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ENHANCING THE LIFE CYCLE SUSTAINABILITY ASSESSMENT OF BUILDINGS THROUGH INTEGRATION OF DIGITAL TWIN AND BLOCKCHAIN

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Doctoral thesis presented to the Environmental Engineering Program, Escola Politécnica & Escola de Química, from Universidade Federal do Rio de Janeiro, as part of the requirements for obtaining a Doctor of Science degree in Environmental Engineering.

Advisors:
Prof. Dr. Assed Naked Haddad
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To my husband Igor, who has walked every step of this journey with me.

He is my partner, my best friend, and my greatest supporter.

“Anyone who has common sense will remember that the bewilderments of the eyes are of two kinds, and arise from two causes, either from coming out of the light or from going into the light, which is true of the mind's eye, quite as much as of the bodily eye; and he who remembers this when he sees any one whose vision is perplexed and weak, will not be too ready to laugh; he will first ask whether that soul of man has come out of the brighter life, and is unable to see because unaccustomed to the dark, or having turned from darkness to the day is dazzled by excess of light.”

Plato in The Republic.

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ABSTRACT

FIGUEIREDO, K. V. **Enhancing the Life Cycle Sustainability Assessment of Buildings Through Integration of Digital Twin and Blockchain**. DSc. Thesis (Doctorate in Environmental Engineering), Environmental Engineering Program, Escola Politécnica & Escola de Química, Federal University of Rio de Janeiro, 2024. Advisors: Assed Haddad, Vivian WY Tam, Ahmed WA Hammad.

This thesis presents a comprehensive exploration of decision-making processes in sustainable construction projects, motivated by the numerous challenges encountered in analyzing building life cycles. The challenges primarily arise from the large amount of data that must be considered, as well as the inherent limitations in information management and imposed temporal constraints. These aspects underscore the pressing need for innovative approaches to enhance the effectiveness and adaptability of Life Cycle Sustainability Assessment (LCSA). It is in this context that the proposal to benefit LCSA application through integration with innovative technologies like Digital Twin and Blockchain emerges. By elaborating on integrating Digital Twin and Blockchain concepts, the thesis proposes a dynamic, real-time, and secure framework for sustainability assessments across the entire life cycle of buildings. Across eleven structured chapters, the thesis outlines the development and validation of this integration model, facilitating holistic assessments of sustainability across environmental, economic, and social dimensions. Key results include the development of an advanced software application, ensuring real-time data visualization, data security, and integrity, and the demonstration of this integration in a real-world case study. Through theoretical discussions, empirical research, and case studies, the thesis provides valuable insights and a novel methodology for stakeholders in sustainable construction projects, contributing to the advancement of a smarter and more sustainable built environment. Ultimately, this research represents a significant effort to provide practical solutions to the challenges faced in construction sustainability.

Keywords: Blockchain, Digital Twin, Life cycle sustainability assessment, Machine Learning, Sustainable construction.

RESUMO

FIGUEIREDO, K. V. **Enhancing the Life Cycle Sustainability Assessment of Buildings Through Integration of Digital Twin and Blockchain**. Tese (Doutorado em Engenharia Ambiental), Programa de Engenharia Ambiental, Escola Politécnica & Escola de Química, Universidade Federal do Rio de Janeiro, 2024. Orientadores: Assed Haddad, Vivian WY Tam, Ahmed WA Hammad.

Esta tese apresenta uma exploração abrangente dos processos de tomada de decisão em projetos de construção sustentável, motivada pelos numerosos desafios encontrados na análise dos ciclos de vida dos edifícios. Os desafios decorrem principalmente da grande quantidade de dados que devem ser considerados, bem como das limitações inerentes à gestão da informação e das restrições temporais impostas. Estes aspectos sublinham a grande necessidade de abordagens inovadoras para aumentar a eficácia e a adaptabilidade da Avaliação da Sustentabilidade do Ciclo de Vida (ASCV). É neste contexto que surge a proposta de beneficiar a aplicação ASCV através da integração com tecnologias inovadoras como Digital Twin e Blockchain. Ao desenvolver a integração dos conceitos de Digital Twin e Blockchain, a tese propõe uma aplicação dinâmica, em tempo real e segura para avaliações de sustentabilidade em todo o ciclo de vida dos edifícios. Ao longo de onze capítulos estruturados, a tese descreve o desenvolvimento e a validação deste modelo de integração, facilitando avaliações holísticas da sustentabilidade nas dimensões ambiental, social e econômica. Os principais resultados incluem o desenvolvimento de um software, garantindo visualização de dados em tempo real, segurança e integridade de dados, e a demonstração dessa integração em um estudo de caso de um edifício real. Através de discussões teóricas, pesquisas empíricas e estudos de caso, a tese fornece importantes percepções e uma metodologia inovadora para as partes interessadas em projetos de construção sustentável, contribuindo para o avanço de um ambiente construído mais inteligente e sustentável. Em última análise, esta pesquisa representa um esforço significativo para fornecer soluções práticas para os desafios enfrentados na sustentabilidade da construção.

Keywords: Avaliação de Sustentabilidade do Ciclo de Vida, Blockchain, Construção Sutentável, Gêmeo Digital, Machine Learning.

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ABBREVIATIONS

AEC – Architecture, engineering, and construction

AI - Artificial intelligence

AHP - Analytic Hierarchy Process

BIM - Building information modeling

C&D - Construction and demolition

CE - Circular economy

DEMATEL - Decision-Making Trial and Evaluation Laboratory

DLCA – Dynamic life cycle assessment

DLT - Distributed Ledger Technology

DT – Digital Twin

EoL - End-of-life

FAHP - Fuzzy Analytic Hierarchy Process

GDP - Gross Domestic Product

GWP - Global Warming Potential

IISD - International Institute for Sustainable Development

IFC - Industry Foundation Classes

IoT - Internet of Things

ISO - International Standards Organization

LCA – Life cycle assessment

LCC – Life cycle costing

LCI - Life cycle inventory

LCIA - Life cycle impact assessment

LCSA – Life cycle sustainability assessment

LCT - Life Cycle Thinking

MCDA - Multi-criteria decision analysis

MCDM - Multi-criteria decision-making

NPV - Net Present Value

PROMETHEE - Preference Ranking Organization Method for Enrichment Evaluations

SA - Sensitivity analysis

S-LCA – Social life cycle assessment

TOPSIS - Technique for Order Preference by Similarity to an Ideal Solution

INDEX

1 INTRODUCTION

1.1 GENERAL BACKGROUND

The sustainability concept can be understood as a development that meets the present needs to balance economic, social, and environmental aspects without jeopardizing the ability of future generations to fulfill their own needs and requirements [1]. Considering the construction of buildings and civil engineering works, sustainable development is related to how the attributes of the activities, products, or services contribute to maintaining the built environment for future generations [2]. In this context, for the purposes of this thesis, sustainability for individual buildings and civil engineering works could be understood as the reduction or elimination of negative environmental, economic, and social impacts and the maximization of positive impacts throughout the design, construction, and operation of a building, in addition to considering the end-of-life scenario of the built asset.

The discourse surrounding sustainability in buildings is multifaceted, acknowledging the significant environmental, economic, and social impacts associated with the construction sector. With the industry generating billions of tonnes of building waste annually and accounting for a substantial portion of global gross domestic product (GDP) and employment figures [3–5], the imperative to align construction practices with sustainability principles across all three pillars—economy, society, and environment—is undeniable [6].

However, the pursuit of sustainable building projects poses several challenges. Managing vast amounts of data [7], integrating diverse disciplinary perspectives, such as architectural, structural, and mechanical [8], ensuring effective communication among project stakeholders [9], and addressing information loss over the building lifecycle [10] are just a few of the hurdles encountered. Besides, a considerable amount of time is consumed in the early stages of designing construction projects when comparing different construction materials, resources, and methods [11].

Unfortunately, the project decisions are traditionally based on satisfying only technical requirements or economic limits without profoundly considering the impacts associated with the building project [12]. In this context, the need to apply the Life Cycle Thinking (LCT) approach to benefit the decision-making process of construction projects arises, thus facilitating the creation of more sustainable projects. Life Cycle Thinking refers to providing information to interested parties to make the best decisions regarding the life cycles of products [13]. When it comes to buildings, the life cycle is understood by all the existing phases, from the extraction of raw materials to the building demolition and the consequent disposal, reuse, or recycling of materials and components.

This thinking has grown enormously in recent years among professionals and researchers associated with the construction sector, especially when it comes to assessing the environmental impacts of buildings. This is observed by the growing number of publications on applying the Life Cycle Assessment (LCA) methodology in the construction industry to assess the environmental impacts of construction projects [14]. According to the standard ISO 14040, the Environmental Life Cycle Assessment (E-LCA) methodology, usually referred to just as Life Cycle Assessment (LCA), is the compilation of inputs, outputs, and potential environmental impacts of a product system throughout its life cycle [15].

A four-phase framework represents the LCA, namely: (i) Goal and Scope definition; (ii) Life Cycle Inventory (LCI); (iii) Life Cycle Impact Assessment (LCIA); and (iv) Interpretation. Briefly, it can be said that the first phase involves defining the goal and the scope by determining different aspects of the study, such as the functional unit, the system boundary (i.e., cradle-to-grave, cradle-to-gate, gate-to-gate, gate-to-grave), and the assumptions and limitations to be considered [16]. In turn, the LCI phase represents the compilation and quantification of inputs and outputs for the chosen functional unit regarding the system boundary selected [17], and the LCIA phase consists of evaluating the magnitude and significance of the potential environmental impacts [18]. Lastly, the interpretation phase comprises identifying and assessing all the information from the previous stages so that the results can be communicated to interested parties and that they can be used to aid decision-making [19].

Nevertheless, the LCT approach is not only concerned with environmental issues, as sustainability involves an interaction between a triple-bottom-line framework comprised of environmental, economic, and social aspects. To enhance the sustainability of construction, it is crucial to simultaneously account for all sustainability pillars in an entirely harmonious way. The Life Cycle Sustainability Assessment (LCSA) methodology emerged in this context. This is a more comprehensive methodology built on the LCT approach that recognizes that all phases in a product’s life cycle cause environmental impacts and socio-economic consequences, and to achieve sustainability, all these issues need to be evaluated [20].

LCSA is the result of combining three primary methodologies [21]: i) Life Cycle Assessment (LCA), representing the environmental dimension [22]; ii) Social Life Cycle

Assessment (S-LCA), representing the social dimension [23]; and iii) Life Cycle Costing (LCC), describing the economic dimension [24]. As such, Building LCSA can be represented as in **Figure 1.1**.

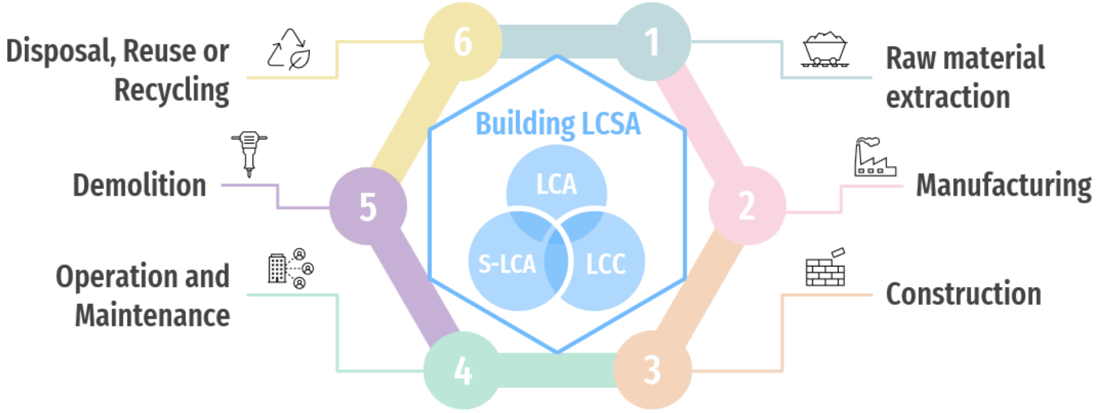


Figure 1.1 - Building Life Cycle Sustainability Assessment Framework

Application of LCSA within the construction industry is not without challenges; a high degree of detail is required when considering an entire building as a functional equivalent of analysis within LCSA. The term “functional equivalent” is introduced at the building level in contrast to the term “functional unit” at the product level and includes all quantified functional requirements and technical requirements of the building used as a basis for comparison in an LCSA analysis [25].

Many questions about the complete application of LCSA are still discussed in the literature [19], and many studies still implement only part of the evaluation. Although the four-phase LCA framework (i.e., Goal and Scope, LCI, LCIA, and Interpretation phases) can also be applied to LCC and S-LCA [26], the three pillars of sustainability have different maturity levels, which makes it challenging to integrate the three approaches together and hinders the broad implementation of Building LCSA.

1.2 MOTIVATION OF THE STUDY

The motivation behind this research arises from the numerous challenges encountered in analyzing the building’s life cycles, primarily due to the large amount of data that must be considered [27,28]. Fauzi et al. [29] extensively discussed various issues in the literature regarding the LCSA application, and one aspect that deserves great emphasis is the fact that not all the environmental and social indicators can be calculated as a function of the study’s functional equivalent, which generates a significant drawback in result interpretation. There is also the issue of the lack of reliable economic and social impact databases that are still under development compared to a range of reliable environmental impact databases.

In response to these challenges, literature suggests that integrating LCSA with other methodologies can offer significant benefits by simplifying the understanding of multiple perspectives in impact assessment. For instance, to facilitate the simulations and data collection required to generate detailed results on impacts associated with building projects, the integration of LCSA and Building Information Modelling (BIM) proved to be adequate [30]. BIM, renowned for its ability to revolutionize construction projects by providing 3D virtual models with parameterized elements, facilitates valuable analyses to reduce costs, detect design errors, and track building timelines. Moreover, BIM serves as an effective tool for building life cycle analysis, aiding in the optimization of various performance aspects, such as thermal [31], acoustic [32], and lighting [33] performances, as well as providing conscious consumption of energy [34] and water [35] and generating less environmental impacts [36].

When using the BIM methodology, the resulting 3D model is a data-rich, intelligent, and parametric digital representation of the facility [37]. BIM provides professionals with the necessary information to perform valuable analyses to reduce costs, detect design errors, and track building timelines. This methodology is commonly adopted for enhancing decision-making by lowering the amount of work involved in evaluating various alternatives in the early design stages of a building project [38]. Furthermore, BIM is considered an effective tool to assist in building life cycle analysis [39].

However, while much attention has been given to integrating BIM and lifecycle techniques, mainly focusing on environmental impacts, there remains a dearth of studies addressing all three dimensions of sustainability—environmental, economic, and social. Llatas et al. [21] conducted a systematic literature review regarding the integration of LCSA and BIM. This study showed that most papers in the literature use BIM solely to assess the environmental impacts of buildings. Only six papers were related to environmental and economic impacts simultaneously, while none of the studies reviewed included the analysis of social impacts.

Furthermore, while the integration of BIM and LCA has advanced, its primary application often occurs during the initial design stages of a project [40]. This emphasis on early-stage integration aligns with the understanding that stakeholders wield the greatest influence over project outcomes during these formative phases, diminishing as the project progresses toward completion [41]. However, the application of lifecycle techniques is severely limited by the lack of information available at the beginning of the project life cycle. This data deficiency poses a significant challenge to practitioners seeking to conduct thorough sustainability assessments, thereby impeding the realization of accurate and realistic evaluations.

Therefore, adopting a more holistic and dynamic approach to sustainability assessments is imperative to address these challenges effectively. This approach should encompass a broad range of factors, including model validation and verification, improved data collection methodologies, enhanced forecasting techniques, and changes in industry practices. By recognizing the temporal and contextual dimensions of sustainability impacts and embracing a coordinated strategy, researchers and practitioners can pave the way for more robust and adaptive sustainability assessments that align with the evolving needs and imperatives of the built environment.

In turn, the implementation of new technologies in building projects needs to be increasingly discussed among researchers and professionals. Research indicates that the construction sector is classified as one of the sectors that least adopt information technology [42]. Even BIM technology, specifically designed for the construction sector, remains underutilized in many projects worldwide. Despite its potential to enhance decision-making processes in building projects, many professionals are confined to using BIM-based tools solely for generating three-dimensional models for geometric representation and rendering. Numerous application possibilities of the BIM methodology, as discussed in the literature, have yet to gain widespread adoption in the market.

The limitations inherent in both information management and temporal constraints underscore the pressing need for innovative approaches to enhance the effectiveness and adaptability of LCSA. This is where emerging technologies like Digital Twin and Blockchain come into play. Integrating Digital Twin and Blockchain holds immense promise in addressing the limitations inherent in sustainability assessments. However, it is essential to note that this discourse is still in its preliminary stages, warranting further exploration and development.

1.2.1 Digital Twin

A challenging issue when implementing BIM to improve decision-making is that the current state of BIM only provides static data from the built environment and is not compatible with the integration of the Internet of Things (IoT) [43]. Implementing IoT in the built environment is essential to carry out accurate building sustainability assessments since IoT allows the digital building model to be updated in real-time, thus assessing the performance of what-if scenarios [44].

Recently, the use of Digital Twins has been proposed to solve this problem. Derived from product engineering, the Digital Twin concept has swiftly expanded into diverse domains, encompassing civil engineering, life sciences, and earth sciences, among others [45]. Recognized by the technology sector as a promising tool for enhancing efficiency and optimization, a Digital Twin is a virtual representation of an object or a system, serving as the real-time digital counterpart of the physical asset during its lifecycle [46]. By dynamically integrating data and information, a Digital Twin can improve the design of new assets and the understanding of existing asset conditions [47].

This concept is applicable in different industries, including the construction industry. From the construction perspective, Digital Twin can be understood as an innovative methodology to enhance existing construction processes by utilizing cyber-physical synchronicity [43]. More specifically, a building Digital Twin is a contextual model of an entire building environment, bringing together third-party data and resulting in a dynamic digital replica that can be used to solve a wide variety of issues [48]. This technology offers the ability to simulate and analyze the performance of buildings in real-time, providing valuable insights for decision-making throughout the building life cycle. By harnessing data from sensors, IoT devices, and other sources, Digital Twin enables predictive maintenance [49], carbon emissions evaluation [50], energy optimization [51], and enhanced occupant comfort [52].

Unlike BIM, which focuses on centralizing data and information and is typically used as a single digital shadow [53], a building Digital Twin can provide timely optimization suggestions by mirroring the building's lifecycle and current status [49]. In this context, Digital Twins of constructed assets can present different complexity levels from design to handover, depending on the availability of data and the model's sophistication [54].

One of the key advantages of Digital Twins is their ability to bridge the gap between the physical and digital worlds, allowing stakeholders to visualize and interact with building information in an intuitive manner [55]. This visualization facilitates better understanding and communication among project teams, leading to more informed design choices and operational strategies.

Furthermore, Digital Twins facilitate the implementation of data-driven approaches to building management and optimization. Through continuous monitoring and analysis of building performance metrics, stakeholders can identify opportunities for improvement and implement targeted interventions to enhance sustainability, energy efficiency, and overall performance. Digital twins promote transparency, accountability, and alignment of goals across different project phases by providing a centralized platform for accessing and analyzing building data.

Overall, integrating Digital Twins in the context of building LCSA offers a powerful tool for enhancing sustainability assessment practices. By providing a comprehensive and dynamic representation of building performance, Digital Twins enable stakeholders to make more informed decisions considering environmental, social, and economic factors throughout the building life cycle. However, realizing the full potential of Digital Twins in this context requires further research and development to address technical, organizational, and regulatory challenges and to ensure interoperability and scalability across different building projects and contexts.

1.2.2 Blockchain

In traditional information systems, ranging from small-scale enterprise setups to large-scale cloud-based internet services, data storage typically relies on centralized databases. In this case, a singular central party assumes ownership and maintenance of the data, wielding absolute authority facilitated by management protocols, business arrangements, organizational hierarchies, or legal frameworks [56]. Consequently, users are compelled to default trust in this central party.

In contrast to this traditional model, Distributed Ledger Technology (DLT) represents a transformative frontier. DLT, by its nature, is distributed, implying that data transactions occur across a network of interconnected nodes rather than relying on a central authority. However, traditional information systems often operate within different network structures, including centralized, decentralized, and distributed models, as illustrated in **Figure 1.2**.

While various DLTs exist, the primary focus within the literature often centers on Blockchain. Blockchain technology, comprising a digital ledger and a distributed peer-to-peer network forming a shared database [57], distinguishes itself from conventional information systems through four key characteristics: *decentralization*, which involves the transfer of control from a centralized entity to distributed network; *security*, which is guaranteed through a transaction log saved in several distributed nodes; *auditability*, which happens with the approval of the transaction validity by the majority of nodes; and *smart execution*, since the processes can be executed by smart contracts [58].

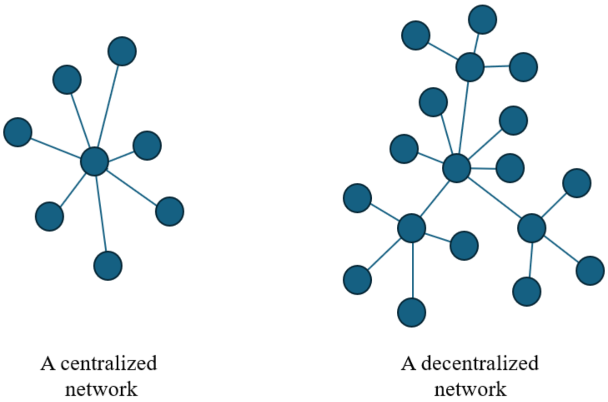


Figure 1.2 - Comparing centralized, decentralized, and distributed networks

As an innovative form of DLT, Blockchain substantially enhances information security and transparency through encryption algorithms [59]. It was first introduced in 2008 by Nakamoto [60] with an initial application in cryptocurrencies such as Bitcoin. Since then, this concept has been widely discussed and used across various sectors, including the construction industry [61]. More specifically, this technology's ability to exchange information quickly and securely at a lower cost has become attractive for researchers and professionals associated with construction [62]. Unfortunately, Blockchain applications outside the finance industry are still experimental [63], which makes integrating LCSA for building projects challenging.

In turn, LCSA evaluation becomes more complex if it is not based on efficient information technology, so Blockchain can serve as a plausible solution to help make the process more effective. Blockchain applications can reduce information uncertainty in an LCSA analysis, decrease the time required for data collection, and ensure perfect traceability of data sources [64]. A Blockchain-based LCSA framework allows instant data traceability and ensures that data integrity is maintained, unlike a traditional LCSA approach [65]. Nevertheless, very few publications use Blockchain to benefit the application of Environmental-LCA, while no article so far has considered the integration of this technology with LCSA.

Likewise, although Blockchain already provides solutions to current problems in building information management, research on this subject continues at a theoretical level. Some authors believe that Blockchain will likely be implemented in generic information technology infrastructures in which construction applications could be developed rather than directly used by construction professionals [66]. Indeed, research shows that these platforms work as a robust backbone system behind the interface layer of applications commonly used by construction professionals [67]. Thus, these professionals would not need to change their work processes significantly or have extensive knowledge about Blockchain. Even so, much still needs to be studied for the Blockchain application to be efficient in constructing sustainable buildings.

Furthermore, some authors already consider BIM and Blockchain technologies as complementary concepts [68], as Blockchain can compensate for the shortcomings of BIM applications, including data reliability in collaborative works. Blockchain can increase the security and transparency of the data generated through digital BIM models, increasing the credibility of construction projects and improving the collaborative work already proposed by BIM. However, this discussion is still in its infancy, and the literature lacks a designer-operable practical framework [69].

Ultimately, one primary application that Blockchain can play a significant role in is ensuring that the sustainability assessment of a building is not tampered with by any of the parties involved in a construction project. This technology, therefore, offers a tamper-proof solution throughout the information supervision of material, production, and inspection processes of a building [70], directly affecting the construction sector.

1.3 STATEMENT OF THE PROBLEM

The current practices surrounding building LCSAs are characterized by their reliance on static and retrospective data, which presents significant limitations. These assessments lack real-time adaptability to accommodate the evolving sustainability needs throughout the project life cycle. Consequently, the accuracy of the results is compromised, impeding the ability to make informed decisions that align with contemporary sustainability imperatives.

Moreover, a comprehensive review of the existing literature reveals several critical gaps and challenges in the field of sustainable construction, which forms the foundation for the focus of this thesis. Despite the increasing emphasis on sustainability within the construction industry, there remains a notable absence of comprehensive frameworks and case studies that comprehensively address all dimensions of sustainability—environmental, social, and economic. Existing research tends to adopt a fragmented approach, often concentrating narrowly on isolated aspects of building systems. This fragmented approach fails to provide a holistic understanding of the intricate interplay between various sustainability factors in building projects.

Furthermore, it is essential to recognize the potential benefit of utilizing BIM-based Digital Twin solutions in addressing the challenges faced by sustainability assessments in the construction industry. BIM is seen by several researchers as the starting point for the implementation of a Digital Twin in the built environment, as a BIM model can be a primary source of data for developing a building Digital Twin [43]. By leveraging BIM technology to develop Digital Twins of building assets, stakeholders can access a comprehensive digital representation of the physical structure throughout its lifecycle. However, despite the potential benefits, the practical implementation of BIM-based Digital Twin solutions in sustainable construction projects remains relatively unexplored, highlighting the need for further research and validation in this area.

It is equally important to recognize the significant role that Blockchain technology can play in enhancing the reliability and transparency of data obtained from building sustainability assessments [71]. Blockchain technology, known for its decentralized and immutable nature, has the capability to synchronize design and document records, thereby increasing the reliability of data throughout the building lifecycle. By providing a secure and auditable platform, Blockchain technology can support transparent processes in building sustainability assessments, ensuring the integrity and accuracy of the data used for decision-making. Thus, integrating Blockchain technology alongside Digital Twin technology presents a holistic approach to improving sustainability assessments in the construction industry.

Nonetheless, while there is widespread acknowledgment of the importance of leveraging technology to enhance sustainability assessments, integrating key technologies such as Blockchain and Digital Twin remains largely unexplored in practical settings. Although theoretical discussions regarding the potential benefits of these integrations are already encountered in the literature, there is a distinct absence of studies that validate their efficacy in real-world construction projects. This gap in the literature impedes progress toward more informed and data-driven decision-making processes in sustainable construction.

Therefore, in order to thoroughly apply the LCSA methodology in building projects, extensions of these integrations for potential benefits to achieving sustainability in the built environment must be profoundly discussed. Research should examine this integration strategically in order to bring the construction sector one step closer to minimizing its negative impacts.

1.4 RESEARCH OBJECTIVES

This thesis aims to explore the potential of enhancing the LCSA of buildings through model-based approaches and data-driven solutions. This objective seeks to fill the existing research gap related to the application of life cycle techniques in buildings that primarily occur in early design stages, thus relying on static and historical data. This practice limits the accuracy of results throughout the project life cycle, as the analysis is constrained by its dependence on fixed, retrospective information, hindering its real-time adaptability to evolving sustainability needs.

Specifically, four specific objectives (SO) are addressed, where there are clear conceptual and technological gaps offering an opportunity to produce original technical material of great interest to the scientific community:

{SO-1} Investigate current trends in Building LCSA and enhance its implementation during the building design phase.

{SO-2} Investigate the role of Digital Twins in enhancing the triple-bottom-line sustainability framework in the built environment.

{SO-3} Examine how Blockchain technology can synchronize design and document records and increase the reliability of data obtained from building sustainability assessments, supporting transparent and auditable processes.

{SO-4} Explore practical ways of combining LCSA, Digital Twin, and Blockchain throughout different phases of the building life cycle to improve decision-making in building projects related to sustainability goals, presenting a conceptual framework and a software application for the integrative platform.

1.5 IMPLICATION OF THE RESEARCH

This research plans to present the key state-of-the-art when it comes to the decision-making process adopted to obtain sustainable construction projects. Aspects covered include the science of enhanced decision-making via the integration of LCSA, BIM-based Digital Twin, and Blockchain in the built environment and how it is implemented in various disciplines such as architecture, engineering, and construction. Overall, the research bridges theoretical insights with practical applications, aiming to advance sustainability efforts in the built environment and contribute to developing smarter and more sustainable buildings.

To this end, this research discusses the environmental, economic, and social aspects of assessing construction projects and proposes an integrated platform that can benefit and facilitate this process. Based on this, the research implications have been divided into two groups: Theoretical Implications and Practical Implications.

1.5.1 THEORETICAL IMPLICATION

This research profoundly discusses the importance of the LCSA application to achieve sustainability in the built environment. Besides, it tests the integration of the LCSA framework with different technologies and concepts in order to facilitate the building sustainability assessment. Therefore, this research will highlight the suitability of these concepts in the built environment, raising application difficulties and possible advantages to be discussed in the literature. It intends to explore practical ways to weigh the various life-cycle impacts of a building, improving the decision-making process of choosing suitable construction materials and methods in the early design project phase and improving the decisions over the following building phases.

1.5.2 PRACTICAL IMPLICATION

The research contributes to the knowledge base for designers, engineers, and architects, offering insights into developing more sustainable building projects. It also provides professionals in the built environment a platform to compare different scenarios, particularly in residential and commercial sectors. This aids in making informed decisions to enhance sustainability. Besides, using Blockchain technology ensures a tamper-proof solution for building sustainability assessment, strengthening the credibility and reliability of the assessment process. By shedding light on the benefits of building assessment tools and aiding in developing sustainable buildings, the research has broader implications for urban sustainability and development.

1.6 THESIS LAYOUT

This thesis is organized into eleven chapters, the first of which is the introduction. Chapter 2 is based on two book chapters related to the LCA and LCSA methodologies, where

I was the first author, serving as the background for this research. Chapters 3 to 10 are structured as articles, each focusing on specific aspects of the research topic. This format allows for a more in-depth exploration of key concepts and research methods, ensuring each chapter's independence while contributing to the overarching theme. Finally, chapter 11 refers to the thesis conclusion, summarizing the thesis and discussing the implications of the findings and future research.

Given the article form adopted for chapters 3 to 10, it is likely that certain key concepts will be repeated throughout the thesis. The repetition of such concepts is justified to guarantee each chapter’s independence from the rest of the thesis. Because of the article form adopted, the research methods used are discussed in more detail in each chapter. This approach allows for a comprehensive understanding of the methodology used in each specific context, providing readers with insights into the research process and the rationale behind the chosen methods.

Chapter 2 presents an overview of the LCA application in the construction industry, extrapolating the concepts to build a comprehensive discussion with the reader on how to apply the LCSA methodology, thus considering the three pillars of sustainability. The idea of this chapter is to present the theoretical aspects of this methodology, in addition to the challenges and opportunities related to the practical application of LCSA.

Chapter 3, published as an article in Building and Environment, discusses the LCSA application during the early design stages of a building project. After identifying critical factors and challenges related to this application, this chapter presents a decision-making framework for sustainable material choice integrating LCSA, BIM, and the Fuzzy Analytic Hierarchy Process (Fuzzy-AHP) technique. The proposed framework is validated using a case study of a residential building, where LCSA is applied across construction, operation, and end-of-life phases.

Chapter 4, published as an article in Energy Reports, introduces a mathematical programming framework aimed at optimizing various building design objectives to enhance energy efficiency. The chapter emphasizes the significant role of building material and component size in energy consumption during the operational phase, which will be important in the following chapters to develop a software proposal for other building life cycle phases. The framework's validity is demonstrated through two realistic case studies, where the proposed mathematical programming method is applied.

Chapter 5, published as a Conference Paper in the Lecture Notes in Operations Research book series, examines the utilization of BIM-based Digital Twins. The concept of BIM-based Digital Twins is introduced as a promising solution to overcome sustainability challenges in the construction and real estate sectors. The chapter presents a structured literature review to delineate recent developments in BIM-based Digital Twin applications for the real estate and construction sectors, particularly in the context of sustainability goals. Based on this review, a discussion on how the accumulated knowledge can be disseminated and implemented within the built environment is presented.

Chapter 6, presented as a Conference Paper, explores the integration of LCSA and BIM-based Digital Twin technology to improve decision-making in building projects towards a smart and sustainable future. The chapter proposes integrating LCSA and BIM-based Digital Twin from the early design stages of building projects to the end-of-life phase. In this proposal, the building Digital Twin enhances real-time data visualization and develops self-learning building capabilities, facilitating simulations and data collection required for detailed sustainability assessments. A conceptual framework is proposed, outlining steps to integrate these concepts throughout the building lifecycle to improve design, fabrication, construction, operation, and deconstruction processes.

Chapter 7, published as an article in the Journal of Cleaner Production, presents a comprehensive literature review on Blockchain for sustainability, aiming to extend key applications discussed in various fields to the construction industry and real estate. A key contribution of this review paper is the in-depth discussion of the next steps in Blockchain research necessary to integrate its applications for achieving a sustainable construction environment. Particularly, the chapter proposes a conceptual framework showcasing the integration of Blockchain with other applications, such as BIM and LCSA, to facilitate the goal of achieving sustainable buildings.

Chapter 8, published as a Book Chapter in Cognitive Digital Twins for Smart Lifecycle Management of Built Environment and Infrastructure by CRC Press, examines the potential of integrating Digital Twin and Blockchain technology to improve sustainability in the built environment, focusing on prefabricated modular construction. A framework is discussed, leveraging BIM as a primary data source to develop a building Digital Twin.

Chapter 9 is an original research article submitted for publication. It contains novel findings and insights that have not yet been published. The chapter addresses the limitations of current LCSA methodologies, which often lack real-time information and are static in nature, primarily focused on early design stages. Drawing from the results of a systematic literature review, the chapter proposes a comprehensive framework demonstrating how the integration of LCSA with Digital Twin and Blockchain technologies can enhance building sustainability. A platform utilizing Smart Contracts is introduced to facilitate this integration. Additionally, a case study is conducted to validate the framework's applicability and demonstrate its benefits in achieving sustainable outcomes in the built environment.

Chapter 10 is another original research article submitted for publication. It also contains novel findings and insights that have not yet been published. Developed using the Design Science Research methodology, the chapter presents a machine-learning-based software application designed to facilitate dynamic sustainability assessments by leveraging real-time data from IoT sensors. A real-world case study is conducted to compare static and dynamic LCSA outcomes, demonstrating the efficacy of the software. The comparative analysis reveals significant disparities in impact assessments, highlighting the transformative potential of integrating real-time data into LCSA frameworks.

Finally, **Chapter 11** encloses all studies with an overall conclusion addressing a combined discussion of specific results, highlighting the main specific findings of all works. Then, **Appendix A** presents a summary of all products derived from this research – including published scientific articles, conference papers, book chapters, and a book publication. **Appendices B-V** unveil front pages and complete bibliographic data of all publications.

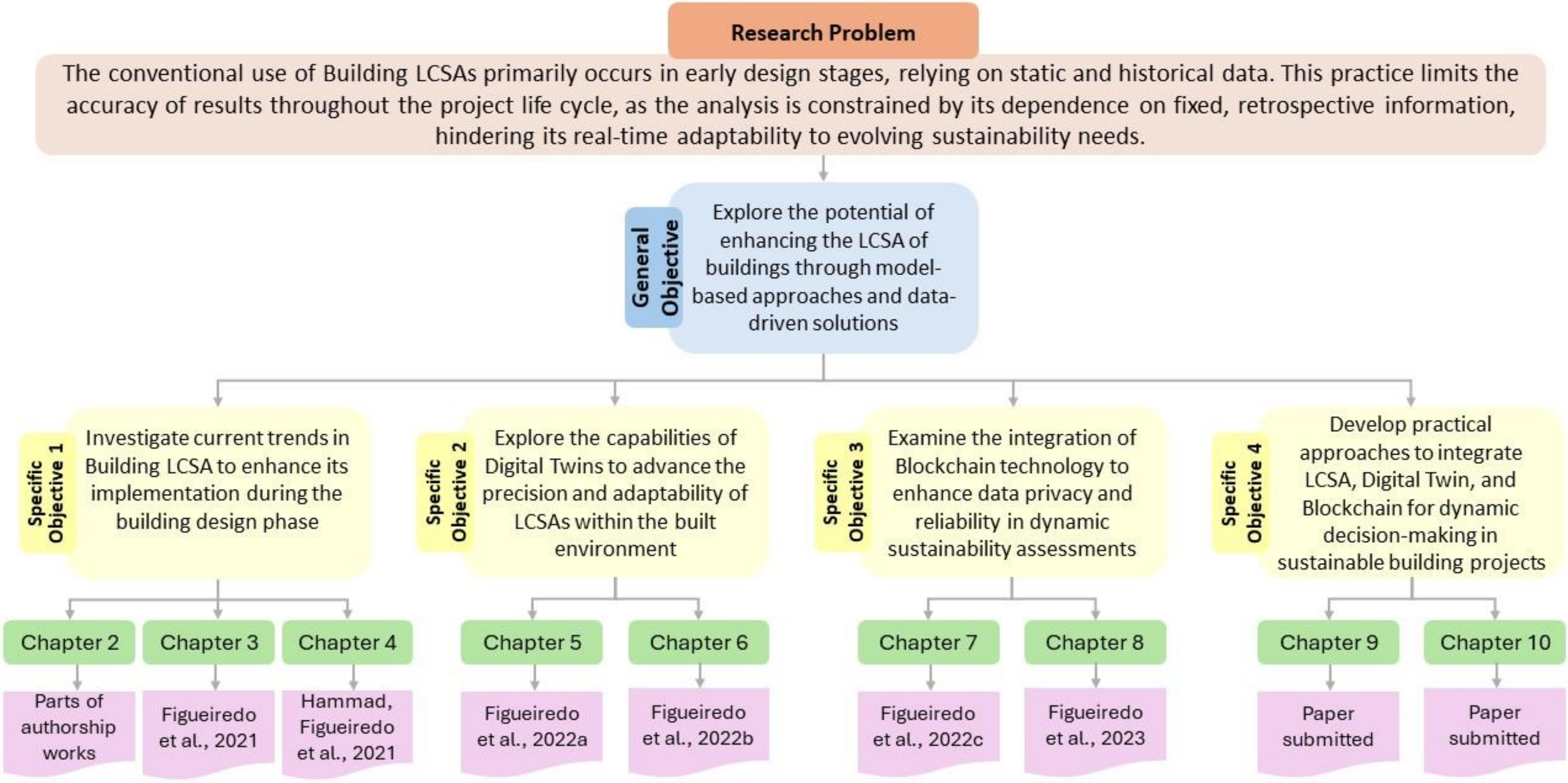
1.6.1 Progressive Integration: Correlating Chapters with Thesis Objectives

Throughout the thesis, a systematic exploration of sustainability assessments within the life cycle of construction projects is presented, aligning closely with the Specific Objectives (SO) outlined for this research. Overall, in the initial chapters, the focus is primarily on sustainability assessments during the design stage. More specifically, Chapters 2, 3, and 4 shed light on the challenges encountered in traditional sustainability assessments and explored potential solutions related to SO-1.

Subsequently, Chapters 5 and 6 present an in-depth examination of the potential of Digital Twin technology, illuminating pathways to enhance real-time data visualization and decision-making mechanisms, encompassing SO-2. The narrative evolves as Chapter 7 meticulously evaluates the practical utility of Blockchain technology within the construction domain, providing a paradigm shift towards robust data security and integrity, thus addressing SO-3.

Building upon this foundation, Chapter 8 initially discusses integrating Digital Twin and Blockchain at a theoretical level, recognizing potential limitations in full integration during the research phase. Therefore, the integration attempts in this thesis are first carried out partially, gradually evolving to integrate all three methodologies, thus enhancing transparency and auditability in sustainability assessments. Finally, Chapters 9 and 10 propose the whole integration of LCSA, Digital Twin, and Blockchain technologies, offering practical avenues to improve decision-making processes in building projects related to sustainability goals, ultimately culminating in rigorous empirical validation and meticulously addressing SO-4.

Therefore, the progression of chapters in the thesis reflects a coherent journey from identifying challenges in sustainability assessments to proposing innovative solutions and validating them through empirical research. The outline of the thesis structure is illustrated in **Figure 1.3**, providing a visual representation of the logical flow of the study.



The conventional use of Building LCSAs primarily occurs in early design stages, relying on static and historical data. This practice limits the accuracy of results throughout the project life cycle, as the analysis is constrained by its dependence on fixed, retrospective information, hindering its real-time adaptability to evolving sustainability needs.

Explore the potential of enhancing the LCSA of buildings through model-based approaches and data-driven solutions

Investigate current trends in Building LCSA to enhance its implementation during the building design phase

Explore the capabilities of Digital Twins to advance the precision and adaptability of LCSAs within the built environment

Examine the integration of Blockchain technology to enhance data privacy and reliability in dynamic sustainability assessments

Develop practical approaches to integrate LCSA, Digital Twin, and Blockchain for dynamic decision-making in sustainable building projects

Figure 1.3 - Outline of Thesis Structure

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2 BACKGROUND: LIFE CYCLE ASSESSMENT AND LIFE CYCLE SUSTAINABILITY ASSESSMENT METHODOLOGIES

The first part of this chapter is based on the following book chapter related to the LCA methodology.

FIGUEIREDO, Karoline and HADDAD, Assed. Life Cycle Assessment for Structural and Non-structural Concrete. In: **Recycled Concrete: Technologies and Performance.** Woodhead Publishing Series in Civil and Structural Engineering, 2022. p. 309-335. Paperback ISBN: 9780323852104.

Additional content is included, based on the following book chapter, to extrapolate the discussion to the LCSA methodology.

FIGUEIREDO, Karoline, HAMMAD, Ahmed and HADDAD, Assed. Chapter 12 - Life cycle sustainability assessment applied in the Built Environment. In: **Materials Selection for Sustainability in the Built Environment: Environmental, Social and Economic Aspects.** Elsevier, 2024. Paperback ISBN: 9780323951227.

2.1 INTRODUCTION: LIFE CYCLE ASSESSMENT METHODOLOGY

According to the standard ISO 14040, the Environmental Life Cycle Assessment (E-LCA) methodology, usually referred to just as Life Cycle Assessment (LCA), is the compilation of inputs, outputs, and potential environmental impacts of a product system throughout its life cycle [1]. This methodology is widely applied in the construction industry to assess the environmental impacts of construction materials [2] and is very useful for improving the decision-making process about concrete and its aggregates [3].

