in Figure 5, it was determined that different samples were used in each of the ten studies examined. However, an examination of the samples utilised has revealed that most of them are composed of cotton-based materials.

Figure 6 shows the number of studies referencing specific standards, highlighting their role within the literature.

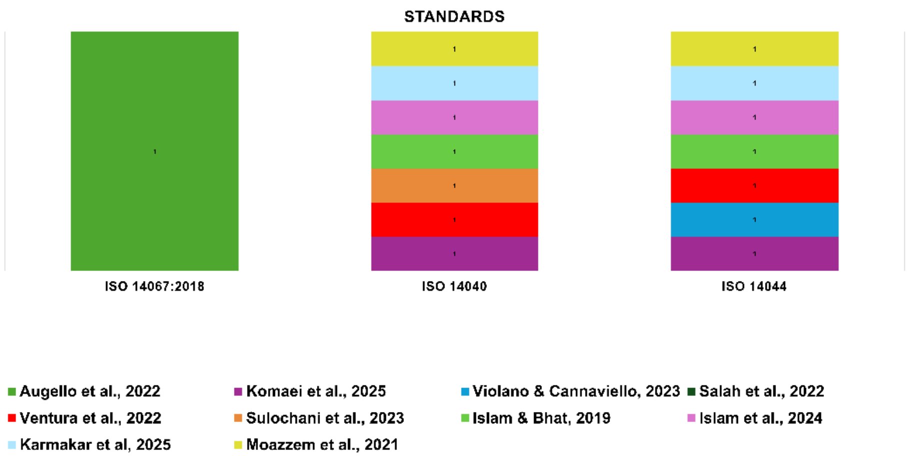

Figure 6. The chart of standards used in studies (Created by author)

According to the chart results, ISO 14040 and ISO 14044 were determined to be the most frequently used standards in seven out of ten studies (Figure 6).

Figure 7 presents the number of studies referencing specific standards, highlighting their application within the literature.

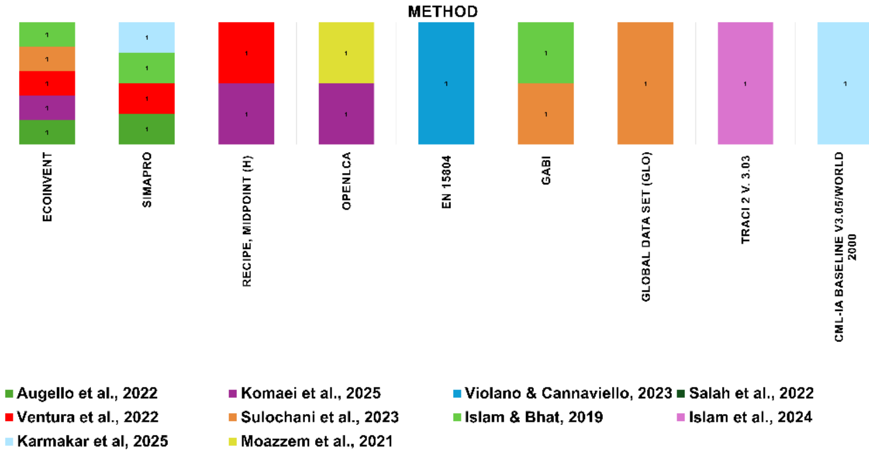

Figure 7. The chart of the method used in studies (Created by author)

According to the chart results, the 'Ecoinvent database' was determined to be the most frequently used method in five of the ten studies, and the 'Simapro software' was determined to be the most frequently used method in four of the ten studies (Figure 7).

Figure 8 presents the number of studies adopting specific system boundaries, highlighting variations in methodological scope.

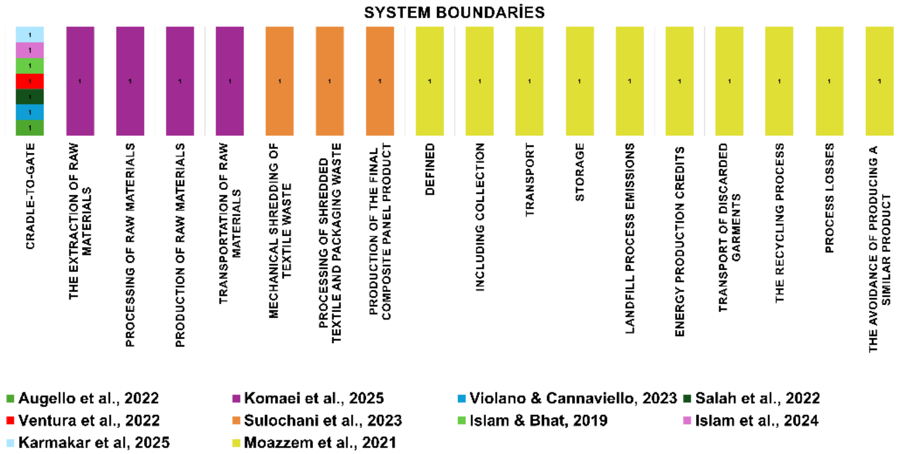

Figure 8. The chart of the system boundaries used in studies (Created by author)

According to the chart results, "Cradle to Gate" was determined to be the most frequently used system boundary in seven of the ten studies. (Figure 8). Figure 9 presents the number of studies evaluating specific alternatives, highlighting their role in comparative assessments.

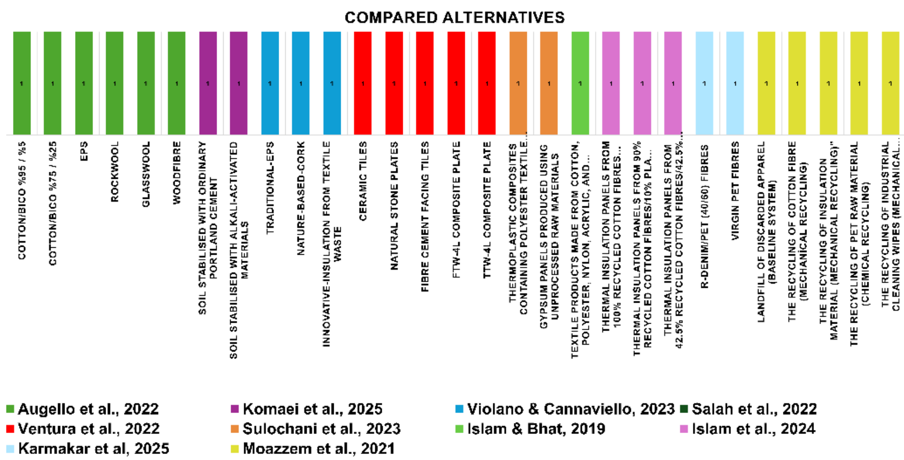

Figure 9. The chart of the compared alternatives used in studies (Created by author)

As shown in Figure 9, it was determined that different comparison alternatives were used in each of the ten studies examined. However, an examination of the compared alternatives utilised has revealed that most of them are composed of cotton-based materials.

Figure 10 presents the number of studies that analysed specific alternatives, highlighting their role in comparative evaluations.

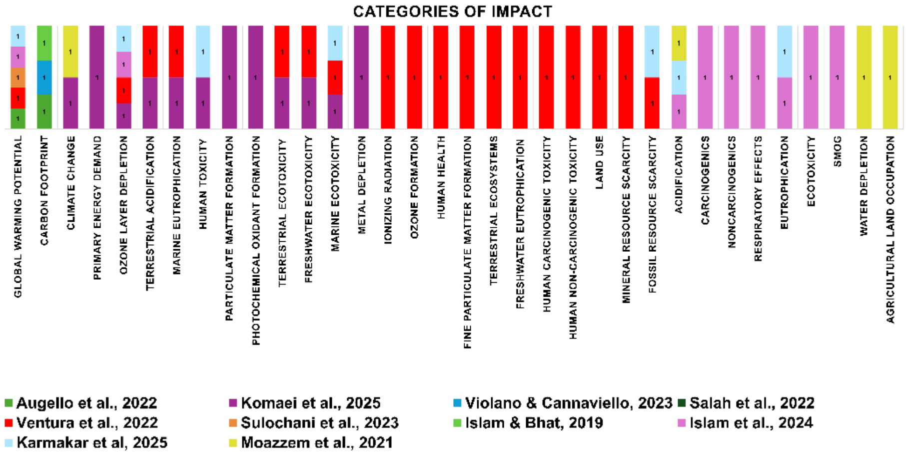

Figure 10. The chart of the categories of impact used in studies (Created by author)

According to the chart results, “Global warming potential” was determined to be the most frequently used impact category in six of the ten studies. (Figure 10).

This study concluded that the majority of the studies focused on insulation. Figure 11 illustrates the categorisation of study results under specific headings, providing a graphical overview of the findings

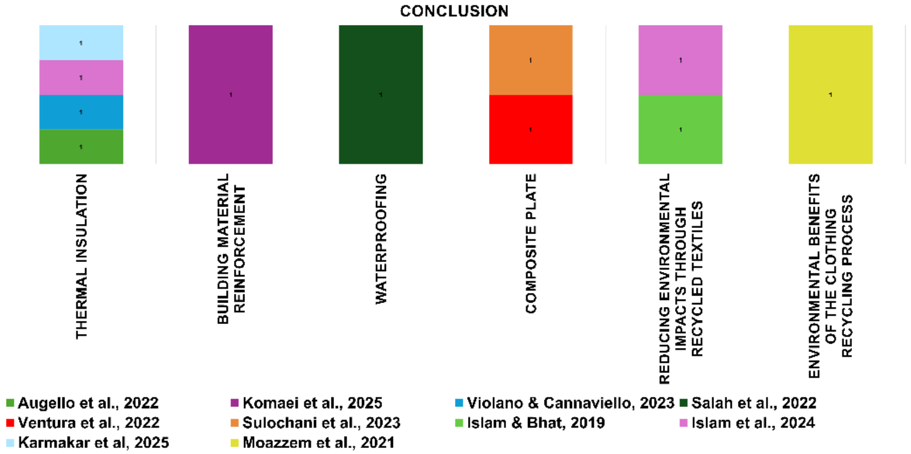

Figure 11. The chart of the conclusion used in studies (Created by author)

In conclusion, the most frequently used keywords in the ten articles examined were life cycle assessment and textile waste, while the most frequently used keyword in construction materials was thermal insulation. The most frequently used raw materials were cotton waste and cotton-based textile waste, and cotton-based products were also found to be the most common in the samples. The investigation revealed that the most frequently used standards were ISO 14040 and ISO 14044, while Ecoinvent was determined to be the most preferred database, and SimaPro was determined to be the most preferred software. The products compared were diverse, but those obtained from textile waste were particularly noteworthy. The most highly assessed impact category was determined to be global warming. The majority of studies have indicated that the use of textile waste in thermal insulation has the potential to reduce environmental impact.

4. Conclusion and Suggestions

This literature review, conducted through a systematic search of the Scopus database using defined keywords, highlights a substantial research gap concerning the life cycle assessment (LCA) of building materials derived from textile waste. Current studies reveal that textile waste has predominantly been applied to the production of insulation materials; however, emerging research indicates its potential for application in a broader spectrum of innovative construction products. These include, but are not limited to, façade cladding, interior decorative components, and other surface materials.

The reviewed studies demonstrate that the integration of textile waste into building material production, when assessed through LCA methodologies, not only provides a foundation for sustainable material innovation but also raises new research questions regarding performance, durability, and scalability. From an environmental perspective, the valorisation of textile waste in construction has the capacity to reduce landfill dependency, lower embodied carbon, and contribute meaningfully to circular economy strategies within the built environment.

Based on these findings, this study proposes the exploration of building components that form the visible and tactile texture of architectural spaces-such as façade claddings, interior surfaces, and decorative elements-produced from textile waste. Such initiatives should be systematically supported by LCA-based evaluations to ensure environmental performance, while also addressing technical standards and regulatory frameworks. Future research is encouraged to expand beyond insulation applications, incorporate comparative LCA analyses with conventional materials, and explore interdisciplinary collaborations that bridge material science, design innovation, and sustainable construction policy.

Acknowledgements and Information Note

The article complies with national and international research and publication ethics.

Ethics Committee approval was not required for the study.

Author Contribution and Conflict of Interest Declaration Information

1st Author % 100 contributed. There is no conflict of interest.

References

Augello, A., Carcassi, O. B., Pittau, F., Malighetti, L. E., & De Angelis, E. (2022). Closing the loop of textile: Circular building renovation with novel recycled insulations from wasted clothes. *Acta Polytechnica CTU Proceedings*, 38, 203-209. https://doi.org/10.14311/APP.2022.38.0203

Buluç, M, Beceren Öztürk, R. & Çahantimur, A. (2024). The Use of Textile Recycling in Building Facades and Finishing Materials. Dal, M. & Karataş, L.(Eds.). *Architectural Sciences and Theory, Practice and New Approaches-III*. 2024, Chapter:10, 276-314. ISBN: 978-625-367-828-9. Iksad Publications. DOI: 10.5281/zenodo.13757979

Çelebi, N.G. & Arpacıoğlu, Ü. T. (2023). Comparative Analysis of Steel and Reinforced Concrete Structural Frames in Terms of Environmental Impact. Gül et. al. (Eds.). *III. International Architectural Sciences and Applications Symposium. III. INTERNATIONAL ARCHITECTURAL SCIENCES AND APPLICATIONS SYMPOSIUM (IArcSAS-2023)* (pp. 447-455). Naples, Italy. IKSAD Publishing. https://doi.org/10.5281/zenodo.10032598

Çelebi, N.G. & Arpacıoğlu, Ü. T. (2024). Structural Frames in the Context of Earthquake and Environmental Impact. Karadağ, A.A. & Ertaş Beşir, Ş. (Eds.). *Earthquake Resistant Cities and Disaster Management*. Iksad Publications (2024), Chapter 4. (pp. 84-107). ISBN: 978-625-367-633-9.Ankara.