A four-phase framework represents the LCA, namely: (i) Goal and Scope definition; (ii) Life Cycle Inventory (LCI); (iii) Life Cycle Impact Assessment (LCIA); and (iv) Interpretation. Briefly, it can be said that the first phase involves defining the goal and the scope by determining different aspects of the study, such as the functional unit, the system boundary, and the assumptions and limitations to be considered [4]. In turn, the LCI phase represents the compilation and quantification of inputs and outputs for the chosen functional unit regarding the chosen system boundary [5], and the LCIA phase consists of evaluating the magnitude and significance of the potential environmental impacts [6]. Lastly, the interpretation phase comprises identifying and assessing all the information from the previous stages so that the results can be communicated to interested parties and used to aid decision-making [7]. Each of these phases will be further detailed and explained in the following sub-sections.

Although the LCA methodology is already standardized and widely discussed in several industries, it is clear that its application in the construction sector still needs further advances. For example, a recent landmark study conducted by the International Institute for Sustainable Development (IISD) has shown that LCA is the best approach to measuring the carbon emissions of construction products at each stage of their life cycle [8]. However, the report also discusses the need for more data, transparency, and robust LCA standards for the built environment. Therefore, this chapter intends to help professionals linked to the construction industry use this powerful tool and fully understand the concepts and opportunities generated by the LCA application.

The application of LCA is interesting for several target audiences. The environmental analyses are critical for policymakers to adopt conscious public policies and for ecological standards developers to create realistic standards for sustainable buildings. Besides, these analyses are also very useful for builders, civil engineers, and architects. With a reliable database and representative results of their regions and projects, professionals can minimize the environmental impacts of their constructions more easily. Furthermore, with the dissemination of this information and the growing awareness of the global population about the importance of sustainable development, end users are increasingly interested in obtaining green buildings and can benefit from LCA studies.

It is important to stress that the LCA is not a decision-maker per se but rather a tool to provide useful information to interested parties using a standardized and transparent approach [9]. For the LCA to be a handy tool to minimize the environmental impacts of construction projects, it is essential that the professional knows how to correctly choose which approach to use according to the objective of the study, what level of detail is required in each case, what software and databases to use and what functional unit and system boundaries should be more representative. Therefore, these concepts will be deepened in the following sub-sections so that the reader can use them as a reference for future studies.

2.2 LCA PHASES AND RELATED CONCEPTS

The LCA methodology has its structure standardized by the ISO 14040 series. Until 2006, this series consisted of the following standards: ISO 14040, which dealt with general principles and guidelines; ISO 14041, aimed at the phases of defining the objective and scope and analyzing the life cycle inventory; ISO 14042, regarding the life cycle impact assessment phase; and ISO 14043, focused on life cycle interpretation. As of 2006, the technical standards were compressed into only two standards currently responsible for guiding LCA practitioners worldwide: ISO 14040 and ISO 14044. The first deals with the principles and structure of LCA [1], while the second addresses its requirements and guidelines [10].

There are also international technical reports and a technical specification published by ISO, which can be used in conjunction with the ISO 14040 series to guide LCA applications: ISO/TR 14047 [11], ISO/TS 14048 [12], and ISO/TR 14049 [13]. The two technical reports aim to provide examples to illustrate the current practice of life cycle inventory analysis (LCI) and life cycle impact assessment (LCIA) according to ISO 14044. In turn, the technical specification ISO/TS 14048 provides the requirements and a structure for a data documentation format to be used in LCA studies.

This section will be divided into four main parts related to the four phases of the LCA framework and will be based on these ISO standards and reports. The order of the concepts to be explained was chosen to build a comprehensive discussion with the reader, from the theoretical aspects to a practical application of LCA for structural and non-structural concretes, but it can be used for any construction material or construction system.

2.2.1 Goal and Scope

The first phase of LCA corresponds to the goal and scope definition. The aspects defined at this point depend on the subject and the intended use of the LCA study. It can be said that the objective of applying the LCA is linked to one of two main aspects: the practitioner hopes to identify opportunities to improve the environmental performance of a given product, or it is expected to make an environmental comparison between different products that fulfill equivalent functions. In both cases, LCA has proven to be a valuable tool to benefit the decision-making process about products and services.

Regarding concrete analysis, the goal of each study can vary enormously: it can be choosing the best concrete mixture proportions for a specific purpose, defining the carbon footprint for concrete structures during a given stage of a building life cycle, or defining how the concrete production process could be improved to reduce a specific impact category, among several other possibilities. According to the ISO 14040 standard, the study's goal is to communicate the intended LCA application and the target audience [1]. This is essential for the LCA to help the future decision-making process, as knowing the intended audience ensures that the professional will choose the most coherent impact categories. With the objective well defined, it is necessary to determine the scope of the analysis.

For the scope definition, the ISO 14040 standard suggests that some crucial aspects be determined for the complete study realization. First, the practitioner must define the product system to be evaluated with its respective functions. The product system corresponds to the product and its upstream and downstream processes, including components manufacturing, distribution, product use, and final disposal. Besides, it is essential to consider all transportation and energy used during the process because this information has to be part of the product system. **Figure 2.1** presents an example of the processes that could be considered during a concrete LCA analysis.

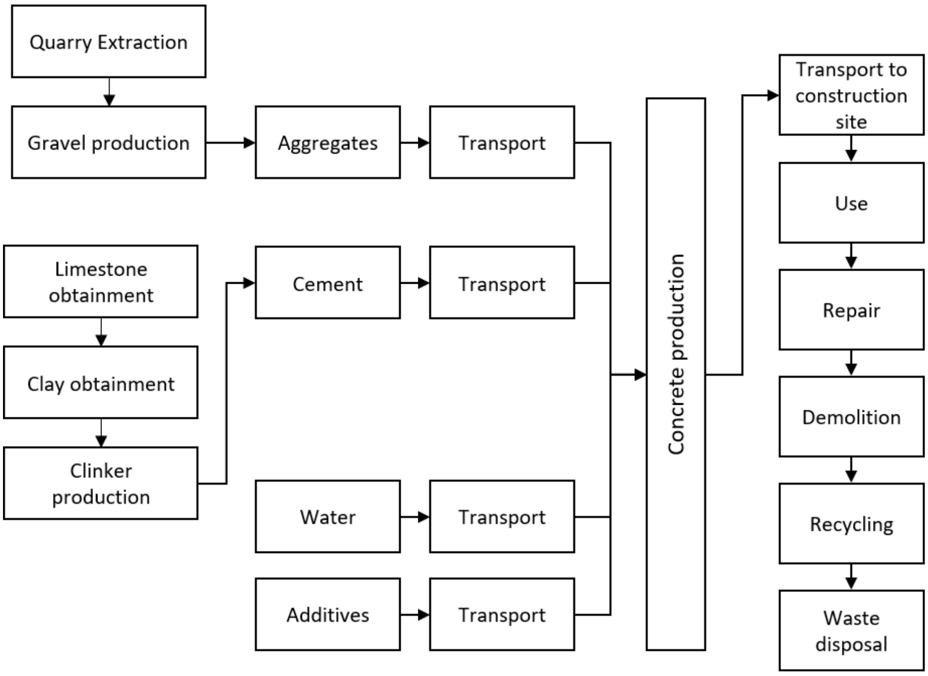

Figure 2.1 - Processes associated with the concrete life cycle

The practitioner must define the level of detail required to determine the processes that constitute the product's life cycle to be analyzed. There is no correct answer to this definition;

the more detailed the processes, the more realistic the analysis, but the more labor-intensive the data collection and evaluation. The level of detail chosen and the assumptions adopted must be clearly communicated so that this does not interfere with interpreting the results at the end of the study.

Another example of a product system is shown in **Figure 2.2**. In this second example, the processes necessary for the construction of a reinforced concrete building are considered. Therefore, the processes that involve not only the production of concrete but also steel and wood formwork are exposed. Note that recycling processes were not considered in this case. The formwork could be reused for other constructions, and after the building's demolition, the concrete could be used as recycled aggregates. This level of detail is at the discretion of the LCA practitioner, who must make all decisions in an informed manner.

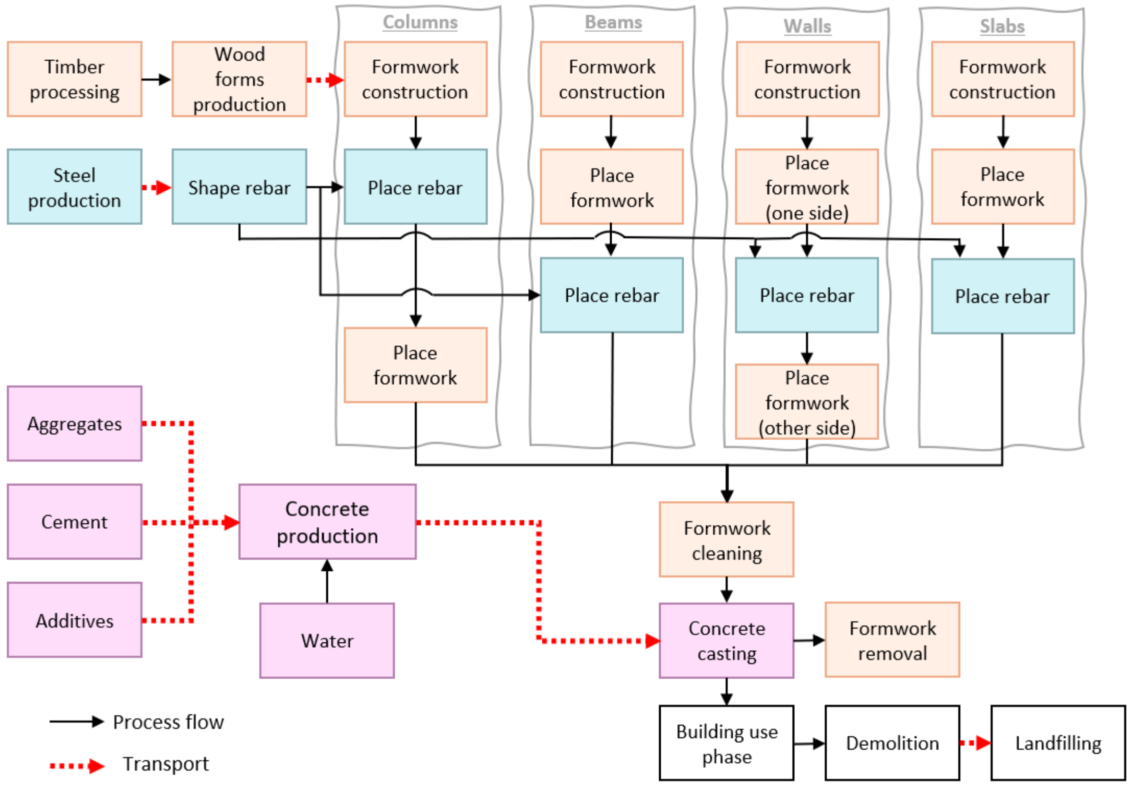

Figure 2.2 - Processes associated with the construction of a building using reinforced concrete

A final example regarding the concrete recycling process is given. In this case, the professional considers that after the building is demolished, there will be an on-site sorting of the construction and demolition (C&D) waste, with subsequent processing of the recycled concrete. Considering that recycling or reusing all the waste generated will not be possible, several materials will be transported to landfills. This product system is represented in **Figure 2.3**.

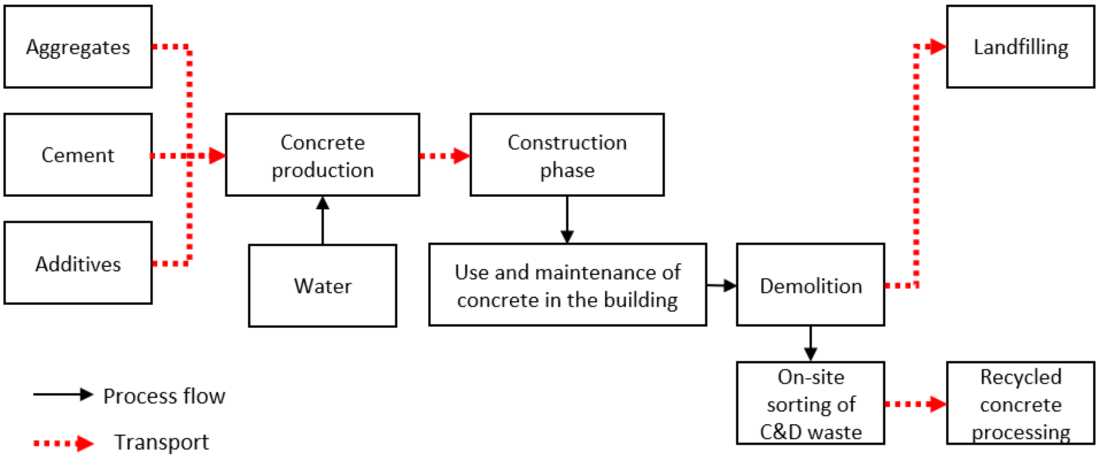

Figure 2.3 - Life cycle of concrete, considering the recycling stage

Then, the functional unit and the reference flows have to be determined. The functional unit refers to a quantified product description that serves as the reference basis, while the system boundary determines which elementary processes should be included in the study. Regarding the concrete analysis, the functional unit could be one cubic meter ($1m^3$) of concrete with a given compressive strength, for example. In this case, the environmental impacts will be calculated concerning this volume of concrete with this specification. Instead, the practitioner could decide to use one square meter ($1m^2$) of construction or one kilometer (1km) of bridge as the functional unit. This decision must make sense for the study and be consistent with the objectives already defined.

On the other hand, the reference flow represents the amount of product necessary to fulfill the established function. For example, if the professionals choose one square meter of ready-mixed concrete as the functional unit, they can analyze different reference flows that fulfill the same function: different ready-mixed concrete elements and products to make one square meter of concrete.

From these first definitions, it remains for the practitioner to determine the system boundary in the study. It means determining which unit processes from the product system shall be included in the analysis. Ideally, all processes should be included. Nevertheless, this decision is often neither possible nor practical due to data and cost constraints. Again, this decision must be made consciously and communicated to all interested parties. The system boundary definition needs to be done to answer the questions that interest the target audience completely.

A possible example of a system boundary would be considering only the processes associated with concrete production without going through the construction, use, and end-of-life phases. This system boundary type is called cradle-to-gate because the assessment is based on a partial product life cycle from resource extraction (cradle) to the factory gate (i.e., before being transported to the construction site). It is represented in **Figure 2.4**. When the analysis contemplates the entire life cycle, from resource extraction to the end-of-life phase, it is said that the system boundary is cradle-to-grave. It is represented in **Figure 2.5**.

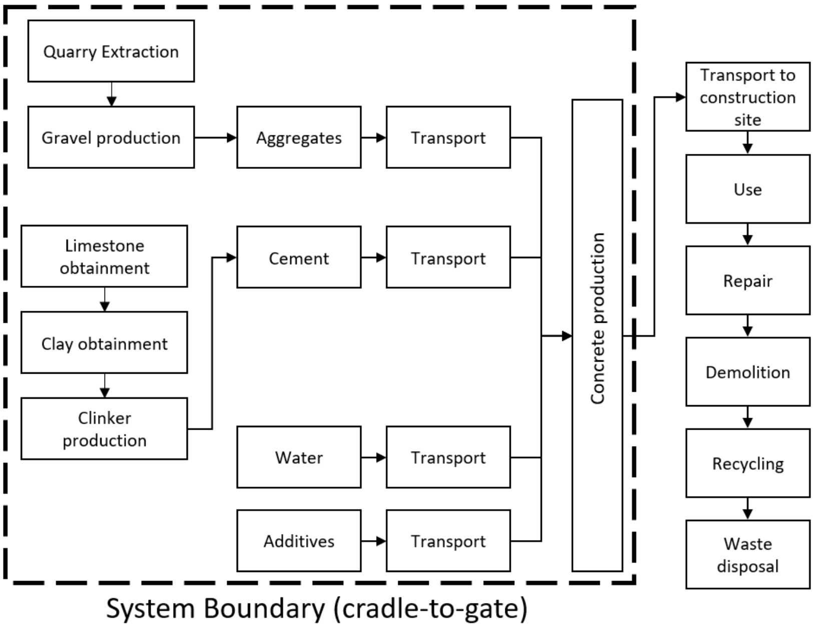

Figure 2.4 - Example of a cradle-to-gate system boundary for a concrete LCA

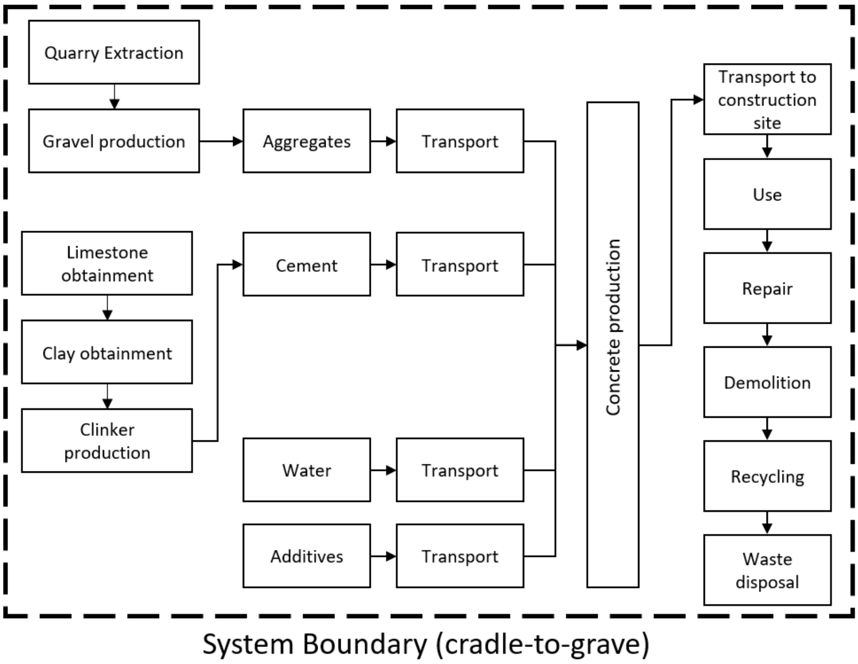

Figure 2.5 - Example of a cradle-to-grave system boundary for a concrete LCA

A cradle-to-gate approach is usually considered in most of the cement and concrete LCAs in the literature, including only the main processes related to producing these materials in the system boundary. For example, regarding cement production, many studies consider the following processes: extraction of raw materials, raw material preparation, pyroprocessing, clinker cooling, finish milling, packaging handling, and transportation [14].

It is noteworthy that it is up to the practitioner to define which parts of the system will be left out, and often, this decision is made based on quantitative cut-off criteria. It means that processes whose cumulative contribution in terms of total mass or energy is less than some certain percentage defined by the practitioner must be excluded from the system. However, this method can lead to distortion of LCA results, impairing the interpretation of the study. Even though the environmental impacts concerning the studied functional unit can be considered negligible, the impacts generated by these neglected processes can represent a large number when global production volumes are considered. To avoid this, it is recommended to consider each process's environmental relevance and conduct sensitivity analyses to increase the study's reliability.

While defining the scope, the practitioner may perceive that some allocation method will be needed. This is because some processes are responsible for producing more than one product; in this case, it may be necessary to divide the environmental impacts of this process among its products. Therefore, allocation in LCA refers to partitioning the input or output flows between the product system under study and other product systems. The ISO 14044 standard establishes some general considerations and procedures regarding allocation. For example, allocation procedures for reuse and recycling should consider some physical property (i.e., mass), economic value, or the number of subsequent uses of the recycled material as a basis for the allocation [10].

Although it is preferable to avoid the use of impact allocation, it is sometimes impossible or not realistic to decide not to use it, as is the case of utilizing by-products as aggregates to improve the concrete's characteristics and make it more suitable for a specific use. In this particular case, the practitioner needs to analyze whether or not it would be more appropriate to allocate a part of the environmental impacts of these products to concrete production [15]. In order to define an adequate allocation procedure, it is crucial to be able to clearly distinguish which are the primary production processes, responsible for producing the main product and the by-products, and the secondary processes, which aim to treat the by-product to become suitable for its use as a concrete component [16].

Finally, the practitioner must report all limitations and assumptions to be adopted in the study so that the scope of the LCA is unambiguous and well-defined. The ISO 14040 standard also suggests that the impact assessment and interpretation methods should be defined at this phase, as well as the impact categories to be used. Then, with the objective and scope determined, it proceeds to the inventory phase.

2.2.2 Life Cycle Inventory (LCI)

The second phase of LCA corresponds to data collection and calculation procedures to quantify a product system's relevant inputs and outputs. This process is considered iterative because as data is collected, knowledge about the system increases, and changes may occur. These changes may be linked to new requirements or limitations of the study or even changes in data collection procedures so that the study objectives can still be met.

The inventory can be considered as the basis of LCA. All essential data related to the production chain are quantified at this phase so that analyses can occur in the following phases. Consequently, it is considered that most of the limitations found in LCA studies arise at this stage of data collection. Often, the practitioner is faced with the unavailability of specific and reliable sources of information to carry out the study. This is because it is not always possible to conduct the entire study using only primary data obtained from direct measurements. It may also be necessary to use secondary data.

Different data types can be used to build the life cycle inventory, such as on-site data, data obtained from the literature, international databases, or data provided by third parties, such as companies, government agencies, trade associations, and analysis laboratories. Data quality requirements are determined by the geographical, temporal, and technological coverage adopted for the study. The ISO 14044 standard states that, in practice, all data used in the study may include a mixture of measured, calculated, or estimated data [10]. For example, in a publication on applying LCA to compare the impacts of recycled and ordinary concretes, the authors found that some company-specific processes resemble those modeled by an international database, but raw data information is more detailed [17]. Therefore, in this study, all essential data relating to materials and processes were obtained directly by the company, but the professionals used background environmental data from the international database.

2.2.2.1 Databases available

There are more than 40 national and international databases currently available. These databases vary in terms of the amount of data and territorial coverage. Some of the most important ones are highlighted in **Figure 2.6**.

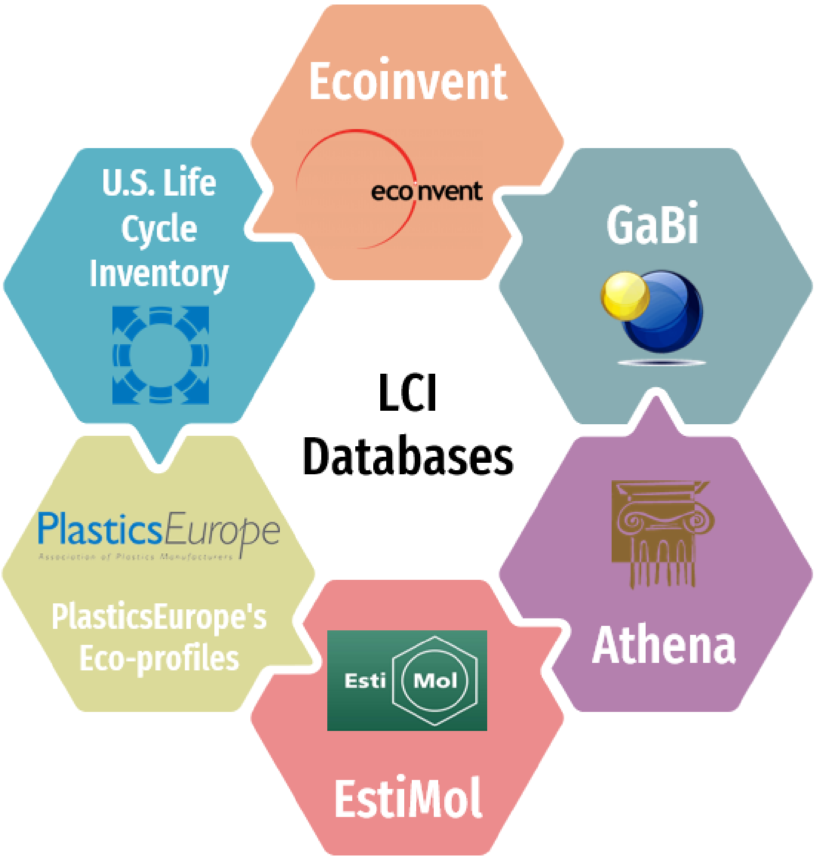

Figure 2.6 - LCI databases available

Unfortunately, not all available databases have information on building materials [18]. Among the most used databases to support life cycle analysis in the construction sector, Ecoinvent, GaBi, Athena, and the U.S. Life Cycle Inventory Database can be mentioned. These four databases provide information on concrete and cement but with different degrees of detail and coverage. The advantage of the Ecoinvent and GaBi databases is that they are representative of various countries. The Ecoinvent database is one of the most comprehensive international LCI databases, with 18,000 LCI datasets in many areas, such as energy supply, agriculture, transport, construction materials, wood, and waste treatment [19]. Users can consult the data online, download the data directly, or use the database in an LCA-based software. In turn, GaBi Databases offer over 15,000 datasets based on primary data collection worldwide in different areas, such as agriculture, building and construction, chemicals, and energy [20]. Also, GaBi presents regionalized water and land use data that can be used with the practitioner's regionalized data.

On the other hand, the Athena and U.S. Life Cycle Inventory databases present data from specific countries. Regarding the Athena database, the information offered to the users includes data for construction materials, energy, transport, construction and demolition processes, maintenance, repair, and waste disposal [18]. However, the information is specifically about the manufacturing process in Canada and the United States. Finally, the U.S. Life Cycle Inventory database considers materials' input and output flow about the United States. This database focuses on metals, wood materials, and plastics but also presents information about cement and concrete product manufacturing [21].

2.2.2.2 LCA-based software tools

Data research can be time-consuming, and, therefore, many professionals resort to some software based on the LCA methodology. Some companies offer a combination of an LCI database and a tool for assessing environmental impacts. As an example, we have GaBi Solutions, offering a powerful LCA engine and an international LCI database. Other companies provide computational tools based on the LCA framework that accept the insertion of different LCI databases. Thanks to agreements between the providers of these software tools and the institutions that make different LCI databases, different LCA-based programs can act as resellers for these databases. **Figure 2.7** shows the most used LCA-based software tools worldwide.

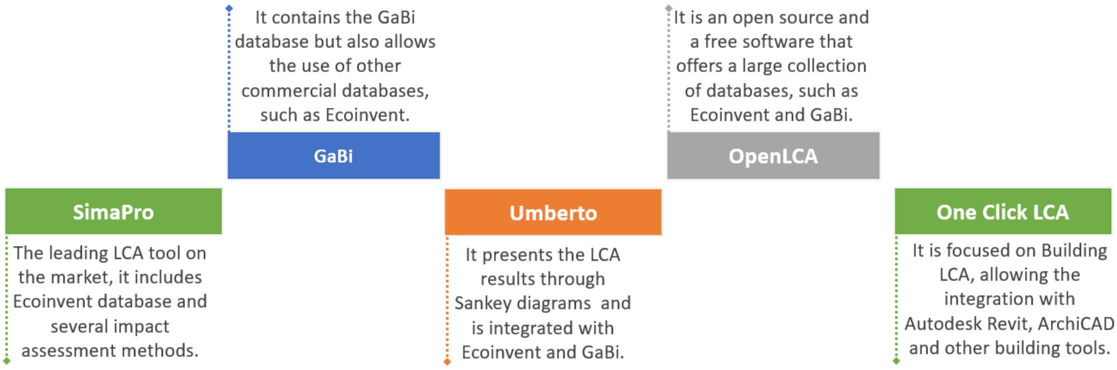

Figure 2.7 - Examples of LCA software tools

Studies show that sometimes differences are identified in the LCA results, depending on which software and database are used [22]. This issue must be increasingly debated among software developers and all LCA professionals. This concern proves the importance of careful analysis and interpretation by LCA practitioners during the whole process.

2.2.3 Life Cycle Impact Assessment (LCIA)

In the LCIA phase, the elementary flows and all data collected in the inventory phase are converted into environmental impacts. It is from the LCIA results that it will be possible to conduct the interpretation of the study. Therefore, the ISO 14040 and ISO 14044 standards suggest some steps to be followed so that the impact assessment can take place reliably: selection, classification, characterization, normalization, grouping, and weighting. These standards also determine that three of these steps are mandatory (i.e., selection, classification, and characterization), while the remaining three are optional. These steps are represented in **Figure 2.8**.

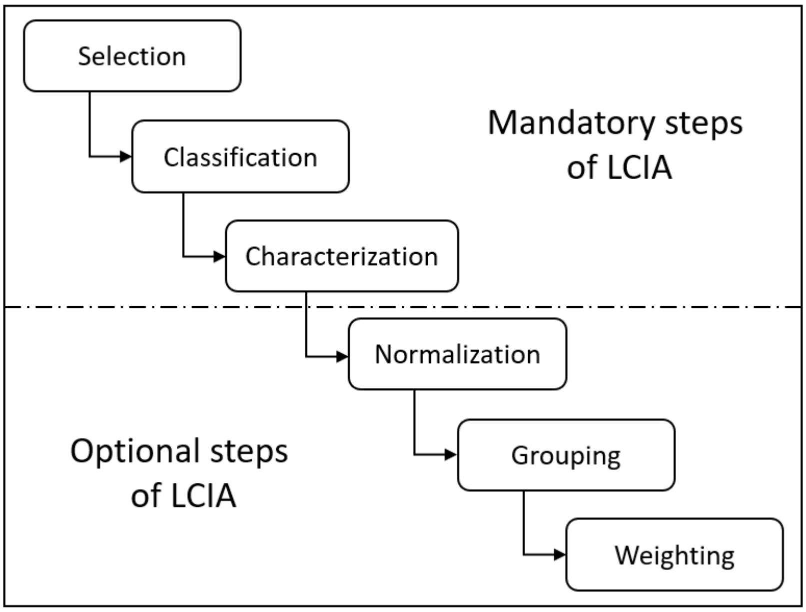

Figure 2.8 - Steps of the LCIA phase

Regarding the mandatory parts of an LCIA, the first step is to select impact categories, indicators, and characterization models. This decision has to be made following the goal defined at the beginning of the study. For most LCA studies for concrete, the practitioners choose impact categories widely discussed in the literature, as is the case of recent studies that considered global warming potential, acidification potential, and ozone depletion potential [23,24]. However, this decision is up to the practitioner and must satisfy the objective and scope defined for the LCA. If this is not possible through existing impact categories, new categories are defined, making it necessary to create new characterization models for those indicators.

The second mandatory step is classification, which corresponds to assigning LCI results to the selected impact categories. Finally, the third mandatory step refers to the characterization, which calculates the category indicator results by multiplying the amount found in LCI with a characterization factor. The result of this calculation is a numerical result that represents the indicator [10]. For this, the practitioner uses categorization models based on a specific impact assessment method.

The main difference between the existing impact assessment methods is related to which stage of the cause-effect chain will be examined to calculate the impact. In this way, methods are classified into midpoint or endpoint. A midpoint method analyzes the impacts that occur earlier along the cause-effect chain. On the other hand, an endpoint method analyzes the environmental impact at the end of this chain, focusing more on the damages that occur with the production of the analyzed product. Therefore, it can be said that midpoint methods quantify problem-oriented impacts, while endpoint methods quantify damage-oriented impacts associated with the analyzed process.

For example, regarding concrete analysis, the professional could use a midpoint method, choosing impact categories such as ozone depletion, water scarcity, and climate change. On the other hand, if it makes more sense to use an endpoint method according to the study's objective and the target audience, the professional can consider impact categories related to human health, ecosystem health, or resource availability. It is noteworthy that the calculation of endpoint impact categories is usually associated with greater uncertainties when compared to midpoint indicators [25]. In addition, the practitioner may decide to assess midpoint and endpoint impacts in the same study as long as this makes sense for the analysis.

Several LCIA methods are available, each corresponding to a set of impact categories. These methods can contain a midpoint approach, an endpoint approach, or both. The practitioner must choose the method that best suits their needs for each new LCA study. For some widely used impact categories, many LCIA methods use the same units. For example, all midpoint methods consider CO_2-equivalents (CO_2eq) as the unit for global warming potential, representing the number of metric tons of CO_2 emissions with the same global warming potential as one metric ton of another greenhouse gas. However, using standardized units is not valid for all existing impact categories. It is crucial, thus, to deeply understand how the chosen method performs its characterization calculations and what each unit means. Some of the most used LCIA methods around the world are shown in **Figure 2.9**.

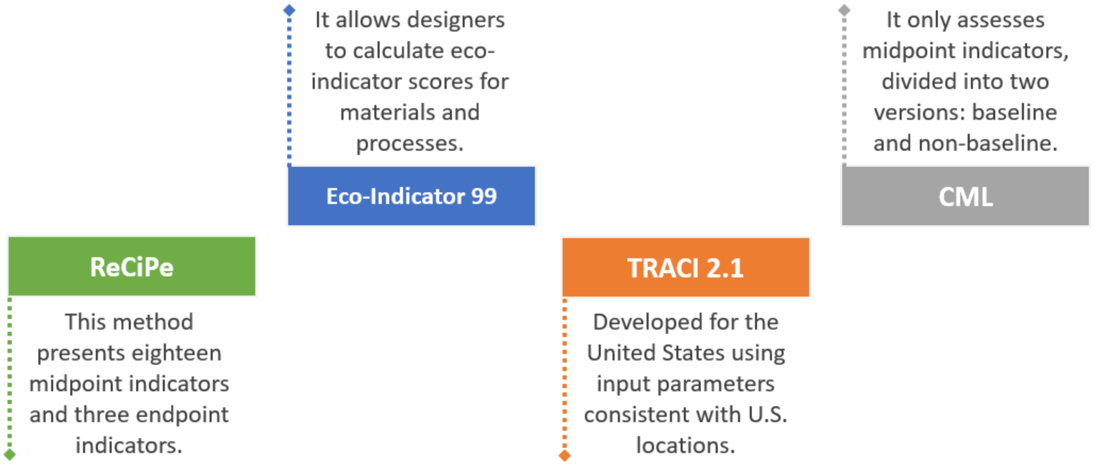

Figure 2.9 - Different LCIA methods used worldwide

Another important point about choosing which characterization method to use is that this choice is directly linked to the study's uncertainties. Commonly, a professional chooses one method indiscriminately, without comparing results from different methods. Besides, this choice is generally left to the user's discretion in LCA software. Thus, inappropriate methods for a specific situation can be chosen, directly influencing the analysis and interpretation of data. An example would be using an LCIA method with inappropriate global warming time intervals in a study with a specific time scope [26]. The practitioner must make these decisions consciously, always considering the objective and scope outlined at the beginning of the analysis.

After characterizing the impacts, the professional can choose to follow the optional LCIA steps: normalization, grouping, and weighting. The normalization step is beneficial in LCA studies because the results found for the indicators are often reported in different metrics, making the interpretation phase more difficult. In this way, the normalization process helps the analysis by presenting the relative magnitudes of the impact indicators, all on the same scale. Different approaches can be used in this step, and they are divided into internal and external normalization approaches [27]. Internal normalization brings non-commensurate impact indicator scores into a standard metric, while the external one uses an external reference system and generally at a larger scale.

With the normalized results, the practitioner can still decide to follow the other two optional steps. The grouping step refers to assembling impact categories into one or more groups. The impact categories analyzed can, for example, be grouped according to a given hierarchy that makes sense for the target audience of that study. Finally, the LCA practitioner may decide to weigh the results. The weighting step corresponds to applying weighting factors that represent the importance assigned to each impact category. With that, the LCIA phase ends.

2.2.4 Interpretation

Interpretation is the last phase of LCA, where the questions posed in the goal definition are answered. The results obtained throughout the study cannot be interpreted anyhow; the life cycle interpretation is a systematic technique to identify, quantify, check, and evaluate information from LCI and LCIA phases [1]. As a result of this phase, the practitioner can determine the confidence level in the study's results and accurately communicate them [28].

To start the interpretation process, the practitioner must keep in mind that it is essential to understand the accuracy of the results, ensuring they meet the LCA's goal. For this, the professional has to evaluate the sensitivity of the data used, assess the study's completeness and consistency, and draw conclusions and recommendations [29]. The vast importance of this phase is related to the possibility of transforming the LCI and LCIA results into comparable and comprehensible ones [30].

A fundamental topic to emphasize is that although the interpretation corresponds to the last phase of the LCA, this phase can accompany all the previous ones. The professional can start to perform the life-cycle interpretation from the goal and scope definition phase. An example is when the definition of the functional unit and the system boundary is not intuitive. In this situation, the practitioner must check and evaluate the proposals before continuing LCA. Another recurrent situation is analyzing the quality of data collected at the end of the LCI phase before continuing the study. This would also be another example of when the interpretation phase occurs concurrently with the other study phases.

For this reason, the ISO 14040 standard presents a conceptual framework of LCA in which the interpretation phase is directly linked to the other three phases of the methodology. Based on the image found in ISO 14040 standard, **Figure 2.10** is presented to facilitate the reader's understanding and condense all the knowledge discussed so far.

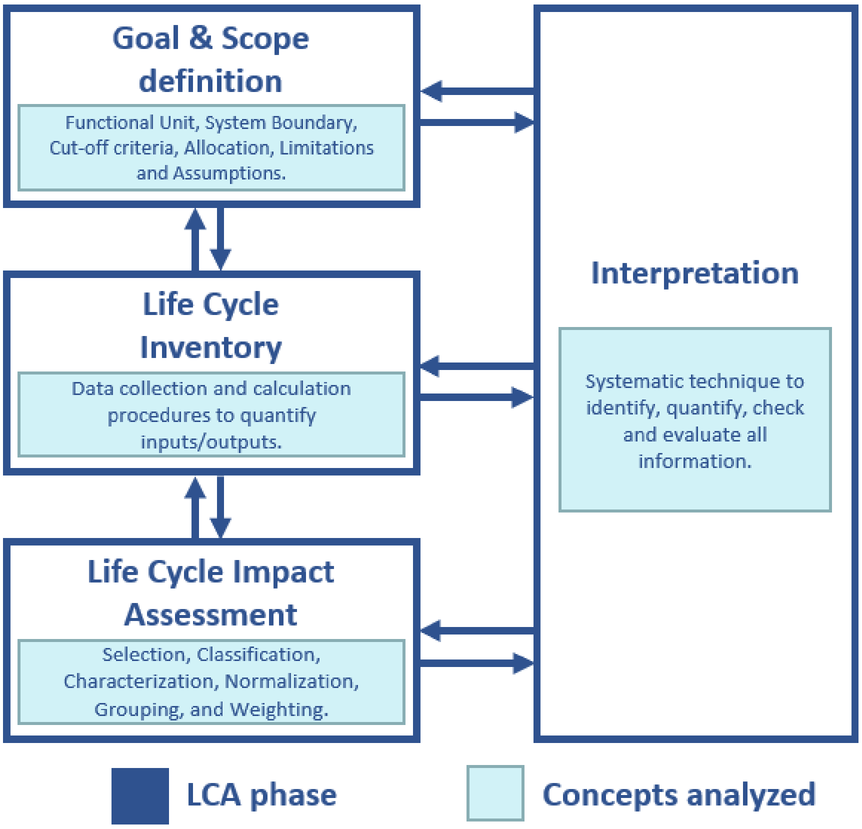

Figure 2.10 - LCA framework

2.3 TRIPLE-BOTTOM-LINE APPROACH AND THE LCSA METHODOLOGY

Undeniably, working to minimize the environmental impacts generated by the building and construction industries is urgent and imperative. The construction industry is responsible for large consumption of water, abundant depletion of natural resources, and massive emission of greenhouse gases. Nevertheless, when thinking about sustainable development, a common misconception is to consider only the environmental concerns of a product or service since sustainability is related to a triple-bottom-line framework composed of environmental, social, and economic factors. It is essential to reduce a product's resource use and emissions to the environment, but this goal must be accompanied by improving the socio-economic performance of the product. In this context, the Life Cycle Sustainability Assessment (LCSA) methodology emerged.

LCSA is a comprehensive and integrative methodology, based on the life cycle thinking approach, that intends to evaluate the environmental, social, and economic impacts of products and services throughout their life cycles and that can be used to improve the decision-making process of different projects. LCSA represents the combination of three well-known methodologies: i) Life Cycle Assessment (LCA), focused on the environmental dimension of sustainability [31]; ii) Social Life Cycle Assessment (S-LCA), related to the social dimension of sustainability [32]; and iii) Life Cycle Costing (LCC), describing the economic dimension of sustainability [33]. Therefore, the LCSA application considers that the sustainability concept is based on a triple-bottom-line framework comprised of environmental, social, and economic facets, as illustrated in **Figure 2.11**.

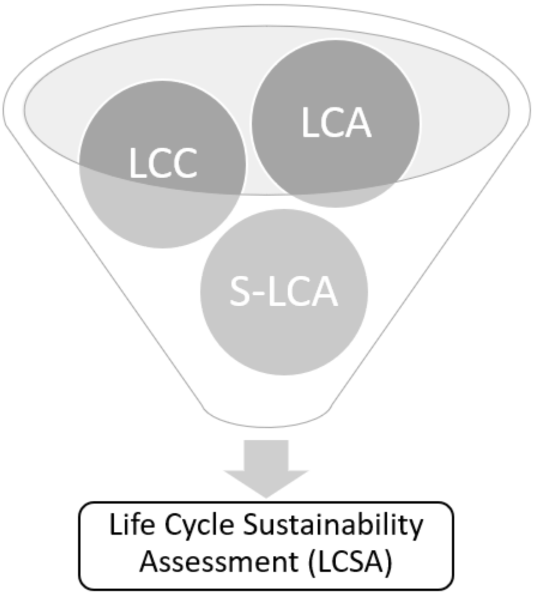

Figure 2.11 - Life Cycle Sustainability Assessment concept

Nevertheless, many questions about the complete application of LCSA still need to be discussed [34], and many practitioners still implement only part of the evaluation. Although LCA, LCC, and S-LCA methodologies were developed in the 1990s, the concepts and definitions related to the LCSA approach were clearly presented in 2003. That year, Klöpffer presented a proposal to combine LCA with LCC and s-LCA, but the term LCSA was not used at the time [35]. The first time this term was used was in 2007. Still, the authors only analyzed the impacts of climate change and resource depletion on their LCA, combining this analysis with an LCC, which does not entirely meet the triple-bottom-line model of sustainability [36].

Two years later, a study conducted by the Institute of Environmental Sciences at Leiden University presented a guideline for LCSA when implemented on general products [37]. However, despite the passing of the years and the growth of the discussion about this methodology, the literature still lacks specific methods for applying LCSA in the built environment, and only a few applications have been seen in the construction industry so far.

A considerable issue LCSA practitioners face is the lack of inventory data, especially for developing countries, since collecting sustainability-related data requires time, money, and labor intensity [38]. Many studies need to consider sources from different countries due to the unavailability of databases, but using data from a different location where the analysis was performed can turn into a misinterpretation of the impacts [39]. Besides, there is no database comprehensively enough to address all materials and components utilized in a project, making it necessary to make some assumptions, thus increasing the uncertainties of the LCSA results. It happens due to the variety of materials, construction techniques, locations, energy sources, and manufacturing differences in construction projects.

Many other challenges arise when practitioners try to apply LCSA in their projects associated with the built environment. The three methodologies that compose this integrative process have different maturity levels, which can hinder the broad implementation of LCSA. Therefore, the following sub-sections aim to present the state-of-the-art relevant to applying LCSA in the built environment, focusing on buildings and construction materials choice.

2.3.1 *LCA for construction projects*

The four-phase LCA framework presented in the ISO 14040 standard and already discussed in this chapter can also be applied to LCC and S-LCA [40], thus being also applicable to Building LCSAs [41]. Particularly, when applying the LCA methodology to a building, the life cycle stages to be considered include the production and construction stages (Module A), the building use stage, including processes such as maintenance, replacement, water use, and operational energy (Module B) and the building end of life (module C) [42]. Each module includes several parameters that can be defined based on measurements, individual expertise, or some assumptions derived from accepted conventions, and all these possibilities can bring some reliability issues in building LCA studies [43].

2.3.2 *LCC for construction projects*

Life Cycle Cost (LCC) is the assessment of all costs linked to the product life cycle and associated with one of the actors, such as the manufacturer, supplier, or consumer [44]. The main goal of the LCC approach is to optimize the product life-cycle costs without losing performance [45]. Therefore, this approach provides a suitable way of specifying the estimated total incremental cost of developing, producing, utilizing, and retiring a particular product [46].

When applied in a project associated with the built environment, the LCC approach estimates the Net Present Value (NPV) of all relevant costs throughout the project's life cycle, and it can include material costs, construction costs, maintenance, repair and replacement costs, energy costs, and residual values [47]. In this vein, the practitioner can consciously compare the cost of different alternatives since NPV transforms all building-related expenses and revenues that occur at different times into a present value [48]. Besides, this methodology can be applied to quantify the life-cycle costs of whole buildings and infrastructures or specific systems, building components, and building materials. In all scenarios, the LCC approach can improve the decision-making process in the built environment by offering a new angle to evaluate economic aspects.

The importance of evaluating economic aspects from a life cycle perspective is to offer decision-makers an adequate evaluation of investment options, taking into account the impact of all life-cycle costs rather than just initial expenses [49]. LCC can then be considered a suitable approach to planning the management of buildings and infrastructures over their lifetime. During an LCC study, practitioners should consider cost, benefit, and profit.

As previously reported in the literature, two different LCC approaches are currently accepted: a financial LCC, related to a financial and economic analysis of a product or service, and the environmental LCC, which weighs the environmental impacts analyzed in an LCA study in monetary terms. Besides, some authors have proposed that monetizing environmental impacts can support the integration of LCA and LCC, leading to a single score for LCA and LCC simulation results [50]. In this context, a considerable challenge is related to the fact that a building's lifespan ranges across decades. Then, the study may present inaccuracy and uncertainty of costs within the building's operational stage (i.e., predicted inflation rates, changes in legislation, local taxes, and labor costs) [51].

2.3.3 *S-LCA for construction materials*

Social Life Cycle Assessment (S-LCA) refers to a systematic method that accounts for all impacts borne by society throughout a product's life cycle [52]. By applying this methodology, the practitioner deals with positive and negative effects on society, being necessary to analyze several aspects during the study to find the optimum solution that depends on the context [53].

Regarding the use of this approach in the construction sector, different social impacts can be examined, such as impacts on workers' safety, noise pollution in the neighborhood, and degradation of cultural heritage [54]. However, when it comes to selecting construction materials, Hosseinijou et al. [55] showed that applying the S-LCA is still under development and that there are still many limitations in the application. In that study, the authors investigated the social implications around the life cycle of concrete and steel, but it was evident that the methodology's application still requires further adjustments to compare different construction materials.

In turn, according to Ekener et al. [56], there is still a need for social-LCA applications that fully incorporate all critical stakeholders, particularly from an environmental and financial standpoint. It is essential to start the selection of social impact categories by selecting the stakeholders' categories to be considered. In this context, it is usual to observe the social impacts focused on the perspective of only one group of stakeholders; for example, only the consumer's viewpoint is considered, ignoring the workers' perspective. However, in order to fully evaluate the social aspect of sustainability, it is advisable to consider different stakeholder categories and sub-categories to assess various aspects of social concerns.

2.3.4 *The harmonization process of the three methodologies*

There is increasing recognition of the need to consider not only the environment but also the social and economic aspects during a sustainability assessment. This requires the inclusion of additional indicators and assessment methods beyond traditional environmental LCA methods. Therefore, to enhance sustainability in the built environment, it is crucial to simultaneously account for all sustainability pillars (i.e., environment, economy, and society) in an entirely harmonious way.

Nevertheless, a closer look at the literature reveals a number of gaps and shortcomings in this realm. Although integrating environmental, economic, and social building assessments has been widely discussed in the literature, several methods are being proposed and applied as independently developed approaches focused on a specific type of project. Therefore, a number of questions regarding the harmonization process of LCA, LCC, and S-LCA remain to be addressed [57].

Recent papers have discussed the challenges and difficulties in harmonizing the three LCSA methods [57,58]. Integrating and harmonizing all dimensions of sustainability in order to guarantee a better understanding of how effects fluctuate across life cycle phases can lead to several interpretation problems. Therefore, crucial points need to be taken into account during the LCSA application. Specifically, when applying this methodology to a project related to the built environment, other challenges arise due to the complexity and extensive lifespan of built assets.

The first point to be highlighted is that assessment completeness is essential when applying LCSA. Many studies in the literature still implement a part of the evaluation considering only two of the sustainability pillars, thus hindering the broad implementation of LCSA [41]. To be considered an LCSA, it is imperative that the study be complete and that the three methodologies cover all building life cycle stages within the specified boundaries with a proper explanation of any exclusions.

Another aspect being considered is the improvement of assessment accuracy. LCSA accuracy depends on the data quality used to quantify the environmental, social, and economic impacts. Thus, it is essential to consider high-quality data from reliable sources specific to the assessment’s local context. Besides, it is necessary to consider appropriate assessment methods suited to the particular system being assessed, which may involve combining multiple techniques. Finally, carrying out a sensitivity analysis is highly encouraged. It consists of testing the robustness of LCSA results by varying the assumptions and parameters considered in the assessment, which can benefit the identification of the most significant drivers of environmental, social, and economic impacts and assess the uncertainties associated with the results.

The definition of the system boundaries is also a challenging task during an LCSA application. The practitioner should ensure that all relevant unit processes that impact one or more pillars of sustainability will be considered and will be within the system boundaries [59]. Unfortunately, it is common to observe the exclusion of some unit processes from the assessment considering the low impacts on the environment, as opposed to also evaluating the effects on society and the economy before defining the final system boundary. Besides, some LCSA applications that contradict the assumptions can be seen in the literature, preventing fair comparisons during the interpretation phase.

Ultimately, it is imperative to guarantee that the results for each sustainability pillar will match in regard to the locations of the databases and where the study was performed [39]. Due to the complexity and size of an LCSA application, it can be easy to observe problems like lack of transparency and data unsuitability for the project conditions. However, differences in the levels of detail and background information for each pillar can make communication of results more difficult to understand, hindering the decision-making process of construction projects.

2.4 KEY ASPECTS TO CONSIDER DURING A BUILDING-LCSA PRACTICE

After fully understanding the LCSA application and the challenges associated with the harmonization process, it is important to discuss different concepts related to LCSA in the literature that can benefit the decision-making process in the construction industry. Therefore, this section is divided into four parts to present critical aspects to consider during a building-LCSA practice, indicating future exploratory directions in this domain.

2.4.1 Dynamic LCSA

It takes much effort to gather all the information required to conduct a building LCSA. Frequently, assumptions are used to simplify the analysis, but, unfortunately, those assumptions typically do not reflect the building's reality. In conventional LCSA, utilizing a fixed time horizon during the assessment is common. However, this decision deprives decision-makers of essential information [60]. In this vein, an innovative approach arose to improve LCSA applications: the Dynamic Life Cycle Sustainability Assessment (D-LCSA) framework.

A D-LCSA intends to consider the temporalization of background and foreground systems in the assessment, thus improving the LCSA accuracy by addressing the inconsistency of temporal evaluations [61]. The dynamic characteristic can be applied during the LCI and LCIA phases, allowing the practitioner to consider different temporal parameters involved in the processes within the system boundaries [62]. The idea is to incorporate time-dependent parameters and information into the analysis, temporally explicit sources of life cycle inventory data, and life cycle impact assessment characterization factors [63].

Considering this application in the built environment, a dynamic approach is essential since construction assets are associated with constant internal and external changes, directly affecting sustainability [64]. When based on real-time data, LCSA applications can be utilized for rapid corrective actions in the building. Some papers in the literature have already considered time-dependent parameters for the environmental LCA application, such as the variation in occupancy behavior [65]. However, the expression Dynamic Life Cycle

Sustainability Assessment has been used only a few times in the literature so far, mainly in a theoretical and conceptual way. This topic still lacks deep discussion and further applications.

2.4.2 Circular Economy

The circular economy (CE) is a concept directly linked to sustainability, and its application results in energy savings, reduced resource consumption, reduced waste, and new job generation [66]. The circular economy approach takes into consideration all production processes to outline how to reuse, repair, and recycle items, thus increasing sustainability. In this sense, the idea consists of a continuous positive development cycle to preserve natural resources, optimize resource production, and minimize systemic risks [67].

The circular economy can occur in a closed or open loop. Applying the closed-loop principle entails reusing the material for the identical purpose as before [68]. An open-loop circular economy approach, by contrast, relates to the utilization of waste to manufacture other materials [69], which can occur for a variety of reasons, such as the change in the material's physical and chemical properties. Both strategies bring many advantages to society since new items may be produced using fewer resources and processes owing to the reuse and recycling of materials. Besides, the circular economy approach assists in minimizing fossil fuel consumption and, consequently, the emission of greenhouse gases [70].

Several researchers have discussed the importance of integrating circular assessment methods in analyzing buildings' environmental, social, and economic performance [71]. However, research has shown that the building sector's maturity regarding a systemic shift to circularity as an alternative to the prevailing linear economy growth thinking is still insufficient [72]. This shift should consider the difficulties in integrating environmental, economic, and social aspects as well as the higher level of complexity of built assets from a cradle-to-cradle perspective.

In this context, several studies are reported in the literature to implement the circular economy approach in a specific construction material as opposed to considering the whole building in the assessment. For example, a recent study assessed greenhouse gas emissions during the life cycle of wood bio-concrete production utilizing recycled wood shavings to apply the circular economy strategy to the assessment [73]. By evaluating the life-cycle impacts of two mixtures of wood bio-concrete, the authors concluded that wood waste might be advantageous for manufacturing low-carbon materials in the concrete industry. However, it is essential to note that the triple-bottom-line sustainability framework was not considered.

Future investigations are necessary to facilitate the integration of LCSA and circular economy. Overall, many papers associated with the built environment that apply the CE concept demonstrate a strong prioritization of economic aspects with primary environmental benefits, only implicit considering the social perspective. To change this reality, professionals and researchers should work to improve the transparency of assumptions, data reliability, and critical interpretation of results [74] so that the LCSA application can occur more supportedly.

2.4.3 A broad sensitivity analysis

Overall, applying life-cycle approaches to buildings and civil engineering works does not consider all the assumptions' uncertainties. For example, determining an accurate lifespan of the built asset is a prerequisite for reducing errors in LCSA applications. Research has shown inconsistency between the conceptual service life used in modeling and calculations and the actual lifespan of the facility [75], which can result in inaccurate LCSA results. Besides, several construction materials and components have a lower lifespan than the building itself, and to correctly define their effective service life, it would be necessary to consider the possibility of failure, dissatisfaction, and change in consumer needs [76]. Since LCSA applications are based on the whole life cycle of products and processes, the facility's lifespan is a sensitive parameter for calculating the overall environmental, social, and economic impacts [75].

Another critical aspect to be pointed out is that the nature of end-of-life (EoL) procedures is incredibly unclear among researchers and professionals associated with the construction industry. Since the LCSA methodology is usually applied to compare different building solutions, understanding EoL assumptions and the corresponding uncertainties is imperative. Research shows that the practitioners should be aware of various aspects that can influence the final LCSA results, such as the consideration of EoL phases, whether recycling of incineration should be assumed in the disposal, and which approach should be used for modeling the disposal processes (i.e., a substitution or cut-off approach) [77].

The sensitivity analysis is utilized to critically identify data and assumptions that significantly influence the LCSA outcomes in order to guarantee that the robustness of the results is not compromised. Although different methods are already presented in the literature, further development of more reliable approaches for characterizing uncertainties during the LCI and LCIA phases of an LCSA is necessary.

2.4.4 Integrating LCSA and Building Information Modelling (BIM)

Applying the LCSA methodology for buildings and civil engineering works necessitates carrying out different types of simulations and complex data collection to generate detailed results on impacts [41]. In this context, Building Information Modelling (BIM) can be considered beneficial during sustainability assessments since BIM represents a repository of digital information, enabling the management of all data in a centralized way [78].

Different BIM-based tools are available in the market and can be used to generate the three-dimensional model of the facility. This 3D model is a parametric and data-rich representation of the built asset [79], allowing stakeholders to centralize all the necessary project information. This characteristic, in turn, can be used to compare different materials and construction methods, thus facilitating the achievement of different sustainable goals, such as the thermal optimization of the building [80], the minimization of energy consumption during the building service life [81], and the assessment of water consumption [82].

Therefore, the BIM methodology is typically adopted to enhance the decision-making process of building projects as it reduces the amount of work involved in the comparison of different alternatives for the project [83]. Regarding integrating BIM and life-cycle approaches, many studies have been published on the advantages and challenges of integrating BIM and environmental LCA [84–89]. Nevertheless, the literature still lacks a more in-depth discussion about this integration covering the three dimensions of sustainability.

Specifically, Llatas et al. [57] conducted a systematic literature review on integrating BIM and LCSA, and the authors concluded that most papers utilize BIM tools solely for assessing environmental impacts. However, although few applications are to be discussed in the literature, many researchers agree that this integration can ensure LCSA practitioners make more informed decisions, allowing them to genuinely consider the three pillars of sustainability [41].

2.5 FINAL REMARKS

The LCSA application for buildings and civil engineering works can be valuable for several target audiences. Sustainability assessments are critical for policymakers to adopt conscious public policies and create realistic standards for sustainable buildings. In turn, this tool can also be attractive for builders, architects, and civil engineers since they can minimize the impacts of their constructions more efficiently with a reliable database and representative results of their regions and projects. Ultimately, with the growing global awareness of the importance of sustainable development and the dissemination of this information, end users are increasingly interested in obtaining green buildings and can benefit from LCSA applications.

Further work is certainly required to disentangle the complexities of applying LCSA in the built environment and the construction industry. This is an urgent and critical discussion, given the significant negative impact of the construction sector on the environment and various socio-economic factors globally. Further research and Building LCSA applications will ultimately facilitate the development of more sustainable and responsible construction practices, which are critical to mitigating the sector’s adverse effects.

2.6 REFERENCES FOR CHAPTER 2

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3 SUSTAINABLE MATERIAL CHOICE FOR CONSTRUCTION PROJECTS: A LIFE CYCLE SUSTAINABILITY ASSESSMENT FRAMEWORK BASED ON BIM AND FUZZY-AHP

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ABSTRACT

Construction professionals and researchers are increasingly looking for sustainable solutions for buildings in a bid to reduce some of the negative impacts associated with the sector. A common misconception is to consider sustainability as only concerning environmental issues, without regard for the interaction between a triple bottom line framework that is comprised of social, economic, and environmental factors. Material choice is known to impact building sustainability directly since the use of certain materials can dramatically alter the footprint generated over the life cycle of the building. However, the construction industry is not yet equipped with approaches that simultaneously account for all three aspects of sustainability when it comes to deciding on materials to adopt. This paper proposes a decision-making framework for construction professionals and researchers involving the integration of Life Cycle Sustainability Assessment (LCSA), Multi-Criteria Decision Analysis (MCDA), and Building Information Modeling (BIM) to choose suitable materials for buildings. The framework is built based on a literature review of relevant papers to identify critical factors and challenges to implementing this integration. The Fuzzy Analytic Hierarchy Process was chosen as the MCDA method within the proposed framework, given that the problem of material choice often contains subjectivity, uncertainty, and ambiguity, which is best solved with fuzzy logic. A residential building was adopted as a case study to validate the proposed framework, and LCSA is applied, covering the construction, operation, and end-of-life phases of the building.

Keywords:

Life Cycle Sustainability Assessment; Multi-Criteria Decision Analysis; Building Information Modeling; Sustainable buildings; Fuzzy Analytic Hierarchy Process.

3.1 INTRODUCTION

The construction industry is responsible for the significant consumption of natural resources, along with the generation of large amounts of waste [1]. In the last decade, researchers have attempted to study alternative materials, technologies, and design concepts that are less damaging to the environment. However, sustainability is not only concerned with environmental issues, as it involves an interaction between a triple bottom line framework comprised of social, economic, and environmental factors. In addition, several stakeholders are involved in a construction project, leading to the generation of various information from different parties and thus increasing uncertainty revolving around the decisions made [2]. Thus, there is a need for tools and technologies that facilitate a comprehensive analysis of a building and which cover all dimensionalities of sustainability.

Many decisions are made across the design, construction, and operation phases of a construction project. Such decisions can impact multiple aspects of a project. Hence, it is crucial to understand how such impacts reflect on several factors, including economic, environmental, and social ones. There are several examples in which a decision in the construction field impacts multiple criteria: the process to determine the best energy retrofit decision for a building, defining the impacts of different retrofit scenarios [3]; the equipment selection for construction projects [4]; and the definition of the construction system productivity [5]. One method to handle the simultaneous criteria that need to be evaluated before a decision is made is through multi-criteria decision analysis (MCDA), whereby concerns about various conflicting criteria can be formally incorporated into the decision-making process [6].

Of particular relevance in this study is the selection of suitable materials for building projects, which is a task that is linked to multiple criteria that require analysis and interpretation concurrently. Material selection in projects is traditionally based on satisfying technical requirements or economic limits, such as material strength and price, respectively, without considering the life cycle impact associated with the material [7]. In addition, almost 60% of the time is wasted in the early stages of designing construction projects on comparing different materials, resources, and construction methods [8]. To improve the selection of appropriate materials, this study proposes a framework that is based on Life Cycle Sustainability Assessment (LCSA) to evaluate the environmental, social, and economic impacts of building materials and make an appropriate choice. LCSA is the result of combining three main processes: i) Life Cycle Assessment (LCA), representing the environmental dimension [9]; ii) Social Life Cycle Assessment (S-LCA), representing the social dimension [10]; and iii) Life

Cycle Costing (LCC), describing the economic dimension [11]. As such, LCSA can be represented in equation form as follows [2]:

$$\text{LCSA} = \text{LCA} + \text{S-LCA} + \text{LCC} \tag{1}$$

Application of LCSA within the construction industry is not without any challenges; a high degree of detail is required when considering an entire building as a functional equivalent of analysis within LCSA. The term 'functional equivalent' is introduced at the building level in contrast to the term 'functional unit' at the product level and includes all quantified functional requirements and technical requirements of the building used as a basis for comparison [12]. There are difficulties that exist in analyzing the building's life cycles due to the large number of data that needs to be considered [13,14].

When it comes to analyzing the environmental impacts of construction materials choices, the literature shows that the combination of LCA and MCDA is significantly beneficial, as it can simplify the basic understanding of multiple perspectives in impact assessment [15]. Several MCDA methods have been discussed previously, including AHP (Analytic Hierarchy Process) [16], TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) [17], PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) [18], and DEMATEL (Decision Making Trial and Evaluation Laboratory) [19].

In this study, the MCDA method chosen is the Fuzzy Analytic Hierarchy Process (FAHP), a semiquantitative technique aimed to enrich its precedent, the Analytic Hierarchy Process (AHP) [20]. AHP uses a scale of numbers that shows how many times more important or dominant one item is over another item related to the criterion against which they are compared [20]. However, the method assumes that the users have complete information on the subject analyzed and that all respondents are equally qualified, which rarely is the case [21]. Coping with inaccuracies and ambiguities not addressed by the AHP method, fuzzy logic is integrated into the process. The FAHP substitutes the subjective scale of numbers used in AHP with fuzzy triangular numbers, permitting a pairwise comparison matrix to cope with criteria measurement. In recent years, researchers have applied fuzzy logic to explore and solve problems in construction projects, including type-2 fuzzy logic systems (IT2FLS) and fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL) [22,23].

Finally, to facilitate the simulations and data collection required to generate elaborate results on impacts associated with material choices, Building Information Modeling (BIM) is utilized in this work. BIM can improve the application of LCSA for construction material choice, as it represents a repository of digital information that enables the management of all data in a project [24]. Although the LCSA, MCDA, and BIM methodologies are already widespread in the literature, few applications integrate these concepts into a decision-support framework for design decisions in the construction sector.

The novelty of this study is based on the presentation of a framework that applies Building LCSA during the project design phase using an MCDA and BIM to provide a choice on the most suitable and sustainable construction materials in a project. The framework is designed to be applied in the project design phase to ensure maximum control over material decisions and thus avoid further modifications in later stages of the project when the costs of implementing change are higher.

The remainder of the study is organized as follows: a literature review is presented in Section 2. Section 3 explains the research methods, applying the proposed framework on a residential building. The results and discussions of the study are presented in Section 4. Finally, concluding remarks are presented in Section 5.

3.2 LITERATURE REVIEW

A literature review of the proposed methodologies (LCSA, MCDA, and BIM) is presented in this section to highlight the use of such approaches in the construction literature. The review also focuses on methods deployed to support contractors and designers in the choice of materials for construction projects.

3.2.1 Life Cycle Sustainability Assessment

The Life Cycle Sustainability Assessment (LCSA) is an interdisciplinary framework that evaluates the impacts associated with products and processes from an environmental, social, and economic perspective simultaneously [25]. In this way, LCSA comprises three main aspects, including LCA, LCC, and S-LCA. In the literature, however, many questions about the full application of LCSA are still discussed [2] and many studies still implement only part of the evaluation. This is mainly because the three pillars of sustainability have different maturity levels, which hinders the broad implementation of LCSA.

The International Standards Organization (ISO), in the 1990s, published the most recognized standards of Environmental Life Cycle Assessment (E-LCA) methodology, usually referred to just as Life Cycle Assessment (LCA). According to ISO 14040, LCA is the compilation of inputs, outputs, and potential environmental impacts of a product system throughout its life cycle [26]. This approach has been widely applied in the construction sector as an essential tool to evaluate construction materials' environmental impacts in the different phases of the project life cycle [27]. LCA can be performed to analyze new buildings over their whole life cycle and can be implemented on existing buildings over their remaining life [28].

The LCA methodology is broken down into four main steps [29]: (i) Goal and Scope definition; (ii) Life Cycle Inventory (LCI) analysis; (iii) Life Cycle Impact Assessment (LCIA); and (iv) Interpretation. This four-phase LCA framework can also be applied to LCC and S-LCA [30]. The first step in LCA involves defining the main aspects of the study, including i). the Functional Equivalent, which describes the primary function fulfilled by a product system and indicates how much of this function is to be considered in the LCA study; ii) the System Boundary, which refers to how far the analysis will be done (i.e., cradle-to-grave, cradle-to-gate, gate-to-gate, gate-to-grave); iii) the study's assumptions and limitations; and iv) the choice of the impact categories to be used, such as global warming potential (GWP), acidification, and eutrophication.

The second phase of the methodology involves the compilation and quantification of inputs and outputs for the Functional Equivalent throughout the product's life cycle. The third step aims at understanding and evaluating the magnitude and significance of the potential environmental impacts. Lastly, the interpretation phase represents a technique for identifying and assessing all the information from the previous stages concerning the defined goal and scope.

In addition to LCA, several LCC and S-LCA approaches have been developed. LCC is defined as an assessment of all costs associated with a product’s life cycle linked, as perceived by the supplier, manufacturer, or consumer [31]. LCC thus provides a way of specifying the estimated total incremental cost of developing, producing, using, and retiring a particular product [32]. The primary objective of LCC is to optimize the lifecycle economic costs of a project. When implemented in the construction sector, the LCC approach estimates the net present value of all relevant costs throughout the building's life cycle, including construction costs, maintenance, repair and replacement costs, energy costs, and residual values [33].

On the other hand, S-LCA refers to a systematic method that accounts for all impacts borne by society throughout the life cycle of a product [34]. Using the S-LCA approach, the practitioner deals with positive and negative effects on society [35]. Regarding the use of this approach in the construction sector, different social impacts can be examined, such as impacts on workers' safety, fair salary, and access to material resources [36].

When it comes to selecting construction materials, applications of the LCSA method are still under development, and there are some limitations in the process. Fauzi et al. [37] discussed several issues found in the literature on the LCSA application, and one aspect that deserves great emphasis is the difficulty of integrating the three approaches together (i.e., LCA, LCC, and S-LCA). In addition, not all the environmental and social indicators can be calculated as a function of the study's functional equivalent, which generates a significant drawback in result interpretation. There is also the issue of the lack of reliable economic and social impact databases that are still under development in comparison to a range of reliable environmental impacts’ databases.

3.2.2 Multi-Criteria Decision Analysis

In construction, it is necessary to consider different views of the stakeholders involved to decide on specific aspects of a project, including quality, security, ethics, finance, and human resource aspects. Hence, multiple criteria are often embodied in a significant number of the decisions undertaken during the design stage of a project, and these have to be analyzed to ensure an optimum decision. A high number of methods in the scientific literature support strategic decision makings such as mathematical optimization [38], fuzzy set theory [39], and the analytic hierarchy process (AHP) [40]. The use of the MCDA method is encouraged to generate effective, sustainable solutions in construction [15]. However, implementing these techniques requires systematic tools and methods to be developed.

Regarding the construction materials choice, several MCDA methods are already applied in the literature. Nadoushani et al. [41] used the Delphi and AHP methods to identify the most sustainable façade system, among five different alternatives, to replace a real building's existing worn façade. The authors considered environmental, social, and economic criteria in the analysis. Akadiri et al. [42] proposed a model for selecting sustainable construction materials for single-family housing in the United Kingdom using Fuzzy AHP.

In this work, the Fuzzy Analytic Hierarchy Process (FAHP) method is used. The FAHP approach enriches its precedent, Analytic Hierarchy Process (AHP), combining it with fuzzy logic theory [20]. AHP is based on the Newtonian and Cartesian way of thinking, which consists of breaking down the problem into smaller parts as many times as necessary until a precise and scalable level is reached. AHP requires the use of experts, and one-to-one comparison judgments are applied among similar criteria, generating the priorities for classifying the alternatives [43]. To counter the AHP method's deficiency in its reliance on expert input [44], the Fuzzy AHP method is deployed, employing the fuzzy set theory concepts in hierarchical structure analysis using fuzzy numbers instead of real numbers.

3.2.3 Building Information Modeling

The concept of Building Information Modeling (BIM) revolutionized the way construction projects are conceived by developing virtual models with parameterized elements. It allows a constant update of the project in a dynamic fashion. Thus, the resulting model is a data-rich, intelligent, and parametric digital representation of the facility [45]. It provides professionals with the necessary information to perform useful analysis. BIM-based software enables professionals to reduce costs, detect design errors, and track building timelines.

The adoption rate of BIM has increased significantly in recent years. BIM is commonly adopted for enhancing decision-making by reducing the amount of work involved in evaluating various alternatives in the early design stages [46]. Furthermore, BIM is considered an effective tool to assist in building life cycle analysis [47]. Many studies in the literature discuss the advantages and challenges of integrating BIM and LCA. However, a more in-depth discussion covering the three dimensions of sustainability is necessary. Llatas et al. [2] conducted a systematic literature review regarding the integration of LCSA and BIM. This study showed that most papers found in the literature use BIM solely for assessing environmental impacts produced by buildings. Only six papers were related to environmental and economic impacts simultaneously, while none of the studies reviewed included the analysis of social impacts.

Obrecht et al. [47] performed a systematic literature review of studies relating to BIM as a tool to facilitate Building LCA application. They found that BIM is mainly used as a repository of information in LCA analysis; the BIM-based software is utilized to generate the materials take-off. The quantities are exported to other software to perform the LCA analysis. In this case, the BIM-LCA integration occurs manually. Conversely, there are studies that propose how the exchange process could be automated. However, this discussion contemplates only the environmental dimension of the life cycle analysis.

In this study, BIM is considered the primary tool for creating the inventory database used in the LCSA. Modeling the building using a BIM platform will allow the automatic generation of material quantities. This would also enable simulations to be carried out of the building, which can be useful for generating additional data for the LCSA analysis. BIM simulations are already enabled by tools developed in the market, such as Navisworks and Synchro [48].

3.3 MATERIALS AND METHODS

The environmental, social, and economic assessments involved in building construction are guided by a set of European standards entitled 'Sustainability of construction works — Sustainability assessment of buildings,' which were utilized. These standards are divided into four main parts: Part 1 - General framework [49], Part 2 - Framework for the assessment of environmental performance [28], Part 3 - Framework for the assessment of social performance [50], and Part 4 - Framework for the assessment of economic performance [51]. The four-phase LCA framework presented by ISO Standards can be applied to LCSA [52]. As such, the conceptual framework proposed in this research, which is given in **Figure 3.1**, is based on recommendations from ISO 14040 and 14044 standards on LCA [26,53]. ISO 15686-5, entitled ‘Buildings and constructed assets - Service life planning - Part 5: Life-cycle costing’, was used to guide the LCC application [54]. The UNEP ‘Guidelines for Social Life Cycle Assessment of Products’ was used as the basis for the application of S-LCA [55]. Finally, LCA, LCC, and S-LCA's harmonization was implemented into the proposed method according to what has already been discussed in the literature [2,37].

BIM is utilized to facilitate the material quantity take-off and as a simulation tool to calculate and understand the impacts of the building's whole life cycle [2]. The Fuzzy Analytic Hierarchy Process (FAHP) method is adopted as the MCDA method.

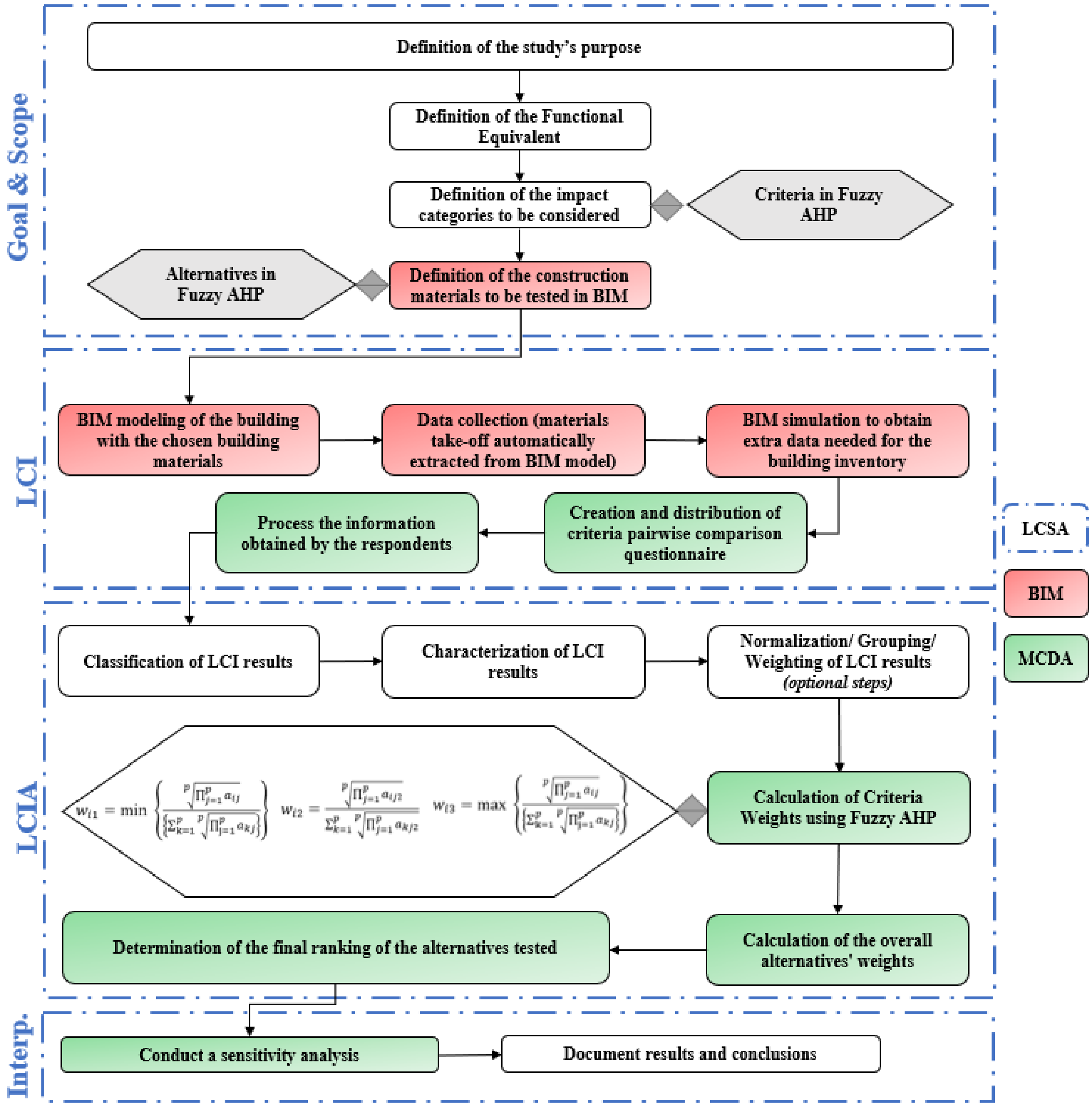


Figure 3.1 - Conceptual framework proposed in this work

The first stage of the framework in **Figure 3.1** involves defining all the features of the project. For LCSA, it is necessary to identify the goal and scope of the analysis clearly and accurately, including functional equivalent, system boundary, target audience, assumptions, and limitations of the study. A cradle-to-grave analysis is adopted in this study, where the following phases are considered: extraction of raw materials, transportation, fabrication, construction, operation, and demolition of the building. However, the study may also be restricted to only some stages of the building's life cycle depending on the goals of the decision-maker. The decision-maker can determine the study's system boundaries, considering the purpose of the analysis and its target audience [56]. The impact categories are to be chosen in line with the most relevant to the goals of the analysis. Construction materials are also clearly defined in this step. The impact categories from LCSA will be the criteria utilized in the decision-making process with MCDA, while the construction materials modeled in BIM will be the alternatives to be compared via MCDA.

It is necessary to choose the most appropriate MCDA method for the project, defining a multi-objective formulation that is the aim of the decision-maker to optimize. In this study, FAHP was proposed based on the constrained fuzzy arithmetic instead of the concept of standard fuzzy arithmetic. The constrained fuzzy arithmetic is a recent approach that has the advantage of eliminating the false increase of uncertainty of the overall fuzzy weights. In this study, it corresponds to a fuzzy extension of the geometric mean method, as it is the most applied approach in the literature [20].

The second step herein is to define the LCI and the three-dimensional (3-D) model developed in a BIM-based software. This step will be the primary tool to assist data collection and inventory creation. Utilizing BIM makes it possible to gather environmental, economic, and social data in the same model [57]. At this stage, all building data (i.e., construction materials and alternative construction methods) must be inserted into the BIM digital model to facilitate the analysis's continuity and data collection. Depending on the impact categories chosen for the study, it may be necessary to enrich the data collection with supplementary information. Therefore, it is suggested to use the BIM model to perform simulations and analyses that enable the determination of these additional data. Developments in BIM mean that professionals can make use of the interoperability between software so that there is no information loss during the process. Finally, regarding the application of FAHP, it is necessary to create a questionnaire tool to obtain professionals' opinions on their preferences among the impact categories tested, based on a pairwise comparison. The professionals' opinions must be collected at this stage so that the data can then be evaluated.

The third phase of the study necessitates evaluating the LCIA of the environmental, social, and economic pillars. At this analysis level, the LCIA methods assess the data collected during the LCI phase (i.e., ReCIPe [58], TRACI [59], CML [60], etc.). The classification and characterization steps are mandatory in LCIA, while normalization, grouping, and weighting are optional. In order to rank the alternatives, the MCDA method chosen is utilized. **Figure 3.2** shows how the analysis would be organized at this phase.

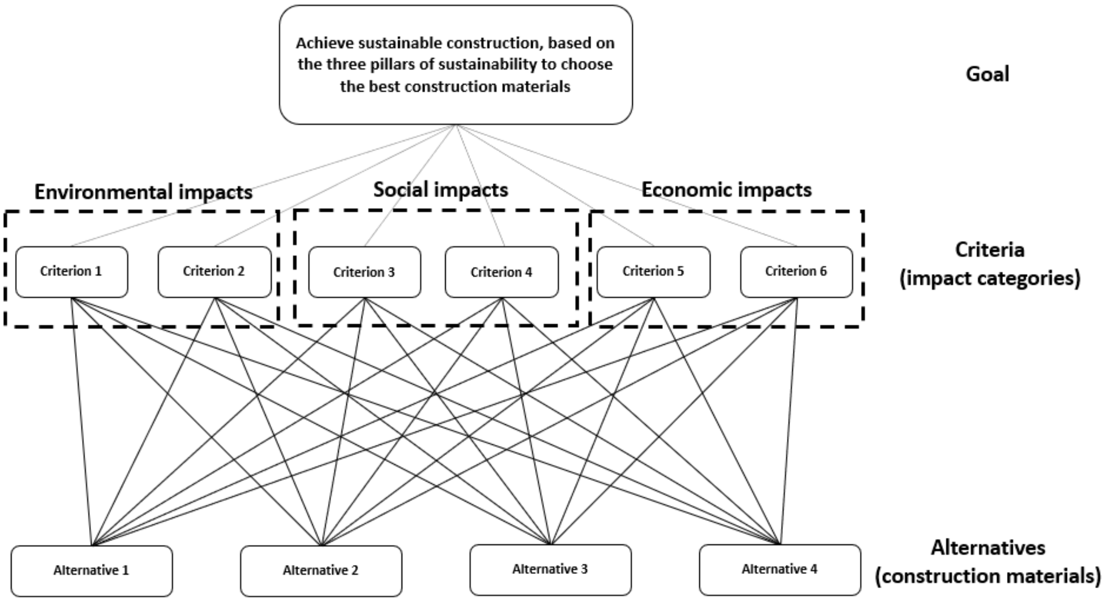


Figure 3.2 - Hierarchy used in the proposed framework

Depending on the project and the stakeholders involved, the ranking can be made in different ways since different impact categories can be prioritized in each case. For example, in a given project, environmental impacts may have a greater weight in comparison to the economic impacts for the target audience; this, however, may not be true for all projects. As such, the MCDA method is applied in this stage to calculate the criteria weights.

In FAHP, the process of pairwise comparison, similar to AHP, is conducted based on a questionnaire to determine how many times more important one object is over another. The respondents use a scale of integers from 1 (equally important) to 9 (extremely more important) in the questionnaire, as was proposed by Saaty in the crisp AHP method. The results are then transformed into triangular fuzzy numbers (TFN) to solve uncertainties in the response given. A TFN is a fuzzy number whose membership function is determined by three real numbers $c_1 \leq c_2 \leq c_3$ and it is commonly represented by $\tilde{c} = (c_1, c_2, c_3)$.

Let $\tilde{A} = \{\tilde{a}_{ij}\}_{i,j=1}^{p}$, $\tilde{a}_{ij} = (a_{ij1}, a_{ij2}, a_{ij3})$ be the fuzzy pairwise comparison matrix for any $i, j \in \{1, \dots, p\}$, obtained after transforming the responses of the questionnaire distributed among professionals into TFNs. $\tilde{A}$ is a square matrix whose elements are TFNs defined in the range $[\frac{1}{9}, 9]$ and with the main diagonal equal to (1, 1, 1), since these elements represent the comparison of one object with itself, $\tilde{a}_{ii}$.

According to the fuzzy extension of the geometric mean method, the criteria weights are obtained by normalizing the geometric means of the rows of the pairwise comparison matrix

$\tilde{A}$. The problem found in this method, when the concept of standard fuzzy arithmetic is utilized, is that different values of the same variables enter the calculation simultaneously (for more details, see Krejcí et al. [61]), which means that the resulting TFNs do not represent the true ranges for fuzzy weights.