Eryuruk, S. H. (2015). Life cycle assessment method for environmental impact evaluation and certification systems for textiles and clothing. Muthu, S. S. (Eds.). *Handbook of Life Cycle Assessment (LCA) of Textiles and Clothing*. Elsevier Inc. (pp. 125–148). ISBN: 978-0-08-100169-1. Woodhead Publishing. ISBN: 978-0-08-100169-1. Woodhead Publishing. https://doi.org/10.1016/B978-0-08-100169-1.00007-1.

Hunt, R.G. & Franklin, W.E. (1996). LCA-How it came about. *Int. J. LCA*, 1, 4–7. https://doi.org/10.1007/BF02978624.

Islam, S., & Bhat, G. (2019). Environmentally-friendly thermal and acoustic insulation materials from recycled textiles. In *Journal of*

Environmental Management (Vol. 251). Academic Press. https://doi.org/10.1016/j.jenvman.2019.109536.

Islam, S., Bhat, G., & Mani, S. (2024). Life cycle assessment of thermal insulation materials produced from waste textiles. *Journal of Material Cycles and Waste Management*, *26*(2), 1071–1085. https://doi.org/10.1007/s10163-023-01882-7.

Karmakar, S., Majumdar, A., & Butola, B. S. (2025). A sustainable recycling process and its life cycle assessment for valorising post-consumer textile materials for thermal insulation applications. *Waste Management and Research*, *43*(5), 749–761. https://doi.org/10.1177/0734242X241270933.

Komaei, A., Mosaddegh, A., Hemmati, M., & Fahimifar, A. (2025). Stabilization of rammed earth with waste materials for sustainable construction under rainfall Conditions: With consideration of life cycle assessment (LCA). *Developments in the Built Environment*, 23, 1-18. https://doi.org/10.1016/j.dibe.2025.100701.

Moazzem, S., Wang, L., Daver, F., & Crossin, E. (2021). Environmental impact of discarded apparel landfilling and recycling. *Resources, Conservation and Recycling*, *166*. https://doi.org/10.1016/j.resconrec.2020.105338.

Rana, S., Karunamoorthy, S., Parveen, S., & Fangueiro, R. (2015). Life cycle assessment of cotton textiles and clothing. Muthu, S. S. (Eds.). *Handbook of Life Cycle Assessment (LCA) of Textiles and Clothing*. Elsevier Inc. (pp. 195–216). ISBN: 978-0-08-100169-1. Woodhead Publishing. https://doi.org/10.1016/B978-0-08-100169-1.00009-5.

Resta, B. & Dotti, S. (2015). Environmental impact assessment methods for textiles and clothing. Muthu, S. S. (Eds.). *Handbook of Life Cycle Assessment (LCA) of Textiles and Clothing* Elsevier Inc. (pp. 149–191). ISBN: 978-0-08-100169-1. Woodhead Publishing. ISBN: 978-0-08-100169-1. Woodhead Publishing. https://doi.org/10.1016/B978-0-08-100169-1.00008-3.

Roos, S., Zamani, B., Sandin, G., Peters, G. M., & Svanström, M. (2016). A life cycle assessment (LCA)-based approach to guiding an industry sector towards sustainability: the case of the Swedish apparel sector. *Journal of Cleaner Production*, *133*, 691–700. https://doi.org/10.1016/j.jclepro.2016.05.146

Salah, F., Vololonirina, O., & Gidik, H. (2022). Development of fibrous materials applied in timber-framed construction using recycled fibers from textile waste. *Journal of Cleaner Production*, *347*. https://doi.org/10.1016/j.jclepro.2022.131203.

Simonen, K. (2014). Life Cycle Assessment. Smith, R. E. (Ed.). *Pocket Architecture: Technical Design Series Life Cycle Assessment*. New York: Routledge.

Sulochani, R. M. N., Jayasinghe, R. A., Fernando, C., Nilmini, A. H. L. R., & Priyadarshana, G. (2023). Life Cycle Assessment (LCA) of a Textile Waste Thermoplastic Composite Material for Wall Partitioning Applications. Dissanayake et al. (Eds.), *Lecture Notes in Civil Engineering: Vol. 362. International Conference on Sustainable Built Environment 2022* (p. 441–450). Singapore: Springer. https://doi.org/10.1007/978-981-99-3471-3_31.

Tok, G. (2015). *Refrakter tuğla üretiminin yaşam döngüsü analizi ve yaşam döngüsü maliyeti yöntemleriyle değerlendirilmesi [Evaluation of Refractory Brick Production Through Life Cycle Assessment and Life Cycle Cost Methods]. (Master of Science Thesis). Anadolu Üniversitesi, Eskişehir. Yükseköğretim Kurulu Ulusal Tez Merkezi.*

Ventura, H., Álvarez, M. D., Gonzalez-Lopez, L., Claramunt, J., & Ardanuy, M. (2022). Cement composite plates reinforced with nonwoven fabrics from technical textile waste fibres: Mechanical and environmental assessment. *Journal of Cleaner Production*, *372*. https://doi.org/10.1016/j.jclepro.2022.133652.

Violano, A., & Cannaviello, M. (2023). The Carbon Footprint of Thermal Insulation: The Added Value of Circular Models Using Recycled Textile Waste. *Energies*, *16*(19). https://doi.org/10.3390/en16196768.

Graduate Student Merve BULUÇ

E-mail: 502312004@ogr.uludag.edu.tr

Educational Status: Graduate student in Bursa Uludağ University, Graduate School of Natural and Applied Sciences, Department of Architecture

License: Balıkesir University, (2006-2010)

Faculty of Architecture, Department of Architecture.

Degree: Uludağ University, (2023-ongoing)

Graduate School of Natural and Applied Sciences, Department of Architecture

Professional experiences:

Architect, Peko Construction Ltd., Bursa (2010-2011)

Architect and Construction Supervisor, Taşyakan Construction Ltd., Bursa (2011-2013)

Architect, DRN Architecture, Bursa (2013-2014)

Architect, Çanakkale Geyikli Municipality, Directorate of Zoning, Çanakkale (2015-2016)

Architect, Çanakkale Bayramiç Municipality, Directorate of Zoning, Çanakkale (2016-2020)

Founder architect, ARK Architecture, Bursa (2020-ongoing)

Circular Economy and Life Cycle Assessment (LCA) Based on Physico-Chemical Effects in Pneumatic (Inflatable) Structured Sports Buildings: Bursa Case Study

Msc. Yasemin BAL [1]

[1] Bursa Uludağ University, Faculty of Architecture, Department of Architecture, Görükle Campus, Bursa/Türkiye.
ORCID: 0000-0003-0876-813X
E-mail: mimar.yasemin.bal@gmail.com

Prof. Dr. Filiz ŞENKAL SEZER [2]

[2] Bursa Uludağ University, Faculty of Architecture, Department of Architecture, Görükle Campus, Bursa/Türkiye.
ORCID: 0000-0002-8376-5177
E-mail: filizs@uludag.edu.tr

Citation: Bal, Y. & Şenkal Sezer, F. (2025). Circular Economy and Life Cycle Assessment (LCA) Based on Physico-Chemical Effects in Pneumatic (Inflatable) Structured Sports Buildings: Bursa Case Study. Beceren Öztürk, R. & Çahantimur, A. (Eds.). **Contemporary Approaches in Architecture: The Role of Architecture in the Circular Economy.** 2025, Chapter:13, 345-380. ISBN: 978-625-378-348-8. Iksad Publications. DOI: https://doi.org/10.5281/zenodo.17321763

1. Introduction

Consumption and physico-chemical deterioration that may occur throughout a building's lifespan are directly affected by its structure and the materials used in it. Contemporary construction systems constructed using innovative technologies and materials, such as the pneumatic (inflatable) structures examined in this study, also experience building physics problems over time. This directly impacts structural deterioration and resulting costs during the material procurement, construction, use and post-use evaluation phases of the building. Identifying factors that can lead to structural deterioration and taking precautions during the design process can extend the lifespan of the building and prevent potential damage and costs. Compared to traditional construction methods, pneumatic structures have potential advantages and disadvantages within the context of LCA (Life Cycle Assessment). Therefore, this study aimed to evaluate temporary pneumatic sports structures within the context of building physics deterioration in the LCA process, according to the circular economy, during the use phase.

Pneumatic systems, examples of which have been implemented in temporary sports facilities in Bursa, require special precautions for structural components and membrane materials. Environmental factors such as climate, temperature, precipitation, sunlight and pollution adversely affect inflatable structures. A field study was conducted to investigate structural physics problems arising from environmental factors in pneumatic structures, which are supported by membranes and are used as load-bearing structures. Three single layer structures operating as swimming and sports facilities in Bursa were selected. Long-term physical and chemical deterioration detected through observation over a 10 year period was examined. These physico-chemical effects were grouped under four headings: long-term solar and radiation effects, corrosion effects, various atmospheric effects and sudden fires. Significant structural deteriorations observed in the inflatable structures selected based on these parameters, such as discoloration, yellowing, abrasion, perforation, contamination, corrosion and loss of structural stability; and their causes are presented in the findings section. Changes caused by time dependent physico-chemical effects on pneumatic structures were identified and the problems that arise in membrane covers were investigated. Membrane materials directly affect the changes in the main structure of the pneumatic system in terms of structural life and durability. In this context, the aim was to demonstrate the positive effects of LCA evaluations on wide span pneumatic structures constructed using innovative textile based membranes, a contemporary structure, based on LCA analysis of sample structures using parameters determined by physico-chemical effects. By identifying environmental factors that could damage pneumatic structures, it is anticipated that potential life long structural defects can be mitigated by selecting appropriate materials, production and construction methods for future constructions. Thus, the advantages of using pneumatic structures as temporary covers in sports facilities can be evaluated through LCA in terms of both the structural lifespan and the cost consumed during the service life.

Pneumatic, or inflatable, systems are stable structures or buildings stabilized by using air pressure to create a pressure difference between the exterior and interior to ensure structural integrity (Marcipar, Oñate &

Canet, 2005). Pneumatic systems are structures that become load-bearing by pressurizing membrane surfaces, usually with air. Pneumatic structures can be applied to many different functions, qualities and purposes in architecture. Furthermore, due to their flexible and transformable structures, they also offer integrated applications. Architectural applications of pneumatic structures include load-bearing systems, auxiliary load-bearing systems, structural elements and formwork elements. Material properties vary depending on their structural characteristics and application areas. Therefore, the materials, their structural properties and their impacts as a result of physical and chemical effects are explained in detail below.

Pneumatic systems are, in their most general definition, structures that become carriers by pressurizing a membrane surface, usually with air. Therefore, having a single or double layer membrane is one of their main structural characteristics. Pneumatic systems used entirely as carriers are generally classified into two main groups: single layer (low-pressure) and double layer (high-pressure). Single and double walled pneumatic systems have various unique features. For example, single layer pneumatic structures offer features such as continuous air support, specially detailed openings and ground anchor systems, while double layer systems do not require continuous air support and prevent the entire system from collapsing due to any tear, abrasion or perforation on the membrane material surface. Pneumatic systems can also be implemented in conjunction with other carrier systems such as cable-supported systems, space frame systems and tensegrity carriers (Bal, 2022). The carrier system typologies and pressurized areas of single and double layer pneumatic structures are illustrated below Figure 1.

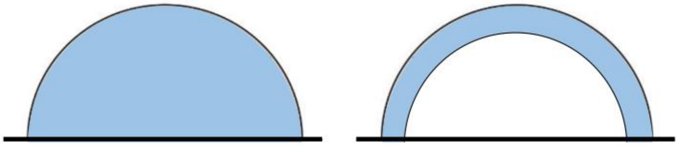

Figure 1. Layers of Pneumatic Structures (Prepared by the Authors)

The two main structural elements of pneumatic systems are the membrane surface and the pressurized gas. Air is generally preferred as the pressurizing agent for both economic and accessibility reasons. Metal structural elements used in ground anchors and joint details provide the integral load-bearing properties of the pressurizing agent and membrane material. Membrane material, on the other hand, becomes load-bearing as a result of the surfaces gaining strength in conjunction with air. Therefore, membrane material is a fundamental element of pneumatic structures. Membrane materials can be applied to many areas and building typologies in architecture, including pneumatic systems (Bal & Arpacıoğlu, 2023). When examining pneumatic structures within the scope of LCA, which provides an assessment system encompassing the lifespan of a structure, the structural typology and membrane material type mentioned above can be the primary factors determining the strength properties and sustainability of a structure from design to use.

Sustainability, "meeting the needs of today without compromising the ability of future generations to meet their own needs" (UN, 1987), has become a concept applied to all building components and materials, from cities with targets such as environmental impacts, emissions, and efficiency. The UN's Sustainable Development Goals 2030 indicate 17 goals, including 169 targets. They all have the common aim of enabling a healthier, better and safer world (UN Department of Economic and Social Affairs). In the context of architecture and within the scope of this study, Goal 11, sustainable cities and communities, focuses on the structure and materials of buildings. According to report by the United Nations Environment Programme, the building sector consumes significant amounts of energy; and buildings construction industry is responsible for 38% of total global energy-related carbon dioxide emissions (UNEP, 2020). This negative impact of the construction sector requires a holistic design process in light of sustainability principles (Duru, Dinçer & Koç, 2022). Various approaches have been developed to identify, measure and reduce these negative environmental impacts of buildings during their design, production, use, and dismantling/demolishing processes, one of which is Life Cycle Assessment (LCA) (Buyle, Braet & Audenaert, 2013). LCA is a scientific method that evaluates products and processes throughout their entire life cycle and expresses their environmental impacts with clear results. It is used to identify the material and energy flows and environmental impacts in the system during the extraction, production, distribution, use and disposal of raw materials in the production of building materials and buildings (Gentil, Gallo & Christensen, 2011). A large amount of energy is used in the extraction of building materials from nature, their processing in factories, their transportation to the construction site, their placement at the construction site, maintenance and repairs during the building's use, and their demolition and disposal at the end of its lifespan. This is referred to as embodied energy (Duigou et al., 2016). The circular economy aims to narrow, slow down, and close material cycles by transforming the current linear "take-make-dispose" economy into a circular economy (Crome et al., 2023). In this context, fewer material consumption in buildings, no maintenance and repair requirements, long-lasting materials applied, and resistance to environmental and physical impacts throughout the building's lifespan can reduce consumption within the context of LCA and the circular economy. In the membrane systems used in pneumatic structures, which are the focus of this study, it is known that features such as spanning wide spans without the use of vertical carriers, low material consumption, the use of long-lasting membrane materials, and ease of transportation reduce energy consumption.

Membrane materials are produced with various types; weave types, coatings and foils to make them suitable for use in construction systems. Membrane materials are examined in three groups with different qualities: homogeneous membranes, knitted (woven) membranes and a combination of the two, homogeneous/knitted membranes (Türkçü, 1997). Knitted (woven) membrane materials, which can be used in pneumatic systems, which are a subgroup of membrane structures, are divided into three subgroups based on the yarn weaving material: organic (natural) fiber membranes, synthetic (artificial) fiber membranes and mineral-based membranes (Say, 1998). Membrane materials; these are textile fabrics produced for architectural use, typically consisting of a mesh weave containing various components such as rubber, silicone, polyethylene, polyurethane, polytetrafluoroethylene (PTFE), PVC, PVC-based foils, neoprene, polyamide-polyester, polyvinylidenefluoride (PVDF), fiberglass fabrics, teflon, steel or aluminum sheets. Coating membranes with these types of materials has enabled larger spans in architecture, typically 50-150 meters (Özşen & Yamantürk, 1991). Plastic-polymer based membranes, used as the primary material of pneumatic systems, also have distinct properties. Problems that may arise in membrane materials covering building surfaces can directly affect the structures themselves. Therefore, membrane types and coatings should be selected and applied to buildings based on their purpose and expected qualities throughout their lifespan.

Material deterioration can occur due to physical, mechanical, chemical and various changes or transformations that may occur in response to various events, such as production, use, or environmental factors. Therefore, it is crucial to plan structures holistically, from design to use, incorporating structural elements (Eriç, 1994). The importance of the material becomes even more critical in some structural systems because it is the primary element of the load-bearing system. The factors affecting inner gas thermo-dynamic behavior therefore also the pneumatic system are shown in Figure 2 (Bögle, Schlaich & Hartz, 2009). It explains the effects of the membrane material, environmental factors and pressure control on the interior and structure of pneumatic structures. The strength of the membrane material directly affects the entire structure. Thus, the factors affected by the membrane material directly affect the structural stability and physical structure of the pneumatic system. The tensions, force balance, surface temperature and hardness of the membrane material determine load-bearing properties. For pneumatic systems, which become carriers through pressure, pressure control can become risky due to leakage, perforation, damage and abrasion, depending on the membrane material. Maintaining the integrity of membrane surfaces is a crucial criterion, especially for single-walled pneumatic structures. Membrane materials directly affect interior temperature, air pressure, thermodynamic behavior and user comfort. Environmental factors, in parallel with membrane materials, also have a significant impact on pneumatic systems. All climatic conditions wind, precipitation, sun, temperature, air pressure, directly impact the air and structure.

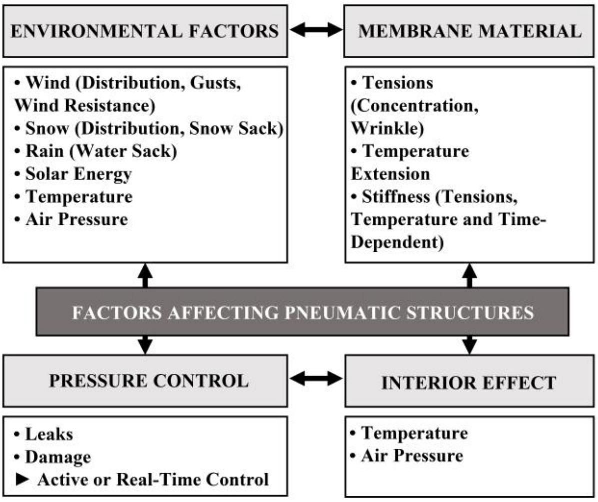

Figure 2. Factors Affecting the Pneumatic System, Prepared by the Authors Using the Source: (Bögle, Schlaich & Hartz, 2009)

Physical and chemical changes and transformations in the membrane material resulting from environmental factors directly affect the pneumatic system. While these effects can sometimes cause visual discoloration, contamination, yellowing and deterioration, in other cases, they can lead to risks that can affect durability and load-bearing properties. Therefore, membrane types should be selected considering the function, purpose, intended use and lifespan of the structure where they will be applied. The environmental, structural (membrane and pressure) and interior spaces affecting the pneumatic system should be planned optimally and holistically. Measures and solutions should be developed, from design to application and usage, to address the physical and chemical effects that may impact pneumatic structures and the structural physics issues they may cause.

2. Material and Method

A five-stage method was used to assess the impact of physico-chemical factors on pneumatic structures based on LCA parameters, which comprise five main stages: raw material supply, transportation, production or construction, use, and waste recycling. In the first stage, research was conducted on the structure and membrane materials of pneumatic systems. This information is presented in the introduction section of the study. In the second stage, the structural cycle of pneumatic structures within the five stages identified within the LCA context and the impact of potential effects on the construction cycle during the use phase, which is the focus of the study, were evaluated. In the third stage, long-term physico-chemical effects that could affect pneumatic structures were identified and investigated. The effects of environmental factors that can lead to deterioration, durability issues, and material problems on the structure's lifespan were investigated. Physico-chemical impact parameters were examined under four main headings: solar and radiation effects, corrosion, various atmospheric effects and fire parameters. The parameters determined in the second and third stages were evaluated in the fourth stage of the study on three different single-walled pneumatic structures implemented with the wide-span temporary cover typology in Bursa. In the fifth stage, the differences resulting from physical and chemical effects between the cases current state 10 years ago and 2025, the additional costs or problems they may create during the use phase of the cases life cycle, their positive aspects, and the costs in terms of the circular economy were evaluated using field surveys and observations. The theoretical framework for all stages of the study method is shown in Figure 3 below. The parameters examined within the study are indicated by red frames.

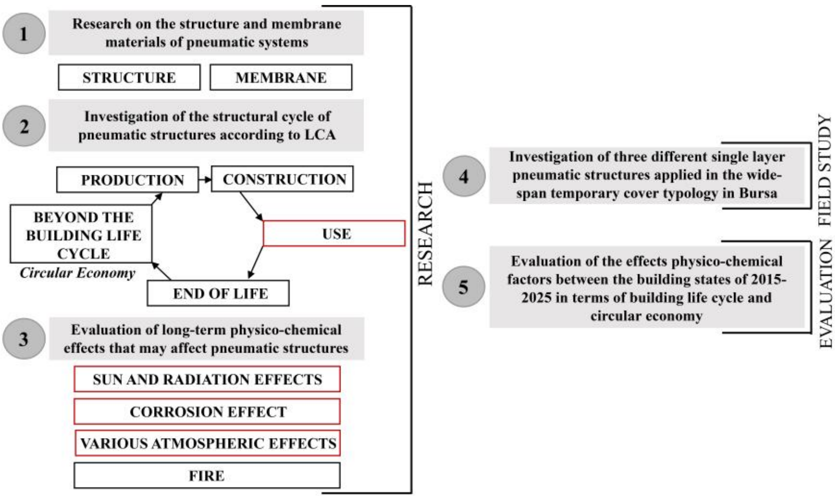

Figure 3. Theoretical Framewok of Study (Prepared by the Authors)

The LCA stages and the effects of physico-chemical factors on pneumatic structures are explained and the structures in which these parameters will be examined in the context of the field study carried out in the Bursa sample are explained under three subheadings below.

2.1. LCA Stages in Pneumatic Structures

When examining pneumatic structures within the context of LCA stages, the process begins with the procurement of plastic based raw materials for the membrane material and its production in sheets in factories. During the design process, the membrane material is cut to the desired dimensions and assembled by sewing, gluing or mechanical means. This allows it to be transported to the construction site. During transportation, it can be transported in much smaller volumes compared to traditional construction methods. On-site pneumatic structures span wide openings in very thin layers, saving material. The physical performance of the membrane material during its use can be degraded by environmental factors. After the membrane layers are fixed to the on-site structural system, they are inflated to become carriers. The physico-chemical effects of pneumatic structures during the use phase, the longest of the LCA stages, directly affect the structure's lifespan, consumption and durability. Therefore, selecting membrane materials with qualities such as dirt repellency, abrasion resistance, resistance to cracking and longevity directly extends the lifespan of the pneumatic structure, reducing energy consumption and economic costs. At the end of its lifespan, the membrane can be recycled and reintroduced into the cycle, although the ratio varies depending on the material type. Figure 4 below illustrates the LCA stages of pneumatic structures in a cyclical manner.

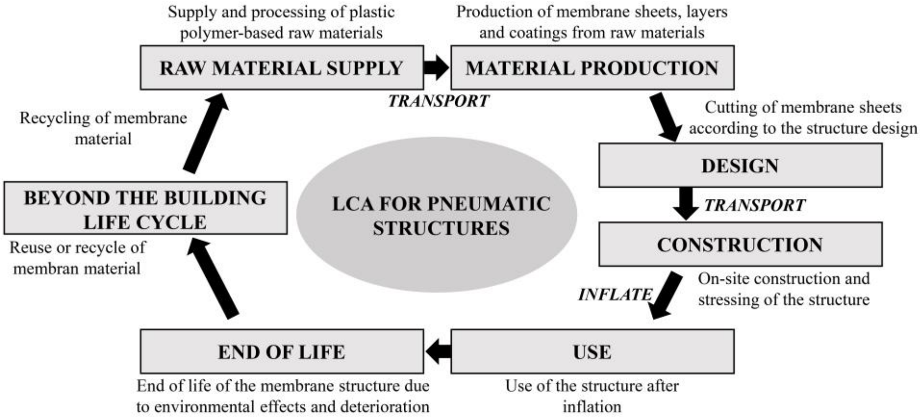

Figure 4. LCA Stages About Pneumatic Structures (Prepared by the Authors)

2.2. Physico-Chemical Effect Parameters in Pneumatic Structures

Buildings can suffer from structural defects that can arise from a variety of causes. The primary causes of structural defects in buildings stem from issues arising from the design, application and usage phases (Avlar, 2000). Structural defects during the design phase can be caused by failure to take necessary precautions against external factors or by incomplete or incorrect measures regarding detail solutions, material, and product selection. During the implementation phase, structural defects can be caused by issues such as construction of building products, workmanship errors, lack of inspection and inadequate or incorrect product or material storage. During the usage phase, errors in maintenance and repair, as well as user related problems, can negatively impact structures (Güzelçoban Mayuk & Avlar, 2014). Adverse events occurring during the design, application and usage phases of buildings are called structural problems. In this context, buildings must be designed holistically, from beginning to end, with each element encompassing the physical defects to be minimized and potential damage to be optimized.

Building physics encompasses all physical conditions affecting users in the interior and exterior environments of a building. These physical environments, where a significant portion of human life is spent, consist of various elements such as temperature, air movement, breathing air qualities, sun effect and radiation, sunlight, sound and noise, thermal flows and color (Şerefhanoğlu Sözen, 1999). From design to use, the physical environment has a direct impact on human comfort, safety and health. Therefore, minimum building physics conditions must be designed and planned in a holistic manner. The components of building physics defects are examined under five main headings: mechanical problems, thermal problems, water and humidity problems, sound problems and physico-chemical problems (Güler, Şenkal Sezer & Ülkü, 2010). Figure 5 shows the building physics problems and the physico-chemical effects examined on pneumatic cases within the scope of study, outlined in red.