Therefore, when the standard fuzzy arithmetic is used, the calculation leads to a false increase in the model's uncertainty. This work proposes the use of constrained fuzzy arithmetic to calculate criteria weights. The fuzzy weight $\tilde{w}$ of each criterion of the analysis is calculated based on the results of the pairwise comparison. For TFN, three different formulae are needed to calculate the lower, middle, and upper significant values. The criteria weights are determined by Eq. (2) - (4) [62], where $\tilde{w}_i$ represents the fuzzy weight of criterion i and w_{i1}, w_{i2} and w_{i3} are real numbers, corresponding to the significant values of the triangular fuzzy number denoted as $\tilde{w}_i = (w_{i1}, w_{i2}, w_{i3})$, $w_{i1} < w_{i2} < w_{i3}$.

$$w_{i1} = \min\left\{\frac{\sqrt[p]{\prod_{j=1}^{p} a_{ij}}}{\left\{\sum_{\mathrm{k}=1}^{p} \sqrt[p]{\prod_{\mathrm{j}=1}^{p} a_{kj}}\right\}};\ a_{rs} \in [a_{rs1}, a_{rs3}], \qquad r, s = 1, \dots, p, \qquad r < s\right\} \tag{2}$$

$$w_{i2} = \frac{\sqrt[p]{\prod_{j=1}^{p} a_{ij2}}}{\sum_{k=1}^{p} \sqrt[p]{\prod_{j=1}^{p} a_{kj2}}} \tag{3}$$

$$w_{i3} = \max\left\{\frac{\sqrt[p]{\prod_{j=1}^{p} a_{ij}}}{\left\{\sum_{\mathrm{k}=1}^{p} \sqrt[p]{\prod_{\mathrm{j}=1}^{p} a_{kj}}\right\}};\ a_{rs} \in [a_{rs1}, a_{rs3}], \qquad r, s = 1, \dots, p, \qquad r < s\right\} \tag{4}$$

The defuzzification process is then carried out, in which a fuzzy set is mapped to a crisp set. An example of a defuzzification method widely used in the literature is the center of gravity (COG) method [63], in which the crisp set is obtained via the arithmetic mean of the elements of the fuzzy set. In this study, the authors propose the following formula:

$$COG(w_i) = \frac{\sum_{t=1}^{3} w_{it}}{3} \tag{5}$$

Defuzzified values are then normalized, and it is possible to evaluate the alternatives of construction materials, taking into account the ranking already created among the criteria and the results obtained from LCIA. The LCIA results should also be normalized, so that data from different impact categories can be compared on a common scale. The LCIA normalized values are considered as the weights of the alternative concerning each criterion, with u_i^k being the representation of the weight of the k-th alternative concerning criterion i. Then, the overall weight of alternative k will be calculated by Eq. (6), presented below:

$$u_k = \sum_{i=1}^{p} w_i \, . \, u_i^k \tag{6}$$

The last step herein is the interpretation phase, which corresponds to the MCDA method's application to assist the professionals in the decision-making process. The decision-maker must be able to select the optimum sustainable material for the project based on the three pillars of sustainability. In these terms, performing a Sensitivity Analysis (SA) is encouraged, as it allows the LCSA practitioner to compare all available alternatives that have been highlighted as suitable from the previous steps. Sensitivity analysis seeks to determine the effect of a given item's variation on the total impact assessed for that item. A sensitivity analysis is conducted to monitor the preference ranking's robustness among the alternatives tested in this work.

3.4 TOOLS TO VALIDATE THE PROPOSED FRAMEWORK

This part illustrates the practical application of the four phases of LCSA proposed in this study.

3.4.1 Goal and Scope

The scope of this study is to determine the best building materials among a pre-defined material list, considering environmental, economic, and social aspects. This work's functional equivalent consists of a 36-unit residential building composed of 10 stories (ground floor, eight floors, and a roof) constructed in Rio de Janeiro, Brazil. Each unit consists of two bedrooms, a sitting room, a kitchen, a bathroom, and a service area. The building service life considered in this work is 60 years. Finally, a gate-to-grave system boundary is used, comprising the following stages of the building life-cycle: construction, operation and maintenance (O&M), and end-of-life. For the end-of-life phase of the building, it was assumed that the building would be imploded, and the analysis would include the relevant material collection rates and landfilling rates. The same system boundary is adopted during the environmental, economic, and social analyses so that the harmonization of the three approaches occurs satisfactorily.

The environmental impact categories chosen for this study are widely discussed in the literature [64] and include Global Warming Potential (GWP), Acidification Potential (AP), and Eutrophication Potential (EP). GWP represents a measure of greenhouse gas emissions that may have adverse impacts on the ecosystem and human health. The acidification potential represents the ability to increase the concentration of H^+ in a molecule in the presence of water, which includes potential effects such as forest decline and deterioration of construction materials. The eutrophication potential measures excessively high levels of macronutrients, such as nitrogen and phosphorus, and can cause an undesirable change in species composition and high biomass production [65].

For the economic analysis, the impact category is the life-cycle cost associated with the building phases considered in the system boundary. During the O&M phase, in addition to the annual building maintenance and repair costs, it was decided to consider the annual energy cost for lighting and HVAC. Improving energy efficiency in buildings plays a crucial role in ensuring sustainable developments in the future, as it is known that energy resources are limited. Besides, construction material choice directly influences the energy efficiency and the sustainability of a building [66]. Lastly, for the social analysis, the stakeholder category adopted in this work refers to the workers. From this perspective, the impact category analyzed is fair salary, with Fair Wage Potential (FWP) adopted as the quantitative indicator.

To implement FAHP, each impact category is considered as a criterion. Since the evaluation criteria for building materials can have various connotations and meanings, there is no logical reason to treat them as if they are each of equal importance [15]. The dimensions and criteria chosen are presented in **Table 3.1**, where D_i refers to the dimension i, while C_j refers to the criterion j.

Table 3.1 - Dimensions and criteria to be considered in the analysis

Dimensions (D_i)	**Criteria (C_j)**	**Units**
(D_1) Environmental	(C_1) Global Warming Potential	kg CO_2 eq.
	(C_2) Acidification Potential	kg SO_2 eq.
	(C_3) Eutrophication Potential	kg N eq.
(D_2) Economic	(C_4) Life-cycle cost	Brazilian Real (R$)
(D_3) Social	(C_5) Fair Wage Potential	FWeq.

3.4.2 Life-Cycle Inventory

The building prototype for the case study was developed in Autodesk Revit®, a BIM-based software [67]. In this work, BIM is used as a tool to facilitate the material take-off process and the simulation needed to compare different building materials' behavior in terms of energy consumption. All materials to be used in the building must be defined in the BIM 3D model, with the definition of their physical and thermal properties. Therefore, the modeling was developed based on Level of Development (LOD) 400, in which the components are graphically represented as a specific object with detailing, fabrication, assembly, and installation information. The 3-D view and the plan view of the building are shown in **Figure 3.3**.

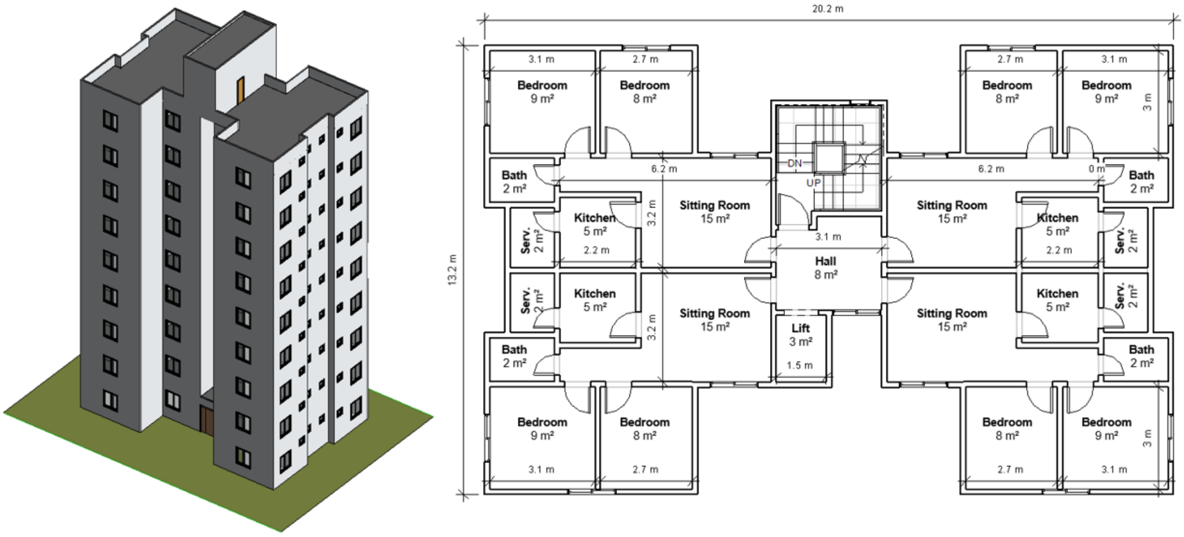


Figure 3.3 - Case study modeled in a BIM-based software

The materials for the different alternatives have been defined based on the experience of the professionals involved in this work, as shown in **Table 3.2**. Each alternative's material take-off was determined via four different BIM models, allowing an automatic quantitative data collection. Regarding the environmental analysis, the service life, in years, for each material, in addition to the transportation distance, in kilometers, from the manufacturer location to the building site by diesel truck, were defined.

An energy model was created for each alternative in the same BIM-based software used to model the structure regarding the economic analysis. An energy model in Autodesk Revit® is a particular form of geometry used by the energy simulation mechanism, capturing the building's main heat transfer paths. It is developed with Green Building XML schema (gbXML), a language designed to facilitate the transfer of building data stored in Building Information Models (BIM) to environmental analysis tools [68]. The assumptions made to create the energy models were the following: the building type is Multi-Family; the Sliver Space Tolerance is 0.3048m, and the building HVAC system is Split System with mechanical ventilation via cooling. The building's annual energy use was calculated, considering the energy for HVAC and lighting, as shown in **Table 3.3**.

Table 3.2 - Database concerning the four alternatives, where B.L. stands for 'Building Life.'

BIM Category	**Alternative 1**			
	Materials	**Material mass (kg)**	**Service Life (years)**	**Transportation distance (km)**
Ceilings	Acoustic ceiling system, fiberglass	4,390	50	72
	Suspended grid	1,827	50	72
	Paint, interior acrylic latex	318.6	7	24
Doors	Kiln-dried Ash hardwood lumber of 4"	5,810.31	50	38
	Wood stain, water-based	36.87	10	38
Slabs	Structural concrete, 4001-5000 psi	565,175	60 (B.L.)	17
	Steel	5,448	60 (B.L.)	17
Floors	Ceramic tile, unglazed	35,242	60	72
	Cement mortar	6,294	60	72
	Cement grout	780.6	60	72
Walls	Brick, 1/2" joint	929,061	150	17
	Lime mortar	161,037	60	72
	Grout fill: thickset mortar	260,827	60	72
	Reinforcing Steel	16,451	60	17
	Paint, exterior acrylic latex	1,052	10	24
Windows	Glazing, monolithic sheet, tempered	6,610	40	40
	Aluminium, (100x20x2) mm, 1,28 kg/m	1,002.45	60	63
	Paint, enamel, solvent-based	63.9	15	63

BIM Category	**Alternative 2**			
	Materials	**Material mass (kg)**	**Service Life (years)**	**Transportation distance (km)**
Ceilings	Ceiling tile, aluminium (3.37kg/m²)	5,498	70	63
	Suspended grid	1,827	50	63
	Powder coating, metal stock	636.3	50	1
Doors	Domestic softwood, US, AWC - EPD	2,333	30	38
	Polyurethane foam (PUR) rigid board	135.68	75	29

Table 3.2 - Database concerning the four alternatives, where B.L. stands for 'Building Life,' Continued.

Slabs	Glass Fibre Reinforced Concrete	567,321	60 (B.L.)	40
	Steel	81,409	60 (B.L.)	18
Floors	Terracotta tile	89,152	75	72
	Thickset mortar	13,280	60	72
	Cement grout, Latricrete - EPD	372,1	60	72
Walls	Concrete masonry unit (CMU), solid	1,217,571	100	72
	Mortar type N	71,158	60	72
	Paint, exterior acrylic latex	1,052	10	24
Windows	Glazing, double, insulated (air)	4,715	40	40
	Aluminium extrusion, anodized, AEC - EPD	3,318.6	60	63
	Paint, exterior metal coating, silicone-based	20.95	30	24
BIM Category	**Alternative 3**			
	Materials	**Material mass (kg)**	**Service Life (years)**	**Transportation distance (km)**
Ceilings	Acoustic ceiling tile - galvanized steel	7,962	75	43
	Suspended grid	1,827	50	43
Doors	Redwood decking, AWC - EPD	4,876	25	24
Slabs	Glass Fibre Reinforced Concrete	567,321	60 (B.L.)	40
	Fabricated steel reinforcement	81,409	60 (B.L.)	18
Floors	Tile backer board	16,270	40	72
Walls	Perlite filled clay block, Poroton	345,789	150	12
	Lime mortar (Mortar type K)	107,267	60	72
	Thickset mortar	260,941	60	72
	Fabricated steel reinforcement	16,458	60 (B.L.)	18
	Paint, exterior acrylic latex	1,052	10	24
Windows	Glazing, triple, insulated (air)	7,139	40	40
	Aluminium extrusion, anodized	3,318.6	60	63
	Paint, exterior metal coating, silicone-based	20.95	30	24
BIM Category	**Alternative 4**			
	Materials	**Material mass (kg)**	**Service Life (years)**	**Transportation distance (km)**
Ceilings	Ceiling tile, steel mesh	9,658	75	31
	Suspended grid	1,827	50	43
	Zinc coating (galvanized) for steel G60	298.6	60 (B.L.)	31
Doors	White oak lumber, 4 inches	190.5	50	38

Table 3.2 - Database concerning the four alternatives, where B.L. stands for 'Building Life,' Continued.

Slabs	Structural concrete, 4001-5000 psi	548,060	60 (B.L.)	24
	Steel	5,448	60 (B.L.)	17
Floors	Granite tile	60,178	50	21
	Cement mortar, Latricrete - EPD	7,143	60	72
	Cement grout, Latricrete - EPD	372.1	60	72
Walls	Perlite filled clay block, Poroton - EPD	345,789	150	12
	Lime mortar (Mortar type K)	107,267	60	72
	Thickset mortar	260,941	60	72
	Steel, concrete reinforcing steel	3,515	60 (B.L.)	17
	Paint, Brillux, Silicone facade paint - EPD	1,052	15	24
Windows	Electrochromic glass, Saint-Gobain, Sage Glass	8,386.3	50	40
	Aluminium extrusion, anodized, AEC - EPD	3,318.6	60	63
	Paint, exterior metal coating, silicone-based	20.95	30	24

Table 3.3 - Results of energy simulations in the BIM models

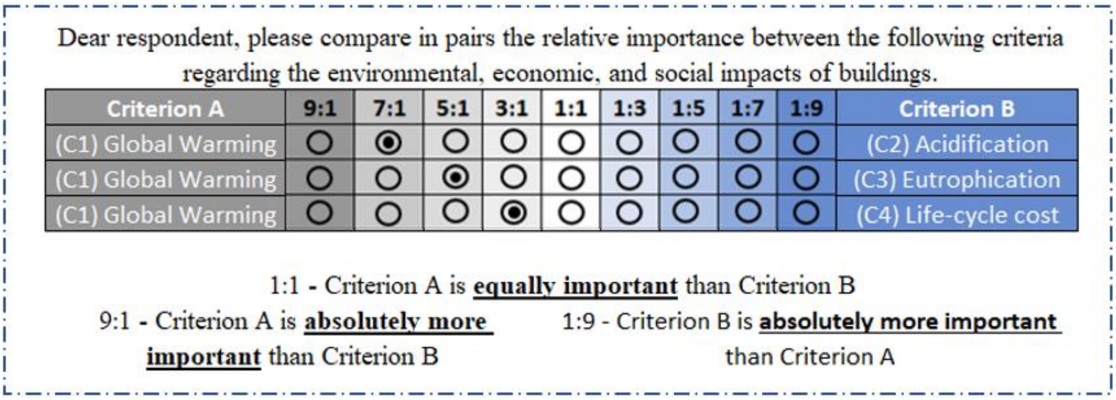
Alternatives	Annual Energy Consumption for Lighting (kWh)	Annual Energy Consumption for HVAC (kWh)
Alternative 1	21,591	81,225
Alternative 2	19,802	62,709
Alternative 3	20,234	71,739
Alternative 4	23,606	63,825

Data regarding the prices of materials, equipment, and construction services were used to analyze the economic impacts of the alternatives, and data about the construction workers in Rio de Janeiro, Brazil, were used to analyze the social implications. Depending on the materials and construction methods chosen for the building, different skills will be required to carry out the associated activities. The budget for materials and services and the number of professionals required for each alternative were determined based on the data found in SINAPI, which can be translated as ‘the Brazilian System of Costs and Indices Research of Civil Construction.’ SINAPI aims to produce monthly series of costs and indices for the Brazilian construction sector, along with a monthly series of average labor wages and average prices for materials, equipment, and construction services [69]. The data collected are summarized in **Table 3.4**.

Table 3.4 - Brazilian data regarding the resource requirement of workers in the construction sector

		Professionals needed in each alternative			
		Construction phase			
Category	Brazilian average wage *(Brazilian Real – R$)*	Alternative 01	Alternative 02	Alternative 03	Alternative 04
Bricklayer's mate	R$ 1,442.05	14	10	14	10
Bricklayer - level 1	R$ 1,507.78	0	3	0	0
Bricklayer - level 2	R$ 2,010.37	10	9	7	8
Bricklayer - level 3	R$ 2,372.24	2	0	4	5
Bricklayer - level 4	R$ 2,734.10	0	2	0	0
Master builder	R$ 3,091.89	1	1	1	1
Site engineer	R$ 9,483.29	1	1	1	1
		O&M phase			
Bricklayer/painter	R$ 1.846,12	2	2	2	2
		End-of-life phase			
Bricklayer's mate	R$ 1,442.05	2	2	2	2
Master builder	R$ 3,091.89	1	1	1	1

Finally, a questionnaire was distributed to the respondents to obtain their preferences among criteria, following what is proposed in the AHP method. The survey had been sent to 12 Brazilian engineers, but only 7 of them responded. All respondents had to have at least two years' experience in the LCA approach. Among them, four respondents work or have worked as site engineers, while three are sustainability engineers. The questionnaire required the engineers to conduct a pairwise comparison among the material sustainability criteria adopted in this study, as presented in **Figure 3.4**. The arithmetic mean of the responses from the seven professionals was calculated for each pairwise comparison. The final results are shown in **Table 3.5** and treated in the next stage of the proposed framework to transform crisp numbers into fuzzy ones.



Dear respondent, please compare in pairs the relative importance between the following criteria regarding the environmental, economic, and social impacts of buildings.

Criterion A	9:1	7:1	5:1	3:1	1:1	1:3	1:5	1:7	1:9	Criterion B
(C1) Global Warming	○	●	○	○	○	○	○	○	○	(C2) Acidification
(C1) Global Warming	○	○	●	○	○	○	○	○	○	(C3) Eutrophication
(C1) Global Warming	○	○	○	●	○	○	○	○	○	(C4) Life-cycle cost

1:1 - Criterion A is **equally important** than Criterion B

9:1 - Criterion A is **absolutely more important** than Criterion B

1:9 - Criterion B is **absolutely more important** than Criterion A

Figure 3.4 - Part of the questionnaire distributed to the engineers

Table 3.5 - Results of the pairwise comparison questionnaire based on crisp AHP.

	C_1	**C_2**	**C_3**	**C_4**	**C_5**
C_1	1	3	5	$^1/_3$	$^1/_3$
C_2	$^1/_3$	1	3	$^1/_5$	$^1/_3$
C_3	$^1/_5$	$^1/_3$	1	$^1/_7$	$^1/_5$
C_4	3	5	7	1	3
C_5	3	3	5	$^1/_3$	1

3.4.3 Life Cycle Impact Assessment

Life Cycle Impact Assessment is the third phase of the LCSA application. Different LCIA methodologies are available in the literature that represent different ways of evaluating the data collected during the LCI phase. The results of this phase are presented separately for each of the environmental, economic, and social impacts, as follows.

3.4.3.1 Environmental Impacts

TRACI 2.1 characterization scheme was adopted in this work to classify and characterize the environmental impacts [65]. Within the TRACI methodology, the impact categories are characterized at the midpoint level, drawing cause-effect chains to show the point at which each category is characterized. The Tally® application was used in this study to match each material in the 3-D BIM model in Autodesk Revit® with the GaBi database materials, allowing an automated exchange process [70]. The results for the four alternatives are presented in **Table 3.6**.

Table 3.6 - Environmental impacts for the alternatives evaluated in this study

	Impact Category	Construction phase	O&M phase	End-of-life phase	Total
Alt. 01	(C1) Global Warming (kg CO_2eq)	3,123	50,521	44,940	**98,584**
	(C2) Acidification (kg SO_2eq)	14.47	311.7	191.6	**517.77**
	(C3) Eutrophication (kg Neq)	1,178	17.23	10.49	**1,205.72**
Alt. 02	(C1) Global Warming (kg CO_2eq)	6,364	216,551	41,924	**264,839**
	(C2) Acidification (kg SO_2eq)	29.49	885.1	187.4	**1,101.99**
	(C3) Eutrophication (kg Neq)	2.40	41.82	9.99	**54.21**
Alt. 03	(C1) Global Warming (kg CO_2eq)	2,636	212,205	32,161	**247,002**
	(C2) Acidification (kg SO_2eq)	12.21	951	134.3	**1,097.51**
	(C3) Eutrophication (kg Neq)	0.99	45.35	7.49	**53.83**
Alt. 04	(C1) Global Warming (kg CO_2eq)	2,599	547,488	51,254	**601,341**
	(C2) Acidification (kg SO_2eq)	12.04	4,817	172	**5,001.04**
	(C3) Eutrophication (kg Neq)	0.98	112	11	**123.98**

3.4.3.2 *Economic Impacts*

For the economic analysis, the calculation was performed in Microsoft Excel. The prices and costs provided by SINAPI concerning the city of Rio de Janeiro, published on January 21, 2021, were imported to Microsoft Excel to determine the life-cycle cost for each alternative [69]. Regarding the annual expenses associated with the O&M phase, the net present value (NPV) formula was used in Excel, a metric to calculate the present value of a succession of future payments, deducting a capital cost rate. A rate of 3% was considered in the calculations.

The values presented in Table 3 regarding the annual consumption of energy in each alternative were multiplied by the tariff charged by the private company responsible for the electricity generation, distribution, and sale in Rio de Janeiro. The low voltage tariff for residential units that consume up to 300 kWh in January 2021 is 0.84183 [71]. It was considered that the annual consumption measured by BIM simulations would be the same throughout the building service life, that is, for 60 years. Regarding the annual maintenance and repair costs, an estimate was made considering the materials' service life for each alternative and the values presented in SINAPI. Elevator maintenance costs were not considered in the analysis, as the objective of this study is to focus on the choice of construction materials. The final results are shown in **Table 3.7**.

Table 3.7 - Life-cycle cost for the alternatives evaluated in this study, with the costs presented in Brazilian Real

Alternatives	Construction cost	Energy cost	Maintenance cost	End-of-life cost	Total life-cycle cost
Alt. 01	R$ 4,149,370.18	R$ 15,056,422.71	R$ 465,604.26	R$ 58,000.00	R$ 19,729,397.15
Alt. 02	R$ 4,225,102.32	R$ 12,082,950.40	R$ 614,177.41	R$ 58,000.00	R$ 16,980,230.13
Alt. 03	R$ 5,730,095.63	R$ 13,468,569.17	R$ 749,241.23	R$ 58,000.00	R$ 20,005,906.03
Alt. 04	R$ 5,426,852.74	R$ 12,803,436.88	R$ 619,001.18	R$ 58,000.00	R$ 18,907,290.80

3.4.3.3 Social Impacts

For the social analysis, the calculation was also performed in Microsoft Excel. The social impact category used the characterization model proposed by Neugebauer et al. [72] to transfer the qualitative midpoint impact category named 'Fair Wage' into a quantitative one. The inventory results of the actual average remuneration and the actual working time are multiplied with the regionalized inequality characterization factor. The Gini Coefficient related to Brazil, a measure of the deviation of income distribution among individuals or households within a country from a perfectly equal distribution, was adopted [73]. For this coefficient, a value of 0 represents absolute equality, and a value of 1 represents absolute inequality. Brazil occupies the 84^{a} position in the rankings, with a Gini Coefficient of 0.539.

Neugebauer et al. [72] proposed the following formula to characterize this impact category:

$$FWP_n = \frac{RW_n}{MLW_n} \times \frac{CWT_n}{RWT_n} \times \left(1 - {IEF_n}^2\right) \tag{7}$$

Where FWP_n indicates the Fair wage potential [expressed in FWeq.] representing process n within a product's life cycle taking place at a defined location; RW_n indicates the average monthly wages paid to the workers employed in process n; MLW_n is the minimum living monthly wages in the respective country or region; CWT_n represents the contracted working time per country or sector [hours/week]; RWT_n indicates the real working time [hours/week] of workers performing the process n; and IEF_n represents the inequality factor [expressed in percentages] of the country or region where process n is performed.

The MLW_n is the Brazilian minimum wage in January 2021, taken as R$ 1,100.00, while CWT_n equals 40 hours per week. RWT_n is equal to 49 hours for bricklayer's mates, 41 hours for site engineers, and 44 hours for the other categories. The Fair Wage Potential was calculated in Microsoft Excel, and the results are shown in **Table 3.8**.

Table 3.8 - Fair Wage Potential for the different workers' categories

Category	FWP_n (FWeq.)
Bricklayer's mate	0.7593
Bricklayer - Level 1	0.8841
Bricklayer - Level 2	1.1788
Bricklayer - Level 3	1.3910
Bricklayer - Level 4	1.6031
Master builder	1.8129
Site Engineer	5.9674
Bricklayer/Painter	1.0825

In order to assign this indicator to the functional equivalent, this work proposes to calculate a weighted average of these values, with the weights corresponding to the number of professionals in each category. With this, the fair wage potential for each alternative was obtained.

Finally, it is important to note that the FWP indicator is the only one to be maximized in this study; all others correspond to negative impacts and should be minimized. In order to facilitate the application of the MCDA method and the ranking of alternatives to be tested, the authors suggest that the inverse of FWP_n be used as the final indicator in the analysis. In this way, all the indicators used will be minimized. This calculation was performed, and the final results are presented in **Table 3.9**.

Table 3.9 - Social impacts for the alternatives evaluated in this study

Alternatives	Final results for social analysis
Alt. 01	0.858
Alt. 02	0.830
Alt. 03	0.884
Alt. 04	0.805

3.4.3.4 Weight Generation

The MCDA method is used to weigh the criteria established. The results obtained in the opinion questionnaire, presented in Table 5, need to be transformed into triangular fuzzy numbers. Among the several AHP fuzzification approaches to convert a crisp set to a fuzzy set, it was decided to apply the fuzzy extension of the geometric mean method based on constrained fuzzy arithmetic. Therefore, the pairwise comparison matrix elements were modeled by triangular fuzzy numbers, as shown in **Table 3.10**.

Table 3.10 - Fuzzy pairwise comparison matrix of the criteria

	C_1	**C_2**	**C_3**	**C_4**	**C_5**
C_1	$(1,1,1)$	$(2,3,4)$	$(4,5,6)$	$(\frac{1}{4},\frac{1}{3},\frac{1}{2})$	$(\frac{1}{4},\frac{1}{3},\frac{1}{2})$
C_2	$(\frac{1}{4},\frac{1}{3},\frac{1}{2})$	$(1,1,1)$	$(2,3,4)$	$(\frac{1}{6},\frac{1}{5},\frac{1}{4})$	$(\frac{1}{4},\frac{1}{3},\frac{1}{2})$
C_3	$(\frac{1}{6},\frac{1}{5},\frac{1}{4})$	$(\frac{1}{4},\frac{1}{3},\frac{1}{2})$	$(1,1,1)$	$(\frac{1}{8},\frac{1}{7},\frac{1}{6})$	$(\frac{1}{6},\frac{1}{5},\frac{1}{4})$
C_4	$(2,3,4)$	$(4,5,6)$	$(6,7,8)$	$(1,1,1)$	$(2,3,4)$
C_5	$(2,3,4)$	$(2,3,4)$	$(4,5,6)$	$(\frac{1}{4},\frac{1}{3},\frac{1}{2})$	$(1,1,1)$

With the pairwise comparison matrix constructed, criteria fuzzy weights can be obtained by Eq. (2) - (4). Then, the triangular fuzzy numbers were deffuzified using Eq. (5), and the nonfuzzy normalized weights were also calculated, as highlighted in **Table 3.11**. In order to facilitate the application of the formulas, the R Project for Statistical Computing was used, a free software environment for statistical computing and graphics [74].

Table 3.11 - Fuzzy and nonfuzzy criteria weights

Criteria	**Fuzzy Weights**	**Defuzzified Weights**	**Nonfuzzy Normalized Weights**
C_1	$\widetilde{w}_1 = (0.1216; 0.1616; 0.2184)$	$w_1 = 0.167$	$w_1 = 0.166$
C_2	$\widetilde{w}_2 = (0.0638; 0.0849; 0.1172)$	$w_2 = 0.089$	$w_2 = 0.088$
C_3	$\widetilde{w}_3 = (0.0337; 0.0417; 0.0544)$	$w_3 = 0.043$	$w_3 = 0.043$
C_4	$\widetilde{w}_4 = (0.3800; 0.4610; 0.5234)$	$w_4 = 0.455$	$w_4 = 0.451$
C_5	$\widetilde{w}_5 = (0.1876; 0.2508; 0.3218)$	$w_5 = 0.253$	$w_5 = 0.252$

With the weights of the criteria properly calculated, the process of evaluating the alternatives begins. The environmental, economic, and social LCIA results, referring to the four different material alternatives for the building, are normalized. The final normalized values will be considered as the weights of the alternative concerning each criterion. The normalization process results are presented in **Table 3.12**.

Table 3.12 - Alternative weights concerning the particular criteria

	A₁	**A₂**	**A₃**	**A₄**
C₁	$u_1^1 = 0.081$	$u_1^2 = 0.219$	$u_1^3 = 0.204$	$u_1^4 = 0.496$
C₂	$u_2^1 = 0.067$	$u_2^2 = 0.143$	$u_2^3 = 0.142$	$u_2^4 = 0.648$
C₃	$u_3^1 = 0.839$	$u_3^2 = 0.038$	$u_3^3 = 0.037$	$u_3^4 = 0.086$
C₄	$u_4^1 = 0.261$	$u_4^2 = 0.225$	$u_4^3 = 0.265$	$u_4^4 = 0.250$
C₅	$u_5^1 = 0.254$	$u_5^2 = 0.246$	$u_5^3 = 0.262$	$u_5^4 = 0.238$

With this, it is possible to create the final ranking of the alternatives utilizing Eq. (6) to calculate the alternatives' overall weights. As all the criteria chosen in this study indicate impact categories that should be minimized, the best alternative is the one with the lowest overall weight. The results are presented in **Table 3.13**.

Table 3.13 - Overall weights of the alternatives

Alternatives	**Overall weights**	**Ranking**
A₁	$u_1 = 0.2372$	3rd
A₂	$u_2 = 0.2137$	1st
A₃	$u_3 = 0.2332$	2nd
A₄	$u_4 = 0.3159$	4th

3.4.4 Interpretation

The consistency ratio (CR) of the criteria pairwise comparison matrix is 0.062; that is, CR is less than 0.1. Hence, the study is considered consistent and acceptable. The consistency ratio of a matrix can be determined by using Eq. (8), as follows:

$$CR = \frac{CI}{RI} \tag{8}$$

Where CI and RI are respectively the consistency index and the random index.

Alternative 2 is the most recommended for the analyzed building, corresponding to the alternative that achieves the best results concerning the sustainability criteria adopted. However, it is essential to note that the alternatives' overall ordering is strongly dependent on the criteria chosen. A sensitivity analysis is required to monitor the robustness of the preference ranking among the alternatives. The sensitivity analysis is carried out by gradual changes of the values of each criterion, whether global warming potential (C1), acidification potential (C2), eutrophication potential (C3), the life-cycle cost (C4), or fair wage potential (C5), and then observing the rank order due to such changes. In this way, the behavior of the ranking of alternatives could be monitored. Each criterion's weights were changed until reaching the null value, and then a new ranking was generated in each case. **Table 3.14** shows these results.

Table 3.14 - Sensitivity analysis results

	C_1 = null value		C_2 = null value	
Alternatives	Overall weights	Ranking	Overall weights	Ranking
A_1	$u_1 = 0.2237$	3rd	$u_1 = 0.2313$	3rd
A_2	$u_2 = 0.1774$	1st	$u_2 = 0.2011$	1st
A_3	$u_3 = 0.1994$	2nd	$u_3 = 0.2207$	2nd
A_4	$u_4 = 0.2336$	4th	$u_4 = 0.2589$	4th
	C_3 = null value		C_4 = null value	
Alternatives	Overall weights	Ranking	Overall weights	Ranking
A_1	$u_1 = 0.2011$	1st	$u_1 = 0.1195$	3rd
A_2	$u_2 = 0.2120$	2nd	$u_2 = 0.1124$	1st
A_3	$u_3 = 0.2316$	3rd	$u_3 = 0.1139$	2nd
A_4	$u_4 = 0.3122$	4th	$u_4 = 0.2032$	4th
	C_5 = null value			
Alternatives	Overall weights		Ranking	
A_1	$u_1 = 0.1731$		3rd	
A_2	$u_2 = 0.1517$		1st	
A_3	$u_3 = 0.1673$		2nd	
A_4	$u_4 = 0.2559$		4th	

The changes made to criteria 1, 2, 4, and 5 did not differ in the final choice of alternative (that is, alternative 2 remained the most suitable, followed by alternatives 3, 1, and 4, respectively), which increases the credibility of the decision made in this study.

3.5 DISCUSSION

The approach presented in this study has great potential to contribute to selecting materials for the construction industry. Specifically, an emphasis needs to be placed on the possibility of considering environmental, economic, and social aspects simultaneously when choosing construction materials. This is extremely important to achieve more sustainable goals in a sector proven to be responsible for causing significant environmental and socio-economic impacts.

In order to use the BIM methodology as the primary tool in the data collection of the case study, quantitative indicators were chosen that could be related to the defined functional equivalent modeled in BIM. This, however, results in a limitation of the study, as there are only a few social indicators that can be related to the functional equivalent so far [37]. The social indicator was related only to an issue faced by workers; extension of the social indicators in the proposed framework is required in future works.

Even though the case study covered a large part of the analyzed building's life cycle, it is also essential that future works encompass the construction materials production phase, from the extraction of raw materials to the manufacturing processes. This has not yet been possible due to the absence of reliable databases, mainly on the social impacts related to these processes [2]. The creation of national and international databases is necessary and urgent so that the decision-making in the materials choices happens even more consciously.

The analysis of buildings' energy performance during the operation phase is a promising way to improve energy use. However, energy simulations performed in Autodesk Revit software may not provide accurate results, as the simulation may fail to capture some heat transfer paths from the building. To avoid this problem, a building of typical architecture was chosen in this paper's case study without using overhangs and side fins in the room divisions. The spaces' definition was made cautiously in Autodesk Revit before the modeling was transferred to the gbXML format.

The normalized LCIA results of the case study were placed on the graphs shown in **Figure 3.5**. Applying the integrated proposal among LCSA, BIM, and MCDA, Alternative 2 was the most sustainable option for the analyzed building. It can be seen that this alternative is the best choice, based on the two different criteria (i.e., C1 and C2). However, if the decision-makers had chosen to analyze the proposed building considering only criteria C3 and C4, Alternative 2 would have been considered the second option in the final ranking. Therefore, it is important to clearly define the impact categories by considering the objective of the analysis and the target audience. Ultimately, the use of fuzzy logic is strongly recommended as it helps deal with the subjectivity of choices made by decision-makers and, therefore, offers an avenue to handle a high degree of uncertainties.

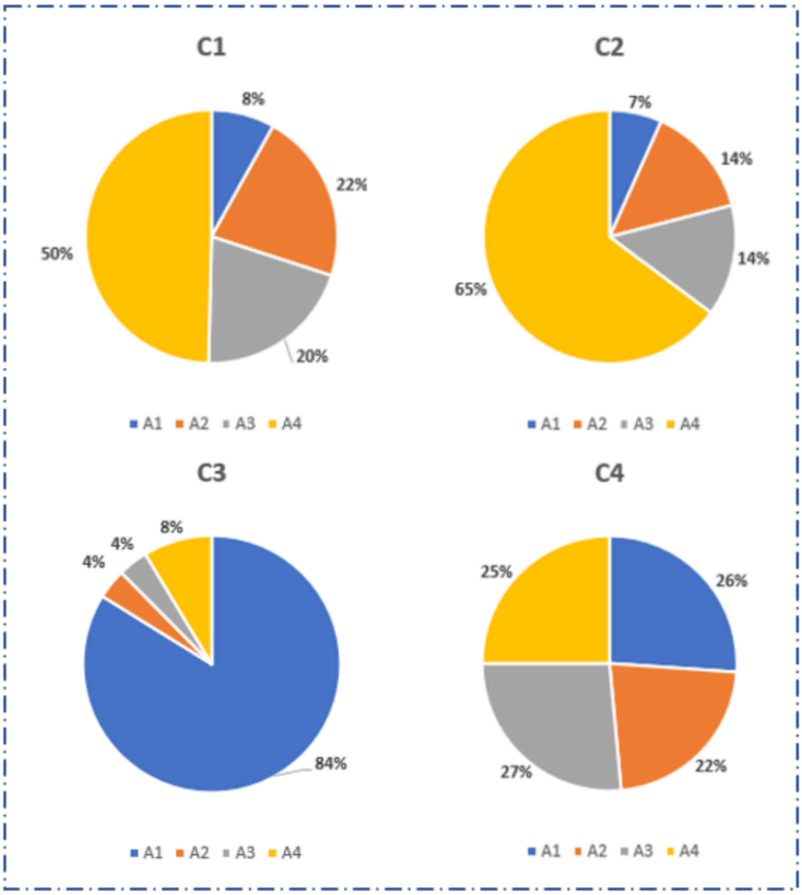


Figure 3.5 - Comparison of the four alternatives tested via LCSA

3.6 CONCLUSION FOR CHAPTER 3

This work presents an innovative proposal for integrating LCSA, BIM, and MCDA to determine the most sustainable choice of materials for construction projects. Although a significant number of studies have adopted the previously listed approaches, none have yet implemented them simultaneously to improve the construction material choice. A case study of a residential building was evaluated to present the application of the developed framework. It is worth mentioning that this same framework can be easily applied in other construction projects with different impact categories by expanding the impacts database.

In the case study presented, four different material lists were tested for the same building to decide which alternative would be the most sustainable. Among the selected alternatives, a variation of up to 509.97% in global warming potential was found through the LCSA-BIM-MCDA integration. Also, a 16.11% variation in the energy cost for lighting and 22.80% variation in the energy cost for HVAC were detected. These variations can be even more significant when testing a greater number of material alternatives. The framework proposed allows construction professionals to quickly conduct a comparison between the alternatives.

In this work, the project was modeled for a proposed building, which brings certain limitations to the study compared to a real construction project, such as the impossibility of collecting data from the region's inhabitants and the need to make some assumptions on the construction methods used. Also, only one social impact category was assessed in the case study, which is a significant drawback of this work. These limitations must be considered in the interpretation phase, but this was deemed to be acceptable for this work since the purpose was to prove the framework's usability. There is also great difficulty in obtaining all the data related to the building, covering the environmental, economic, and social spheres. This study's future direction is to explore the use of the proposed framework in real buildings, identifying effective ways to weigh the various impacts and accurately measure the qualitative aspects.

3.7 REFERENCES FOR CHAPTER 3

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4 ENHANCING THE PASSIVE DESIGN OF BUILDINGS: A MIXED INTEGER NON-LINEAR PROGRAMMING APPROACH FOR THE SELECTION OF BUILDING MATERIALS AND CONSTRUCTION BUILDING SYSTEMS

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ABSTRACT

Consumption of energy in buildings accounts for a considerable proportion of worldwide energy use. There is a dire need for enhancing the energy efficiency of building to limit their demand for operating energy as this leads to enhanced reductions in environmental impacts. Of particular relevance to the amount of energy utilised in a building during the operation phase is the nature of material and size of components utilised in the building. In this work, a mathematical programming framework is presented to optimise a number of building design objective functions, including heat gain, daylight and economic cost of material utilised. The variables that are focussed on in this study are the sizes of windows, type of material adopted for the building, embodied in the construction building systems used for various building components, and the type of lighting adopted. To validate the framework, two realistic case studies obtained from an industry partner are adopted and solved via the use of the proposed mathematical programming method. Results indicate that compared to the solutions proposed by an experienced engineer, the daylight, heating and cost of the building is enhanced by up to 39%, 43% and 23% respectively. The framework is hoped to help policy makers introduce more streamlined guidance for the building sector when it comes to optimised material choice and window sizing to result in energy-efficient and economical buildings.

Keywords:

Energy efficiency; Heat gain; Daylight; Building materials; Multi-objective optimisation; MINLP.

4.1 INTRODUCTION

Buildings have a large impact on global energy and climate (Allouhi et al., 2015). Their energy consumption account for approximately 40% of global energy used, primarily due to the energy needed to generate thermal comfort throughout operation phase (Yang et al., 2014). Almost 24% of energy is utilised to operate residential buildings, while the remaining is utilised by commercial buildings (Berardi, 2017). In terms of electricity use, buildings consume more than 55% of total electricity consumption in the world (IEA - International Energy Agency, 2019). Given that the building sector is one of the largest consumers of a nation's energy (IEA - International Energy Agency, 2019) there is a dire need for energy policies that are targeted towards enhancing energy efficient measures in buildings in order to ensure that the associated negative impacts are minimised. Enhancing the energy efficiency of buildings leads to a national energy consumption reduction due to the significant amount of energy that is consumed to operate buildings in a nation (Bakar et al., 2015). Thus, countries would highly benefit from reduced energy consumption if operational energy in a building is lowered to preserve national resources and decrease environmental impacts. Measures must be implemented at the individual scale first so that significant reductions collectively result within the building industry (Andersen et al., 2020).