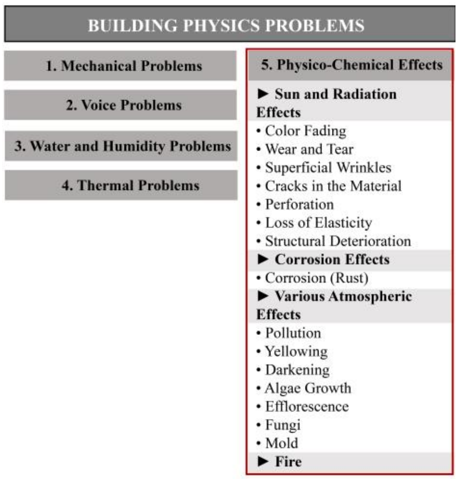

Figure 5. Building Physics Problems, Prepared by the Authors Using the Source: (Güler, Şenkal Sezer & Ülkü, 2010)

Mechanical problems include cracks and breaks that occur in structures due to various loads. Thermal problems generally affect indoor thermal comfort by resulting from heat conduction of surfaces and materials where heat flow occurs throughout the entire shell of the building. Water and humidity problems according to Ertaş, 2001; can cause problems in buildings, such as corrosion, deterioration, mold and bacteria on the material or structural system, due to the effects of capillarity and vapor diffusion. These are can pose problems for both structural durability and human health, safety and comfort. All these parameters, reflected in buildings over time, affect numerous structural elements, including materials and structural systems. This can lead to damage or even more significant problems, such as thermal, acoustic, visual and other comfort conditions; safety; human health; and the risk of collapse. Physico-chemical effects, which are included in building physics defects, are examined under the subheadings of long-term effects of sunlight and radiation, corrosion and various atmospheric effects, and sudden-onset fires. Physico-chemical effects encompass the changes and transformations caused by long-term chemical effects on structural elements, materials or structural systems. The problems caused by sunlight and radiation, corrosion and various atmospheric effects on structures, as well as their effects on pneumatic structures, are explained below.

a) Sun and Radiation Effects: The most negative impact of sunlight on buildings today is the lack of thermal comfort. The detrimental effects of sunlight on thermal comfort can be mitigated with thermal insulation solutions. Thermal insulation in buildings is an important factor in terms of both comfort and heating and cooling costs, which constitute a significant portion of the cost, as well as energy consumption and savings (Dağsöz, Işıkel & Bayraktar, 1999). Sunlight and radiation reach the earth through conduction, convection, and radiation. While solar radiation varies from place to place, it generally causes similar effects on all buildings. Urban heat islands, overheating, thermal comfort conditions, expansion and contraction can negatively impact building elements, structural systems or materials. When solar radiation reaches buildings as heat and light, the texture and color of the surfaces become decisive factors for the changes, transformations and deteriorations that will occur. Bright surfaces reflect solar radiation, while dark surfaces absorb it. Solar radiation has adverse physico-chemical effects on building materials, such as atomic structure degradation, discoloration, aging, abrasion, color change, thermal stress, cracking, deformation and deformation. Despite these negative effects of solar radiation, its use in conjunction with natural lighting, heating, solar panels, photovoltaic cells or energy systems in buildings offers many advantages. For pneumatic structures, the effects of solar and radiation can lead to problems such as loss of flexibility, color fading, abrasion, wear and perforation on membrane materials. Furthermore, sunlight also affects indoor thermal comfort and the pressure system. In the context of pneumatic systems, the negative effects of solar and radiation can be converted into advantages by producing more durable membrane surfaces, improving them with foils and coatings, or utilizing solar energy through solar cells.

b) Corrosion Effect: The effects of water and moisture in buildings can lead to negative physicochemical effects such as capillarity, water vapor and vapor diffusion (Ertaş, 2001), reaching the interior of materials, ensuring an optimum humidity effect (35%-70%) in the interior environment (Güler, Şenkal Sezer & Ülkü, 2010); decay, swelling and damage in unventilated environments, deterioration of structural strength or durability and corrosion. One of the most significant problems caused by water exposure in buildings is corrosion. Corrosion, which occurs as a result of water and moisture exposure, can cause serious problems and damage to structural systems. Corrosion is defined as the deterioration of metals through chemical and electrochemical reactions that cause undesirable changes (Yüzer, 2003). Rusting, or rather corrosion, occurs when water and oxygen reach metals in buildings. Corrosion, which occurs when water reaches structural elements such as steel, especially those found in reinforced concrete, can affect structural stability and even lead to destruction. Despite these negative effects, water is a material present in every stage of construction, materials and production. Water is the primary ingredient in many binding materials such as concrete, plaster, screed and mortar. Building a structure without water is therefore impossible (Yavan, 2017). Considering the positive and negative properties of water, the necessary insulation or impermeability measures in structures should be designed and implemented holistically. Corrosion effects on pneumatic structures are not considered due to the water impermeability of plastic-polymer based membrane materials and their lack of metal. No corrosion occurs on membrane surfaces, the main structure. However, corrosion can occur with water on metal based cables, supports and anchors in pneumatic systems.

c) Various Atmospheric Effects: Atmospheric effects include those caused by bacteria and fungi. This refers to the appearance of algae, efflorescence, mold and fungi in structures. Problems such as discoloration and contamination on materials also arise as a result of atmospheric effects. Long-term effects on structural elements or materials can negatively impact the durability and strength of products due to atomic deterioration. For pneumatic structures, depending on the membrane material, various atmospheric effects can manifest as contamination, yellowing or darkening due to bacteria. The problems that atmospheric effects can cause on the membrane vary depending on the type and nature of the material. Membrane materials are now being made resistant to atmospheric effects with the use of foils, mesh systems, coatings and fibers, thanks to advancements in production technologies.

d) Fire: In buildings, combustion is seen as slow burning, oxidation (rusting-corrosion) and rapid burning or fire. In this study, the term "fire" covers rapid burning. Combustion requires an exothermic chain reaction involving fuel, oxygen and heat. These elements are always present in buildings and pose various fire risks. The stages of fire in buildings are initiation, the flaming combustion process known as "flashover," fire growth, hot joints and fire spread (Şimşek, 2013). Physically, fire events include thermal deformation, melting, overheating and expansion, while chemically, they include molecular structure degradation, carbonization, smoke emission and the release of toxic gases. Many materials exhibit different behaviors in the face of fire. In this context, flammable and non-flammable materials and products are classified by various regulations.

In buildings, passive and active structural or mechanical measures, in addition to materials, are taken to address various risks in terms of fire. Passive measures include planning the structure using masses, volumes and blocks; creating compartments with partitions or partitions between volumes; dividing horizontal and vertical circulation elements; selecting and implementing building materials and elements (doors, walls, floors, elevators, etc.) that are fire-resistant for a specific period; ensuring that building materials do not emit toxic or suffocating gases upon combustion; avoiding the juxtaposition of materials with different thermal expansions; avoiding the use of flammable grades of materials in the load-bearing system; and continuously designing fire safety halls, fire escape stairs and fire-safe areas throughout the building to serve every area. Active measures include the use of mechanical systems, including manual warning buttons or smoke, flame and heat detectors with sensors, and fire detection systems; the addition of smoke extraction systems; the use of water, dry, foam or gas extinguishing systems; and the placement of up-to-date and usable fire extinguishers in designated locations within the building. It includes elements such as the presence of audible or visual warning devices in escape routes. In order to ensure that buildings are fire-resistant, holistic solutions and systems should be planned and implemented in accordance with regulations from the design phase. For pneumatic structures, measures taken for the flammability class, flame conductivity, toxic gas release status and flammability characteristics of the membrane material used for fire; pressurization conditions; all fire escapes are passive measures. In addition to these, mechanical systems, water or gas extinguishing systems, fire detection or alarm systems are active measures. It is important for fire safety that all passive and active fire precautions are taken and pneumatic structures are constructed with fire-resistant materials (Bal & Şimşek, 2025). In the scope of this study, the fire parameter was excluded because it is a sudden event and its long-term effects are examined.

2.3. Field Study

Building physics problems caused by long-term physical and chemical effects were investigated by demonstrating them on pneumatic structures selected for field research. The designated field study area was Bursa, Türkiye's fourth largest city. Three sports facilities, all single layer pneumatic structure swimming pools, were selected for the study. These structures represent all currently operational inflatable structures in Bursa. The locations of the selected inflatable structures within Bursa are marked on map in Figure 6.

Figure 6. Showing the Locations of Pneumatic A, B and C Case Studies in Bursa (Shown by Marking on the Image Taken From Google Maps, 2025)

Case study A was opened to the public in 2015 (Bursa Metropolitan Municipality, 2015). It's a swimming pool and sports facility located within Osmangazi, Bursa. The sports facility, provided as a social service within the city park, is open to public use. The structure is an example of a single layer pneumatic structure. It consists of white semi-permeable membrane surfaces supported by cross braided cables. The facility houses a semi-olympic swimming pool with five lanes. It also includes dressing rooms, administrative units, and instructor rooms. The site plan of the building; general information and structural properties are shown in Figure 7 below.

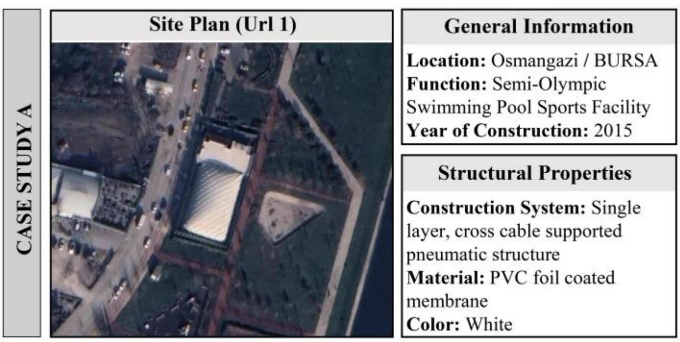

Figure 7. Case Study A (Prepared by the Authors)

Case study B is a pneumatic structure sports facility located in the Güzelyalı, Bursa. During the hot summer months, the cover is deflated and removed, and temporarily re-inflated during the winter months. After its construction, it was closed to use for certain periods and the inflatable cover was replaced. For this reason, the year of construction cannot be given as an exact date. It has a single layer pneumatic system. It consists of white, semi-permeable membrane surfaces with no cable support. The facility includes semi-olympic swimming pool. The building includes dressing rooms, administrative units and instructor rooms. The information about the structure are shown in Figure 8 below.

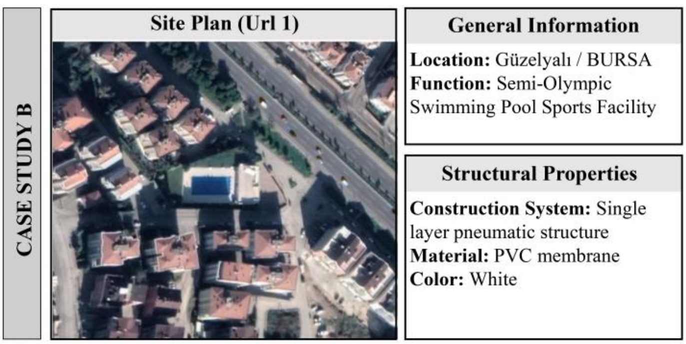

Figure 8. Case Study B (Prepared by the Authors)

Case study C was opened to the public in 2015 (Bursa Metropolitan Municipality, 2011). It’s an inflatable system located in Umurbey, Bursa. The structure, constructed of white membrane surfaces, has no cable supports. It houses a semi-olympic swimming pool. The building includes dressing rooms, administrative units and instructor rooms. The information about the structure are shown in Figure 9 below.

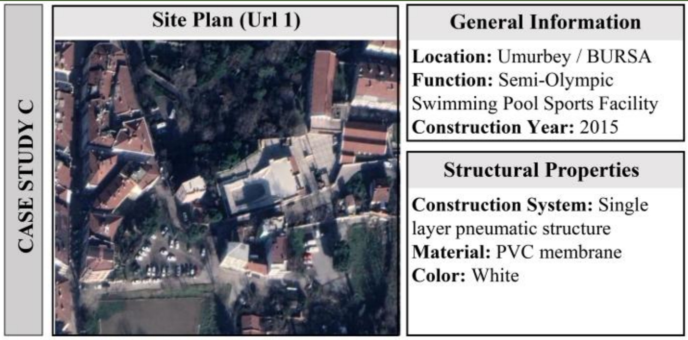

Figure 9. Case Study C (Prepared by the Authors)

The structures selected within the city of Bursa share common characteristics: they are single layer pneumatic structures, inflated onto reinforced concrete building, constructed of semi-permeable white membrane material, can be inflated and deflated seasonally and used for sports facilities. The structures differ in terms of location, material type and cable support. In this context, the negative impact of differences in environmental and structural characteristics on structural deterioration is investigated and explained visually in the next findings section, based on the structures life cycle.

3. Findings and Discussion

This section of the study describes the changes caused by long-term physical and chemical effects on single layer pneumatic structure swimming pool covers examined in Bursa. Identified problems are illustrated through photographs to demonstrate changes over time. Pneumatic structures, along with the changes they have undergone over 10 year period, are shown in Figure 10. While the same cover system was used over the years in case studies A and C, the membrane cover was replaced in case B. Therefore, a comprehensive evaluation for case study B could not be clearly performed.

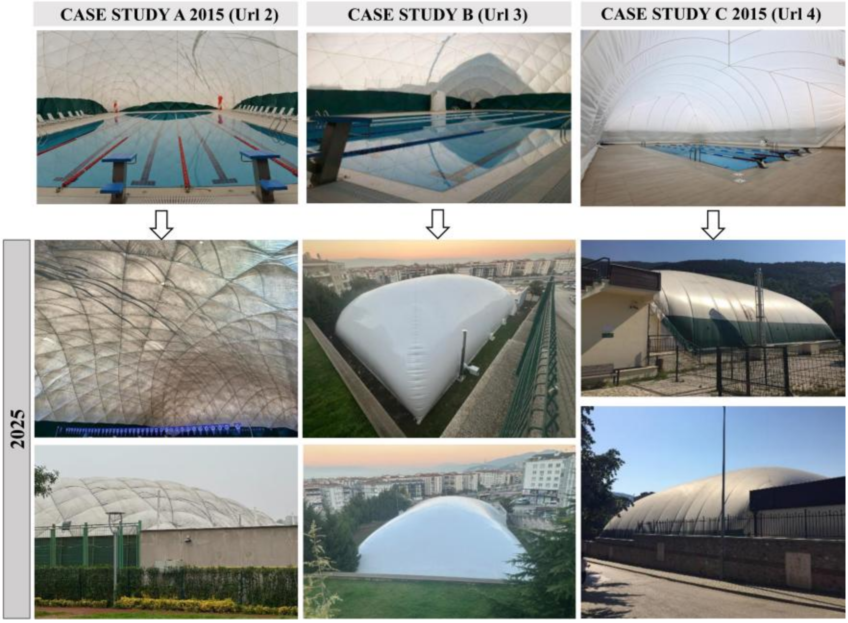

Figure 10. Images of Case Studies A, B and C from Sources (Bursa Metropolitan Municipality, 2015; Bursada Bugün, 2011; Bursa Metropolitan Municipality, 2011) Images Photographed by the Authors

Long-term exposure to sunlight and radiation can lead to problems such as loss of durability, discoloration and loss of elasticity in membrane materials. Corrosion from water and moisture is not directly visible in pneumatic structures due to the plastic-polymer composition of the membrane material. However, corrosion can be observed in iron or steel based metals at locations such as anchor points, load-bearing struts, cables and system details, as seen in case study A. Figure 11 is the structure where deterioration such as contamination, yellowing, wrinkles, loss of elasticity, loss of structural stability and corrosion due to environmental pollution, atmospheric effects and intensive use are most severe. While various atmospheric effects can cause problems such as contamination and yellowing in membrane materials, since they are plastic in structure, they may not cause defects such as mold, efflorescence or algae formation. Fire effects, vary depending on the type of membrane material and are examined using parameters such as toxic gas emission, smoke effect, flame conductivity, flame or fire permeability and thermal resistance.

Figure 11. Case Study A: Deterioration of Materials (Photographed by the Authors)

Physico-chemical effects on structures observed in case studies based on physical and chemical effect parameters are shown in Figure 12 below. The intensity of physical and chemical effect parameters in case studies is shown in three levels using the change in color intensity of the circle. The severity of the deterioration detected in the structures is shown in the black circle representing high intensity, dark gray representing medium intensity and light gray representing low intensity. Sun and radiation effects are examined under the headings of color fading, abrasion and wear, superficial wrinkles, cracks in the material, perforation, loss of elasticity and structural deterioration. Various atmospheric effects are examined under the headings of contamination, yellowing, darkening, moss growth, efflorescence, fungi and mold. The loss of elasticity of the membrane material due to sunlight and atmospheric effects manifests as wrinkling and deformation on the structure's surface. Extensive darkening of the structure's surface has been observed, thought to be due to traffic and environmental pollution due to heavy use and its location in the city at case study A. Dirt has accumulated on the surface along the capillary membrane cracks. Sunlight, radiation and various atmospheric effects, along with discoloration, yellowing, dirt, abrasion and wear are observed on the membrane surface. This also impacts the structure's overall durability, strength and load-bearing capacity. These structural effects also have a negative visual impact on the interior. While moss, efflorescence, fungus and mold are not observed in the structures due to atmospheric effects, pollution, yellowing and darkening are observed. Case study A, in particular, exhibited intense darkening, abrasion, pollution and yellowing due to sunlight and atmospheric factors. Regarding the damage caused by water and moisture to the structure, there is no corrosion effect on the waterproof membrane surfaces. However, corrosion is observed in some metal elements supporting the load-bearing system at case study A. Corrosion is observed at the connection points of structural elements or ground anchors, and it is anticipated that it may lead to future structural stability deterioration. Too thin wrinkles observed but loss of elasticity were not observed on the structure's surface and its form remained stable. In case study B, long-term change couldn't observed due to the replacement of the membrane cover. The observed deterioration severities are significantly different in case studies A and C, which were constructed in the same year (with the deterioration severity being greater in A). This is due to the location of the structure, environmental influences and material type. In this respect, the texture, chemical composition, type, weave type, coating types and composition of the membrane material, along with environmental influences, have a direct impact on the structure's lifespan, deterioration and durability. Case study B and C, no corrosion effects were observed on the metal elements of the structure. In addition to these slow acting physical and chemical effects, which develop over a long period of time, the sudden fire factor poses a common risk for inflatable structures. Because sudden fire events cannot be observed, this issue has been considered common to all structures. Passive and active fire safety measures must be implemented for all pneumatic structures made of membrane materials to prevent irreversible deterioration following a fire.

	PHYSICO-CHEMICAL EFFECTS	CASE STUDIES A	CASE STUDIES B	CASE STUDIES C	PRECAUTIONS
DETERIORATIONS RESULTING FROM LONG-TERM IMPACT	**SUN AND RADIATION EFFECTS**				
	• Color Fading	●	●	●	Sunlight and radiation can cause structural deterioration in the membrane material within the building envelope. Therefore, the selection of the membrane material is a key precaution. The weave and coating properties of the membrane material can prevent visible solar and radiation-induced effects. Furthermore, material deterioration directly affects the structural stability and form of the pneumatic structure. In this context, supporting the structure with cables or supports can be precaution in terms of structural stability.
	• Wear and Tear	●		●	
	• Superficial Wrinkles	●		●	
	• Cracks in the Material	●			
	• Perforation				
	• Loss of Elasticity	●		●	
	• Structural Deterioration	●			
	CORROSION EFFECT				
	• Corrosion (Rust)	●			Since the membrane is a plastic-polymer based waterproof material, no corrosion effects are observed. Water-induced corrosion affects metals. In pneumatic systems, anchor points, connection elements and metal elements in the ground can exhibit corrosion. Precautions can be taken to make metal elements resistant to corrosion through alloying, cathodic protection, or surface protective coating.
	VARIOUS ATMOSPHERIC EFFECTS				
	• Contamination	●	●	●	These are the deteriorations observed on the membrane surface, the fundamental element of the pneumatic structure. Precautions can be taken against contamination, yellowing and darkening caused by environmental factors through the selection of the membrane material's weave type and foil coating materials.
	• Yellowing	●	●	●	
	• Darkening	●		●	
	• Algae				
	• Efflorescence				
	• Fungus				
	• Mold				
SUDDEN EVENT	**FIRE**				
	• Deterioration of materials as a result of sudden fire caused by flaming combustion	It is common to all structures.			Fire was not examined during the field study due to its sudden development compared to other long-term physical and chemical effects. Depending on the membrane material type, parameters such as toxic gas emission, smoke effect, flame conductivity, flame or fire permeability and thermal resistance may vary in the event of a fire. Passive and active fire safety measures specific to the structure should be implemented in case of a fire.

Figure 12. Physico-Chemical Deteriorations Observed in Cases and Precautions (Prepared by the Authors)

Inferences from structural analyses have led to the conclusion that a significant portion of deterioration caused by physico-chemical effects in pneumatic structures can be prevented by taking precautions regarding various materials. A common deterioration in membrane materials, often due to solar and atmospheric influences, is noted in all structures examined. Therefore, selecting the membrane materials weave type and coatings appropriately for environmental conditions can prevent potential deterioration from solar, radiation and atmospheric influences. Corrosion occurs in metal elements supporting the membrane structure, external to the membrane material, due to water. In terms of corrosion, the membrane material is a water-impermeable plastic that can also be used for insulation purposes in architecture. Thus, it has been determined that the membrane material is more affected by long-term physical and chemical parameters from solar and atmospheric influences. Furthermore, the characteristics of the selected membrane material and environmental influences directly influence potential deterioration in the pneumatic structure.

Corrosion can occur in metal structural elements at the connection details, ground and material anchor points. Rust formed by metal structural elements can transfer and flow to the membrane surface, causing discoloration and yellowing. Therefore, making metal elements resistant to corrosion through alloying, cathodic protection or surface protective coatings is a viable option. Passive and active fire safety measures should be implemented in pneumatic fire-resistant structures. Passive fire safety measures include material selection and escape routes. The membrane material should be selected based on its ignition temperature, flammability, flame transmission, dripping, toxic gas or smoke release, and the flammability of the pressurizing agent. This will reduce the risk of material-related fires. Escape routes should be designed as a holistic route serving every area within the structure and reaching a safe area outside the structure. Special escape doors should be used for the pneumatic structure envelope. Active measures include detection, warning and extinguishing systems. The integration of smoke or flame sensors, manual or automatic fire buttons, illuminated signs indicating escape routes and exits, and extinguishing system elements into the pneumatic structure must be addressed. Because the membrane surface of the pneumatic structure is susceptible to perforation or the attachment of other elements, active fire safety measures must be designed into an additional to structure or the ground. Single-wall pneumatic structure shells can be damaged in the event of a fire due to their single skinned surface, membrane perforation, failure to maintain the structural integrity of the building and collapse. In addition, fire scenarios specific to each structure must be developed to prevent potential hazards and ensure the safety of life and property. As seen in the examples examined, material damage and deterioration negatively impact structural systems.

Membrane materials are innovatively developed with coatings to become composite materials; providing mechanical strength, hydrophobicity (water repellency), protection against fire and sunlight, increased carrying capacity, and resistance to fungi and tearing (Monjo-Carrió & Tejera, 2011). In membrane materials lacking these durability, deterioration generally results from physical and chemical effects. This is because architectural membranes absorb chemicals in their environment, causing damage to their coatings. The membrane material planned for use in a structure is expected to be resistant to climatic and physico-chemical factors throughout its lifespan (Luo, Hu & Fangueiro, 2008). The lifespan of the membrane material directly affects the lifespan of the structure because it is the main load-bearing layer in pneumatic structures.

The choice of structure of a building has a major impact on the environmental impact of the building, with the building elements and load-bearing system constituting a significant percentage of the total building material (Çelebi & Arpacıoğlu, 2023). Circular economy and LCA for building components monitor the use of an average value in a circular system over a specific period (van Stijn et al., 2021). In this context, the type and selection of membrane material used in buildings impacts the durability of the structure against adverse factors and its economic costs. Membrane materials, like many materials used in architecture, are exposed to physico-chemical effects over time. The properties of the membrane material are determining factors in many aspects, such as the load-bearing capacity of the pneumatic system, its resistance to environmental factors, its structure, design, form and the lifespan of the structure. This requires holistic planning of structures throughout the design, production and usage phases. The resistance or behavior of membrane materials against adverse environmental effects over time will be more advanced and efficient thanks to advancing technology and production capabilities. Thus, by taking precautions against potential adverse factors, the negative physico-chemical effects on structures can be optimized.

4. Conclusion and Suggestions

All structures produced should be planned to consistently ensure their durability, strength and safety at all stages, from design to use. Throughout a building's lifespan, physical and chemical effects and the resulting structural physics problems negatively impact its qualities. As seen in the pneumatic structure examples examined, environmental factors can cause adverse effects on membrane materials over time, such as yellowing, loss of elasticity, discoloration, contamination, corrosion, and reduced material strength, depending on the structure's location. Membrane structures are most affected by sunlight and atmospheric elements, while metal elements deteriorate due to corrosion. In pneumatic systems, deterioration resulting from physico-chemical effects on products and materials can negatively impact structures from all perspectives, including structural and environmental. From a sustainability perspective, when considering the use of pneumatic structures in the context of LCA, the structure is expected to withstand the longest-term environmental impacts in its built state, require no maintenance or repair and exhibit no deterioration. Thus, in the context of LCA, with a design that is resistant to the problems that arise as a result of the analysis conducted within the scope of the article; the life of the structure can be extended, the costs in the maintenance phase of the structure can be reduced, material consumption can be reduced and negative environmental impacts can be reduced. Innovative use of membrane materials and pneumatic systems in architecture will also offer improved solutions for building life, durability, strength, load-bearing capacity, cost effectiveness, efficiency, comfort and user satisfaction. Consequently, it is anticipated that in the future, more durable and optimized membrane materials can be used in pneumatic structures to develop more efficient systems against physical and chemical effects.

Acknowledgements and Information Note

The article complies with national and international research and publication ethics.

Ethics Committee approval was not required for the study.

Author Contribution and Conflict of Interest Declaration Information

All authors contributed equally to the article. There is no conflict of interest.

References

Avlar, E. (2000). *Yapılarda Su ve Nem Korunumu (Water and Moisture Protection in Buildings)*. Yıldız Teknik Üniversitesi Basım/Yayın Merkezi.

Bal, Y. (2022). *Geçmişten Günümüze Dünya'da ve Türkiye'de Pnömatik Sistemlerin İncelenmesi ve Değerlendirilmesi (Examination And Evaluation of Pneumatic Systems in the World and in Turkey from past to Present) (Master's Thesis). Bursa Uludağ University, Graduate School of Natural and Applied Sciences, Department of Architecture, Bursa.*

Bal, Y., & Arpacıoğlu, Ü. (2023). Model Proposal for the Use of Pneumatic (Inflatable) Structures in the Case of Earthquake Disaster. *Journal of Architectural Sciences and Applications*, 8(Special Issue), 241-258. https://doi.org/10.30785/mbud.1334419

Bal, Y., & Şimşek, Z. (2025). Fire Risk and Precautions in Pneumatic Inflatable Systems. *PLANARCH - Design and Planning Research*, 9(1), 117-132. https://doi.org/10.54864/planarch.1598861

Bögle, A., Schlaich, M. & Hartz, C. (2009). Pneumatic Structures in Motion. *Proceedings of the International Association for Shell and Spatial Structures Symposium (IASS)*, 2019-2030, Valencia.

Bursa Metropolitan Municipality. (2011). Bursa ipeği yeniden can buluyor. Access (26.07.2025) https://www.bursa.bel.tr/haber/bursa-ipegi-yeniden-can-buluyor-20599

Bursa Metropolitan Municipality. (2015). Mihraplı Yüzme Havuzu kadınların hizmetinde, Bursa Büyükşehir Belediyesi. Access (26.07.2025) https://www.bursa.bel.tr/haber/mihrapli-yuzme-havuzu-kadinlarin-hizmetinde-19016

Bursada Bugün. (2011). Güzelyalı yüzme havuzu kışa hazır. Access (26.07.2025) https://www.bursadabugun.com/haber/guzelyali-yuzme-havuzu-kisa-hazir-65051.html

Buyle, M., Braet, J. & Audenaert, A. (2013). Life Cycle Assessment in The Construction Sector: A Review. *Renewable and Sustainable Energy Reviews*, vol. 26, 379-388. https://doi.org/10.1016/j.rser.2013.05.001

Crome, C., Graf-Drasch, V., Hawlitschek, F. & Zinsbacher, D. (2023). Circular Economy is Key! Designing A Digital Artifact to Foster Smarter Household Biowaste Sorting, *Journal of Cleaner Production*, vol. 423, 138613. https://doi.org/10.1016/j.jclepro.2023.138613

Çelebi N. G. & Arpacıoğlu, Ü. (2023). Comparative Analysis of Steel and Reinforced Concrete Structural Frames in terms of Environmental Impact. *III. International Architectural Sciences and Applications Symposium*, Naples, 447-455. ISBN: 978-625-367-371-0. www.doi.org/10.5281/zenodo.10032598

Dağsöz, A. K., Işıkel, K. & Bayraktar, K. G. (1999). Yapılarda Sıcak Etkisinin Getirdiği Problemlerin Isı Yalıtımı ile Çözümü ve Enerji Tasarrufu (Solution to the Problems Caused by the Effect of Heat in Buildings and Energy Savings with Thermal Insulation). *IV. Ulusal Tesisat Mühendisliği Kongresi ve Sergisi*, 329-339.