Energy consumption in residential and commercial buildings results from a combination of thermal loads and lighting needs (Cao et al., 2016; Sadeghifam et al., 2015). Thermal loads are associated with heat flow into and out of a building, acting as a significant determinant of thermal comfort for building users (Elghamry and Hassan, 2020). Heat flow in a space is related to several design aspects of a building; for example, the thermal transmittance of materials making up the exterior walls of a building significantly influences the heat flow (Latha et al., 2015). Other design aspects that will influence heat flow in a building include the exterior envelope of the building, choice of fenestration systems and the lighting that is adopted. Lighting fixtures generate heating that often remains embedded in the housing structure, thus exerting extra pressure on cooling loads and enhancing energy requirements.

Current requirements for enhancing the energy efficiency of buildings are based on the past experiences of designers to determine appropriate design parameters in buildings. Such an approach may lead to ineffective solutions, particularly given the interrelation between all the various building design parameters involved, leading to a largely combinatorial and complex decision problem. Even though sophisticated energy simulation software exists to assess a building design's energy efficiency, simulations still lack due to their time-consuming nature and the iterative workflow that is prone to result in non-optimal design solutions (Delgarm et al., 2016). Targeting heat gains in buildings helps achieve thermal comfort and alleviates the loads imposed on Heating, Ventilation, Air Conditioning and Cooling (HVAC) processes for buildings.

It is important to consider how a buildings energy performance can be improved from the onset of the design phases. Doing so requires the design process to embed a number of design consideration that are not only concerned with thermal loadings and heat gains. Other aspects that can directly impact the operational energy behaviour of a building include the sizes of windows adopted and the lighting system that is utilised. Windows can severely impact the heating and cooling loads required in a building; up to 40% of a building's heating energy is lost via windows, and up to 87% of its heat is gained through windows (Cuce, 2017). Improving windows' thermal performance reduces energy costs and greenhouse gas emissions (Lolli and Andresen, 2016). Daylight is an imperative measure in building design as it directly impacts visual comfort, reduces the need for artificial lighting, and enhances occupants' well-being (Hafiz and Mhatre, 2020).

Considering all possibilities of design measures requires solving multiple simulations, which can be time-consuming. An alternative is to rely on a mathematical optimisation process, whereby all alternatives can be considered simultaneously (Machairas et al., 2014). This study presents a mathematical optimisation framework for the appropriate selection of materials that reduce thermal loadings in buildings by targeting heat transfer in buildings. Mathematical programming has been a traditional tool in energy planning, emphasising its application to reduce the cost of energy production (Mavrotas et al., 2010, 2010). Its suitability lies in its ability to represent discrete choices applicable in energy planning, including choice of technology and logical conditions. In this study, a mixed-integer programming model will be deployed to enhance energy consumption efficiency in buildings via optimising the choice of materials adopted.

Policy makers must issue guidelines to help the building sector achieve a sustainable and energy-efficient industry. However, a significant number of variables can be challenging to consider when analysing the energy requirements that would result if specific materials were adopted in the building (Thomas et al., 2018). Moreover, decision-makers are confronted with the complex problem of deciding the most suitable combination of building components when designing projects, which would lead to an overall energy-efficient building. The proposed solution in this study relies on setting up the problem as a mathematical optimisation problem that involves optimising the design decisions associated with material choices when it comes to exterior envelopes, ceilings, roofs, doors and windows and lighting fixtures in commercial and residential buildings. A number of mathematical programming frameworks proposed in energy planning involve multiple objective functions that denote economic, environmental and social objectives (Ahmed and Sarkar, 2019). These multi-objective models are applied for large systems related to energy planning of services buildings such as hospitals (Mavrotas et al., 2008), optimising the energy system of commercial buildings (Liu et al., 2010), along with optimising energy production (Cristóbal et al., 2012).

The problem examined in this study involves choosing among a large number of alternatives for building components and lighting systems, each impacting building energy consumption in a specific way. Growing public awareness regarding environmental impacts of buildings, along with increased pressure on governments to act in order to reduce energy consumption at the national level, results in an urgent need for efficient solution approaches that can be utilised at the onset of a project to bring down energy consumption associated with the operations of a building (Alam et al., 2019). Through adopting an optimisation framework, policies on material choices to adopt in the building sector in order to reduce the load on the power grid in a country can be drastically reduced.

The remainder of the paper is organised as follows: in the next section, state-of-the-art literature is presented to give an overall view of methods proposed in the literature for predicting and minimising energy consumption of buildings and heat gain due to building materials. Besides, this section presents the energy policies that have been initiated by governments in Brazil and Australia to control and lower the operating energy of buildings. In section 3, a mixed-integer non-linear programming (MINLP) mathematical optimisation framework is presented and described, with each section of the mathematical model then formulated. An explanation of the solution approach is then given, followed by demonstrating the framework on two main case studies. The study ends with some concluding remarks.

4.2 LITERATURE REVIEW

Given the significant energy consumption attributed to buildings, and the national and global impacts that such energy consumption can have (Yang et al., 2014), it is essential to study ways to minimise operational energy consumption in buildings. Operational Energy (OE) is defined as the annual amount of non-renewable primary energy used during the building's operational phase (Giordano et al., 2017). It is related to the energy required for operating building appliances and the processes of lighting, heating, cooling, and ventilating the building.

Studies on energy performance in buildings have been mostly examined over the years with the main aim of estimating the thermal load profile and consequently estimating the energy required to guarantee thermal comfort and reduce energy consumption. The analysis of energy performance is based on the simplified calculation of thermal loads according to the following parameters: thermal characteristics of the building, ventilation, passive solar system, indoor / outdoor climatic conditions and energy end-uses (Poel et al., 2007). As the prediction of energy consumption is not so easy and requires a large amount of information, researchers, industry and governments have dedicated themselves to generating different methods and tools for estimating energy performance (Fumo, 2014).

According to Pedersen, load and energy estimations in buildings are primarily based on three methodologies: statistical approaches or regression analyses, energy simulation programs and intelligent computer systems (Pedersen, 2007). Consequently, different methods can be developed based on these foundations to fulfill the energy planner's requirements for an accommodated estimation tool. On the other hand, Wang et al. (Z. Wang et al., 2020) introduced another classification, where the approaches to forecasting building thermal load were classified into three main categories: i) white-box physics-based models that predict building loads with detailed heat and mass transfer equations; some software as EnergyPlus and TRNSYS can set-up with it; ii) gray-box reduced-order models that try to simplify the dynamics of the building thermal to reduced order Resistance and Capacity (RC) models, where Rs and Cs represent the thermal zone or building envelope; and iii) black-box data-driven models predict building thermal load using historical data; some of these popular models include support vector machine (SVM) and Artificial Neural Networks (ANN).

With the advancement of technology, a vast amount of building materials is developed, and numerous experimental works are performed to analyse the influence of these materials on the thermal load of a building. For instance, Navarro et al. (Navarro et al., 2012) experimentally analysed the phase change materials (PCM) performance in a scenario with internal thermal gains. The experiment allows the authors to evaluate the impact of using PCM in a typical Mediterranean building. Haggag et al. (Haggag et al., 2014) examined the use of green façades to reduce heat gain in indoor spaces as a strategy to lower cooling demand in a school building in the United Arab Emirates. Shen et al. (Shen et al., 2011) evaluated the impact of reflective coatings on indoor environment and building energy consumption during summer and winter in Shanghai. Cho et al. (Cho et al., 2013) used EnergyPlus to evaluate the thermal energy consumption patterns and potential benefits of the load sharing system compared to the conventional systems. Zheng et al. (Zheng et al., 2017) developed a method for the estimation of heating and cooling load profiles, which is based on piece-wise linear regression analyses.

Other researchers used the Design of Experiments (DOE) method to improve the statistical analysis associated with predicting the energy profile of buildings. For example, Sadeghifam et al. (Sadeghifam et al., 2015) identified the energy consumption patterns and determined the optimal level of energy usage by replacing some components with energy efficient materials. Then, the authors used DOE to evaluate the best combination factor. Schlueter and Geyer (Schlueter and Geyer, 2018) presented a methodology integrating DOE and Building Information Modelling (BIM) in order to provide a better understanding of the influence and interactions of different architectural and technical design factors on building energy performance of a specific design task. It is important to consider that the construction materials also influence operational energy since all the materials used interfere in the building's thermal dissipation (Shoubi et al., 2015; Zhu et al., 2013).

Selecting suitable materials can consume less energy, and the improvement in the material selection process can also minimise environmental pollution and greenhouse gas generation (Yüksek, 2015). For example, it is possible to reduce overall operational energy by using high-performance insulation materials due to their capacity to save heating and cooling power (Tuladhar and Yin, 2019). Several materials can be utilised as insulators due to the ability to decrease the heat flow rate, such as fiberglass, mineral wool, and foam (Aditya et al., 2017).

Many researchers have been developing other methods, such as mathematical programming approaches for optimising the energy efficiency of the building sector. Genetic algorithm was deployed to optimise energy efficiency and thermal comfort in building design (Jin and Jeong, 2014; Wright et al., 2002; Yu et al., 2015). Moayedi et al. (Moayedi et al., 2019) employed six machine-learning techniques to solve the problem of designing energy-efficient buildings. Le et al. (Le et al., 2019) proposed a comparative study to optimise the heating load forecast. The study suggested four techniques based on the potential of artificial neural network (ANN) and meta-heuristics algorithms, including artificial bee colony (ABC) optimisation, particle swarm optimisation (PSO), imperialist competitive algorithm (ICA), and genetic algorithm (GA).

Bambrook et al. (Bambrook et al., 2011) presented a case study of a house in Sydney, Australia, performing building energy simulation and optimisation analysis to reduce the annual need for heating and cooling. During the investigation, parameters such as the walls and roof's insulation thickness, the type of windows, the thickness of an internal thermal mass wall, and the air exchange rate for night ventilation were considered. As a conclusion of the analysis and to minimise the operational energy consumption, the authors designed a photovoltaic system capable of covering domestic electricity consumption over a year.

A comparison of the main optimisation methods utilised for building energy optimisation in some relevant studies in the literature is shown in **Table 4.1**.

Table 4.1 - Comparison of reviewed literature on building energy optimisation.

Author	**Performance metrics**	**Design parameters**	**Optimisation method**	**Character**
Bruno (2016) **(Bruno et al., 2016)**	Thermal load	Building envelope	5R1C model and analysis	Single-objective optimisation
Cho (2013) **(Cho et al., 2013)**	Thermal energy consumption	Building envelope and HVAC system settings	EnergyPlus and analysis	Single-objective optimisation
Djedjig (2015) **(Djedjig et al., 2015)**	Energy performance	Climatic data outside/inside and Green envelope	Thermo-hydric model +TRNSYS	Single-objective Optimisation
Geysen (2018) **(Geysen et al., 2018)**	Thermal load	Outdoor temperature, Thermal load dataset, and control signals	LR + ANN + SVM + ETR + Graphical analysis	Single-objective Optimisation
Guimarães (2012) **(Guimarães and Carlo, 2012)**	Energy performance	Building design	EnergyPlus	Single-objective Optimisation
Haggag (2014) **(Haggag et al., 2014)**	Energy demand	Wall temperature and building envelope	Graphical analysis	Single-objective Optimisation
Jin (2014) **(Jin and Jeong, 2014)**	Thermal load	Building shape	GA	Single-objective Optimisation
Le (2019) **(Le et al., 2019)**	Heating load	Building design, orientation, and glazing settings	ABC-ANN, PSO-ANN, ICA-ANN, and GA-ANN	Single-objective Optimisation
Melo (2012) **(Melo et al., 2012)**	Energy performance	Building design, WWR, solar factor, shading size, and weather data	EnergyPlus	Single-objective Optimisation

Table 4.1 - Comparison of reviewed literature on building energy optimisation, Continued.

Moayedi (2019) **(Moayedi et al., 2019)**	Heating load	Building design, orientation, and glazing settings	Ecotect + (MLPr, LLWL, AMT, RF, ENet, RBFr) and analysis	Single-objective Optimisation
Navarro (2012) **(Navarro et al., 2012)**	Thermal load and energy consumption	Wall material and internal load	Graphical analysis	Two closely related objective about energy performance
Ngo (2019) **(Ngo, 2019)**	Cooling load	Building design, Building envelope, internal loads	ANN, CART, LR, and SVR + analysis	Single-objective Optimisation
O'Leary (2016) **(O'Leary et al., 2016)**	Energy consumption	Building envelope and weather data	Regression analysis	Single-objective Optimisation
Sadeghifam (2015) **(Sadeghifam et al., 2015)**	Cooling load	Building envelope and indoor temperature	DOE + EnergyPlus	Single-objective Optimisation
Schlueter (2018) **(Schlueter and Geyer, 2018)**	Energy performance	Building envelope + solar energy transmittance + Shading control	DOE + Graphical analysis	Single-objective Optimisation
Shen (2011) **(Shen et al., 2011)**	Thermal comfort, Energy consumption, and Coating performance	Building envelope	Graphical analysis	Three closely related objective about energy performance
Whaley (2017) **(Whaley et al., 2017)**	Energy performance and Cost estimation of energy improvement	Building envelope and climatic data	FirstRate + Graphical analysis	Two-objective Optimisation
Wright (2002) **(Wright et al., 2002)**	Energy cost and Thermal comfort	HVAC system settings	GA + Graphical analysis	Two-objective Optimisation

Table 4.1 - Comparison of reviewed literature on building energy optimisation, Continued.

Yu (2019) **(Yu et al., 2020)**	**Thermal load**	**Building data and weather data**	**NARX-ANN + Graphical analysis**	**Single-objective Optimisation**
Yu (2014) **(Yu et al., 2015)**	Energy performance and Thermal comfort	Building design and building envelope	GA-Back-Propagation network + NSGA-II	Two-objective Optimisation
Zheng (2017) **(Zheng et al., 2017)**	Thermal load	Outdoor temperature and electricity consumption	Graphical analysis + Regression analysis	Single-objective Optimisation

As shown in **Table 4.1**, different building design parameters are already discussed and optimised in the literature, although many of these articles focus on use of meta-heuristics such as Genetic Algorithms (GA). In this work, a multi-objective optimisation method applying mixed-integer non-linear programming (MINLP) approach is presented to obtain optimal design solutions in terms of selection of building materials and building construction systems. To do so, it is necessary to connect the optimisation model to a building information model (BIM), which involves collecting building data to simulate the building operations accurately (Monetti et al., 2015). The application of the techniques adopted in this work can be compared to other recent articles that utilise relevant information from case study analysis. For example, (O’ Donovan et al., 2019) presented room-level air temperature predictions in a net-zero energy building. The authors compared two different approaches to model both occupancy schedules and opening control strategies. Data related to occupation and occupant interaction were collected manually. In a more recent paper, (O’ Donovan et al., 2021) presented a simulation method to determine the comfort resilience of ten passive cooling control strategies. The authors used theoretical ventilation with one opening per façade and combined natural ventilation and solar shading during the analysis. This article proves that the best scenarios considering comfort and energy are those that combined multiple control interventions.

Other relevant articles discuss in depth the optimisation of several parameters related to buildings. For instance, (Pilechiha et al., 2020) optimised the design of office windows. The work focused on the quality of view, daylight, and energy efficiency based on window characteristics and window-to-wall ratio. The authors only examined the configuration of window systems for office buildings’ designs. (Wang et al., 2020)examined the impact of natural ventilation and architectural window design of a residential building via optimising energy consumption and thermal comfort. The work however did not evaluate different building materials. (Giouri et al., 2020) used multi-objective optimisation to understand better the impact of design decisions towards zero energy buildings. The building properties examined were the window-to-wall ratio, the wall U-value, the glazing construction U-value, the glazing g-value, and the airtightness. However, the study did not examine the impact of different material choices for the building.

(Pathirana et al., 2019) studied the effect of shape, zones, orientation, and WWR (window-to-wall ratio) on the lighting energy requirement and the thermal comfort of naturally ventilated residential buildings. However, the study did not optimise the selection of materials via mathematical programming. (Chen et al., 2016) adopted a passive design strategy and developed a multi-objective optimisation model considering thermal comfort, lighting quality, and ventilation. Some of the parameters adopted were the building orientation, thermal resistance and specific heat of the external wall, window-to-ground ratio, and infiltration air.

Based on the literature reviewed, it is clear that there is a gap in the use of operational research techniques to help guide decision-makers and policymakers on the best combination of building materials and building systems to enhance the passive design performance of a building, while minimising economic cost of construction. Specifically, to the authors' best knowledge, there is a lack of use of a MINLP approach to optimise the choice of materials and building systems for various elements of a building, such that daylighting, heat gain and net present value costs of the building are optimised.

4.2.1 Building Energy Policy

Governments' energy policies and measures play a crucial role in minimising operational energy consumption. Many countries have already set regulatory targets to achieve low or zero energy consumption in the coming decades (J. Wang et al., 2020). However, there is still an annual increase in operating energy in many countries. For example, Brazil's electricity consumption has increased by an average of 4.4% per year over the past two decades (Agora Energiewende & Instituto E+ Diálogos Energéticos, 2019). Without public policy intervention, the country could triple its energy consumption by 2050.

Concerning Australia, which is the country adopted in the case study of this work, the Government established minimum energy performance requirements for residential buildings in the 1990s by creating a Nationwide House Energy Rating Scheme (NatHERS) (Moore et al., 2019), which integrates the National Construction Code (NCC) minimum building energy efficiency requirements. The NatHERS (Nationwide House Energy Rating Scheme) assessment predicts the amount of heating and cooling a building will need to stay comfortable all year round and converts the value into a star rating, varying from 1 to 10 stars (most efficient). NatHERS energy performance requirements have become an integral part of Australia's National Building Code since 2003 (Hurlimann et al., 2018).

Nonetheless, there is evidence that the housing market rarely exceeds minimum regulatory standards in Australia, and it is the same in other countries (Australian Energy Market Operator Limited (AEMO), 2018). Some works in the literature have focused on evaluating these data. For example, O'Leary et al. (O'Leary et al., 2016) investigated Australian houses' energy performance and compared NatHERS modelling against measured household energy consumption. The results showed that higher-star houses use less heating and cooling energy than lower-rated houses. On average, the 7.5-star houses of a specific place in Australia used 60% less of the heating and cooling energy demanded by homes built over a decade earlier. Whaley et al. (Whaley et al., 2017) evaluated the cost-benefit of revitalising six existing houses in South Australia with FirstRate software. These houses were constructed before the adoption of NatHERS. The renovations could bring older houses up from star ratings of 1-3 to the current minimum performance of 6, which reduced the demand for heating and cooling devices.

4.3 METHOD

4.3.1 Energy-efficient buildings

A representation of the heat flow and energy make up of a building is shown in **Figure 4.1**. As can be noticed, a significant proportion of energy in buildings is expended on lighting, cooling and heating. In hot climates, heat gain imposes a major load on the HVAC systems, which need to maintain cool temperatures to compensate for the heat flows indoor via the exterior walls, roof, floors, ceiling, and windows. The building's lighting generates internal heat that can raise the indoor temperature to unpleasant levels (Almeida and Martins, 2014). Typically, heat gain across a building's envelope occurs due to convection and solar heat (Tao et al., 2020). For cold climates, heat loss from a building's envelope poses a challenge in terms of satisfying the thermal heating comfort required by the building's occupants, which again imposes large loads on the HVAC system. As such, it seems vital to optimise the building's envelope through appropriate material selection such that heat gain/loss is minimised while ensuring an energy-efficient building design that minimises lighting needed via maximising daylighting through windows. In this study, the mathematical optimisation model proposed focuses on heat gain and daylighting, given these are imperative objectives to achieve in the majority of Australian cities. However, the framework can be easily expanded to cover heat loss in cold climates.

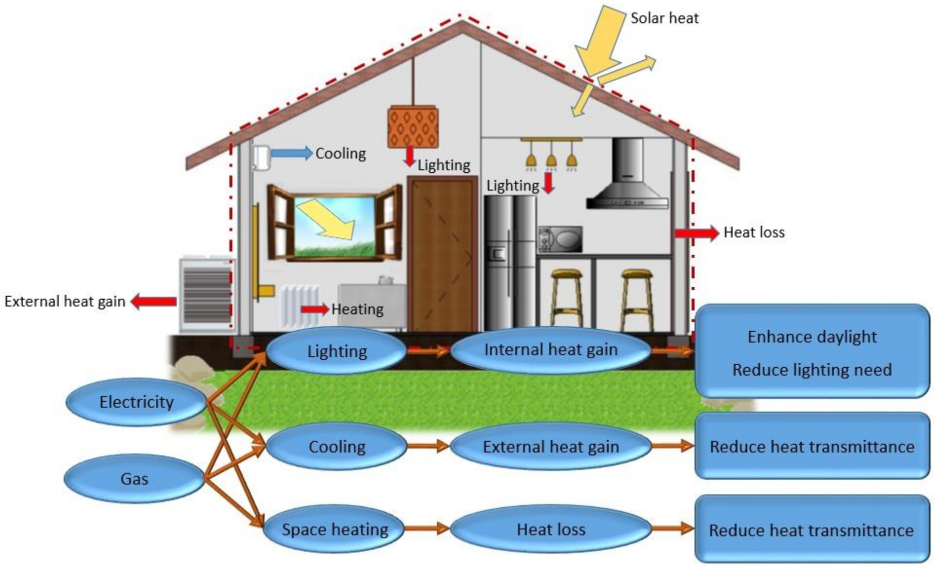


Figure 4.1 - Representation of heat flow in a building and with its energy system

4.3.2 Proposed framework

The framework for the research method adopted in this study is shown in **Figure 4.2**. As a first step, a set of databases needs to be generated from possible materials that will be adopted for the following classes of building element categories: i) Windows (including glazing); ii) Doors; iii) Flooring; iv) Exterior walls and interior finishes; and v) Roof and Ceiling. **Figure 4.3** defines some important descriptions that will be used in this study, namely building space, element category, building component systems.

The databases will encompass the system associated with each material (i.e., for walls, the various layers making up the wall), the economic cost of each alternative, the reflectance associated with the interior finishes of walls, floors and ceilings, the glazing options, U-value of the element alternatives, initial costs of each material alternative, maintenance costs associated with each material alternative and the replacement time period associated with each material, lumen output per lighting to be used for the space and the lighting requirements for illuminating each space in the building.

A building Information Model (BIM) of the project is then generated to estimate the areas of the element categories, the sky angle visible from the windows of the building and the average indoor and outdoor temperatures for the building (based on the location of the project). The databases are then feed into the BIM model to allow for any easy integration and access to relevant data for each building element.

For the Assessment Module of the framework, a multi-objective MINLP mathematical programming approach is adopted whereby a model is formulated to minimise heat gain in the building, maximise daylighting and minimise the net present value of costs. The choice of multiple objectives to be optimised is due to the conflicting nature of the objectives and their relevance in the energy design of a building. For example, if heat gain is minimised without consideration for daylighting and economic costs, it is possible to end with a solution that minimises the window sizes and the lumen produced by lighting fixtures, though economic costs and daylighting would be neglected. As such, an integrated approach is adopted with the utilisation of multi-objective optimisation to ensure a realistic solution.

Once the objective functions are formulated, a set of constraints delineating the problem's feasible region is devised. The constraints represent realistic restrictions and regulations in place in reality; for instance, the National Construction Code in Australia requires windows to be at least 10% of the associated space's floor area (Australian Institute of Building, 2016). This can be formulated as a constraint in the model to ensure that the solutions produced comply with regulations.

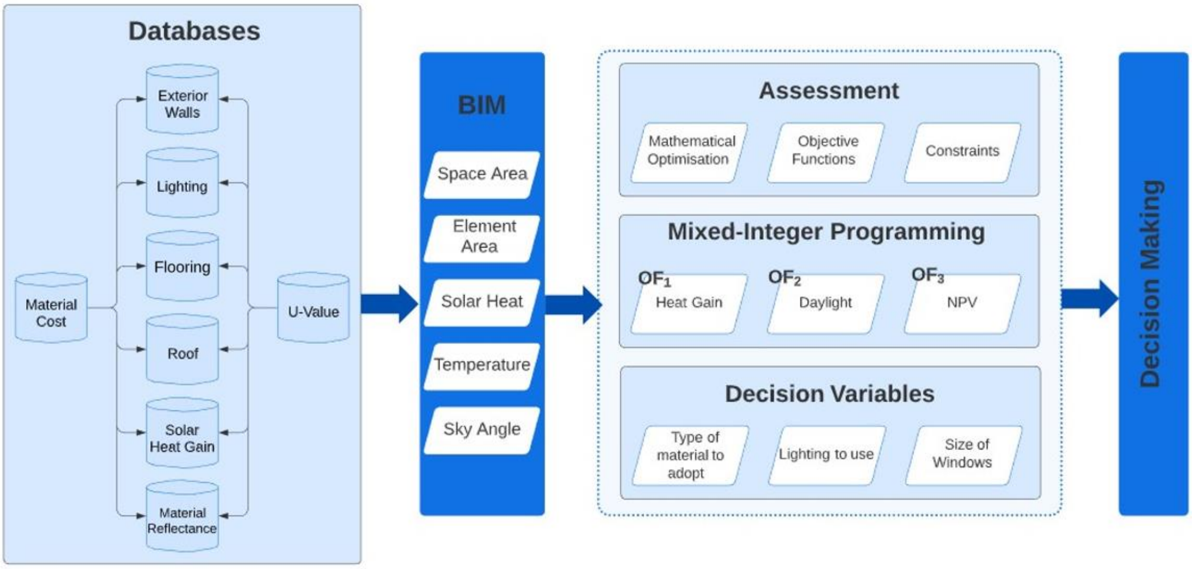


Figure 4.2 - Overall framework proposed in this study

In order to formulate the objective functions and constraints, a number of relevant decision variables (i.e. variables that are optimised) need to be defined. For this study, the following decisions variables are optimised: i) type of material adopted for each element in the element categories set; ii) the lighting to use for each space in the building; iii) the widows' size to adopt in each space.

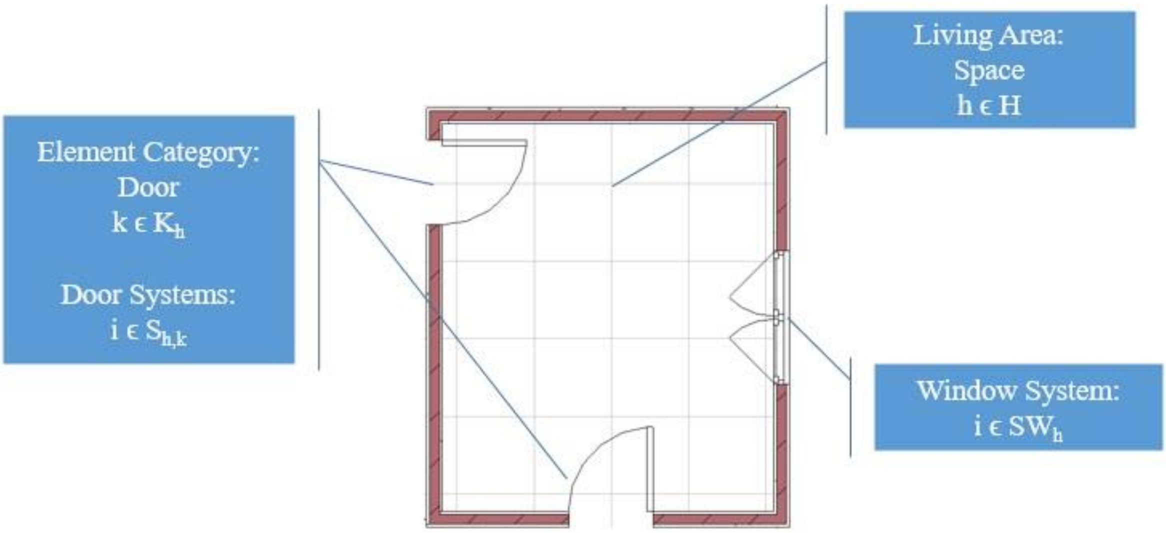


Figure 4.3 - Schematic description of terms used in the mathematical model

The final module in the framework is the Decision-Making Module, where optimised solutions are displayed for decision-makers to choose the best solution that suits their goals.

4.3.3 Mathematical Model

4.3.3.1 Notation

Table 4.2 denotes the notation that is adopted in the mathematical optimisation model.

Table 4.2 - Summary of mathematical notation

Notation	**Description**
Objective functions	
$\boldsymbol{OF1}$	Objective function 1: Maximise daylight in the building
$\boldsymbol{OF2}$	Objective function 2: Minimise net present value of total costs associated with material selection
$\boldsymbol{OF3}$	Objective function 2: Minimise heat gain due to convection, solar heat and internal light heat
Sets	
$\boldsymbol{k \in H}$	Set of spaces in the building
$\boldsymbol{k \in K_h}$	Set of building element categories (excluding windows) applicable for space h
$\boldsymbol{i \in S_{hk}}$	Set of building systems (excluding windows) applicable to category k in space h
$\boldsymbol{j \in J_{hk}}$	Set of building elements (excluding windows) belonging to category k in space h
$\boldsymbol{i \in SW}$	Set of window systems to choose from
$\boldsymbol{j \in JW_h}$	Set of window elements belonging to space h
Parameters	
$\boldsymbol{CC_{hki}}$	Parameter, indicating initial cost associated with building system i belonging to category k in space h
$\boldsymbol{OM_{hki}}$	Parameter, indicating maintenance cost associated with building system i belonging to category k in space h
$\boldsymbol{\gamma}$	Parameter, indicating discount factor
$\boldsymbol{n_{hki}}$	Parameter, indicating number of years before a maintenance is due
$\boldsymbol{wc_i}$	Parameter, indicating the initial cost of window system i
$\boldsymbol{OMW_i}$	Parameter, indicating the maintenance cost of window system i
$\boldsymbol{UV_{hki}}$	Parameter, indicating the U-value associated with building system i belonging to category k in space h
$\boldsymbol{A_{hkj}}$	Parameter, indicating the area of element j belonging to category k in space h
$\boldsymbol{\Delta T}$	Parameter, indicating Difference between outdoor and indoor temperature
$\boldsymbol{UVW_i}$	Parameter, indicating the U-value of window system i
$\boldsymbol{\varpi_L}$	Parameter, indicating the total wattage associated with light system l
$\boldsymbol{UF}$	Parameter, indicating the utilization factor of all the lights in the building

Table 4.2 - Summary of mathematical notation, Continued.

$\boldsymbol{AF}$	Parameter, indicating the allowance factor of all the lights in the building
$\tilde{N}_{\boldsymbol{hl}}$	Parameter, indicating the number of lamps required in light system l to light up space h
$\boldsymbol{TW_i}$	Parameter, indicating the window glazing transmittance factor associated with window system i
$\boldsymbol{\theta_{hj}}$	Parameter, indicating the sky angle for window j located in space h of the building
$\boldsymbol{\bar{A}_h}$	Parameter, indicating the total area of space h in the building
$\boldsymbol{M}$	Parameter, denoting a large number
$\boldsymbol{E_h}$	Parameter, indicating the lux required for each space h in the building
$\boldsymbol{\bar{\Gamma}_l}$	Parameter, indicating the lumen output associated with each single lamp of light system l
$\boldsymbol{LLF}$	Light maintenance factor
Binary variables	
$\boldsymbol{x_{hkij}}$	Binary variable, which equals 1 if element j of building element system i of category k is located in space h
$\boldsymbol{wx_{hij}}$	Binary variable, which equals 1 if window j of window system i is located in space h
$\boldsymbol{y_{hl}}$	Binary variable, which equals 1 if light system l is chosen to light up space h, and 0 otherwise
Continuous variables	
$\boldsymbol{DF_{hij}}$	Continuous variable, denotes the daylight factor associated with element j of window system $i \in SW$ located in space h
$\boldsymbol{WA_{hij}}$	Continuous variable, indicating the size of window j of window system i is located in space h
$\boldsymbol{R_h}$	Continuous variable, indicating the reflectance factor associated with space h of the building
$\boldsymbol{\Gamma_{hki}}$	Continuous variable, indicating the reflectance factor associated with building system i belonging to category k in space h

Variable types

Two main variable types define what material choice is attributed to which element in the building. Variable wx_{hij} is specified for window system choice, while variable x_{hkij} denotes the selection of appropriate materials/systems for all other elements such as floors, doors, roofs, ceilings, and exterior walls. The split in the variable is done given the separate nature of daylight and heat gain calculations that result from the elements.

Daylight Objective Function

The first objective function formulated aims to maximise the daylight in the building. **Eq. (1)** has two main terms that are multiplied with one another. DF_{hij} denotes the daylight factor associated with window j located in space h, of system type i. This variable is multiplied by the binary variable wx_{hij}, which equals 1 if window system type i is selected for window j located in space h, and 0 otherwise.

$$OF_1 = \max \sum_{j \in JW} \sum_{i \in SW} \sum_{h \in H} DF_{hij} \, . \, wx_{hij} \tag{1}$$

Economic Cost Objective Function

The second objective function formulated, Eq. (2), minimises the net present value of the initial cost and maintenance cost associated with acquiring each material type for each element category analysed. Specifically, the first term, $CC_{hki} \, . \, x_{hkij}$ considers the initial cost associated with all element categories apart from windows, the second term is the maintenance cost of all element materials/systems apart from windows $\frac{OM_{hki} \, . x_{hkij}}{(1+\gamma)^{n_i}}$, the third term $WA_{hij} \, . \, wc_j$ denotes initial window cost, and final term $\frac{OMW_i \, . wx_{hij}}{(1+\gamma)^{n_i}}$ is the maintenance cost attributed to windows. The maintenance costs of all element categories are discounted based on the discount factor gamma. For the purpose of this study, the discount period $\boldsymbol{n_{hki}}$ is assumed as five years for all materials/systems.

$$\begin{aligned} OF_2 = & \sum_j \sum_i \sum_k \sum_h CC_{hki} \, . \, x_{hkij} + \sum_h \sum_k \sum_i \sum_{n_i} \sum_j \frac{OM_{hki} \, . x_{hkij}}{(1+\gamma)^{n_{hki}}} \\ & + \sum_j \sum_i \sum_h WA_{hij} \, . \, wc_j + \sum_h \sum_i \sum_{n_i} \sum_j \frac{OMW_i \, . wx_{hij}}{(1+\gamma)^{n_{hki}}} \end{aligned} \tag{2}$$

Heat Gain Objective Function

The third objective function minimises heat gain through the building envelope. Precisely, in **Eq. (3)**, the first term $UV_{hki} \, . A_{hkj} \, . \Delta T . \, x_{hkij}$ is associated with the heat gain via conduction, while the second term $UVW_{hi} \, . WA_{hij} \, . \Delta T . \, wx_{hij}$ computes the heat gain via *solar heat*. In the third term, $\varpi_l . \, UF . \, AF . \, \tilde{N}_{lh} . \, y_{lh}$ the heat gain resulting from the lighting adopted in the building is computed by multiplying the wattage of the light ϖ_l, by the utilisation factor UF, the allowance factor AF and the number of lamps that are needed for each space in the building

$\tilde{N}_{lh}$. The variable y_{lh} denotes a binary variable which equals 1 if light system l is chosen for space h, and 0 otherwise.

$$\begin{aligned} OF_3 = & \sum_j \sum_i \sum_k \sum_h UV_{hki} \, . \, A_{hkj} \, . \, \Delta T . \, x_{hkij} \\ & + \sum_j \sum_i \sum_h UVW_{hi} \, . \, WA_{hij} \, . \, \Delta T . \, wx_{hij} \\ & + \sum_h \sum_L \varpi_l . \, UF . \, AF . \, \tilde{N}_{lh} . \, y_{lh} \end{aligned} \quad (3)$$

Constraints

Daylight factor constraints

In order to control the DF_{hij} variable in **Eq. (1)**, a number of constraints are established. First, **Eq. (4)** is formulated as the main definition of daylight factor. Specifically, the area of the window, WA_{hij} is multiplied with the transmittance value of the window TW_i and the visible sky angle θ_{hj}. This is then divided by the area of the space $\bar{A}_h$ multiplied by $1 - R_h$, where R_h represents the reflectance of the indoor surface.

$$DF_{hij} = \frac{WA_{hij} . TW_i . \theta_{hj}}{\bar{A}_h . (1 - R_h)} \qquad \forall h \in H, i \in SW, j \in JW_h \quad (4)$$

Second, **Eq. (5)** computes the reflectance of the indoor space, R_h, by computing an average of all reflectance values of the inner surface of the ceiling, walls, floors and doors.

$$R_h = \frac{\sum_j \sum_k \sum_h \Gamma_{hki} \, . \, x_{hkij}}{\sum_{h,k,i,j} x_{hkij}} \quad \forall \, h \in H \quad (5)$$

Window constraints

For determining the windows' area, **Eq. (6)** is formulated, specifying that a window system must be chosen for window element j before its area can be determined. Here, M denotes a large number, typically set to $0.6\bar{A}_h$

$$WA_{hij} \le M \, . \, wx_{hij} \qquad \forall \, h \in H, i \in \; i \in SW, j \in JW_h \quad (6)$$

In **Eq. (7)**, the minimum window area is specified as being at least 10% of the total indoor space region, according to the National Construction Code in Australia (Australian Institute of Building, 2016).

$$WA_{hij} \geq 0.1 \, . \bar{A}_h . wx_{hij} \quad \forall \, h \in H, i \in SW, j \in JW_h \tag{7}$$

To ensure that exactly one window system is chosen for each window element in the building j, **Eq (8)** is defined.

$$\sum_{i \in SW} wx_{hij} = 1 \qquad \forall \, h, j \in JW_h \tag{8}$$

Choice of Materials for elements excluding windows

In order to ensure that for each of the walls, floors, roofs, ceiling and doors in the building, a single material type is assigned, **Eq. (9)** is defined.

$$\sum_{i \in S_{hk}} x_{hkij} = 1 \qquad \forall h \in H, k \in K_h, j \in J_{hk} \tag{9}$$

In addition, **Eq. (10)** ensures that for individual elements belonging to the same category and located within the same space in the building, the same material choice is specified. This is a reasonable assumption to make since, for instance, all four walls located in a bedroom are most likely to be of the same material composition.

$$x_{hkij} = x_{hkij'} \qquad \forall h \in H, k \in K_h, i \in S_{hk}, j, j' \in J_{hk} : j < j' \tag{10}$$

Light Choice

Eq. (11) specifies that only one single light is chosen for each lighting fixture.

$$\sum_{l \in L} y_{l,h} \geq 1 \qquad \forall \, \mathrm{h} \in H \tag{11}$$

Variable domain

Eq. (12) – Eq. (16) define the domains of the variables in the model.

$$x_{hkij} \in \{0,1\} \quad h \in H, k \in K_h, i \in S_{hk}, j \in J_{hk} \tag{12}$$

$$wx_{hij} \in \{0,1\} \quad \forall h \in H, i \in SW\ j \in JW_h \tag{13}$$

$$y_{lh} \in \{0,1\} \quad \forall\, l \in L,\ h \in H \tag{14}$$

$$R_h \quad \forall h \in H \tag{15}$$

$$WA_{hij} \geq 0 \qquad \forall h \in H, i \in SW\ j \in JW_h \tag{16}$$

4.3.4 Multi-objective Solution Approach

In order to solve the model proposed, an exact solution method was applied. Solutions that are yielded from meta-heuristic algorithms such as NSGA do not guarantee the optimality of the solution and were thus avoided (Gendreau and Potvin, 2010). The model presented can be solved by optimising each objective function separately. For cases where it is desired to solve all the objectives simultaneously, goal programming can be implemented. A representation of the workflow involved to solve the model defined in **Figure 4.4**.

First, a BIM model of the building is utilised as a digital representation and information repository for the project. The materials, construction building systems and glazing systems for all building elements are compiled in a database, and this is then linked with each of the associated elements in BIM. The algorithm then generates a list of elements and their potential corresponding material properties from BIM, and this is stored in a CSV file. At the same time, the MINLP is coded in the algebraic modelling system AMPL (Robert Fourer et al., 2015); the BIM file is used to construct the model for each of the spaces in the building, and an AMPL mod file is produced. BIM is also used to construct the accompanying AMPL data files, while the run files are generated after embedding the goal programming approach, which is described in the next section.

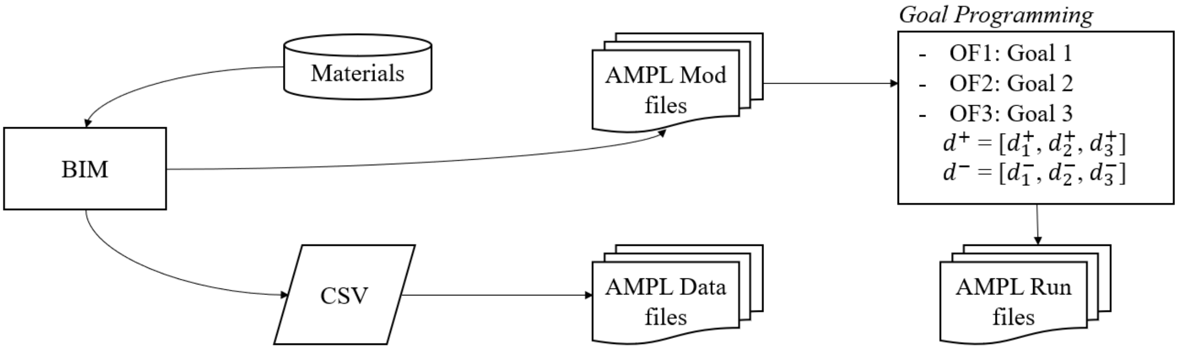


Figure 4.4 - Solution flow chart demonstrating the algorithm implemented in Python

4.3.4.1 Goal Programming

The classification of solution approaches for solving multi-objective optimisation problems is based on two main categories, namely generating methods and preference-based methods (Rangaiah and Petriciolet, 2013). For generation methods, the decision-maker does not play a role in the solution pool generated for the multi-objective problem and is only involved in selecting one choice from the range of generated solutions. On the other hand, preference-based methods utilise input from a decision-maker to generate the most applicable solution for the problem solved. One fundamental strategy for solving multi-objective optimisation problems classified as a preference-based method is goal programming. Goal programming is defined as an a priori method involving the transformation of the multi-objective optimisation problem into a single objective one via assigning goal levels to each of the objective functions involved. The aim is to produce a solution such that all aspirations set for each of the objectives are met. This study implements goal programming as the solution method as it is the most utilised approach for solving multi-objective optimisation problems in the literature and in practice (Chang, 2011).