Duigou, J. Le, Gulbrandsen-Dahl, S., Vallet, F., Söderberg, R., Eynard, B. & Perry, N. (2016). Optimization and Lifecycle Engineering for Design and Manufacture of Recycled Aluminium Parts. *CIRP Annals*, 65 (1), 149–152. https://doi.org/10.1016/j.cirp.2016.04.111

Duru, M. O., Dinçer, S. G. & Koç, İ. (2022). Mimari Tasarım Sürecinde Çevresel Etki Hesaplanmasında Görsel Programlama Dillerinin (VPL) Kullanılabilirliğinin İrdelenmesi (Examinaton of the Usage of Visual Programming Languages (VPL) in Calculation of Environmental Impact in the Architectural Design Process). *Kent Akademisi*, 15 (D.Ü. 2. Uluslararası Mimarlık Sempozyumu Özel Sayısı), 72-90. https://doi.org/10.35674/kent.1013859

Eriç, M. (1994). *Yapı Fiziği ve Malzemesi (Building Physics and Materials)*. Literatür Yayıncılık, İstanbul.

Ertaş, K. (2001). Binalarda Buhar Difüzyonu Olayının İrdelenmesi (Investigation of Vapor Diffusion in Buildings), *TMMOB Makina Mühendisleri Odası Yalıtım Kongresi ve Sergisi*, 7-19, Eskişehir. ISBN: 975-395-441-7.

Gentil, E. C., Gallo, D. & Christensen, T. H. (2011). Environmental Evaluation of Municipal Waste Prevention. *Waste Management*, 31(12), 2371–2379. https://doi.org/10.1016/j.wasman.2011.07.030

Google Maps. (2025). Google Maps. Access (15.07.2025) www.googlemaps.com

Güler, H., Şenkal Sezer, F. & Ülkü, S. (2010). Binalarda Yapı Fiziği Problemleri: Bursa'da Bir Kamu Kurumu Örneği (Building Physics Problems in Buildings: Public Institution Example at Bursa), *Uludağ Üniversitesi Mühendislik-Mimarlık Fakültesi Dergisi*, 15 (2), 53-64.

Güzelçoban Mayuk, S. & Avlar, E. (2014). Dış Etkenler Sonucu Yapılarda Oluşan Hasarların Nedenlerinin Belirlenmesi (Specifying the Causes of Building Failures Occured by Environmental Factors). *I. Ulusal Yapı Fiziği ve Çevre Kontrolü Kongresi*, İstanbul.

Luo, Y., Hu, H. & Fangueiro, R. (2008). Tensile and Tearing Properties of PVC Coated Biaxial Warp Knitted Fabrics Under Biaxial Loads. *Indian Journal of Fibre & Textile Research*, vol. 33, 146–150.

Marcipar, J., Oñate, E. & Canet, J. M. (2005). Experiences in the Design Analysis and Construction of Low Pressure Inflatable Structures. In: Oñate, E., Kröplin, B. (Ed.) *Textile Composites and Inflatable Structures. Computational Methods in Applied Sciences*, vol 3. Springer, Dordrecht. https://doi.org/10.1007/1-4020-3317-6_15

Monjo-Carrió, J. & Tejera, J. (2011). 12-The Use of Textile Materials for Architectural Membranes. In: Fangueiro, R. (Ed.) *Fibrous and Composite Materials for Civil Engineering Applications*, Woodhead Publishing: Cambridge, 325–387. https://doi.org/10.1533/9780857095583.3.325

Özşen, E. G. & Yamantürk, E. (1991). *Taşıyıcı Sistem Tasarımı (Structural System Design)*. Birsen Yayınevi, İstanbul.

Say, F. N. (1998). *Çağdaş Yapılarda Strüktür - Biçim İlişkisi (Structure - Form Relationship in Contemporary Buildings) (Master's Thesis). University of Balıkesir, Institute of Science, Architecture, Balıkesir.*

Şerefhanoğlu Sözen, M., (1999). Yapı Kabuğunda Isı ve Ses Yönünden Denetim-Konfor İlişkisi (The Relationship Between Heat and Sound Control-Comfort in the Building Envelope). *TMMOB Makina Mühendisleri Odası, Yapıda Yalıtım Konferansı Bildiriler Kitabı*, İstanbul.

Şimşek, Z. (2013). *Sağlık Yapılarında Yangın Güvenliğinin ve Duman Kontrolünün Sağlanmasına İlişkin Modelleme Yöntemi (Modeling*

Metod of the Fire Safety Provision and Smoke Control in Health Care Buildings)(Doctoral Thesis). Uludağ University, Graduate School of Natural and Applied Sciences, Department of Architecture, Bursa.

Türkçü, H. Ç. (1997). *Çekmeye Çalışan Taşıyıcı Sistemler (Tensile Structural Systems)*. Eylül Yayınları, İzmir.

UN (United Nations) Department of Economic and Social Affairs, Sustainable Development, SDGs 2030 (Sustainable Development Goals 2030), https://sdgs.un.org/goals (access date: 16.07.2025)

UN (United Nations), (1987). Brundtland Report, Our Common Future, Report of the World Commission on Environment and Development (WCED).

UNEP (United Nations Environment Programme) (2020). 2020 Global Status Report for Buildings and Construction: Towards a zero-emissions, efficient and resilient buildings and construction sector, https://globalabc.org/sites/default/files/inline-files/2020%20Buildings%20GSR_FULL%20REPORT.pdf (access date:16.07.2025)

van Stijn, A., Malabi Eberhardt, L. C., Wouterszoon Jansen, B. & Meijer, A. (2021). A Circular Economy Life Cycle Assessment (CE-LCA) Model for Building Components. *Resources, Conservation and Recycling*, vol. 174, 105683, https://doi.org/10.1016/j.resconrec.2021.105683

Yavan, Y. (2017). *Yapılarda Nem ve Isı Değişkenliğinin Malzeme Üzerindeki Etkileri ve Yapı Elemanlarının Uğradıkları Deformasyonlar (The Influences of the Humidity and the Temperature Variability on the Constructions, and the Deformations of the Construction Elements) (Master's Thesis). TC. Haliç University, Institute of Science, İstanbul.*

Yüzer, N. (2003). Betonarme Yapılarda Korozyon Ölçüm Yöntemleri ve Hasar Tespiti (Corrosion Measurement Methods and Damage Detection in Reinforced Concrete Structures). *TMH Türkiye Mühendislik Haberleri*, issue 426, 2003/4, 134-138.

Msc. Yasemin BAL
E-mail: mimar.yasemin.bal@gmail.com
Educational Status: Ms.c.
License: Akdeniz University, Faculty of Architecture, Department of Architecture, 2015-2019
Degree: Bursa Uludağ University, Graduate School of Natural and Applied Sciences, Department of Architecture, 2020-2022
Doctorate: Bursa Uludağ University, Graduate School of Natural and Applied Sciences, Department of Architecture, 2022-in progress

Prof. Dr. Filiz ŞENKAL SEZER
E-mail: filizs@uludag.edu.tr
Educational Status: Ph.d.
License: Trakya University, Faculty of Engineering and Architecture, Department of Architecture, 1990-1994
Degree: Trakya University, Institute of Science, Department of Architecture, 1995-1997
Doctorate: Trakya University, Institute of Science, Department of Architecture, 1998-2002
Professional experiences: Professor at Bursa Uludağ University, Faculty of Architecture, Department of Architecture

Bibliometric Analysis of the Relationship Between the Adaptive Reuse of Cultural Heritage and the Circular Economy

Dr. Bengisu ÖZKILAVUZ [1]

[1]Bursa Uludağ University, Faculty of Architecture, Department of Architecture, Görükle Campus, Bursa/Türkiye.
ORCID: 0000-0001-7973-4338
E-mail: bengisu@uludag.edu.tr

Citation: Özkılavuz, B. (2025). Bibliometric Analysis of the Relationship Between the Adaptive Reuse of Cultural Heritage and the Circular Economy. Beceren Öztürk, R. & Çahantimur, A. (Eds.). **Contemporary Approaches in Architecture: The Role of Architecture in the Circular Economy.** 2025, Chapter:14, 381-403. ISBN: 978-625-378-348-8. Iksad Publications. DOI: https://doi.org/10.5281/zenodo.17338354

1. Introduction

Cultural heritage is not merely a matter of preserving the physical remains of the past; it has also become a dynamic field where social identity, economic vitality and environmental sustainability intersect. Over the past twenty years, the preservation of heritage sites has increasingly been addressed not only as an aesthetic or historical necessity, but also as an integral component of sustainable development policies (Throsby, 2010; Licciardi & Amirtahmasebi, 2012). In this context, the adaptive reuse approach has emerged as a multi-layered method that combines both conservation principles and economic and social sustainability goals.

Adaptive reuse is a practice that directly contributes to the circular economy concept through the reuse of the existing building stock. Converting existing buildings instead of constructing new ones both reduces resource consumption and enables the preservation of spatial and historical continuity (Bullen & Love, 2011; Foster, 2020). However, repurposing is not merely a physical transformation; it is a process of reconnecting the social, economic, and cultural values of a structure with contemporary life. In this respect, it has become an important application area for sustainable and circular economy models that balance the economic value of heritage with the production of social benefits (Foster, 2025).

The economic dimension of this transformation is supported by empirical studies on the impact of cultural heritage on regional revitalisation. Bowitz and Ibenholt (2009) classified the direct, indirect, and derivative effects of cultural heritage investments, demonstrating that heritage-based tourism and restoration activities create a multiplier effect in local economies. This proves that cultural heritage is a tangible component of economic growth and employment. However, for this effect to be sustainable, economic growth must be carried out in a manner consistent with conservation principles, social identity, and environmental balance.

In recent years, circular business models (CBM) have emerged to explain the economic value of cultural heritage in a more holistic way. This model, developed by Saleh and Ost (2025), defines heritage sites as ‘circular ecosystems’ in their economic, social and environmental dimensions. The CBM approach evaluates heritage conservation not only in terms of financial return on investment but also through multi-dimensional value creation (economic, social, cultural and ecological benefits). this process as a model based on multi-stakeholder and iterative learning cycles; thus, heritage sites become a platform for community-based production, social entrepreneurship, and creative economies.

Zhang, Gruhler, and Schiller (2023) have demonstrated that the implementation of circular economy principles in the built environment is directly related to spatial characteristics. Factors such as urban density, morphology, accessibility, and resource cycles are key variables that determine the scale and effectiveness of adaptive reuse strategies. This perspective demonstrates that the repurposing of cultural heritage should be evaluated not only in terms of conservation and economics but also in the context of spatial sustainability and resource efficiency.

From an economic sustainability perspective, the re-functionalisation of cultural heritage creates new employment and investment opportunities in local economies through public-private partnerships, creative industries, social entrepreneurship, and tourism-based development models (Shipley et al., 2006; Duxbury & Richards, 2019). However, in this process, qualitative values such as conservation ethics, authenticity, social memory, and identity must be taken into account; otherwise, approaches focused on economic benefit risk weakening the layers of meaning represented by the heritage (Rodwell, 2016).

At this point, the principle of 'heritage for people and by people' set forth in the Faro Convention (Council of Europe, 2005) emphasises that re-functionalisation processes must be addressed not only in economic terms but also in terms of participatory and democratic governance. The knowledge, experience and production capacity of communities are seen as the most important source of cultural heritage sustainability (Smith & Waterton, 2013; Logan, 2007). Consequently, the contemporary approach transforms cultural heritage into a holistic sustainability paradigm that addresses its economic, social and environmental components.

Consequently, the re-functionalization of historic buildings represents a new approach to conservation that brings together the principles of spatial circularity, economic sustainability, and social participation This article examines how this transformation is reflected in the literature and evaluates the relationship between the circular use of cultural heritage and sustainable economic discourses through academic studies published between 2020 and 2025.

2. Material and Method

This study examines the effects of the sustainable reuse of cultural heritage on the curcilar economy using the bibliographic analysis method. The Web of Science database was searched using the keyword "adaptive reuse" along with the keywords "economy" and "heritage". The search was limited to studies conducted between 2020 and 2025 on the topics of 'Environmental Studies' and 'Architecture'. Of the 33 articles obtained, one was excluded from the study as it was not relevant to the topic. The distribution of the 32 articles by year and how they addressed the relationship between heritage architecture and circular economy was determined. The articles examined were categorised into themes based on their content and interpreted.

In this study, only the WoS database was utilised in order to maintain methodological focus and data consistency. The exclusive use of WoS ensured that the data could be analysed in a consistent and comparable manner within a single indexing system. This preference is based on the principles of methodological clarity and analytical integrity rather than any qualitative difference between databases.

3. Findings and Discussion

This section presents the findings and interpretations derived from the thematic analysis of thirty-two academic articles identified from the Web of Science database. The aim is to reveal how the adaptable or circular use of cultural heritage is addressed within the context of sustainable and circular economies. First, the scope of the publications included in the analysis is summarised and the composition and characteristics of the data set are explained. Subsequently, the relationship between the thematic categories identified in the articles and the conceptual framework of the circular economy is discussed.

3.1. Publications Included in the Analysis and Examination of the Data Set

As a result of a comprehensive literature review conducted in the Web of Science database, 32 academic articles published between 2020 and 2025 were examined within the framework of the concepts of re-functionalisation of cultural heritage, circular economy, and circular development. These publications reflect current trends and paradigm shifts in the field, covering both theoretical approaches and practical examples. A significant portion of the studies show that cultural heritage is being redefined in terms of economic value creation, social participation, and environmental sustainability. The articles included in the analysis provide a rich comparative field for evaluating the multidimensional effects of adaptive reuse practices. These 32 articles, which form the core dataset of the research, reveal findings directly related to both the community-based approaches envisaged by the Faro Convention and the principles of the sustainable economy in terms of their content and thematic context. Table 1 shows a detailed list of these publications and the sample group used in the literature analysis.

Table 1. Articles Examined within The Scope of The Study (Web of Science).

Year	Author	Article Title
2020	De Gregorio, S et al.	Designing the Sustainable Adaptive Reuse of Industrial Heritage to Enhance the Local Context
2020	Cerreta, M et al.	A Creative Living Lab for the Adaptive Reuse of the Morticelli Church: The SSMOLL Project
2021	Girard, LF & Vecco, M	The Intrinsic Value of Cultural Heritage as Driver for Circular Human-Centered Adaptive Reuse
2021	Gravagnuolo, A et al.	A Participatory Approach for Circular Adaptive Reuse of Cultural Heritage. Building a Heritage Community in Salerno, Italy
2021	Dell'Ovo, M et al.	Enhancing the Cultural Heritage through Adaptive Reuse. A Multicriteria Approach to Evaluate the Castello Visconteo in Cusago (Italy)
2021	Bosone, M et al.	Indicators for Ex-Post Evaluation of Cultural Heritage Adaptive Reuse Impacts in the Perspective of the Circular Economy
2021	Pintossi, N et al.	Assessing Cultural Heritage Adaptive Reuse Practices: Multi-Scale Challenges and Solutions in Rijeka
2021	Kaya, DI et al.	An Empirical Analysis of Driving Factors and Policy Enablers of Heritage Adaptive Reuse within the Circular Economy Framework
2021	Pintossi, N et al.	Identifying Challenges and Solutions in Cultural Heritage Adaptive Reuse through the Historic Urban Landscape Approach in Amsterdam
2021	Marika, G et al.	Adaptive Reuse and Sustainability Protocols in Italy: Relationship with Circular Economy
2021	Pickerill, T	Investment Leverage for Adaptive Reuse of Cultural Heritage
2021	Giani, F	Process Proposal for Adaptive Reuse and Social Promotion of Ecclesiastical Buildings
2021	Cellucci, C	Circular economy strategies for adaptive reuse of residential building
2021	Bosone, M & Lodice, S	Strategies for the Adaptive Reuse of the Former Augustinian Monastery in Vicopelago
2021	Vythoulka, A et al.	Protection and Revealing of Traditional Settlements and Cultural Assets, as a Tool for Sustainable Development: The Case of Kythera Island in Greece
2021	Acri, M et al.	Regenerating the Historic Urban Landscape through Circular Bottom-Up Actions: The Urban Seeding Process in Rijeka
2021	Stanojev, J & Gustafsson, C	Smart Specialisation Strategies for Elevating Integration of Cultural Heritage into Circular Economy
2022	Giannakopoulos, D et al.	Reuse of Historic Buildings in the Medieval City of Rhodes to Comply with the Needs of Sustainable Urban Development

2022	Nocca, F & Angrisano, M	The Multidimensional Evaluation of Cultural Heritage Regeneration Projects: A Proposal for Integrating Level(s) Tool-The Case Study of Villa Vannucchi in San Giorgio a Cremano (Italy)
2023	Pintossi, N et al.	Challenges of cultural heritage adaptive reuse: A stakeholders-based comparative study in three European cities
2023	Vardopoulos, I et al.	Urban buildings sustainable adaptive reuse into tourism accommodation establishments: a SOAR analysis
2023	Della Spina, L	A Prefeasibility Study for the Adaptive Reuse of Cultural Historical Landscapes as Drivers and Enablers of Sustainable Development
2023	Valdiviezo, AC	Adaptive reuse: Its potential role in sustainable architecture and its relationship with restoration and rehabilitation
2023	Mazzetto, S & Vanini, F	Urban Heritage in Saudi Arabia: Comparison and Assessment of Sustainable Reuses
2024	Angrisano, M et al.	Multidimensional Evaluation Framework for Assessing Cultural Heritage Adaptive Reuse Projects: The Case of the Seminary in Sant'Agata de' Goti (Italy)
2024	Andrade, MJ et al.	Reuse of port industrial heritage in tourist cities: Shipyards as case studies
2024	Della Spina, L	A Decision Support Evaluation Framework for Community-Based Collaborative Urban Regeneration Processes
2025	Margono, RB et al.	Revitalizing Japan's Vacant Houses: A Sustainable Approach Through Adaptive Reuse
2025	Alraouf, AA	Msheıreb, Doha: The Urban Regeneration Ofa Deteriorated Herat.Authentic Contemporary And Cultural Localism
2025	Ghoz, L	A multidisciplinary categorization of challenges of reuse of residential buildings
2025	Barelles-Vicente, E et al.	From Ruin to Resource: The Role of Heritage and Structural Rehabilitation in the Economic and Territorial Regeneration of Rural Areas
2025	Xiong, JY et al.	A Study on the Defensive Characteristics and Sustainable Conservation Strategies of Ming Dynasty Coastal Defence Settlements in Fujian

Articles published between 2020 and 2025 that addressed the relationship between the circular use of cultural heritage were found to focus on four distinct themes. These themes are: “Examples of religious/industrial/rural heritage”’, “Economic sustainability and investment models”, "Community-based/social economy models", and "Tourism-based adaptive reuse" (Figure 1).

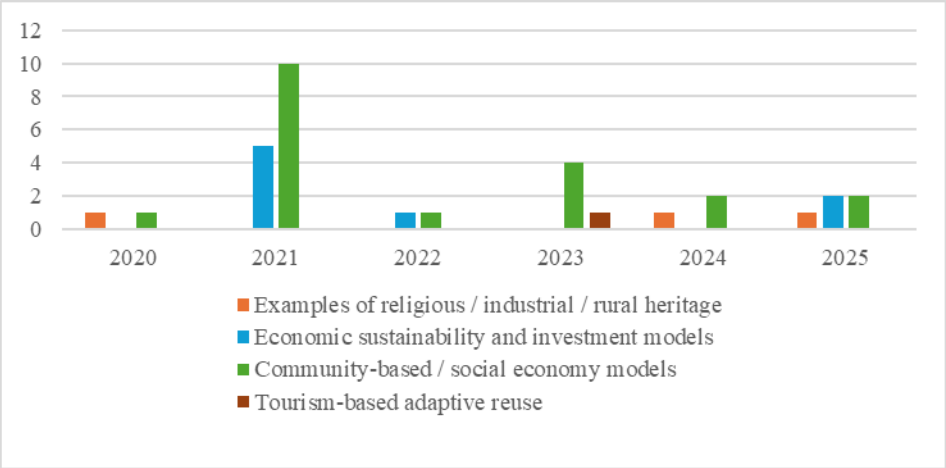

Figure 1. Distribution of the articles examined by year and theme (Created by author)

The graph shows thematic trends in the repurposing of historic buildings in studies published between 2020 and 2025. According to the data, the most significant increase during this period occurred in 2021 under the heading 'community-based/social economy models'. This year, it stands out by a wide margin compared to all other themes, indicating an intense debate in the literature centred on the participation of local communities and social solidarity economies. This is particularly significant as it coincides with a period when the concepts of community solidarity and local development have been brought back to the agenda, especially due to the impact of the COVID-19 pandemic. The Faro Convention emphasises that heritage is not merely an object to be preserved, but a vehicle for human rights, democratic participation and social well-being. Accordingly, cultural heritage is not an element of property but a 'living resource' that strengthens communities' identities, values, and sense of belonging (Council of Europe, 2005; Logan, 2007). The intensity of 2021 in the graph points to a period when this paradigm matured in the academic sphere. Post-pandemic themes of increased solidarity, local production, and the ‘commons’ have led to a re-examination of Faro's community-centred definition of heritage in the current context (Smith & Waterton, 2013; Sofaer et al., 2021).

Looking at 2020, it is seen that the themes were addressed in a very limited number of studies, with ‘religious/industrial/rural heritage examples’ and ‘community-based models’ being explored at a rudimentary level. In 2022, a significant decline was observed across all themes; this year can be interpreted as a transitional period marked by a general weakening of academic output.

A renewed dynamism is noticeable in 2023 and 2024, with ‘community-based/social economy models’ as well as ‘tourism-based re-functionalisation’ and ‘religious/industrial/rural heritage examples’ gaining particular momentum. This trend indicates that the topics of sustainable tourism and the multifunctional use of cultural heritage are being revisited in the literature.

By 2025, it can be said that the thematic distribution has achieved a more balanced structure. The renewed prominence of ‘economic sustainability and investment models’ signals that the financial sustainability dimension of conservation policies is back on the agenda. The continued presence of ‘community-based’ and ‘tourism-focused’ approaches during the same period indicates that re-functionalisation practices have entered a multidimensional paradigm shift.

Ultimately, the graph reveals a general trend towards social-economic participation models in 2021, followed by a transition to a balanced approach incorporating economic, tourist and typological diversity. This finding points to a holistic transformation process in which community participation, economic sustainability and tourism-based strategies are addressed in a complementary manner in the re-functionalisation of cultural heritage.

3.2. The Relationship Between Themes and Circular Economy

This section analyses the methodological approaches developed by the examined articles to increase the contribution of the reuse of cultural heritage to a sustainable economy. Although these studies can be conceptually linked to one another, the recommendations have been categorised under four main themes and addressed within a thematic framework to enable a detailed assessment.

3.2.1. Community-based and social economy models

The theme consists of studies focusing on the active engagement of local communities in heritage conservation and the production of social value. These studies argue that community ownership of heritage, as envisaged by the Faro Convention (2005), increases conservation success. Defined by concepts such as 'heritage commons,' 'participatory governance,' and 'social innovation,' these approaches aim to involve local communities in decision-making processes and enable them to benefit directly from economic gains. Thus, conservation moves beyond mere physical intervention to become part of processes of social solidarity, identity building, and inclusive development.

3.2.2. Economic sustainability and investment models

Articles highlighted in the second theme reveal that economic sustainability is a decisive factor in the success of repurposing projects. Models proposed in this context include public-private partnerships (PPPs), social entrepreneurship approaches, heritage funds, and micro-investment mechanisms. The studies indicate that traditional public funding is insufficient for the preservation of heritage sites, and therefore multi-source financial models (e.g. EU funds, local development agencies, private sponsorships) have become important. This finding shows that the economic value of cultural heritage is increasingly recognised, but that it must be managed within a framework that respects preservation principles and ethics.

3.2.3. Examples of religious, industrial and rural heritage

This group includes studies that comparatively examine the processes of re-functionalising heritage sites of different typologies. Concepts such as identity, sanctity and belonging come to the fore in the re-functionalisation of religious structures (e.g. churches, monasteries), while in industrial heritage examples, spatial transformation is observed to be integrated with cultural production, museology and creative industries. In the context of rural heritage, agricultural production, ecotourism, and local craft practices are instrumentalised in preserving heritage. This theme generally reveals that typological diversity enriches adaptive reuse approaches and that each type of structure requires its own unique socio-cultural sensitivities.

3.2.4. Tourism-based adaptive reuse

The studies included in this theme emphasise that cultural heritage structures can integrate with the tourism sector to bring together the goals of economic vitality, identity representation, and sustainable conservation. It is stated that, particularly in urban centres and coastal areas, tourism-focused re-functions directly contribute to the conservation of structures, but that excessive commercialisation can weaken their authenticity and memory values. The studies suggest that experience-based tourism, cultural routes, and management models that prioritise local participation produce sustainable results in tourism-focused adaptive reuse. Thus, tourism is positioned not merely as an economic tool but as a 'living' part of heritage.

4. Conclusion and Suggestions

This study thematically analysed thirty-two academic publications published between 2020 and 2025, demonstrating how the re-functionalisation of cultural heritage has been reconceptualised through the lens of the circular economy paradigm. The findings indicate that cultural heritage has evolved beyond a mere focus on preservation, becoming increasingly intertwined with the principles of community well-being, economic resilience, and environmental circularity.

Thematic distributions reveal that the theme of 'community-based/social economy models,' which rose significantly in 2021, has strengthened the academic counterpart of the 'producing heritage for people and by people' paradigm envisaged by the Faro Convention (Council of Europe, 2005) in cultural heritage management. This trend has redefined heritage preservation around the axes of human rights, democratic participation, and social welfare, making participatory governance a central principle in heritage management (Smith & Waterton, 2013; Logan, 2007). In the post-pandemic period, increased global solidarity, local production, and the influence of ‘commons’ practices have transformed heritage sites into collective production areas that enhance the economic and social resilience of communities.

After 2023, the resurgence of the themes of ‘economic sustainability and investment models’ and ‘tourism-based adaptive reuse’ signals a new phase of integration in the literature. Accordingly, adaptive reuse ensures the physical continuity of heritage while creating circular economic ecosystems through local entrepreneurship, creative industries, and social cooperatives.

These findings also deepen classical approaches to the economic impacts of cultural heritage. While Bowitz and Ibenholt (2009) reveal the direct, indirect, and derivative economic impacts of heritage investments, the thematic analysis of this study shows that these impacts are not only financial but also vary in terms of participatory and circular production forms. This situation reveals that cultural heritage has the potential to generate social capital and a solidarity economy beyond being an ‘economic asset.’

On the other hand, the principles of spatial circularity emphasised by Zhang, Gruhler, and Schiller (2023) remind us of the importance of local context and the built environment in the re-functionalisation of heritage. The findings show that tourism-based approaches concentrated in urban areas are integrated with ‘slow loop’ (reuse, repair) strategies, while ‘close loop’ (material recycling, local resource use) strategies are integrated in rural and industrial areas. Thus, cultural heritage has become a cyclical economic practice sensitive to spatial scale.

Overall, the literature from the 2020–2025 period points to a paradigm shift centred on three main axes regarding the repurposing of cultural heritage:

1. The rise of participatory social models (Faro principles and community-centred governance),
2. The strengthening of economic sustainability and investment-focused approaches (CBM and creative economy),
3. The redefinition of heritage as a living, productive ecosystem through tourism and spatial circularity.