For each of the objective functions, a goal is defined; all goals are grouped in a vector $[Goal_1, Goal_2, Goal_3]$. Following that, a number of continuous nonnegative variables are defined, d^+ and d^- which represent the positive and negative deviation of each objective function value from the goals defined. The resultant problem is then formulated such that each objective function becomes a constraint with its corresponding goal, and a new objective function is defined that minimises $d^+ + d^-$.

4.4 CASE STUDY

Two case studies are examined to validate the applicability of the MINLP model. The first case study is a granny flat with two bedrooms, one bathroom, a laundry and a living room with a kitchen, located in Sydney. The second case study is a commercial building with two floors and nine office spaces per floor; each floor's size is roughly 315 m^2. The three-dimensional views and the floor plans of both projects are shown in **Figure 4.5**. In both case studies, it was desired to select the appropriate materials and construction building systems associated with the following elements: ceiling, roof, floor, windows, doors and exterior walls. Both projects were modelled in Autodesk Revit, with data integrated and extracted to create the required AMPL files using Python as the programming language. The model was run on Microsoft Windows 10 operating system, with an Intel core i9 processor at 2.4 GHz and 32 GB of RAM. SCIP was adopted as the global optimisation solver, where instances are solved with a gap of 0 (Vigerske & Gleixner, 2018).

Figure 4.5 - 3D view and floor plan of A) residential building; and B) commercial building

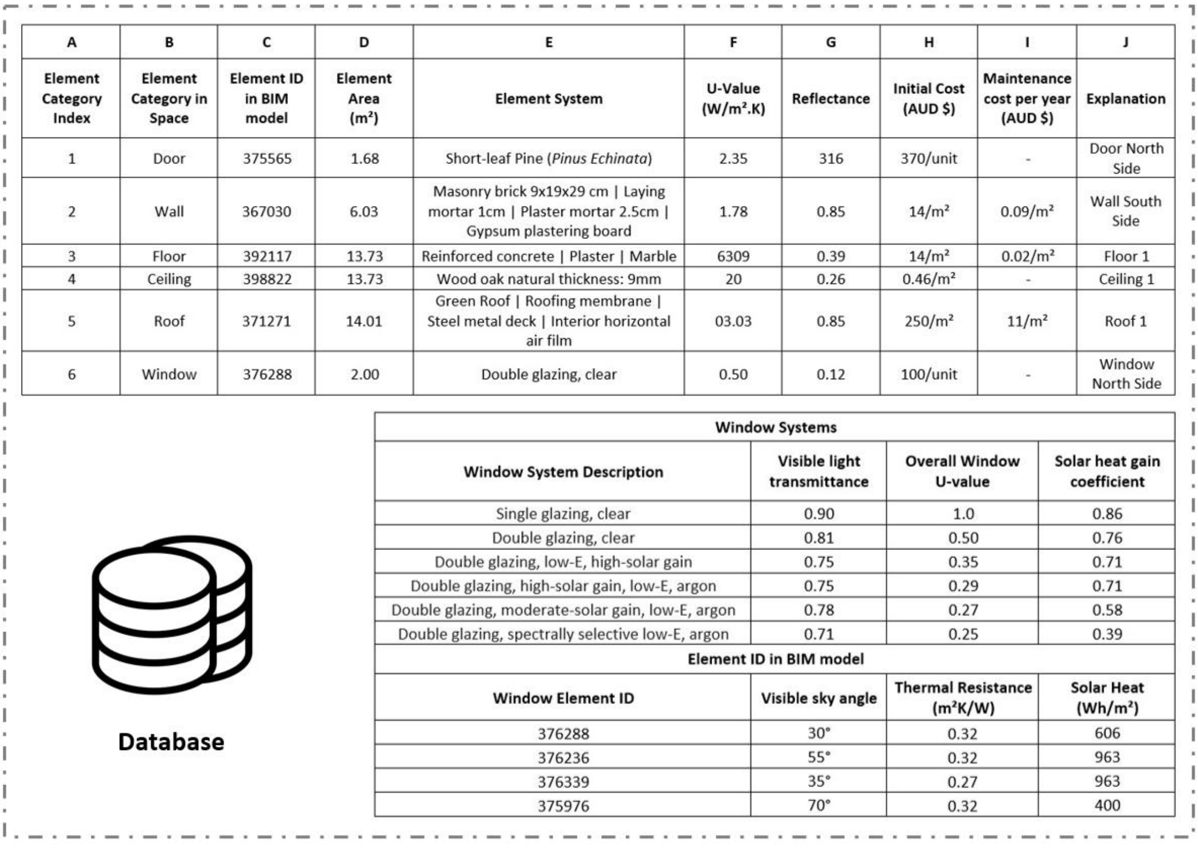
A database consisting of more than 250 materials and construction building systems was obtained from the industry partner, containing information about the physical and thermal properties of the products used, the glazing type of windows and the cost involved with purchase and maintenance. A snapshot of the database is shown in **Figure 4.6** to maintain the discussion's brevity. During the modelling process, physical and thermal information about the building materials used were added from the database into Autodesk Revit to supplement already existing data of building elements. The project's location and the weather station that should be considered for obtaining climatic data were defined. In this way, it was possible to generate simulations of daylighting and solar analysis. For solar analysis purposes, Insight was adopted, which uses the EnergyPlus heat balance method via cloud-based rendering service (Garcia et al., 2018). An example of one of the solar simulations performed to generate the solar heat at each side of the building is illustrated in **Figure 4.7**.

An experienced engineer (12 years' experience) was asked to decide on the materials and building systems to adopt for each of the building elements (to be adopted as the baseline model). Appendix A contains information about the thermal loads for the cases analysed, along with a list of input data for both cases. In total, there were 228 and 694 variables, and 229 and 1732 constraints for Case A and Case B respectively. Optimising the heat gain objective function required the largest computation time (40 s for Case A and 85 s for Case B). On the other hand, optimizing the NPV cost required the least solving time (3 s for Case A and 10 s for Case B).

In order to generate the sets H, Kh, Shk and Jhk, it was necessary to code the space and building elements; an example of how this was done for Case A is shown in **Figure 4.8**. The results generated from running the MINLP are shown in **Figure 4.9**, where the experienced engineer's solution is contrasted with that of the optimization model. As can be noticed from Fig. 9A, for the granny flat (Case A), almost a 33% improvement in daylight measure is noticed when comparing the optimised solution with that of the experienced engineer. On the other hand, for the same case study, the cost and heat gain are improved by 17% and 30%, respectively (**Figure 4.9B and C** respectively) when adopting the optimised approach.

For Case B, more significant improvements are realised due to adopting the optimisation algorithm; there is a 43% improvement in daylight, a 23% improvement in cost and a 39% in heat gain that results from the adopted materials. Even though these results are case specific, with the comparison outcome dependent on the engineer used in the study, the optimisation algorithm will always produce an optimised solution that is difficult for humans to achieve due to the combinatorial nature of the problem (García Sánchez, 2022). The case study thus highlights potential in improving the material choices and construction building systems made by engineers and architects, via use of the MINLP to yield more energy-efficient buildings.

To demonstrate the benefit of considering a multi-objective optimisation approach, the results yielded via goal programming are contrasted with a single objective optimisation approach, displayed in **Table 4.3**. Goals that were set relied on achieving the objective values for single objective optimisation. As shown in **Table 4.3**, most of the results for the objective functions optimized were within ±16% from optimum value of the respective single objective function values. Another point to emphasise is that a trade-off between the objective functions exists, and it is best to adopt a multi-objective optimisation method to solve the problem.



A	B	C	D	E	F	G	H	I	J
Element Category Index	**Element Category in Space**	**Element ID in BIM model**	**Element Area (m^2)**	**Element System**	**U-Value ($W/m^2.K$)**	**Reflectance**	**Initial Cost (AUD $)**	**Maintenance cost per year (AUD $)**	**Explanation**
1	Door	375565	1.68	Short-leaf Pine (*Pinus Echinata*)	2.35	316	370/unit	-	Door North Side
2	Wall	367030	6.03	Masonry brick 9x19x29 cm | Laying mortar 1cm | Plaster mortar 2.5cm | Gypsum plastering board	1.78	0.85	$14/m^2$	$0.09/m^2$	Wall South Side
3	Floor	392117	13.73	Reinforced concrete | Plaster | Marble	6309	0.39	$14/m^2$	$0.02/m^2$	Floor 1
4	Ceiling	398822	13.73	Wood oak natural thickness: 9mm	20	0.26	$0.46/m^2$	-	Ceiling 1
5	Roof	371271	14.01	Green Roof | Roofing membrane | Steel metal deck | Interior horizontal air film	03.03	0.85	$250/m^2$	$11/m^2$	Roof 1
6	Window	376288	2.00	Double glazing, clear	0.50	0.12	100/unit	-	Window North Side

Window Systems			
Window System Description	**Visible light transmittance**	**Overall Window U-value**	**Solar heat gain coefficient**
Single glazing, clear	0.90	1.0	0.86
Double glazing, clear	0.81	0.50	0.76
Double glazing, low-E, high-solar gain	0.75	0.35	0.71
Double glazing, high-solar gain, low-E, argon	0.75	0.29	0.71
Double glazing, moderate-solar gain, low-E, argon	0.78	0.27	0.58
Double glazing, spectrally selective low-E, argon	0.71	0.25	0.39
Element ID in BIM model			
Window Element ID	**Visible sky angle**	**Thermal Resistance (m^2K/W)**	**Solar Heat (Wh/m^2)**
376288	30°	0.32	606
376236	55°	0.32	963
376339	35°	0.27	963
375976	70°	0.32	400

Figure 4.6 - A snapshot of the database of materials and their associated properties, along with building energy performance parameters derived from BIM.

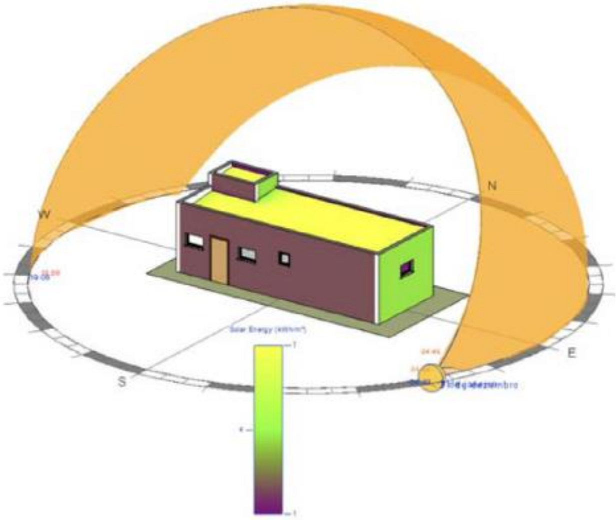


Figure 4.7 - Solar analysis performed on Autodesk Revit for the hottest day of the year in Sydney, Australia

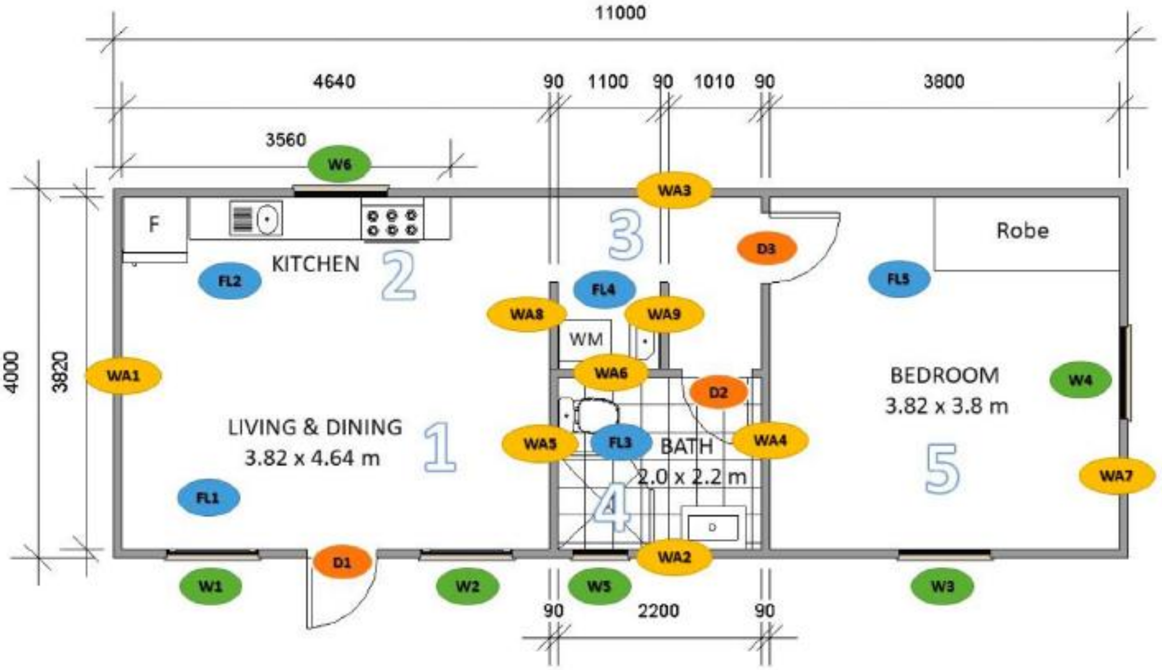
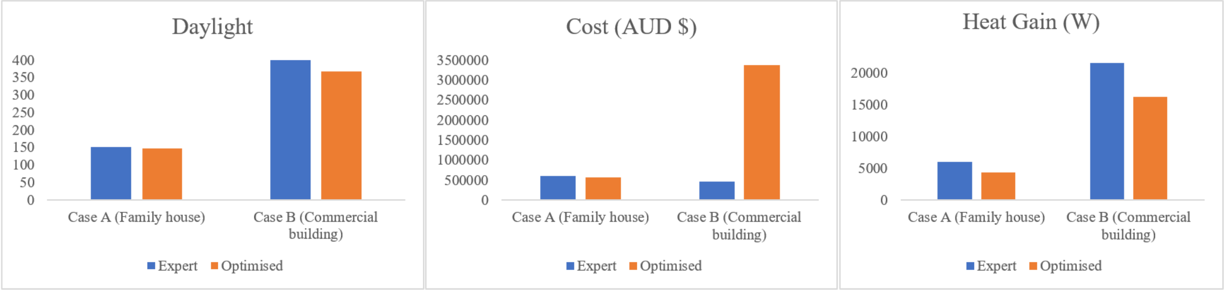


Figure 4.8 - An example of the coding adopted for the element types for creating the sets for Case A [WA:; FL: Floors; D: Doors; W: Windows; CE (not shown): Ceiling]

Table 4.3 - Goal programming solution vs. single objective

	Goal programming		**Single objective**	
	Case A	Case B	Case A	Case B
OF1: Daylight	4	13.9	4.5	16.6
OF2: Cost	70424.76	286320.2	59682	255643
OF3: Heat gain	7067	26727.7	6254	24079



A **B** **C**

Figure 4.9 - Comparing expert's solution with the optimised solution obtained via MINLP for A) Daylight; B) Cost; C) Heat Gain

4.5 DISCUSSION

The application of the proposed mathematical model to the case studies in the previous section reveals some interesting insight. First, the importance of using operational research techniques when it comes to selecting appropriate materials for a project can be demonstrated via the following example: assume a building where materials need to be decided for 4 main elements, namely a floor, a wall, a door, and a roof. Assuming the availability of 6 systems for each of the elements listed previously, a total of 1296 combinations need to be examined by the decision maker, a task which is very tedious and time consuming. As projects increase in size, the element numbers will increase, and the combinations that need to be examined will increase exponentially. Second, the use of a mathematical programming approach is more effective contrasted with a human decision-maker. Mathematical optimisation has been proven to be effective in studies that have looked at window size (Zhai et al., 2019), design of low-energy buildings (Longo et al., 2019), and building geometry (Fang & Cho, 2019).

Looking at other studies in the literature that utilised a mathematical programming approach for building design, GHG emissions of the entire community can be reduced by up to 76% at a cost increase of 3% via optimal retrofit scenario selection for buildings (Wu et al., 2017). In (Risbeck et al., 2017), a 9.7% improvement in operational planning of HVAC systems in commercial buildings is realised via use of mixed integer programming, over heuristics. A significant proportion of studies that optimise building parameters related to geometry, windows or material selection tend to adopt genetic algorithm, whose solution cannot be guaranteed to be optimal, rather than an exact approach such as MINLP. The MINLP presented in this study reported improvements in building design that were up to 39%, 43% and 23%

better in daylighting, cost and heat gain, respectively, compared to a human decision-maker. Results obtained are case-specific in nature, thus for various building types and sizes, different daylight, cost, and heat gain improvements will be yielded. In addition, different decision-makers might produce solutions that can vary in how far or close they are from the optimal solution. It is, however, likely that as the size of the building increase, so will the improvements realised from adopting the optimisation algorithm; as the instance size grows, more building elements will be present, and so more materials and construction building systems need to be assigned, which will be combinatorial and thus challenging for any experienced engineer to surpass the results of the optimisation algorithm.

The main contribution of this work is in proposing the novel mathematical model that is hoped to support decision-makers when it comes to selecting buildings that perform well in terms of heat gain, and daylight, and that are cost effective at the same time. The presented approach in this study offers great potential for policymaking regarding material selection for the building industry. Specifically, an emphasis needs to be placed on the process used to choose appropriate building materials and glazing types to minimise building heat gain while maximising daylighting for effective energy management of the building sec-tor. Regulators can develop tools and applications based on the multi-objective optimisation model presented in this work. With the growing government investment in energy efficiency, it is expected that the databases on national building materials will be more readily available and reliable and that it will further facilitate the application of research methods as presented in this article. The decision-making process can thus be facilitated by permitting a more significant number of material alternatives to be tested. This is the great advantage of using mathematical modelling since a wide range of materials can simultaneously be tested for energy efficiency. It is important to note that the mathematical optimisation model can be applied to any building case study, irrespective of location.

Several limitations exist in this study. First, there may be a discrepancy between the total projected and actual energy consumption in buildings (Geraldi and Ghisi, 2020). This is because the thermal load of a building depends not only on the climate, the envelope, and the building systems adopted but also on occupant behaviour, which was not considered in this research. Second, the entire lifecycle of a building’s energy cycle was not studied. Third, since the problem examined is combinatorial in nature, there will be limitations in terms of the ability of the algorithm to obtain a solution in reasonable time for large instances. The MINLP approach is likely not to scale effectively with increased instance size. This is where further developments in terms of decomposition approach that enhance the solving capacity of optimisation algorithms needs to be further examined. These are areas that the authors will be focussing on in their future works.

4.6 CONCLUSION FOR CHAPTER 4

Cost-effective reductions in thermal heat gain via building envelopes, along with maximising the daylighting that a building requires, can be achieved if an optimised choice of materials and construction building systems is conducted. In this study, a mixed integer non-linear programming problem was formulated and solved to enhance the daylighting, net present value cost, and heat gain of buildings. To make the material selection process more comprehensive, this study takes into account the initial cost and the maintenance costs associated with the materials utilised. A solution approach based on the use of goal programming whose input is generated from BIM and is transferred into an algebraic language was coded in Python.

The capacity of the solution method was demonstrated via two realistic case studies. The solution demonstrates that the daylighting, cost and heat gain associated with each building is highly dependent on an optimised selection of materials and construction building systems for each of the elements in the building. Results showed that via use of an optimisation approach, heat gain in the building drops down by up to 34% for the case study solved, while daylighting increases by 11% in some instances, which lead to significant energy savings when contrasted with a solution proposed by an expert engineer. An important implication from the proposed method is regarding the potential of integrating the proposed optimisation approach with regulations for enforcing energy saving policies in building designs through developing smartphone applications and software that optimise material and building system selections based on the mathematical model proposed.

Future studies will focus on three main aspects: (i) enhancing the applicability of the model to large instances via use of decomposition approaches; (ii) examine the impact of the model when contrasted with other heuristic and meta-heuristic approaches; (iii) Inclusion of building code requirements in the model for the selection and design of building elements.

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5 EXAMINING THE USE OF BIM-BASED DIGITAL TWINS IN CONSTRUCTION: ANALYSIS OF KEY THEMES TO ACHIEVE A SUSTAINABLE BUILT ENVIRONMENT

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ABSTRACT

Pursuing more sustainable construction projects has become a global priority. The construction industry is responsible for the massive use of freshwater resources and fossil fuels and several other environmental impacts, in addition to considerably affecting the gross domestic product (GDP) worldwide. In this vein, it is crucial to find strategies to develop a sustainable built environment based on a triple-bottom-line (TBL) strategy, concurrently considering environmental, social, and economic factors. The application of BIM-based Digital Twins seems to offer a tenable solution for overcoming the challenges related to achieving sustainability in the construction and real estate sectors. This concept is associated with developing a digital counterpart of the facility to assist the decision-making process throughout its life cycle, using real-time data and an actual connection between the 3D digital model and the physical asset. A BIM-based Digital Twin can be advantageous for a single building or an entire city and is, therefore, often related to the development of smart cities. This study's novelty is presenting a structured literature review that defines the most recent developments in BIM-based Digital Twin applications for the real estate and construction sectors regarding sustainability goals. Based on this literature review, the authors present a discussion of how the knowledge acquired so far can be diffused into the built environment.

Keywords:

Sustainable Construction; Real Estate; Building Information Modelling (BIM); Digital Twin.

5.1 INTRODUCTION

The Digital Twin concept has been discussed in many industries and sectors for years. In the construction and real estate sectors, this concept still presents divergences in its definition and application. A Digital Twin is generally understood as a series of accurate digital models representing a physical asset's real-time characteristics, state, and behaviour during its entire lifespan [1]. Regarding the application of this concept into the built environment, the benefits of employing a Digital Twin of a building include real-time data visualisation, ongoing asset monitoring, and the growth of self-learning skills [2].

Evidence suggests that the Building Information Modelling (BIM) methodology is a crucial step in developing Digital Twins in the built environment. The BIM methodology represents an innovative work philosophy with which a physical asset may be planned, designed, built and managed within a single 3-D model, allowing a highly collaborative process that involves architects, engineers, real estate developers, builders, manufacturers, and other construction experts. When using BIM-based tools, practitioners can generate a 3-D parametric and data-rich representation of the facility [3]. Therefore, all information related to the physical asset can be centralised within the 3-D digital model, which facilitates performing different types of computer simulations and improves the decision-making process throughout the whole building life cycle.

Nonetheless, the current state of BIM only offers the asset’s static data and is typically incompatible with the Internet of Things (IoT) integration [4]. When evaluating the application of BIM-based Digital Twins in the built environment, it is expected to use 3-D digital BIM models as the first step towards creating a digital counterpart of the facility that is updated with real-time data, in addition to assessing the performance of what-if scenarios. In this context, the application of BIM-based Digital Twins seems to offer a tenable solution for overcoming the challenges related to developing a smart and sustainable built environment.

Several difficulties arise when attempting to develop sustainable building projects, including the need to manage a sizable amount of data [5], communication failures due to the presence of numerous professionals involved in the process [6] and information loss throughout the whole building life cycle [7]. Using a BIM-based Digital Twin has excellent power to solve these problems, and some practices are already discussed in the literature. However, research on this topic continues mainly at a theoretical level, and therefore, much still needs to be studied for the BIM-based Digital Twin application to be efficient in developing sustainable buildings.

The novelty of this paper is related to the presentation of a structured and comprehensive literature review, defining the state-of-the-art of BIM-based Digital Twin applications to achieve sustainability in the construction and real estate sectors. A discussion of how the knowledge acquired so far can be diffused into the built environment is presented.

5.2 MATERIALS AND METHODS

A thorough literature review is suggested to provide a state-of-the-art of BIM-based Digital Twin applications to achieve sustainability in the construction and real estate sectors. This literature review is expected to allow a profound discussion about this subject, with the definition of potential improvements and applications. The following steps were performed in conducting this method:

Stage 1 consists of searching for relevant articles and filtering them based on the topics that need to be addressed. Stage 2 represents the descriptive analysis of the selected papers using text data mining and clustering. Stage 3 involves the evaluation of the filtered documents. Finally, stage 4 defines potential BIM-based Digital Twin applications to improve construction and real estate sustainability.

5.2.1 Stage 1

In order to determine the most recent research status on the BIM-based Digital Twin concept in the built environment, a bibliometric survey was carried out in November 2022, considering SciVerse Scopus as the search engine due to its comprehensive and user-friendly interface. The first search formula was determined as follows: (("BIM" or "Building Information Model" or "Building Information Modeling" or “Building Information Modelling") AND ("Digital Twin" or “data-driven simulation” or “cyber-physical system” or “cyber-physical building”)). These keywords were chosen to incorporate more papers related to this research’s theme since the use of the expression “Digital Twin” is recent in the construction industry. Then, ("Sustainability" or "Sustainable") keywords were also added to the search formula. Only English-language materials were taken into account during this process.

As shown in **Figure 5.1**, 427 papers were found involving the use of the BIM methodology and the Digital Twin concept, with 174 journal articles, 179 conference papers, 29 review articles, 23 conference reviews and 22 book chapters. Unfortunately, BIM-based

Digital Twin applications for achieving sustainability still need to be discussed more in the literature, which is proven from only 51 papers on this topic. After title and abstract screening, 22 articles were filtered to be evaluated. Based on this screening, it was clear that many articles cite keywords such as sustainability, only referring to possibilities for future research and not addressing this issue in depth.

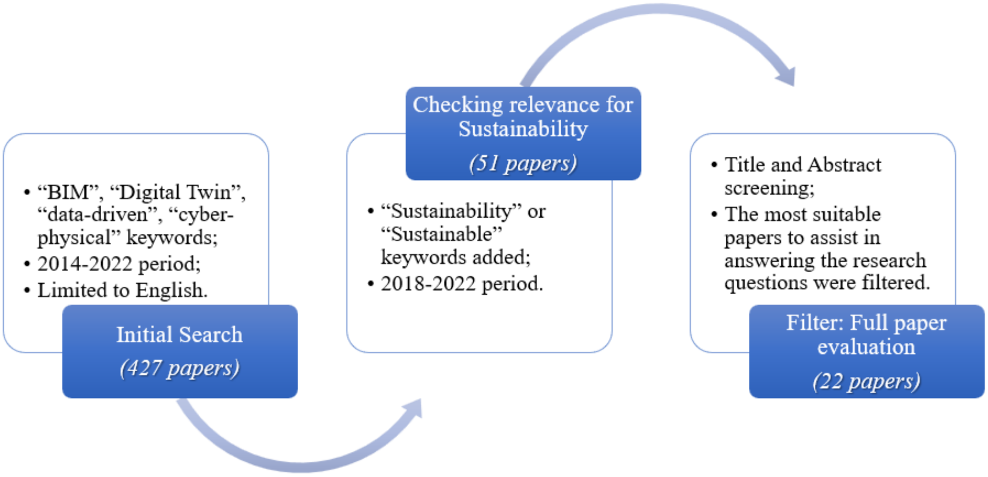

Figure 5.1 - The process adopted in this study for the literature review

5.2.2 Stage 2

A descriptive analysis of the filtered documents was conducted in order to comprehend the nature of the research themes that have developed around BIM-based Digital Twin and sustainability. The country that has published more papers in this research field is the United Kingdom, with twelve publications, followed by China and Italy, with nine publications each, as seen in **Figure 5.2**.

Figure 5.2 - Territories that published the most in this field of research

Besides, a co-occurrence analysis was carried out in order to determine the relatedness of keywords based on the number of documents in which they occur together. VOSViewer software was used for this, with a minimum number of occurrences of a keyword determined as five. As shown in Figure 5.3, the Digital Twin concept in the construction industry is closely linked to the BIM methodology and typically involves using the Internet of Things (IoT) concept, Blockchain technology and Geographic Information Systems (GIS). In turn, when analysing the keyword cluster involving Digital Twin and sustainable development, highlighted in red in **Figure 5.3**, it is possible to observe that most papers are related to Smart City and life cycle assessments. Finally, the term “literature review” appeared several times in the title and abstract screening, which makes sense since most publications on the topic are limited to the theoretical level so far.

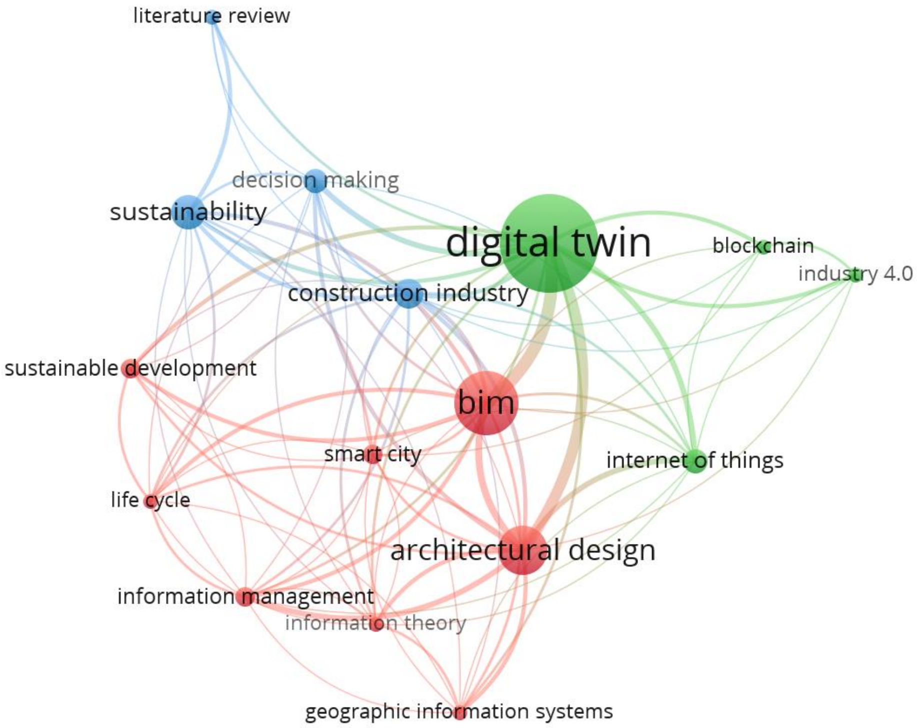

Figure 5.3 - Co-occurrence analysis regarding the analysed papers

5.2.3 Stage 3

The evaluation of the papers is summarised in **Table 5.1**, categorised according to the pillar of sustainability that each paper is most related to (i.e., environment, society, and economy).

Table 5.1 - Most significant publications found in the literature review search

Environmental Pillar		
Ref.	**Source**	**Evaluation of the study**
[8]	Journal: Waste Management	From a point cloud collection using scanners, the authors developed a BIM model of buildings in Hong Kong. They generated a Digital Twin-based demolition plan and the waste transportation plan.
[9]	Journal: Sustainability (Switzerland)	This paper discusses the usage of a BIM-based digital twin for sustainability assessment via the presentation of a case study that encompasses the design and use phases with a primary focus on energy efficiency.
[10]	Journal: Frontiers in Sustainable Cities	This paper reviews the application of Digital Twin to improve sustainability in Positive Energy Districts (PED), divided into three categories: improved BIM model, semantic platforms, and AI-enabled tools for data analysis.
[11]	Journal: Frontiers in Built Environment	Despite the Digital Twin concept being mentioned in the title and abstract, the article presents a case study only focused on BIM. The authors focused on the carbon emission calculation in the railway station building.
[12]	Journal: Energies	The authors present a case study on optimising maintenance processes and energy efficiency to transform port areas into Zero Energy Districts.
[13]	Journal: Buildings	This paper presents a theoretical framework for adopting environmentally sustainable blockchain-based Digital Twins using several BIM dimensions.
[14]	Journal: Energies	This paper suggests a workflow to use BIM to perform what-if tests to determine the energy consumption of a building. The authors briefly addressed Digital Twin, and the case study did not use real-time data.
[15]	Journal: Sustainability (Switzerland)	The case study based on sustainability and vulnerability audit for subway stations does not use real-time data or a real connection with the physical asset, representing only a digital shadow and not a Digital Twin.
[16]	Journal: Sustainability (Switzerland)	The paper presents a systematic mixed-review methodology on the use of BIM to improve building end-of-life decision-making. The authors briefly cite the use of Digital Twin throughout the paper.
Economic Pillar		
Ref.	**Source**	**Evaluation of the study**
[17]	Journal of Cleaner Production	This paper discusses the real-time monitoring of cost and security in prefabricated construction with the purpose of influencing sustainability.
Environmental and Social Pillars		
Ref.	**Source**	**Evaluation of the study**
[18]	Journal: Sustainability (Switzerland)	This paper explores the concept of a smart university campus and discusses the ability of universities to contribute to local sustainability projects. A University in Barcelona, Spain, was used as a case study, in which environmental aspects and occupants' emotions were monitored.
[19]	Journal: Urban Planning	This paper discusses the application of Digital Twin in large panel system (LPS) retrofit projects. It presents an analytical tool for community consultation that enables virtual testing of technical and urban solutions.

Table 5.1 - Most significant publications found in the literature review search, Continued.

[20]	Journal: WIT Transactions on the Built Environment	The paper presents a case study related to the renovation of Italy's national entity for electricity. For this, a Digital Twin was used based on cloud computing, artificial intelligence, machine learning, big data and BIM. The main goal was achieving an active collaboration of all the parties involved.
Environmental and Economic Pillars		
Ref.	**Source**	**Evaluation of the study**
[21]	Journal: Journal of Cleaner Production	The authors focus on visualising detailed materials information, schedule, predicted budgets and sustainable carbon footprint over the whole life cycle of railway infrastructures. Still, they do not discuss the connection with the physical asset, thus only partially addressing the Digital Twin concept.
[22]	Journal: Frontiers in Built Environment	The authors propose a Digital Twin framework for light rail track slab systems that can perform real-time lifecycle assessments with a focus on cost, carbon emission, and energy consumption. The case study presented did not show a real connection with the physical asset.
Papers in which no sustainability pillar was profoundly addressed		
Ref.	**Source**	**Evaluation of the study**
[23]	Journal: Computers and Electrical Engineering	The authors propose a BIM-IoT-based framework to provide a Digital Twin platform limited to real-time monitoring and construction schedule management of road construction. The framework validity was proved on a real pavement construction site. Sensor devices were installed on the rollers before compaction. Sustainability aspects should have been profoundly addressed.
[24]	Journal: Sustainable Cities and Society	This study discusses the application of Digital Twin to develop smart cities. For this, the authors propose the integration of BIM and geographic information system (GIS) data. However, the possibility of achieving sustainable standards in smart cities should have been discussed more.
[25]	Journal: Sustainability (Switzerland)	This paper analyses the utilisation of BIM for lean purposes through a literature review and identifies dominant clusters of research topics. The Digital Twin concept is briefly discussed.
[26]	Journal of Physics: Conference Series	The paper elaborates on transforming the current static digital city into a digital twin city with dynamic online interactivity. The authors propose capturing panoramic images and videos daily to manage and monitor work progress more precisely.
[27]	Journal: Buildings	The paper presents a theoretical framework for integrating IoT, BIM, Digital Twin and blockchain throughout projects' lifecycles.
[28]	Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences	The authors discuss some challenges to the Digital Twin application in urban planning and management and compare this concept to City Information Model (CIM). The authors conducted a scientific literature review, analysing 68 scientific documents. This investigation's conclusions show various definitions of CIM and Digital Twin in the literature, and these concepts remain fuzzy. Sustainable aspects were briefly mentioned.

Table 5.1 - Most significant publications found in the literature review search, Continued.

[29]	International Conference on Smart Infrastructure and Construction 2019	This paper proposes developing a Digital Twin model, using the Cambridge campus as a case study and presenting a system architecture for this implementation at a building level. The authors used IoT sensors to acquire data from the assets, which were then integrated into the digital model. BIM tools were utilised to generate the three-dimensional model.

5.2.4 Stage 4

Based on the literature review, it is possible to list potential BIM-based Digital Twin applications to achieve sustainable outcomes in the construction and real estate sectors. The idea of developing a digital counterpart of the facility to assist the decision-making process can be advantageous for a single building, a quarter or an entire city. On the one hand, a BIM-based Digital Twin may be related to the smart networking and control of domestic appliances, locking mechanisms, heating systems, and other electronic apparatus and IoT sensors for domestic use. On the other hand, this idea can be extrapolated, as developing a Smart City would be the next obvious step in this approach.

Regarding achieving a sustainable built environment, a BIM-based Digital Twin can contribute to the three main pillars of sustainability: environment, society and economy. The idea of physical and digital assets coexisting and feeding each other with data and information has an enormous impact on different areas, including a better provision of energy and water, people’s health and education, and the overall operational cost of buildings, thus affecting environmental, social and economic aspects. Some papers have already presented specific goals for using BIM-based Digital Twins to achieve sustainable outcomes, such as maximising the recycling and reuse of demolition waste [8] and developing Zero Energy Districts [12]. However, the literature review search found no paper simultaneously addressing the three pillars of sustainability through the application of BIM-based Digital Twin.

Another illustration of how BIM-based Digital Twins can improve sustainability, which has not been deeply discussed in the literature so far, is the application intended to improve the Life Cycle Sustainability Assessment (LCSA). This methodology consists of an interdisciplinary framework that integrates the triple dimension of sustainability by investigating the economic, social, and environmental impacts throughout a product’s whole life cycle. This framework can be applied to buildings and infrastructures. Real estate developers, architects, engineers and decision-makers can utilise building LCSA to offer a documentary foundation of the sustainable decisions employed. The data monitoring directly impacts the validity of the findings reported in an LCSA. With a BIM-based Digital Twin, all information and data will be stored in a centralised way, with the possibility of collaborative work in real-time, and this can facilitate more sustainable results.

5.3 DISCUSSION

The BIM-based Digital Twin concept emerges as a facilitator for professionals associated with the built environment to achieve specific results, including sustainability outcomes. However, there is still much to be debated and encouraged among experts to utilise this concept in real projects, given that the construction and real estate sectors have historically been hesitant to accept technological innovations. Along with investments made by the Government and businesses, a fundamental paradigm shift is also necessary among professionals and researchers associated with construction.

Several papers found in the literature review search discuss the use of Digital Twin but do not present an in-depth explanation of its application in building projects. Besides, several articles use the expression “Digital Twin”, but in practice, they do not apply this concept since they do not use real-time data or a real connection with the physical asset, representing only a digital shadow of the facility and not a Digital Twin. The terms BIM and Digital Twin should not be used interchangeably, as a pure BIM model usually involves only static data related to the building. However, it is undeniable that creating a Digital Twin of a construction asset becomes much easier when starting from a 3-D BIM model, which already has several geometric and semantic information in a centralised way.

In turn, a challenging issue that arises when a BIM model is updated to a Digital Twin is related to the interoperability requirements in the BIM domain. The Industry Foundation Classes (IFC) data model is a standardised and digital way to describe the building data by codifying the identity, attributes, semantics, and relationships of objects used in a BIM project. However, when utilising real-time data to create a Digital Twin, a massive amount of information relies on semantic web technologies. In this context, ontology representations of the IFC schema are necessary to structure better the interoperability of BIM-based tools, such as the Web Ontology Language (OWL) for IFC called ifcOWL. This language intends to exploit data distribution, extensibility of data, querying, and reasoning, but its application has been briefly addressed in the literature so far.

It is essential to point out that, in order to utilise Digital Twins to improve sustainable outcomes of physical facilities, it is imperative that information and control systems be applied, in addition to the insertion of a new organisation structure. Some articles have already started to address this need when discussing the integration of BIM-based Digital Twins with Blockchain. Blockchain is a Distributed Ledger Technology that forms a database with interconnected data blocks cryptographically protected against tampering [30]. Both the construction industry and real estate can benefit enormously from Blockchain since this information technology can offer a tamper-proof solution throughout the information supervision of building processes. Nevertheless, an in-depth discussion about new organisational structures needs to be raised in the literature, and real case studies need to be evaluated in this domain.

Ultimately, communication between Academia and the public and private sectors must be intensified. The possibilities for applying BIM-based Digital Twins to achieve a sustainable built environment are numerous and directly depend on advances in research in this regard. From the literature review presented in this research, many applications are still discussed preliminarily and still at the theoretical level. Therefore, innovative research that works collaboratively with researchers, the Government, industry leaders, and other organisations seems crucial and urgent.

5.4 CONCLUSION FOR CHAPTER 5

Through a literature review, this study proposed a discussion on applying the BIM-based Digital Twin concept to achieve sustainability. In this context, it is essential to highlight that sustainability is based on a triple-bottom-line approach comprising environmental, social, and economic aspects. The impacts of these three categories must be considered balanced. From the method proposed in this article, 427 documents were found related to using BIM-based Digital Twin in the built environment. Nonetheless, only 51 documents were related to sustainability in some way, among which only 22 papers proved to be helpful for the discussion proposed in this work.

Unfortunately, the discussion of this topic in the literature is still immature, concentrated at the conceptual and theoretical levels. Among the few articles that present applications in case studies, some misuse the Digital Twin expression, not using real-time data or a real connection with the physical asset. However, with the growing rate of studies published in this field, the research will advance in a direction that will encourage BIM-based Digital Twin applications to achieve sustainability in the construction and real estate sectors, simultaneously considering the three sustainability pillars.