This transformation clearly demonstrates that cultural heritage is not merely a value to be preserved, but a resource at the heart of social, economic and ecological reproduction. Cultural heritage therefore plays a strategic role in building the low-carbon, inclusive and resilient economic systems of the future.

A comprehensive assessment of the findings indicates that future research should particularly focus on deepening the following aspects: (i) measuring the effectiveness of community-based financial models (e.g. social cooperatives and community investment funds), (ii) analysing how circular strategies vary in local contexts at the spatial level, and (iii) developing interdisciplinary models for assessing the economic value of heritage alongside social welfare indicators.

Consequently, the re-functionalisation of cultural heritage, as an emerging paradigm at the intersection of conservation, development, and circular economy policies, is poised to become one of the main axes of sustainable urban and regional transformation in the future.

Acknowledgements and Information Note

The article complies with national and international research and publication ethics.

Ethics Committee approval was not required for the study.

Author Contribution and Conflict of Interest Declaration Information

1st Author % 100 contributed. There is no conflict of interest.

References

Acri, M., Dobričić, S., & Debevec, M. (2021). Regenerating the Historic Urban Landscape through Circular Bottom-Up Actions: The Urban Seeding Process in Rijeka. *Sustainability,* 13(8), 4497. https://doi.org/10.3390/su13084497

Alraouf, A. A. (2025). Msheireb, Doha: the urban regeneration of a deteriorated Herat. Authentic contemporary and cultural localism. *TECHNE - Journal of Technology for Architecture and Environment*, (3), 15–20. https://doi.org/10.36253/techne-18099

Andrade, M. J., Jiménez-Morales, E., Rodríguez-Ramos, R., & Martínez-Ramírez, P. (2024). Reuse of port industrial heritage in tourist cities: Shipyards as case studies. *Frontiers of Architectural Research*, 13(1), 164–183. https://doi.org/10.1016/j.foar.2023.09.005

Angrisano, M., Nocca, F., & Scotto Di Santolo, A. (2024). Multidimensional Evaluation Framework for Assessing Cultural Heritage Adaptive Reuse Projects: The Case of the Seminary in Sant'Agata de' Goti (Italy). *Urban Science*, 8(2), 50. https://doi.org/10.3390/urbansci8020050

Barelles-Vicente, E., Torner-Feltrer, M. E., Llinares Millán, J., & Aparicio-Fernández, C. (2025). From Ruin to Resource: The Role of Heritage and Structural Rehabilitation in the Economic and Territorial Regeneration of Rural Areas. *Land*, 14(9), 1765. https://doi.org/10.3390/land14091765

Bosone, M., De Toro, P., Fusco Girard, L., Gravagnuolo, A., & Iodice, S. (2021). Indicators for Ex-Post Evaluation of Cultural Heritage Adaptive Reuse Impacts in the Perspective of the Circular Economy. *Sustainability,* 13(9), 4759. https://doi.org/10.3390/su13094759

Bosone, M., & Iodice, S. (2021). Strategies for the Adaptive Reuse of the Former Augustinian Monastery in Vicopelago. *IN_BO. Ricerche E Progetti Per Il Territorio, La Città E l'architettura*, 12(6), 162–187. https://doi.org/10.6092/issn.2036-1602/11278

Bowitz, E., & Ibenholt, K. (2009). Economic impacts of cultural heritage: Research and perspectives. *Journal of Cultural Heritage*, 10(1), 1–8. https://doi.org/10.1016/j.culher.2008.09.002

Bullen, P. A., & Love, P. E. D. (2011). Adaptive reuse of heritage buildings. *Structural Survey*, 29(5), 411–421. https://doi.org/10.1108/02630801111182439

Cellucci, C. (2021). Circular economy strategies for adaptive reuse of residential building. *VITRUVIO - International Journal of Architectural Technology and Sustainability*, 6(1), 110–121. https://doi.org/10.4995/vitruvio-ijats.2021.15404

Cerreta, M., Elefante, A., & La Rocca, L. (2020). A Creative Living Lab for the Adaptive Reuse of the Morticelli Church: The SSMOLL Project. *Sustainability*, 12(24), 10561. https://doi.org/10.3390/su122410561

Council of Europe. (2005). *Framework Convention on the Value of Cultural Heritage for Society (Faro Convention)*. Strasbourg: Council of Europe.

Della Spina, L. (2023). A Prefeasibility Study for the Adaptive Reuse of Cultural Historical Landscapes as Drivers and Enablers of Sustainable Development. *Sustainability*, 15(15), 12019. https://doi.org/10.3390/su151512019

Della Spina, L. (2024). A Decision Support Evaluation Framework for Community-Based Collaborative Urban Regeneration Processes. *Sustainability*, 16(15), 6434. https://doi.org/10.3390/su16156434

Dell'Ovo, M., Dell'Anna, F., Simonelli, R., & Sdino, L. (2021). Enhancing the Cultural Heritage through Adaptive Reuse. A Multicriteria Approach to Evaluate the Castello Visconteo in Cusago (Italy). *Sustainability*, 13(8), 4440. https://doi.org/10.3390/su13084440

De Gregorio, S., De Vita, M., De Berardinis, P., Palmero, L., & Risdonne, A. (2020). Designing the Sustainable Adaptive Reuse of Industrial Heritage to Enhance the Local Context. *Sustainability*, 12(21), 9059. https://doi.org/10.3390/su12219059

Duxbury, N., & Richards, G. (2019). *A research agenda for creative tourism*. Cheltenham: Edward Elgar.

Foster, G. (2020). Circular economy strategies for adaptive reuse of cultural heritage buildings to reduce environmental impacts, *Resources, Conservation & Recycling*, 152, 1-14. https://doi.org/10.1016/j.resconrec.2019.104507

Foster, G. (2025). Key Learnings from the “Kultur-Token” Sustainable Business Modelling Case Study. Fusco Girard, L., & Gravagnuolo, A. (Eds.). *Adaptive Reuse of Cultural Heritage: Circular Business, Financial and Governance Models.* (p. 483-493), Springer.

Fusco Girard, L., & Vecco, M. (2021). The “Intrinsic Value” of Cultural Heritage as Driver for Circular Human-Centered Adaptive Reuse. *Sustainability*, 13(6), 3231. https://doi.org/10.3390/su13063231

Ghoz L (2025) A multidisciplinarycategorization of challenges of reuse ofresidential buildings.*Front. Sustain. Cities* 7:1576288. https://doi.org/10.3389/frsc.2025.1576288

Giani, F. (2021). Process Proposal for Adaptive Reuse and Social Promotion of Ecclesiastical Buildings. *IN_BO. Ricerche E Progetti Per Il Territorio, La Città E l’architettura,* 12(6), 108–119. https://doi.org/10.6092/issn.2036-1602/12453

Giannakopoulos, D., Karekou, Z., Menegaki, E., Tsilimantou, E., Ioannidis, C., Maistrou, E., Giannikouris, A., & Moropoulou, A. (2022). Reuse of Historic Buildings in the Medieval City of Rhodes to Comply with the Needs of Sustainable Urban Development. *Land*, 11(8), 1214. https://doi.org/10.3390/land11081214

Gravagnuolo, A., Micheletti, S., & Bosone, M. (2021). A Participatory Approach for “Circular” Adaptive Reuse of Cultural Heritage. Building a Heritage Community in Salerno, Italy. *Sustainability*, 13(9), 4812. https://doi.org/10.3390/su13094812

Ikiz Kaya, D., Pintossi, N., & Dane, G. (2021). An Empirical Analysis of Driving Factors and Policy Enablers of Heritage Adaptive Reuse within the Circular Economy Framework. *Sustainability,* 13(5), 2479. https://doi.org/10.3390/su13052479

Licciardi, G., & Amirtahmasebi, R. (Eds.). (2012*). The Economics of Uniqueness: Investing in Historic City Cores and Cultural Heritage Assets for Sustainable Development*. World Bank.

Logan, W. (2007). Closing Pandora’s Box: Human Rights Conundrums in Cultural Heritage Protection, Silverman, H. & Ruggles, F. (Eds.). *Cultural heritage and human rights (p.33-52)*. Springer.

Marika, G., Beatrice, M., & Francesca, A. (2021). Adaptive Reuse and Sustainability Protocols in Italy: Relationship with Circular

Economy. *Sustainability,* 13(14), 8077. https://doi.org/10.3390/su13148077

Mazzetto, S., & Vanini, F. (2023). Urban Heritage in Saudi Arabia: Comparison and Assessment of Sustainable Reuses. Sustainability, 15(12), 9819. https://doi.org/10.3390/su15129819

Margono, R. B., Ahdika, A., Sulistiyowati, Zuraida, S., & Dewancker, B. (2025). Revitalizing Japan's Vacant Houses: A Sustainable Approach Through Adaptive Reuse. *Sustainability*, 17(4), 1704. https://doi.org/10.3390/su17041704

Nocca, F., & Angrisano, M. (2022). The Multidimensional Evaluation of Cultural Heritage Regeneration Projects: A Proposal for Integrating Level(s) Tool—The Case Study of Villa Vannucchi in San Giorgio a Cremano (Italy). *Land*, 11(9), 1568. https://doi.org/10.3390/land11091568

Pickerill, T. (2021). Investment Leverage for Adaptive Reuse of Cultural Heritage. *Sustainability,* 13(9), 5052. https://doi.org/10.3390/su13095052

Pintossi, N., Ikiz Kaya, D., & Pereira Roders, A. (2021a). Assessing Cultural Heritage Adaptive Reuse Practices: Multi-Scale Challenges and Solutions in Rijeka. *Sustainability,* 13(7), 3603. https://doi.org/10.3390/su13073603

Pintossi, N., Ikiz Kaya, D., & Pereira Roders, A. (2021b). Identifying Challenges and Solutions in Cultural Heritage Adaptive Reuse through the Historic Urban Landscape Approach in Amsterdam. *Sustainability,* 13(10), 5547. https://doi.org/10.3390/su13105547

Pintossi, N., Ikiz Kaya, D., van Wesemael, P., & Pereira Roders, A. (2023). Challenges of cultural heritage adaptive reuse: A stakeholders-based comparative study in three European cities. *Habitat International,* 136,102807. https://doi.org/10.1016/j.habitatint.2023.102807

Rodwell, D. (2016). *Heritage, conservation and communities: Engagement, participation and capacity building*. Routledge.

Saleh, R.& Ost, C. (2025). Circular Business Model for Cultural Heritage Adaptive Reuse: An Iterative Journey. Fusco Girard, L., & Gravagnuolo, A. (Eds.). *Adaptive Reuse of Cultural Heritage: Circular Business, Financial and Governance Models*. (p. 433-461), Springer.

Shipley, R., Utz, S., & Parsons, M. (2006). Does Adaptive Reuse Pay? A Study of the Business of Building Renovation in Ontario, Canada. *International Journal of Heritage Studies*, 12(6), 505–520. https://doi.org/10.1080/13527250600940181

Smith, L., & Waterton, E. (2013). *Heritage, communities and archaeology*. Bloomsbury.

Sofaer, J., Davenport, B., Sørensen, M. L. S., Gallou, E., & Uzzell, D. (2021). Heritage sites, value and wellbeing: learning from the COVID-19 pandemic in England. *International Journal of Heritage Studies*,27(11),1117–1132. https://doi.org/10.1080/13527258.2021.1955729

Stanojev, J., & Gustafsson, C. (2021). Smart Specialisation Strategies for Elevating Integration of Cultural Heritage into Circular Economy. *Sustainability*, 13(7), 3685. https://doi.org/10.3390/su13073685

Throsby, D. (2010). *The Economics of Cultural Policy*. Cambridge University Press. https://doi.org/10.1017/CBO9780511845253

Xiong, J., Ke, C., Xie, M., Chen, K., & Wang, X. (2025). A Study on the Defensive Characteristics and Sustainable Conservation Strategies of Ming Dynasty Coastal Defence Settlements in Fujian. *Sustainability*, 17(18), 8406. https://doi.org/10.3390/su17188406

Valdiviezo, A. (2023). Adaptive reuse: Its potential role in sustainable architecture and its relationship with restoration and rehabilitation. *Revista de Arquitectura (Bogotá),* 25(1), 173-186. https://doi.org/10.14718/RevArq.2023.25.4520

Vardopoulos, I., Giannopoulos, K., Papaefthymiou, E. et al. (2023). Urban buildings sustainable adaptive reuse into tourism accommodation establishments: a SOAR analysis. *Discover Sustainability*, 4(50). https://doi.org/10.1007/s43621-023-00166-2

Vythoulka, A., Delegou, E. T., Caradimas, C., & Moropoulou, A. (2021). Protection and Revealing of Traditional Settlements and Cultural Assets, as a Tool for Sustainable Development: The Case of Kythera Island in Greece. *Land*, 10(12), 1324. https://doi.org/10.3390/land10121324

Zhang, N., Gruhler, K., & Schiller, G. (2023). A review of spatial characteristics influencing circular economy in the built environment. *Environmental Science and Pollution Research*, 30(54), 54280–54302. https://doi.org/10.1007/s11356-023-26326-5

Res. Asst. Dr. Bengisu Özkılavuz
E-mail: bengisu@uludag.edu.tr
Educational Status: Ph.D.
License: Gazi University Faculty of Architecture, Department of Architecture, 2007-2012
Degree: Bursa Uludag University, Ph.D Programme in Architecture, Graduate School of Natural and Applied Science, Department of Architecture
Doctorate: Bursa Uludag University, Ph.D Programme in Architecture, Graduate School of Natural and Applied Science, Department of Architecture (2017-2025)
Professional experiences: Research Assistant at the Faculty of Architecture, Bursa Uludağ University

ISBN: 978-625-378-348-8

20 October 2025

İKSAD
Publishing House