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6 IMPROVING DECISION-MAKING OF BUILDING PROJECTS TOWARDS A SMART AND SUSTAINABLE FUTURE VIA THE INTEGRATION OF LIFE CYCLE SUSTAINABILITY ASSESSMENT AND BIM-BASED DIGITAL TWIN

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ABSTRACT

Buildings play a critical role in sustainability due to the massive environmental, social, and economic impacts generated throughout their life cycles. Although the search for sustainability is growing globally, developing sustainable building projects continues to be a challenging task linked to multiple criteria. The Life Cycle Sustainability Assessment (LCSA) methodology appears as a possible solution to meet the requirements of a sustainable built environment by adopting a lifecycle perspective and simultaneously accounting for all sustainability pillars. Nevertheless, compared to other assets, a building sustainability assessment requires extensive data processing. In this context, integrating LCSA and BIM-based Digital Twin from the early design stages of building projects, when it is possible to ensure maximum control over project decisions, to the building's end-of-life seems appropriate. A building Digital Twin can improve real-time data visualisation and develop self-learning building capabilities. Besides, the digital model can facilitate the simulations and data collection required to generate detailed results on impacts during sustainability assessments. Therefore, this study aims to extrapolate the discussion on integrating BIM and LCSA by adding the Digital Twin concept throughout the whole building’s life cycle and inserting real-time data, thus transforming the application into a dynamic LCSA. To this end, this study proposes a conceptual framework with the steps to integrate LCSA and BIM-based Digital Twin throughout the entire building lifecycle to improve the design, fabrication, construction, operation and deconstruction processes. The advantages and challenges of using these concepts to achieve a smart and sustainable construction industry are discussed.

Keywords:
BIM, Decision-making, Digital Twin, Life Cycle Sustainability Assessment, Sustainable Construction.

6.1 INTRODUCTION

Seeking more sustainable projects in construction has become a primary goal worldwide. The importance of this becomes clear when analysing the massive number of environmental impacts the construction industry generates annually, with significant consumption of freshwater resources (Mannan and Al-Ghamdi, 2020) and fossil energy (Gao et al., 2022). Moreover, this industry is responsible for influencing multiple social and economic aspects, directly contributing to the global employment of labour (Saka et al., 2021) and the global gross domestic product (GDP) (Fu et al., 2022). As a result, it is critical to look for ways to create more sustainable construction projects based on a triple-bottom-line (TBL) strategy, simultaneously considering environmental, social, and economic aspects.

In this vein, Life Cycle Sustainability Assessment (LCSA) emerged as a comprehensive methodology based on the life cycle thinking approach that considers that all phases in a product's life cycle cause environmental impacts and socio-economic consequences, and to achieve sustainability, all these issues need to be assessed. When applied to building projects, the life cycle is understood by all the existing phases, from the raw material extraction to the building demolition and the consequent disposal, reuse or recycling of materials and components. Nonetheless, several difficulties emerge when analysing the whole life cycle of a building due to the large number of data that must be considered.

Therefore, it seems appropriate to utilise tools and technologies that assist in lifecycle data collection, simulations, and real-time data visualisation required to generate detailed results on impacts during the building sustainability assessment. On the one hand, a commonly utilised concept in the construction scenario is Building Information Modelling (BIM), which refers to a working methodology based on a digital representation of the facility and information exchange, allowing the collaboration of all stakeholders involved and making data accessible throughout the project's life cycle (Kubicki et al., 2019). On the other hand, the current state of BIM only provides static data of building projects and is incompatible with the Internet of Things (IoT) integration, a tough challenge currently discussed in the literature (Boje et al., 2020).

IoT adoption is critical for accurate building sustainability assessments since IoT allows the digital building model to be updated in real-time, enabling the performance of what-if scenarios to be assessed (Hunhevicz et al., 2022). Building static data, which describes time-invariant features and parameters, are unquestionably significant for assessing sustainability (Yuan et al., 2021). Nevertheless, in order to evaluate the long-term viability of constructed assets thoroughly, various time-dependent aspects must be considered, such as the effects of seasonal fluctuation, changes in user behaviour, climatic conditions, and the evolution of the physical structure through time. In this context, the concept of a BIM-based Digital Twin arises. Conceptually, a Digital Twin (DT) is a virtual representation of an asset, serving as the real-time digital counterpart of the physical object or system during its life cycle (Kuo et al., 2021). From the construction standpoint, DT may be viewed as a new approach to improving existing building processes through cyber-physical synchronicity (Boje et al., 2020).

Of particular relevance in this research is the improvement of the decision-making process of building projects during the whole life cycle of the asset. In the literature, very few studies utilise DTs to improve the three pillars of sustainability based on a life-cycle perspective. Specifically, this study aims to benefit the project decisions from the early design stages of building projects, when it is possible to ensure maximum control over project decisions, until the building's end of life, when several choices must be carefully analysed to minimise the generation of solid waste, the formation of dust and the emission of greenhouse gases, in addition to the importance of assessing the socio-economic aspects associated with it.

Therefore, this study elaborates on viable ways to integrate the LCSA methodology with a BIM-based digital twin to benefit the decision-making process of building projects throughout their whole life cycle regarding sustainability aspects. This research culminates in presenting a conceptual framework that intends to critically discuss how this integration can benefit sustainability in construction and contribute to the advancement of research in this field.

6.2 METHODOLOGY

This study contributes to achieving a smart and sustainable built environment by proposing the integration of different methodologies and tools, considering the three pillars of sustainability in the proposed assessments. Besides, environmental, economic and social assessments of a building are considered here as an evolutionary process that spans the entire life cycle of the building, i.e., the analyses must occur from the early design stages to the construction's end of life.

In order to achieve this, a literature review of the techniques and methodologies to be employed, namely LCSA, BIM, and digital twin, is proposed. This literature review is expected to allow a profound discussion about this subject, with the definition of potential improvements and applications. As a result, the literature view will introduce the broad notions related to these topics and the role they can play in developing a sustainable built environment. The following steps were performed in conducting this method:

Stage 1 consists of searching for relevant articles and filtering them based on the topics that need to be addressed. Stage 2 involves the evaluation of the filtered documents. Stage 3 defines potential BIM-based Digital Twin applications to improve the LCSA application in the construction industry. Finally, by establishing the challenges and future exploratory directions associated with integrating BIM-based digital twins and the LCSA methodology, Stage 4 aims to propose an exemplary method for integrating the analysed topics throughout the entire life cycle of the building, using real-time data in the whole process. Therefore, a conceptual framework will be presented with the steps to be taken to achieve this outcome.

6.3 LITERATURE REVIEW

In order to determine the most recent research status on the integration of BIM-based Digital Twin and LCSA in the built environment, a bibliometric survey was carried out in October 2022, using SciVerse Scopus as the search engine due to its comprehensive and user-friendly interface. The search formula was determined as shown in **Figure 6.1**. Only English-language materials were considered during this process. Unfortunately, BIM-based Digital Twin applications integrated with LCSA are still not much discussed in the literature, which is proven by only eight papers on this topic. Therefore, it was decided to expand the search, focusing on BIM-based Digital Twin with a focus on sustainability in general. After title and abstract screening, 26 articles were filtered to be evaluated, and the conclusions are stated in the following sections of this work.

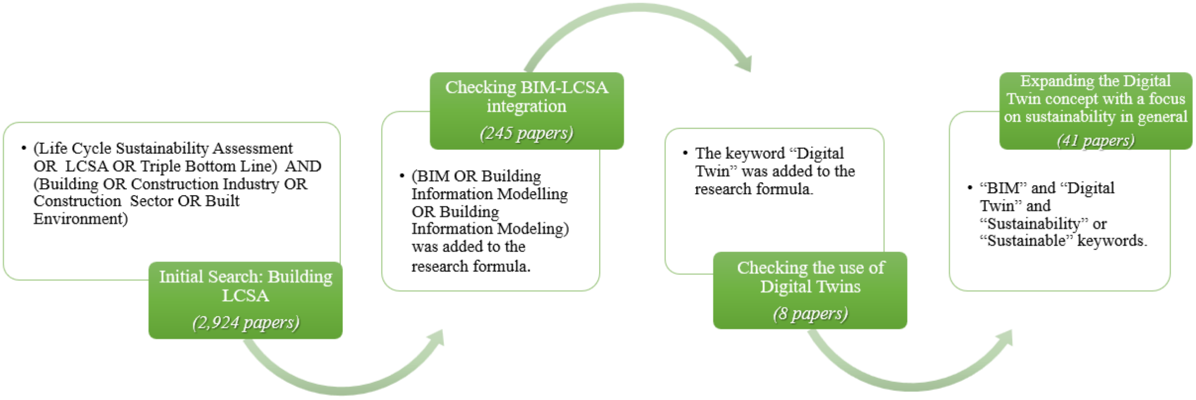

Figure 6.1 - The process adopted in this study for the literature review search

6.3.1 Life Cycle Sustainability Assessment (LCSA)

Life Cycle Sustainability Assessment (LCSA) is an interdisciplinary framework that simultaneously examines the environmental, social, and economic impacts of products and activities, thus integrating the triple dimension of sustainability. In this way, the LCSA methodology consists of three major components: i) Life Cycle Assessment (LCA), a technique that represents the environmental dimension; ii) Social Life Cycle Assessment (S-LCA), which describes the social dimension; and iii) Life Cycle Costing (LCC), a technique related to the economic dimension. These three techniques follow the same methodological structure, based on the ISO 14040 standard, which is composed of four steps: Goal and Scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation (ISO, 2006).

Although the LCA, LCC and S-LCA techniques have similarities, significant differences in each methodology have been identified in the literature (Llatas et al., 2020). For example, not all the social and economic indicators can be estimated as a function of the study's functional unit, resulting in a significant drawback in result interpretation (Fauzi et al., 2019). In this context, numerous issues concerning the full use of LCSA remain unanswered, and many studies continue to execute only a portion of the evaluation. This is primarily due to the varying maturity levels of the three sustainability pillars, which impedes the widespread adoption of LCSA.

Researchers have focused on applying decision-making techniques such as LCSA during the early stages of building design. Nonetheless, when considering using this methodology in different stages of the building's life cycle, a new challenge arises related to the lack of temporal information in the assessments. It becomes necessary to consider a dynamic LCSA approach in which a dynamic life cycle inventory (D-LCI) is considered, along with time-dependent characterisation factors, to assess the impacts by considering real-time impact scores for any time horizon (Levasseur et al., 2010). This is still very little discussed in the literature, especially when considering studies that validate this concept in building case studies.

6.3.2 Building Information Modelling (BIM)

The BIM methodology intends to centralise all building data in a single three-dimensional model, enabling multiple analyses and simulations. Besides, BIM allows practitioners to create an n-Dimensional model, making it possible to add new layers of development to the building project (Fernández-Mora et al., 2022). Thus, a BIM model can be seen as a digital building prototype containing both geometric and semantic data of building materials, components and systems.

Evidence suggests that BIM is a crucial methodology to achieve a smart and sustainable built environment and can be satisfactorily combined with Life Cycle Sustainability Assessment (LCSA). Modelling the building using a BIM platform allows the automatic generation of material quantities and the insertion of sustainability data into the digital model. This also enables simulations to be carried out of the building, which can be helpful in generating additional data for the LCSA application.

In the BIM domain, the Industry Foundation Classes (IFC) data model is utilised to guarantee software-agnostic data interoperability. IFC is a standardised and digital way of describing data in the built environment, including buildings and civil infrastructure (ISO, 2018). For this, the IFC schema codifies the identity, attributes, semantics and relationships of objects, processes and people associated with a project. Nevertheless, regarding the use of BIM as the starting point for DT implementation, robust and knowledge-oriented semantic data storage, which can be exploited by Artificial Intelligence (AI) technologies, is needed (Boje et al., 2020). In this context, a Web Ontology Language (OWL) for IFC, representing a connecting point between semantic web technologies and the IFC standard, is preferable and is called ifcOWL.

6.3.3 Digital Twin in the Construction Industry

A digital twin represents a collection of realistic models that simulates the physical asset's real-time attributes, condition, and behaviour throughout its existence (Haag and Anderl, 2018). Using a digital twin is essential in representing physical assets in a corresponding virtual environment (Lu and Brilakis, 2019). This notion has been employed in various sectors and businesses, including construction. A building digital twin is a contextual model of an entire building environment, bringing together third-party data and resulting in a dynamic digital replica that can be used to solve a wide variety of issues (Coupry et al., 2021). The benefits of using a building digital twin range from real-time data visualisation to continuous asset monitoring and the development of self-learning capabilities (Ramos et al., 2022).

Unlike BIM, which focuses on the centralisation of data and information and is typically used as a single digital shadow, a building DT can timely optimise suggestions based on the building lifecycle mirroring of current status (Peng et al., 2020). For this, digital twins of constructed assets may present different levels of complexity from design to handover, depending on the model's sophistication and the available data (Seaton et al., 2022). Several contributions of using DT in the construction sector are discussed in the literature, such as the real-time building's remote monitoring and management and the maintenance and planning estimation (Celik et al., 2021). Nevertheless, a closer look at the literature reveals some gaps and shortcomings. Although the DT concept already provides solutions to current problems in building projects, research on this subject continues mainly at a theoretical level. Several articles that apply a building DT in a case study upgraded existing modules of a BIM model to a DT system without considering real-time data, thus only partially realising a building DT (Peng et al., 2020).

Regarding sustainability assessments, some papers have already presented specific goals for using BIM-based Digital Twins, such as maximising the recycling and reuse of demolition waste (Kang et al., 2022) and developing Zero Energy Districts (Agostinelli et al., 2022). However, the application intended to improve the LCSA methodology is still briefly addressed in the literature. For example, (Tagliabue et al., 2021) discuss the usage of a BIM-based digital twin for life-cycle sustainability assessment. Still, the case study encompasses the design and operational phases with a primary focus on energy efficiency, not considering all sustainability pillars.

6.3.4 Contributions of the proposed work

This work intends to contribute to advancing the discussion on the use of BIM-based digital twins to achieve sustainable standards in construction, particularly considering a lifecycle approach based on the LCSA methodology. Therefore, the contributions of this paper are based on the presentation of a conceptual framework and a discussion intended to answer the following research questions (RQ):

(RQ1) Is it feasible to extrapolate the discussion on the integration of BIM and LCSA, typically focused exclusively on the early design stages, via the application of different levels of Digital Twins throughout the entire life cycle of the building?

(RQ2) Can a BIM-based digital twin assist in solving the LCSA limitation of typically not considering real-time information throughout the assessment, thus transforming the application into a dynamic LCSA?

6.4 CONCEPTUAL FRAMEWORK DEVELOPMENT

The conceptual framework proposed in **Figure 6.2** addresses the integration of a BIM-based digital twin and the LCSA methodology to ensure sustainability goals. For this, it will be considered that the DT model will evolve and achieve different levels of complexity depending on the available data in each stage. The lowest level will be called a BIM-based descriptive digital twin, which includes detailed information and descriptive data such as construction material characteristics. This 3D model will assist practitioners in collecting and visualising data during the concept design stage. In this phase, the LCSA is used as a decision-support tool to help choose construction materials and methods.

From the later design stages (i.e., detailed design and technical design), DT will evolve into an informative model utilised to run comprehensive building simulations. This level contains more detailed information about the project, and different strategies can be used to collect and analyse data. Some authors suggest exporting the Bill of Quantities (BoQ) from the BIM software to an LCA-specific tool or using plug-ins and add-ons to conduct the LCSA calculation in the BIM tool (Filho et al., 2022). On the other hand, some studies encourage the inclusion of environmental, economic, and social data within the BIM model, using different data sources such as Sustainable Product Declarations (SPDs) (LLatas et al., 2022). This last approach is the most supported here since it represents the evolution of the building's digital model with the centralisation of more data and information, thus transforming a digital shadow in BIM into a building's digital twin.

In turn, during the construction phase, represented in the second part of the framework, real-time data regarding the construction process must be collected and inserted into the digital counterpart of the building. Therefore, the digital model becomes a comprehensive DT, representing a bi-directional connection between the digital and the physical asset. This synchronisation allows real-time data to be used during the LCSA application, resulting in a better decision-making process and the development of a construction data repository to be used in future projects. This BIM-based comprehensive DT also allows constant monitoring and improvement of the construction process since it is possible to conduct construction simulation, virtual job site planning and safety planning using the digital twin model. Direct effects on the three pillars of sustainability could be observed, such as worker safety and the minimisation of material waste during construction.

Finally, during the post-construction, DT may be updated with static data from numerous sources, such as impact databases and data repositories from previous projects, and with dynamic data making use of IoT by installing devices and sensors to capture real-time data. Artificial intelligence (AI) technologies and machine learning can also be used to improve building assessments. Therefore, transitioning to an autonomous and connected DT is expected, reducing dependence on human interventions. Building LCSAs should be applied when renovation or maintenance works are needed, in addition to the possibility of simulating different end-of-life scenarios for the building, so that the project's decisions can follow sustainable goals and a continuous improvement in the physical building is guaranteed. The BIM-based digital twin is expected to facilitate building construction, maintenance, and management, improving sustainability through integration with LCSA.

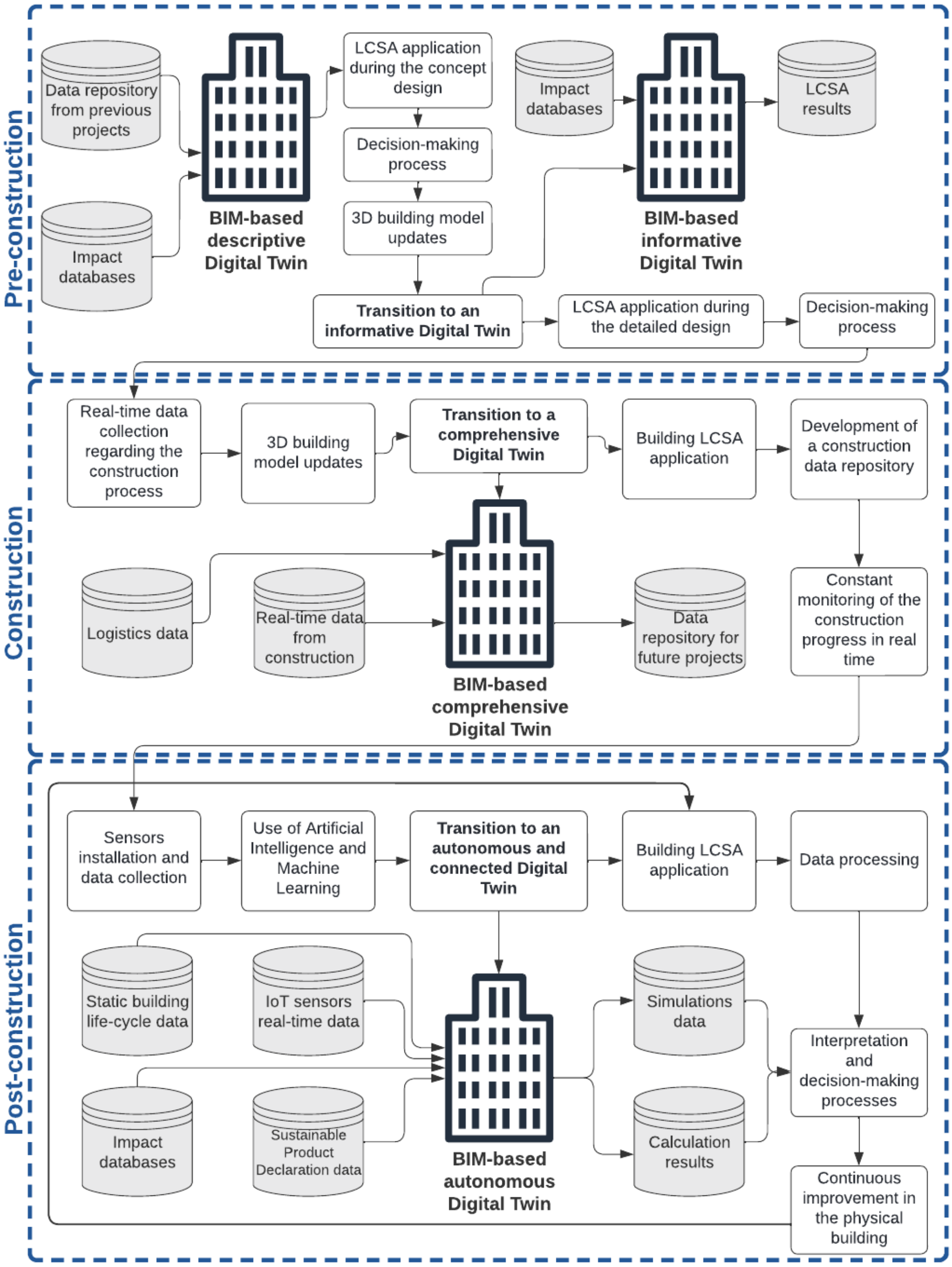

Figure 6.2 - The conceptual framework proposed in this research

6.5 FINDINGS AND DISCUSSION

Although the conversation about sustainability in construction has been gaining steam worldwide among professionals and researchers, the literature still lacks accurate and comprehensive case studies on sustainable construction. This is particularly notorious if one considers the joint assessment of the three pillars of sustainability (i.e., environmental, social, and economic). More recent studies usually focus on the generation of impacts from a particular building material or element (Sharma et al., 2022), sometimes considering only environmental aspects and not satisfying the needs of a complete and realistic sustainability assessment.

From the investigation conducted so far, key findings emerge: it is understood that the construction industry still lacks an integrated and systematised methodology for assessing the triple-bottom-line sustainability of building projects, considering the impacts generated from the extraction of raw materials to the building end-of-life phase and benefiting the decision-making process throughout the whole building lifecycle. In addition, there is still a need to develop more guidelines related to the social and economic impacts generated by construction so that the sustainability assessment encompasses the three pillars comprehensively. This is a significant research gap, directly affecting the achievement of more sustainable buildings.

In this context, the proposed framework adds to a growing corpus of research showing the steps to be taken to create an iterative building sustainability assessment. This addresses RQ1 by offering a strategy to extrapolate the discussion on BIM-LCSA integration, usually focused exclusively on the early design stages of a building project. The workflow proposed in this study demonstrates the possibility of applying LCSA during different building phases with the aid of a building digital twin. By centralising data and information in the same digital model and adopting a project management methodology focused on achieving sustainable goals, it will become much easier to carry out life cycle assessments at different stages of the building's life cycle via the application of different levels of Digital Twins.

Many researchers support the integration of BIM and lifecycle techniques during the building design stage, as at this stage, there is a great ability of stakeholders to influence the project, which decreases as the project progresses toward completion. However, the LCSA methodology is severely limited by the lack of information available at the beginning of the project. Therefore, thinking of sustainability assessment as an iterative process, which evolves along with the building, is essential. It is proposed that the LCSA results in the pre-construction phase improve design decisions and that, later, the digital model continues to be fed with real-time data so that new LCSAs can be applied and assist in the construction, renovation, and maintenance of the building. It is also expected that practitioners consider the future of individual elements and components since their impacts can be calculated and analysed through the integration of LCSA and BIM-based digital twin. Deconstruction practices should be tested and compared in order to benefit the decision-making process during the building's end of life.

In turn, one primary application that a BIM-based digital twin can play a significant role in is ensuring that the sustainability assessment of a building takes into account temporal information. As implemented in conventional LCSA, using a fixed time horizon deprives practitioners of essential information, making sustainability assessments less realistic. The proposed framework, therefore, addresses RQ2 by offering a dynamic LCSA approach to be carried out in different stages of the building. With the aid of the BIM-based digital twin, LCSAs are always expected to be based on real-time data. Using IoT sensors and devices will make it possible to collect the data automated and improve sustainability assessments. Dynamic LCSA can then be applied whenever new decisions need to be made during the building's life cycle.

6.6 CONCLUSION FOR CHAPTER 6

This paper elaborates on viable ways to integrate a BIM-based digital twin with the LCSA methodology, focusing on the sustainability assessment of buildings. This integration is proposed considering the building sustainability assessment as an iterative process, evolving from the earlier design stage to the building's end of life. Although research has illuminated the importance of combining different technologies to aid the application of LCSA to buildings, the integration of LCSA, BIM, and Digital Twin in a building remains briefly addressed in the literature. The combination of these concepts can be used to benefit the decision-making process of which materials and methods would be most suitable for construction, as well as the most appropriate decisions during construction and post-construction, considering the three pillars of sustainability in the assessments.

Ultimately, applying LCSA as an iterative process based on a digital twin of the building is strongly recommended as it helps deal with the subjectivity of choices made by the decision-makers and, therefore, offers an avenue to achieve a more sustainable built environment. The proposed integration can be advantageous throughout the information supervision of building processes, with direct effects on the three pillars of sustainability. Besides, the proposed framework allows continuous monitoring and improvement of the built asset, with real-time analyses performed. The application of LCSA in this context is very beneficial, as it becomes a dynamic approach that considers time-dependent parameters and, therefore, is much more reliable and realistic.

The limitations of this work can be stated as follows. Analysing the lifecycle sustainability of a building while considering the three pillars of sustainability is extremely difficult since it necessitates a thorough understanding of uncertainties as well as the processing of large amounts of data. As a result, several technological challenges may arise while integrating LCSA and BIM-based digital twins. Future works by the authors will focus on addressing these challenges. Besides, future research will concentrate on the practical application of this framework, with validation of its use through an actual building case study.

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7 ASSESSING THE USABILITY OF BLOCKCHAIN FOR SUSTAINABILITY: EXTENDING KEY THEMES TO THE CONSTRUCTION INDUSTRY

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ABSTRACT

Distributed Ledger Technology (DLT) emerged as an innovative computer technology capable of ensuring information security through encryption algorithms. In recent years, this technology has been discussed in different industries, including the construction sector. Although the advantages of applying DLT in construction projects are numerous, several barriers and limitations are associated with its application. The difficulties are even more exacerbated when examining the uses of DLT for achieving more sustainable buildings. In this context, this article conducts a comprehensive literature review on blockchain, the most discussed DLT technology nowadays, for sustainability, focusing on extending key applications discussed in various fields to the construction industry and real estate. The novelty of this review paper is the presentation of an in-depth discussion of what the next steps in blockchain research should be in order to integrate its applications for achieving a sustainable construction environment with cleaner production and resource use efficiency. A conceptual framework is also proposed to showcase the integration of blockchain with other applications for facilitating the goal of achieving sustainable buildings, including Building Information Modelling (BIM) and Life Cycle Sustainability Assessment (LCSA).

Keywords:
Blockchain; Distributed Ledger Technology; Sustainable Construction; Real Estate; Building Information Modelling (BIM); Life Cycle Sustainability Assessment.

7.1 INTRODUCTION

Sustainability in buildings has been widely discussed in the literature from different perspectives. The construction industry is responsible for significant environmental impacts given its high consumption rate of natural resources globally, resulting in the generation of between 2 and 3 billion tonnes of building waste a year (Jain, 2021). There is also an economic and social aspect associated with the industry, given its significant contribution to gross domestic product (GDP), representing 5-7% of the total GDP in most countries (Alaloul et al., 2021), and its employability of at least 7% of the employed population (ILO Publications, 2019). A strong association thus exists between construction and the three main pillars of sustainability, namely economy, society, and environment (Goh et al., 2020).

When trying to create sustainable building projects, several challenges arise, including the need to manage a considerable number of data (Kamali et al., 2018); the difficulty of reconciling projects from different disciplines, such as architectural, structural and mechanical (Jalal et al., 2020); the possible communication failures due to the existence of many professionals involved in the process (Safapour et al., 2020); and information loss over the building life cycle (Liu et al., 2020a). The use of Distributed Ledger Technology (DLT) provides a plausible avenue for dealing with such difficulties.

DLT refers to the technological infrastructure and protocols that allow the information transaction between peers in a decentralised way. This technology consists of a digital ledger and a distributed peer-to-peer network that forms a shared database (Teh et al., 2020), and it differs from other information systems due to four characteristics occurring in its application: decentralisation, which involves the transfer of control from a centralised entity to distributed network; security, which is guaranteed through a transaction log saved in several distributed nodes; auditability, which happens with the approval of the transaction validity by the majority of nodes; and smart execution, since the processes can be executed by smart contracts (Saberi et al., 2019).

Although there are different types of DLT in the market, the focus of the literature has been on blockchain technology. Blockchain represents an innovative DLT that improves information security and transparency by encryption algorithms (Lee, 2019). Blockchain was first introduced in 2008 by Nakamoto (Nakamoto, 2008) and applied to cryptocurrencies such as bitcoin. Since then, this concept has been widely discussed and used in several areas, including healthcare applications (Azbeg et al., 2021), food safety management (Hong et al.,

2021) and business sectors (Gomathi et al., 2021). However, blockchain application outside the finance industry is still experimental (Kshetri, 2018).

Several literature review studies on blockchain have been published. Some focus on the blockchain applicability with the Internet of Things (IoT) (Conoscenti et al., 2016), while some focus on blockchain solutions with big data (Karafiloski and Mishev, 2017). Other studies are concerned with blockchain governance, health and education (Casino et al., 2019). A comprehensive review of blockchain technology's potential to solve trust issues in a shared economy has also been presented (Hawlitschek et al., 2018).

In the built environment, some practices are already discussed in the literature that fit with blockchain or other DLT and can benefit from this application. For example, DLT can be used during the building construction stage to improve the transparency and traceability of supply chains and facilitate the various financial transactions that take place at this stage. Regarding the real estate sector, DLT can optimise property sales, streamline payments, and reduce document authentication time (C. Z. Li et al., 2021). Other issues related to legal and organisational information could be solved by applying DLT, such as knowing who is responsible for each activity's accuracy and correctness during the construction projects (Turk and Klinc, 2017).

Although some studies already discuss the blockchain application in construction, none of them has so far provided an in-depth examination of its application to achieve sustainability. Sustainability is defined as a development that meets the present needs to reconcile economic, social, and environmental aspects without compromising future generations to meet their own needs (Holden et al., 2014). Regarding the construction of buildings and civil engineering works, the sustainability concept is related to how the attributes of the activities, products or services associated with this sector contribute to the ecosystem maintenance for future generations (ISO, 2019). In this context, sustainability for individual buildings could be understood, for the purposes of this paper, as the reduction or elimination of negative environmental, economic, and social impacts throughout the design, construction and operation of a building, in addition to the achievement of cleaner production. Therefore, a sustainable building must generate less environmental waste and not indiscriminately use natural resources and human capital.

One primary application that blockchain can play a significant role in is ensuring that the sustainability assessment of a building is not tampered with by any of the parties involved in a construction project. This technology, therefore, offers a tamper-proof solution throughout the information supervision of material, production, and inspection processes of a building (X. Li et al., 2021), directly affecting the construction and real estate sectors.

The novelty of this study is based on presenting a structured and comprehensive review of the literature, defining the state-of-the-art relevant to the application of blockchain for sustainability in different sectors. An in-depth analysis of how the knowledge acquired in terms of its application can be diffused into the construction industry and real estate to achieve a sustainable industry is presented. Following the review, a conceptual framework is proposed to establish the challenges and future exploratory directions of blockchain applications to attain a sustainable built environment. Three major questions will be answered via the comprehensive literature review conducted in this study:

(Q1) What are possible blockchain applications in order to achieve sustainability?

(Q2) What are the barriers and limitations associated with blockchain applications for the construction and real estate sectors?

(Q3) What should be the next steps in blockchain research to ensure its favourable application to achieving sustainability in the built environment?

The remainder of the study is organised as follows: some background is presented in Section 2. Section 3 explains the review method implemented and presents the literature review search conducted. The evaluation of the papers and the proposed framework for integrating Blockchain in the construction industry to achieve sustainability is presented in Section 4. Finally, concluding remarks are given in Section 5.

7.2 BACKGROUND

Before defining the review methodology and evaluating the material to answer the questions addressed in this study, it is crucial to present a summarised overview of blockchain technology, the most discussed DLT among publications relevant to this work. This section is divided into the general concepts associated with blockchain and the role that blockchain technology can play in the built environment. With these concepts well established and the subsequent presentation of the literature review, the conceptual framework will be presented in Section 4.

7.2.1 What is Blockchain

Blockchain is best understood as a ledger, representing a database with interconnected blocks of data, but with the advantage of being cryptographically protected against tampering (Sanka et al., 2021). Each data block in the chain contains a pointer to the previous block, a timestamp, and a compilation of information (Estevam et al., 2021). The blockchain framework can be divided into six different layers: the data layer, responsible for the encapsulation of the underlying data; the network layer, responsible for data transmission; the consensus layer, which defines who can package the next block; the incentive layer, that function to reward the nodes that comply with their rules; the smart contract layer, which uses code to implement the blockchain algorithm; and the application layer, which encapsulates different decentralised application scenarios (Wen et al., 2021).

The decentralisation characteristic of this technology excludes the need for a trusted third party to control the resources in an application. Instead, a delegation of authority among network contributors takes place to validate transactions, reducing the risk of failures and improving the service trust (Hewa et al., 2021). The blockchain structure is composed of consecutively linked blocks, and any slight modification would represent the creation of a new structure. As such, any data tampering invalidates every consequently created block (Saxena et al., 2021). This ensures that any change in a blockchain is easily identified.

There are two types of blockchain applications: the public blockchain, also known as the permissionless blockchain, and the private (or permissioned) blockchain (Ferdous et al., 2021). The difference between these two forms of applications is whether or not a permit is needed to become part of the blockchain network and contribute to its maintenance. While the public blockchain has proven to be an excellent solution for the currency trading market, the private blockchain is becoming an institutional solution towards conducting business with transactional efficiency and management of provenance and traceability of goods in supply chains (Helliar et al., 2020). User privacy preservation can be an issue in the public blockchain, as the transparency and decentralisation characteristics make it difficult to effectively protect the users' data (Peng et al., 2020). However, privacy risks are already widely discussed in the literature, and solutions have been proposed, including centralised mixing service and off-chain payment channels, so as not to hinder practical applications (Peng et al., 2020).

Although there are numerous advantages associated with blockchain, the technology is still considered immature, creating technical challenges including scalability, usability and interoperability throughout its application (Kouhizadeh et al., 2021a). A recent study presented a list of 24 barriers faced in blockchain projects, categorised as technological, organisational, environmental or relational (Kurpjuweit et al., 2021). Data collection, implementation costs, user resistance, and regulatory conditions are among the challenges raised.

7.2.2 Blockchain application in the Built Environment

From 2017, the use of blockchain in construction projects began to be suggested, based on the perception that these projects are often collaborative and that the legal consequences in case of project failure constitute an ideal use case of the blockchain (Turk and Klinc, 2017). Blockchain is seen as a possible solution to the slow, expensive and fragile transactions in the construction industry, often connected to integrity and transparency problems (Chaveesuk et al., 2020). Therefore, this technology's ability to exchange information quickly and securely, at a lower cost, has become attractive for researchers and professionals associated with construction (Sivula et al., 2018).

Some application potentials discussed in the Built Environment include contract management (Giuda et al., 2020), Electronic Document Management (EDM) (Das et al., 2022), property management (Morena et al., 2020), and supply chain management (Lu et al., 2021), in addition to the use of blockchain with Building Information Modelling (BIM) in order to overcome the transparency problem throughout the construction project lifecycle (San et al., 2019). Other possibilities continue to emerge since blockchain has proven its capability to change construction processes (Perera et al., 2020). For instance, blockchain can be used in construction sites to reduce human error and increase the reliability of decision-making processes through smart contracts (Ciotta et al., 2021). Nevertheless, one barrier that might hamper blockchain implementation efforts in construction is that the industry is classified as one of the sectors that least adopt information technology (McKinsey & Company, 2016). Hence, many proposals still seem to be far from reality.

Among the existed blockchain platforms in the market, two of them can be applied in the construction domain: Ethereum and Hyperledger Fabric (Yang et al., 2020). In a blockchain, the consensus is the process that validates the block of transactions, and it may be implemented in different ways. Ethereum presents the proof-of-stake (PoS) consensus algorithm, while Hyperledger Fabric can work on several consensus mechanisms (Hyperledger Architecture Working and Group (WG), 2020).

In December 2018, the Institution of Civil Engineers (ICE), a professional association for civil engineers in the United Kingdom, published a report entitled “Blockchain technology in the construction industry – Digital transformation for high productivity” (Institution of Civil Engineers (ICE), 2018). Among other applications, the document discusses the use of blockchain to ensure sustainability in buildings. The report states that if all information about the materials used in construction were stored and shared using a blockchain system, it would be much easier to analyse the building's sustainability. However, Smetana et al. (Smetana et al., 2018) showed that the use of blockchain to analyse material flows in real-time is still very limited. Besides, there are still no real case studies in the literature that present and discuss its applicability.

7.3 RESEARCH METHODS

In order to address the research questions posed in this paper, a comprehensive literature review is proposed to present the state-of-the-art on blockchain applications for sustainable construction. The stages taken in this review were the following:

- **Stage 1:** Literature review search, with filtering of the articles found based on the questions to be answered;
- **Stage 2:** Descriptive analysis of the selected articles;
- **Stage 3:** Text data mining and clustering in order to classify the documents found, with subsequent evaluation of the papers;
- **Stage 4:** Definition of potential blockchain applications and perspectives to assist sustainable construction.

7.3.1 Literature Review Search

A bibliometric survey was conducted in November 2021 to reveal the latest research status on blockchain and its applications in the built environment. SciVerse Scopus was chosen as the preferred database for the search conducted in this study due to its complete and friendly interface. The entire research considered only works written in English. First, keywords related to the application of blockchain to achieve sustainability were used, regardless of whether or not these articles were linked to buildings. Then, papers that used blockchain in construction were searched. Finally, papers that applied blockchain to the built environment with a focus on sustainability were filtered. The terms “blockchain” and “digital ledger technology” have been combined with different keywords from each group specified below.

- Group 1 – Keywords related to sustainability, namely: “sustainability”, “sustainable”;
- Group 2 – Keywords related to the built environment, namely: “built environment”, “construction sector”, “construction industry”, “construction project”, “building project”, “real estate”, “real property”;
- Group 3 – Keywords related to sustainable built environment: all possible pairs between the keywords of groups 1 and 2.

Altogether, 1,384 documents were found in the surveys conducted using the three keyword groups. The stages of the review search are summarised in **Figure 7.1**. Although blockchain technology emerged in 2008, articles that met the search criteria were found to have been published from 2016 onwards.

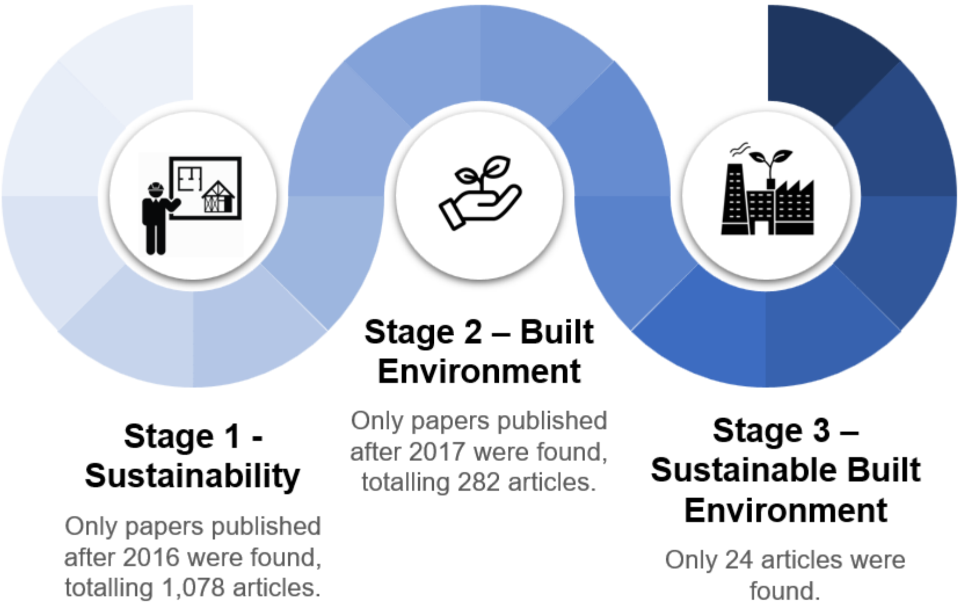

Figure 7.1 - Stages of the literature review search

7.3.2 Descriptive analysis

Considering the articles found in the literature, a descriptive analysis was carried out to understand the nature of the research themes that have evolved around blockchain and sustainability. The studies reviewed were organised by year of publication, and the results are shown in **Figure 7.2**. As can be seen from the figure, the number of publications on the application of blockchain to achieve sustainability has continuously increased in the last six years, with a significant increase from 2018. This proves that blockchain applications in construction are a fast-growing field of research. On the other hand, although the blockchain concept emerged in 2008, this technology was adopted to achieve sustainability outside the construction field only eight years later. Then, in 2017, the first discussion on blockchain applied to the construction industry emerged. One point to note is that blockchain applications for achieving more sustainable constructions are still not much discussed in the literature, as can be seen in **Figure 7.1** from the total of only 24 publications on this topic.

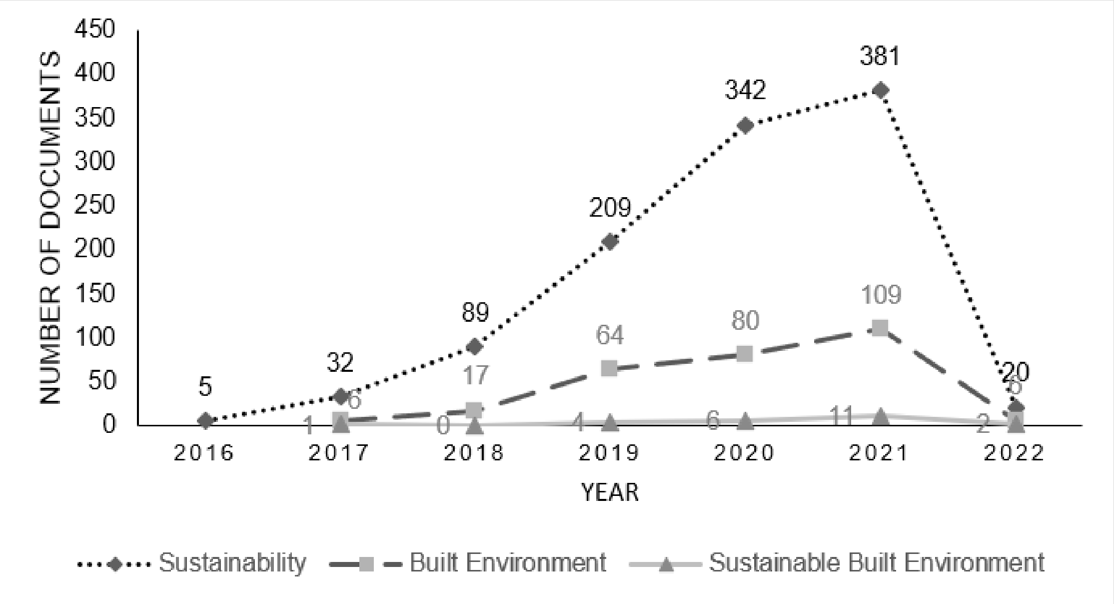

Figure 7.2 - Number of articles on blockchain published by year

Figure 7.3 displays the subject areas in which research papers on the applications of blockchain to achieve sustainability were published. As can be seen from the figure, computer science is one area that has received significant interest from academics researching blockchain. This can be explained by the fact that blockchain is a computer technology that relies on the capabilities of computer algorithms and processes involved in data authentication, consistency, and transparency assessments. It, therefore, seems logical that this technology needs to be increasingly discussed and improved from a computer science perspective. Other subject areas with high volumes of publications on blockchain include engineering, energy, business, and social sciences.

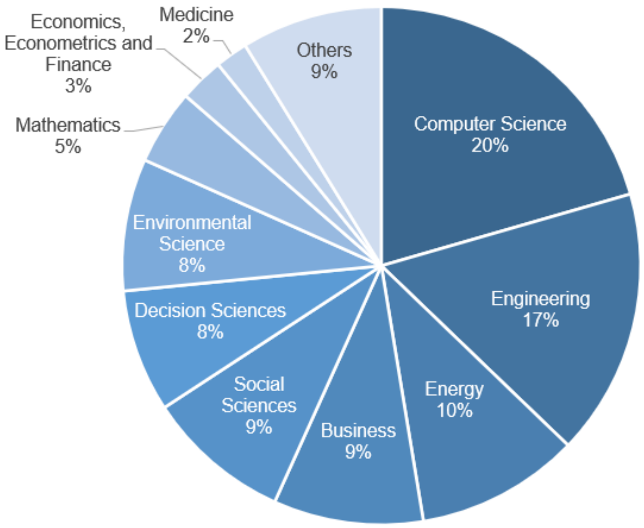

Figure 7.3 - Documents on the application of blockchain to achieve sustainability, divided by subject area

Regarding the application of blockchain in the construction industry and real estate, it is clear that research is still in its initial stage. Still, some countries are already leading the race, based on the number of publications in this subject area. This is the case for countries like India, the United Kingdom, the United States, Australia and China, as shown in **Figure 7.4**.

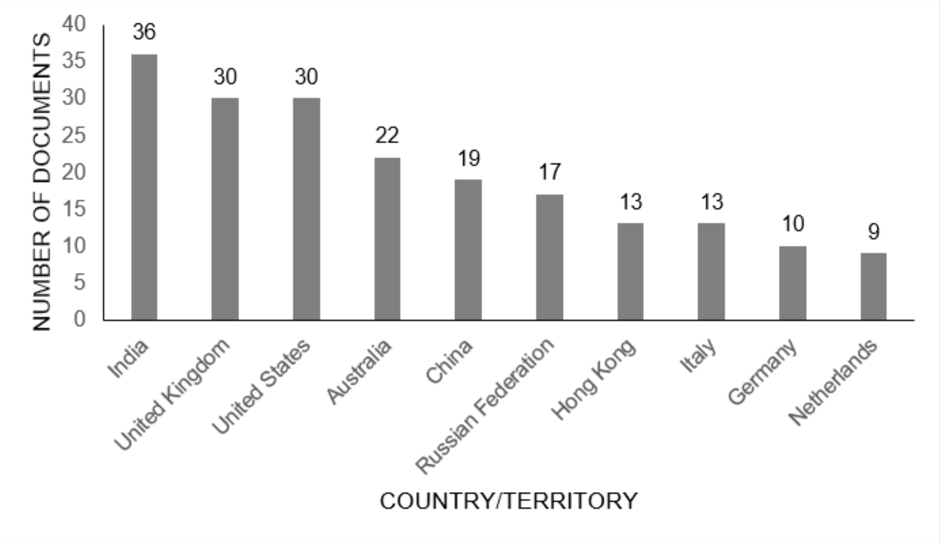

Figure 7.4 - Number of articles related to blockchain applications in the built environment, divided by country

7.3.3 Evaluation of studies

From the articles found during the descriptive analysis, a process of filtering the documents for further careful analysis was conducted. This step was performed to exclude duplicate documents and find the most relevant works to answer the questions raised herein. An illustration of the process involved is summarised in **Figure 7.5**.

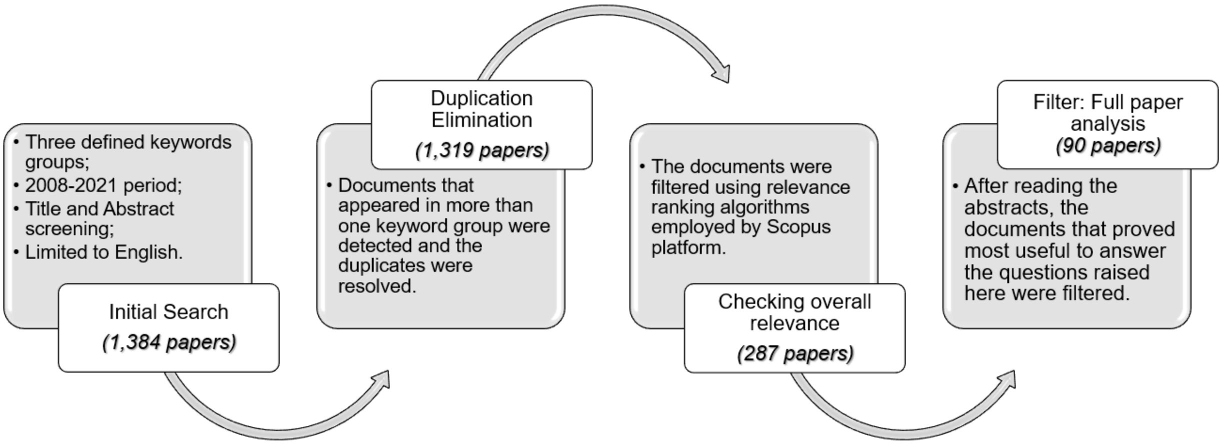

Figure 7.5 - Literature search process

The studies filtered throughout the literature search were classified using text data mining and clustering, with subsequent evaluation of the papers for each keyword group specified in Section 7.3.1. For this, the authors used the text mining functionality of VOSviewer software, version 1.6.11, developed at Leiden University, Leiden, Netherlands, which is integrated with the SciVerse Scopus database.

7.3.3.1 Blockchain for sustainability

The initial analysis was about the publications found from Group 1 of keywords of the review search, corresponding to blockchain application for sustainability. Through text mining and clustering, it was possible to classify the documents found according to the purposes for applying blockchain. In this way, six key areas of blockchain applications were derived that focussed on improving sustainability: supply chain, smart city, commerce, smart power grids, cryptocurrency, and agri-food sector. **Figure 7.6** highlights the key themes of the studies that examined blockchain for sustainability applications. The most significant articles for each area that have been reviewed are shown in **Table 7.1**.

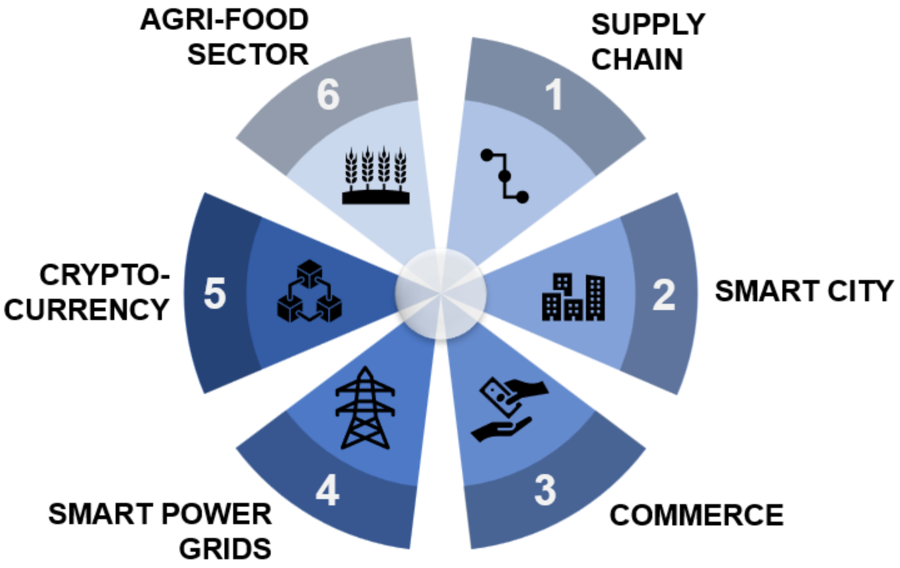

Figure 7.6 - Reported blockchain applications for sustainability in the literature

Table 7.1 - Most significant publications on blockchain for sustainability

Authors	**Document Type**	**Source** *IF: Impact Factor *CS: CiteScore	**Description of the study**
1 - Blockchain application for Supply Chain			
(Yadav and Singh, 2020)	Journal paper	Resources, Conservation and Recycling (IF: 10.204; CS: 14.7)	The authors investigate blockchain driving criteria applied to supply chain practices from the literature and academician and industry expert opinions.
(Di Vaio and Varriale, 2020)	Journal paper	International Journal of Information Management (IF: 14.098; CS: 18.1)	This study investigates blockchain technology applied to airport supply chain management to improve sustainable performance, applying this to a case study.
(Kouhizadeh et al., 2021a)	Journal paper	International Journal of Production Economics (IF: 7.885; CS: 12.2)	This study conducts a literature review and evaluates academic and practitioner perspectives about the barriers to adopting blockchain technology to manage sustainable supply chains.
(Kouhizadeh and Sarkis, 2018)	Journal paper	Sustainability (IF: 3.251; CS: 3.9)	This study presents a literature review on the use of blockchain to reach green supply chains and discuss some opportunities associated with this.
(Venkatesh et al., 2020)	Journal paper	Robotics and Computer-Integrated Manufacturing (IF: 5.666; CS: 12.5)	The authors develop a system architecture that integrates blockchain, the internet of things (IoT), and big data analysis to effectively monitor the social sustainability of supply chains.

Table 7.1 - Most significant publications on blockchain for sustainability, Continued.

(Manupati et al., 2020)	Journal paper	International Journal of Production Research (IF: 8.568; CS: 10.8)	The authors develop a distributed ledger-based blockchain approach for minimising carbon emissions and operational costs within a supply chain, formulating the problem as a Mixed Integer Non-Linear Programming (MINLP) model.
2 - Blockchain application for Smart City			
(Jiang and Zheng, 2021)	Journal paper	Journal of Cleaner Production (IF: 9.297; CS: 13.1)	The study explores the functions of an eco-innovation ecosystem based on the blockchain application for smart cities, presenting policy recommendations and theoretical and practical guidance.
(Shen and Pena-Mora, 2018)	Journal paper	IEEE Access (IF: 3.367; CS: 4.8)	Based on a bibliographic review, the authors present the relationship between blockchain and the four pillars of urban sustainability: social, economic, environmental and governmental.
(Sharma and Park, 2018)	Journal paper	Future Generation Computer Systems (IF: 7.187; CS: 13.3)	The study proposes a hybrid distributed architecture for a sustainable smart city network using blockchain techniques to solve security, privacy, and scalability issues.
(Wong et al., 2020)	Journal paper	Smart and Sustainable Built Environment (IF: 2.054; CS: 2.0)	The authors conduct a literature review on blockchain for a smart and sustainable city and discuss the potentials of applying this technology.
(Singh et al., 2020)	Journal paper	Sustainable Cities and Society (IF: 7.587; CS: 10.7)	This study discusses some critical factors for the convergence of blockchain and Artificial Intelligence (AI) technologies to create a sustainable smart city based on a literature survey.
(Liu et al., 2021)	Journal paper	Sustainability (IF: 3.251; CS: 3.9)	The study assesses the integration of blockchain and building information modelling (BIM) to make buildings more sustainable within smart cities.
(Ahad et al., 2020)	Journal paper	Sustainable Cities and Society (IF: 7.587; CS: 10.7)	The study discusses the challenges of applying blockchain and other technologies in smart cities considering technical, social, and economic aspects, ensuring sustainable smart cities.
3 - Blockchain application for Commerce			
(G. Kumar et al., 2020)	Journal paper	Sustainable Cities and Society (IF: 7.587; CS: 10.7)	This study discusses the use of blockchain for e-commerce from product development to customer acquisition and presents a solution to ensure social and financial sustainability.
(Galanakis et al., 2021)	Journal paper	Trends in Food Science & Technology (IF: 12.563; CS: 16.7)	The authors investigate the potential of blockchain and other concepts for the food sector within the era of the COVID-19 crisis based on food safety, bioactive food compounds, food security, and sustainability.

Table 7.1 - Most significant publications on blockchain for sustainability, Continued.

(Lahkani et al., 2020)	Journal paper	Sustainability (IF: 3.251; CS: 3.9)	The authors identify trends in supply chain financing in China's e-commerce and discuss ways to enable sustainable development through blockchain.
(Neto et al., 2019)	Conference paper	Proceedings of the 2nd International Conference on Blockchain Technology and Applications, China	The study presents a platform based on the marketplace and blockchain concepts to prevent the loss of drugs close to expiration, avoiding fraud and increasing security and transparency.
(Spadoni et al., 2019)	Journal paper	Wine Economics and Policy (IF: 2.949; CS: 4.7)	The study presents the case of a start-up that focuses on improving sustainability and traceability in food and beverage supply chains and, for that, used blockchain and other technologies to track the commercialisation phase.
4 - Blockchain application for Smart Power Grids			
(Mengelkamp et al., 2018a)	Journal paper	Applied Energy (IF: 9.746; CR: 17.6)	The authors evaluate a blockchain-based local energy trading and discuss the possibility that consumers and prosumers can trade self-produced energy in a peer-to-peer fashion on microgrid energy markets, applying the idea to a case study.
(Mengelkamp et al., 2018b)	Journal paper	Computer Science - Research and Development (*archived journal*)	The authors provide a decentralised market platform for trading local energy generation based on blockchain and present the potential electricity cost reductions for users.
(N. M. Kumar et al., 2020)	Journal paper	Energies (IF: 3.004; CS: 4.7)	The study presents a discussion on the application of blockchain and other technologies for smart grids to enhance reliability, security, and sustainability.
(Sestrem Ochôa et al., 2020)	Journal paper	Sensors (IF: 3.576; CS: 5.0)	This article analyses the cost of implementing blockchain in a sustainable power grid scenario using sidechains to make the system scalable and adaptable.
(Mylrea and Gourisetti, 2017a)	Conference paper	Proceedings - 2017 Resilience Week (RWS), USA	The authors analyse the blockchain application to improve smart grid cyber resiliency and secure transactive energy applications through an overview of two unique testbeds.
(Mylrea and Gourisetti, 2017b)	Conference paper	Proceedings of 2017 North American Power Symposium (NAPS), USA	This study assesses the use of blockchain to improve the cyber resilience of the smart grid, helping to reduce transaction energy costs and increase the security and sustainability of the integration of distributed energy resources.

Table 7.1 - Most significant publications on blockchain for sustainability, Continued.

5 - Blockchain application for Cryptocurrency			
(de Vries, 2018)	Journal paper	Joule (IF: 41.248; CS: 37.8)	This study discusses some methods currently used to determine the bitcoin network's current and future electricity consumption.
(Das and Dutta, 2020)	Journal paper	Economics Letters (IF: 2.097; CS: 2.7)	The authors examine the relationship between bitcoin’s energy consumption and miner’s revenue and conclude that this business is not sustainable unless cheap energy sources are relied upon.
(Vranken, 2017)	Journal paper	Current Opinion in Environmental Sustainability (IF: 6.984; CS: 11.7)	The study estimates the total energy consumption of the bitcoin network and presents alternative schemes that are less energy demanding.
(Truby, 2018)	Journal paper	Energy Research & Social Science (IF: 6.834; CS: 9.5)	The author discusses government intervention to minimise adverse environmental externalities caused by high-energy consuming blockchain technology designs.
(Giungato et al., 2017)	Journal paper	Sustainability (IF: 3.251; CS: 3.9)	The authors conduct a literature review on bitcoin's sustainability, considering the environmental, social, and economic impacts.
(Corbet et al., 2021)	Journal paper	Resources Policy (IF: 5.634; CS: 6.3)	This study investigates how bitcoin price volatility affects energy markets and emphasises the importance of environmental impact assessment of cryptocurrency growth.
6 - Blockchain application for the Agri-food sector			
(Saurabh and Dey, 2021)	Journal paper	Journal of Cleaner Production (IF: 9.297; CS: 13.1)	The authors discuss the technology adoption factors for the grape wine supply chain and evaluate what can impact sustainable supply chain practices.
(Köhler and Pizzol, 2020)	Journal paper	Journal of Cleaner Production (IF: 9.297; CS: 13.1)	The article analyses six cases of blockchain-based technologies and discusses the expected sustainability improvements in food supply chains.
(Kamble et al., 2020)	Journal paper	International Journal of Production Economics (IF: 8.796; CS: 12.2)	The study presents an application framework for professionals involved in the agricultural supply chain to develop the capacity for data analysis and achieve the sustainable performance of the processes involved.
(Lin et al., 2017)	Journal paper	Environments (CS: 4.1)	The authors propose an evaluation tool related to agricultural and environmental data management, consisting of an ICT e-agriculture system with blockchain infrastructure.
(Rana et al., 2021)	Journal paper	British Food Journal (IF: 2.518; CS: 3.5)	The paper performs a systematic literature review on blockchain applications for sustainable agri-food supply chain between 2010 and 2020.
(Kramer et al., 2021)	Journal paper	Sustainability (IF: 3.251; CS: 3.9)	The article analyses the economic effects of blockchain on the agri-food supply chain network, also considering the associated environmental factors.

7.3.3.2 Blockchain in construction

A similar analysis to the one described above was carried out for articles that apply blockchain in the construction industry and the built environment. Six main blockchain applications were determined: BIM security, construction management, contract management, real estate, payment automation, and smart city. Although several articles about smart cities were found in both groups of keywords, the studies presented in this section are not focused on using blockchain technology to reach smart and sustainable cities but instead using this technology as a tool to coordinate and control urban services. The main summary of the review findings is presented in **Figure 7.7**.

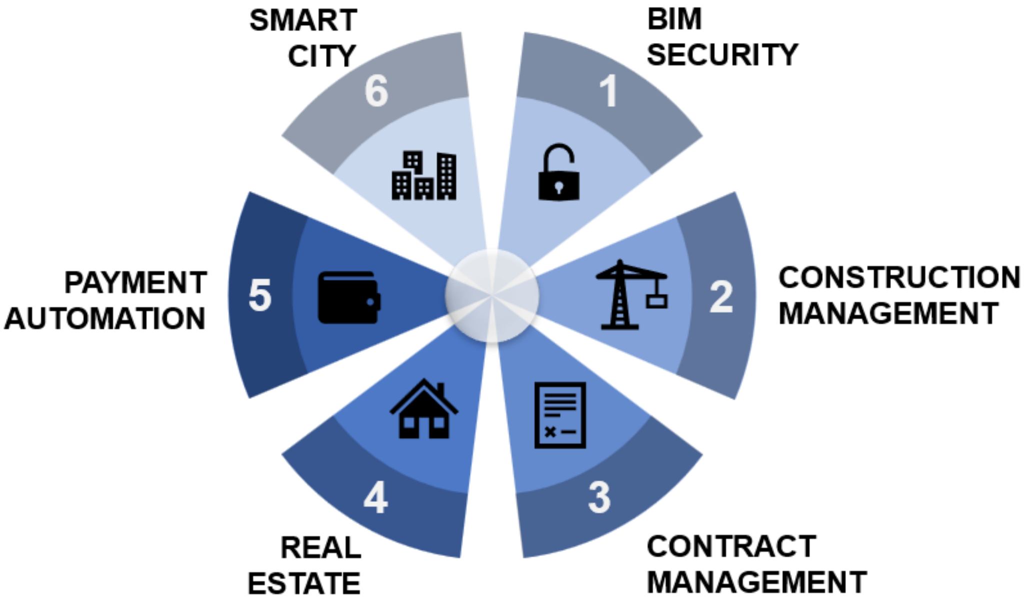

Figure 7.7 - Reported blockchain applications for the built environment in the literature

The articles were also ranked by relevance and by the number of citations, and the most significant ones are shown in **Table 7.2**.

Table 7.2 - Most significant publications on Blockchain for the Built Environment

Authors	**Document Type**	**Source** *IF: Impact Factor *CS: CiteScore	**Description of the study**
1 - Blockchain application for BIM Security			
(Turk and Klinc, 2017)	Journal paper	Procedia Engineering (IF: 1.880; CS: 4.0)	The authors discuss blockchain potential to address some issues found in BIM applications, such as confidentiality, change tracing, and data ownership, and use generic business solutions to manage BIM files using blockchain.

Table 7.2 - Most significant publications on Blockchain for the Built Environment, Continued.

(Xue and Lu, 2020)	Journal paper	Automation in Construction (IF: 7.700; CS: 12)	The authors propose a novel semantic differential transaction (SDT) approach to integrate BIM and blockchain technologies and test this proposal into two different pilot cases, adopting modern data structures to allow the bi-directional operations between these two technologies.
(Das et al., 2021)	Journal paper	Automation in Construction (IF: 7.700; CS: 12)	The study presents a framework to facilitate secure storage and distribution of BIM and a second framework based on blockchain to record BIM changes in a tamper-proof ledger for the non-trusting environment of construction projects.
(Nawari, 2021)	Conference paper	Proceedings of the 18th International Conference on Computing in Civil and Building Engineering, Brazil	The author presents a case study for automated code compliance verification mechanisms to prove how blockchain can address some of the current BIM workflow shortcomings.
(Ye et al., 2018)	Conference paper	Proceedings of the 35th International Symposium on Automation and Robotics in Construction, Germany	The authors conduct a literature review to analyse the possible applications of BIM, the internet of things, and blockchain throughout the life cycle of a building to generate a decentralised common data environment.
(Pradeep et al., 2020)	Conference paper	Proceedings of the Construction Research Congress 2020, USA	The study evaluates the blockchain application to improve confidence in data exchange in BIM models and presents a case study that uses a commercial tool called BIMCHAIN.
(Zheng et al., 2019)	Journal paper	Mathematical Problems in Engineering (IF: 1.305; CS: 1.8)	The authors propose an integration model for BIM and blockchain technologies to facilitate BIM data audit for historical modifications in the mobile cloud with big data sharing.
2 - Blockchain application for Construction Management			
(Wang et al., 2020)	Journal paper	Automation in Construction (IF: 7.700; CS: 12)	The authors propose a blockchain-based framework for precast construction to manage information sharing, control scheduling in real-time and track information.
(Hunhevicz and Hall, 2020)	Journal paper	Advanced Engineering Informatics (IF: 5.603; CS: 8.6)	The paper analyses different use cases for blockchain and other types of distributed ledger technology to increase trust and collaboration within the construction industry.
(Safa et al., 2019)	Journal paper	Strategic Direction (IF: 0.100; CS: 0.2)	The authors evaluate the use of blockchain as a solution to several problems encountered in construction information management, such as confidentiality, provenance tracking, change tracking, and data ownership.

Table 7.2 - Most significant publications on Blockchain for the Built Environment, Continued.

(Wang et al., 2017)	Journal paper	Frontiers of Engineering Management (IF: 1.520)	The study proposes blockchain-enabled applications focused on the construction industry to improve contract management, supply chain management and equipment leasing processes.
(Hargaden et al., 2019)	Conference paper	Proceedings of 2019 IEEE International Conference on Engineering, Technology and Innovation, France	The paper discusses critical aspects of blockchain that can be implemented in construction processes, such as logistics, procurement, and production, to guarantee the application of the 'construction 4.0' concept.
3 - Blockchain application for Contract Management			
(Lu et al., 2021)	Journal paper	Automation in Construction (IF: 7.700; CS: 12)	The authors present the architecture of a blockchain-enabled construction supply chain management system and examine four primary smart contracts in the context of off-site logistics and on-site assembly services.
(Chaveesuk et al., 2020)	Conference paper	Proceedings of the 13th International Conference on Human System Interaction, Japan	The study proposes an evaluation model about adopting and using smart blockchain contracts in Thailand's construction sector to understand stakeholders' needs deeply.
(Ye and König, 2020)	Conference paper	Proceedings of the 18th International Conference on Computing in Civil and Building Engineering, Brazil	The study presents an approach to make contract management in construction projects simpler, more transparent and automated through blockchain and BIM models.
(Pattini et al., 2020)	Conference paper	Proceedings of the International Structural Engineering and Construction, Cyprus	The authors discuss how blockchain technology can support contract execution by ensuring a transparent information flow during the construction process.
(Giuda et al., 2020)	Book Chapter	Book: Digital Transformation of the Design, Construction and Management Processes of the Built Environment, Springer	The study discusses how the BIM model and blockchain technology integration can benefit the main stages of contract execution by drawing up a non-modifiable chronology of all the construction process stages.
(Shojaei et al., 2020)	Conference paper	Proceedings of the Future Technologies Conference (FTC 2019), USA	The study applies blockchain to govern construction project contracts maintaining a tamper-proof record of project progress and ensuring information security. For this, the authors propose a blockchain network using Hyperledger fabric and test this in a sample construction project.

Table 7.2 - Most significant publications on Blockchain for the Built Environment, Continued.

4 - Blockchain application for Real Estate			
(Li et al., 2019)	Journal paper	Computers & Industrial Engineering (IF: 5.431; CS: 7.9)	The authors propose a blockchain-enabled workflow operating system to centralise the heterogeneous logistics resources with different customers for real estate services.
(Huh and Kim, 2020)	Journal paper	Electronics (IF: 2.397; CS: 2.7)	The paper presents an implementation plan for a neural algorithm blockchain-based model for the real estate market that enables the information sharing about sales and links the transactions carried out to form a security monitoring system.
(Dakhli et al., 2019)	Journal paper	Buildings (IF: 2.648; CS: 4.2)	The authors present a case study of a real estate company and evaluate the potential cost savings by applying blockchain technology to the company's processes.
(Veuger, 2020)	Journal paper	Journal of Property, Planning and Environmental Law (IF: 0.490; CS: 1.0)	The paper discusses blockchain applications for real estate and land registration, considering experts from different countries, such as Austria, Brazil, China, Croatia, Spain, and Switzerland.
(Morena et al., 2020)	Journal paper	Property Management (CS: 1.4)	The authors investigate the effective implementation of blockchain technology in the real estate environment, focusing on ensuring assistance for people with severe disabilities.
(Konashevych, 2020)	Journal paper	Journal of Property, Planning and Environmental Law (IF: 0.490; CS: 1.0)	The authors present an overview of blockchain application in real estate, focusing on title rights and property registration in public databases.
5 - Blockchain application for Payment Automation			
(Das et al., 2020)	Journal paper	Automation in Construction (IF: 7.700; CS: 12)	The authors present a blockchain-based key management strategy for data confidentiality in construction projects to automatically enforce the conditions related to interim payments and share payment records at the project level.
(Ahmadisheykhsarmast and Sonmez, 2020)	Journal paper	Automation in Construction (IF: 7.700; CS: 12)	The authors present a novel smart contract payment security system that runs on a decentralised blockchain to eliminate or reduce payment issues in the construction sector. This system is analysed through an actual construction case study.
(Xiong et al., 2019)	Journal paper	IEEE Access (IF: 3.367; CS: 4.8)	The authors design a private-key distribution protocol in blockchains to preserve payment security in the construction sector. A framework is proposed to help recover lost private keys.
(Luo et al., 2019)	Conference paper	Proceedings of the 36th Symposium on Automation and Robotics in Construction, Canada	The study proposes a framework based on a decentralised blockchain to automate construction payments by formalising them into smart contracts.

Table 7.2 - Most significant publications on Blockchain for the Built Environment, Continued.

(Hamledari and Fischer, 2021)	Journal paper	Journal of Legal Affairs and Dispute Resolution in Engineering and Construction (IF: 2.543; CS: 1.7)	The paper discusses how blockchain-based and decentralised smart contracts can assist with the automation of payments in construction and presents a case study to exemplify it.
6 - Blockchain application for Smart City			
(Bhushan et al., 2020)	Journal paper	Sustainable Cities and Society (IF: 7.587; CS: 10.7)	The study reviews existing blockchain efforts in six aspects of smart cities: smart healthcare, smart transportation, smart grid, supply chain management, financial systems, and data centre networks.
(Chen et al., 2021)	Journal paper	Journal of Information Security and Applications (IF: 3.872; CS: 5.7)	The authors develop a post-quantum transaction mechanism secure for blockchain-driven smart cities and discuss how it can resist attacks from quantum computing.
(Rodrigues and Cardoso, 2019)	Conference paper	Proceedings of Smart City Symposium Prague, Czech Republic	The study develops an integrated model based on blockchain application in smart cities to promote the inclusion of persons with disabilities (PWD) through literature review and interviews with experts.
(Fu and Zhu, 2020)	Journal paper	Building Research and Information (IF: 5.322; CS: 8.2)	The authors use the smart transportation subsystem as an object of analysis to develop the operation principle of blockchain and to improve the operation and management efficiency of data and networks.
(Sun et al., 2016)	Journal paper	Financial Innovation (IF: 3.985; CS: 4.2)	The authors present a conceptual framework to evaluate the contribution of blockchain-based sharing services to smart cities.

7.3.3.3 Blockchain to achieve sustainable construction

Limited is discussed about blockchain-based sustainability in the built environment. However, based on the previous analysis of the articles found in the review search, there is great potential for future research in this field. The studies found in the SciVerse Scopus database that apply blockchain with this focus are discussed below.

Some papers already discuss the integration of BIM and blockchain, which can be beneficial for sustainability. BIM is advantageous in centralising all data in the same three-dimensional model, allowing different analyses and simulations to be carried out. This allows for the creation of more sustainable buildings, with optimised thermal (Liu et al., 2020b), acoustic (Aguilar-Aguilera et al., 2020) and lighting (Montiel-Santiago et al., 2020) performances, with conscious consumption of energy (El Sayary and Omar, 2021) and water (Nguyen et al., 2021) and generating less environmental impacts (Santos et al., 2020). Besides, a BIM model allows professionals to accurately assess the costs associated with the construction during the design phase of the project, which ensures the minimisation of economic impacts (Rad et al., 2021).

Liu et al. (Liu et al., 2021) stated, based on their bibliometric analysis, that BIM and Blockchain technology represent complementary concepts, as blockchain can compensate for the shortcomings of BIM applications, including the reliability of data in collaborative works. Blockchain can increase the security and transparency of the data generated through digital BIM models, increasing the credibility of construction projects and improving the collaborative work already proposed by BIM. The authors say that blockchain can help BIM use data more efficiently to evaluate construction projects, achieve environmental protection goals, and efficiently conserve resources.

In another study, Liu et al. (Liu et al., 2019) proposed a conceptual architecture framework integrating BIM and blockchain to improve sustainable building design information management. This framework intends to achieve sustainable design goals through the interactive realisation of smart contracts integrated into the user level. However, the article did not apply what was proposed in a case study, lacking a designer-operable practical framework.

In addition to BIM, other concepts are discussed in the literature regarding their integration into the blockchain application. This is the case with the circular economy, which refers to a strategic concept to reduce, reuse, recover, and recycle materials and energy. Shojaei et al. (Shojaei et al., 2021) propose a blockchain network to enable a circular economy in the built environment, ensuring that all the required information is stored and accessible in a blockchain format. For this, the study defined nine transactions to cover the whole cycle of a circular economy, creating a decentralised network in which all participants receive notifications regarding each transaction. The blockchain network allows users to check the material database regarding new products, in-use products, and salvaged products. The authors tested this model in a synthetic case study to prove its feasibility and showed that this integration helps in the total traceability of material and energy, allowing the user to make predictions for the recycling and reusing materials and goods used in the built environment. In turn, Çetin et al. (Çetin et al., 2021) analysed different enabling digital technologies such as blockchain and explored their potential role in applying the circular economy concept across the life cycle stages of buildings. The authors showed that blockchain is an enabling technology in the circular economy context, particularly for managing complex information networks.

Blockchain also emerges as a facilitator for construction professionals to achieve specific results. Woo et al. (Woo et al., 2020) encourage the use of blockchain to facilitate the construction industry's participation in the carbon market. The authors discuss how this technology can significantly reduce fuel consumption and improve the energy performance of a building, thus reducing greenhouse gas (GHG) emissions. On the other hand, Pellegrini et al. (Pellegrini et al., 2020) presented a brief discussion on the use of blockchain to support the waste management process in the construction industry. The authors believe that the application of this technology can be advantageous in this context, thanks to the immutability and transparency offered. The idea would be to use blockchain to record all construction materials and waste generated from the design phase to the demolition phase, guaranteeing a more effective information flow and ecological and economic benefits.

Other papers cite the use of blockchain as an essential tool to achieve sustainability in construction. Still, the application of blockchain is not profoundly discussed throughout these documents. It happens in the work of Hoosain et al. (Hoosain et al., 2020), which discusses the use of digital technologies such as blockchain but does not present an in-depth discussion about its use in the construction industry. It is imperative that the use of technologies that minimise the impacts caused by buildings throughout their life cycle needs to be incorporated in any concept proposed. Blockchain offers great potential in this realm, based on the critical themes derived from previous works in other fields. It is evident that the use of blockchain for achieving a sustainable built environment still has a long way to go. However, with the given rate of studies published in this field, the research will advance towards a direction that will encourage blockchain applications to achieve a sustainable construction industry and real estate.

7.4 DISCUSSION

In this section, the research questions posed in this article are answered based on the reviewed literature. A framework indicating a future road map for achieving a sustainable built environment via blockchain is also presented.

(Q1) What are possible blockchain applications in order to achieve sustainability?

A key application of blockchain, which researchers increasingly discuss, is the sustainability verification of processes and products (Kshetri, 2018). Although the literature on blockchain application for sustainable purposes has flourished recently, it is still necessary to further analyse the technical limitations of adopting this technology, mainly through case studies. Implementing blockchain to benefit sustainability is a novel and complex task (Bai and

Sarkis, 2020). However, it is believed that this technology's constant growth will help industries achieve the global goals of sustainable development (Giungato et al., 2017).

Several barriers in the blockchain application to achieve sustainability exist, as discussed by academics and professionals. Both groups agree that the most significant challenges are related to the security and immaturity of the technology (Kouhizadeh et al., 2021b). Although few real applications in the literature are to be discussed, several authors agree that blockchain technology can reduce the consumption of natural resources, providing transparency and traceability, which facilitates the provenance of the items (Esmaeilian et al., 2020). In addition, this technology can help minimise negative environmental and social impacts in terms of materials used (Manupati et al., 2020) and human rights (Mengelkamp et al., 2018b). This would ensure that consumers make more informed purchasing decisions, allowing them to consume genuinely sustainable products and services.

A concept that has widely been discussed along with blockchain in different industries is a circular economy. Integrating blockchain with circular economy improves the tracking of products and allows authentication, resale and recovery of materials. In this way, the feedback loops advocated by circular economy become faster and more reliable (França et al., 2020). The benefits of this integration are already seen at the institutional and organisational level, in addition to directly reaching supply chains and consumers (Kouhizadeh et al., 2019). Blockchain capabilities have also shown promising results in waste management, making the recycling process more effective by placing accountability on every chain member rather than just on the producer (Gopalakrishnan et al., 2021).

To ensure sustainability in different sectors, many professionals have also applied the Life Cycle Assessment (LCA) concept, which aims to assess the environmental impacts generated over the entire life cycle of a product or service (ISO, 2006). A discussion on how blockchain's transparent and open nature can help LCA applications is already presented in the literature. LCA is an iterative methodology, and this makes its data credibility extremely important (Teh et al., 2020). Blockchain application can reduce information uncertainty in an LCA analysis, decrease the time required for data collection and ensure perfect traceability of data sources (Kouhizadeh and Sarkis, 2018).

The four LCA stages (i.e., goal and scope definition, inventory analysis, impact assessment, and interpretation) can benefit from blockchain. However, it is known that inventory analysis is one of the most challenging stages of this methodology, as it requires the quantification of inputs and outputs at various stages of the supply chain (Ghaemi and Smith, 2020). A blockchain-based LCA framework allows instant data traceability and ensures that data integrity is maintained, unlike a traditional LCA approach (Zhang et al., 2020).

When it comes to a complete sustainability assessment, a more systemic and integrative methodology has been used in the literature, named Life Cycle Sustainability Assessment (LCSA). LCSA refers to evaluating the impacts of the three pillars of sustainability during the entire life cycle of a product or service (UNEP, 2012). Applying this methodology, the number of data sources increases considerably as it involves information of different natures to be analysed jointly (Kamali et al., 2018). To the best of the authors' knowledge, very few publications use blockchain to benefit the application of LCA, while no article so far considers the integration of this technology with LCSA. The authors believe that research should move towards this direction, as life cycle thinking has been widely discussed as a solution to achieving sustainability in the built environment. It should be noted that LCSA evaluation becomes more complex if it is not based on efficient information technology, and so blockchain can serve as a plausible solution to help make the process more effective.

(Q2) What are the barriers and limitations associated with blockchain applications for the construction and real estate sectors?

Although blockchain already provides solutions to current problems in building information management, research on this subject continues at a theoretical level. Much still needs to be studied for the blockchain application to be efficient in constructing sustainable buildings. Some authors believe that blockchain is likely to be implemented in generic information technology infrastructures on which construction applications could be developed rather than directly used by construction professionals (Turk and Klinc, 2017). Indeed, research shows that these platforms work as a robust backbone system behind the interface layer of applications commonly used by construction professionals (Yang et al., 2020). Thus, these professionals would not need to significantly change their work processes or have extensive knowledge about blockchain.

Discussions on how blockchain technology could accelerate and optimise design and engineering practices are present in the literature. Part of this discussion focuses on using blockchain to solve problems still encountered in applying BIM (Liu et al., 2021), but this proposal is still mainly in the conceptual field. The BIM models concentrate information from different projects and disciplines, allow collaborative work among design stakeholders and guarantee the information management for the entire building life cycle. On the other hand, BIM is not concerned with confidentiality, non-repudiation, traceability, provenance tracking, and data ownership, which can be guaranteed by integrating BIM and blockchain (Nawari and Ravindran, 2019). Besides, there is no chronological record of the changes done in a traditional BIM model since the project revision is made by updating and replacing the existing data (Kiu et al., 2020). With a blockchain platform, possible delays caused by discrepancies in the BIM models or conflicts between stakeholders can be mitigated (San et al., 2019). However, it is essential to note that data from BIM models may require greater computational power to be added to a blockchain, creating technical barriers (Nawari and Ravindran, 2019).

In addition to technical difficulties, several cultural and organisational limitations are related to blockchain applications in the built environment. Knowing that the construction industry and real estate have been slow to adopt process and technology innovations, it is evident that much still needs to be discussed and encouraged among building researchers and professionals to adopt blockchain. A complete paradigm shift is required, in addition to government and industry investment.

(Q3) What should be the next steps in blockchain research to ensure its favourable application to achieving sustainability in the built environment?

Sustainability is the main paradigm in the future development of the built environment and is a topic that is increasingly highlighted (Bhushan et al., 2020). In the last years, construction professionals have adopted assessments based on a triple-bottom-line approach that considers environmental, social and economic aspects (Phillips et al., 2020). However, when it comes to the construction industry, the triple-bottom-line sustainability concept has many limitations (Goh et al., 2020). In order to facilitate analyses based on the life cycle concept in the built environment, different tools and methods have been used, such as the BIM methodology (Hollberg et al., 2020) and mathematical methods to assist decision making (Tan et al., 2021). Blockchain can integrate such methods by providing the platform needed for data validation, thus reducing the risk of data manipulation and increasing confidence in the decisions made by construction professionals.

As already presented in this work, blockchain technology has great potential to assist the process of developing more sustainable buildings. However, the literature still lacks more in-depth discussions about using this information technology to achieve this goal. Based on the literature reviewed, a conceptual framework was derived to present the next steps in blockchain research for the built environment, with a specific focus on the construction industry, given that it is an industry proven to be responsible for a high number of environmental, social and economic impacts worldwide. The proposed framework was organised in order to illustrate the main challenges to be faced, the tools and platforms to be used, and the concepts that could be incorporated into the Blockchain application, as shown in **Figure 7.8**.

The framework was organised according to the priority order that the authors concluded to be realistic from the literature review. It proved to be essential to deal with some challenges before implementing blockchain in a complete sustainability assessment. Therefore, this is the first step proposed in this work, represented in the centre of the figure. First, the discussion on electricity consumption when using blockchain must be deepened. It would make no sense to use this technology to achieve sustainability in construction projects without considering the energy consumption and cost needed to make this application possible. It is believed that with the advancement of this technology and the growing discussion on the topic, the advantages of using blockchain in construction will outweigh the negative impacts that this technology can cause on the environment. However, this certainly needs to be considered in the projects.

The two following challenges mentioned are related to the immaturity of blockchain technology and the often observed delay in the construction industry in the application of new technologies, as already discussed in this work. There needs to be a change in the mentality of professionals and researchers, in addition to government and institutional incentives for this change to happen. Finally, it is essential to discuss the security of user data, especially in public blockchains, and the possibility of cyber-attacks that would put information on various projects, often confidential, at risk.

The second step proposed in this work is related to the tools and platforms to be used. The authors agree that, in order to achieve sustainability in buildings with the aid of a blockchain-based structure, this technology must be fully integrated with BIM platforms. The BIM methodology is a fundamental part of evaluating more sustainable projects. It guarantees the evaluation of all the building information during the initial design phases of the project, which improves the decision-making process. It is then necessary to develop integrated platforms for BIM and blockchain so that the 3D digital model of the building represents a tamper-proof solution for building information management. In addition, it would be interesting to implement blockchain sitting behind the interface layer of BIM-based computer programs that have already been widely implemented and discussed, such as Autodesk Revit and Graphisoft Archicad.

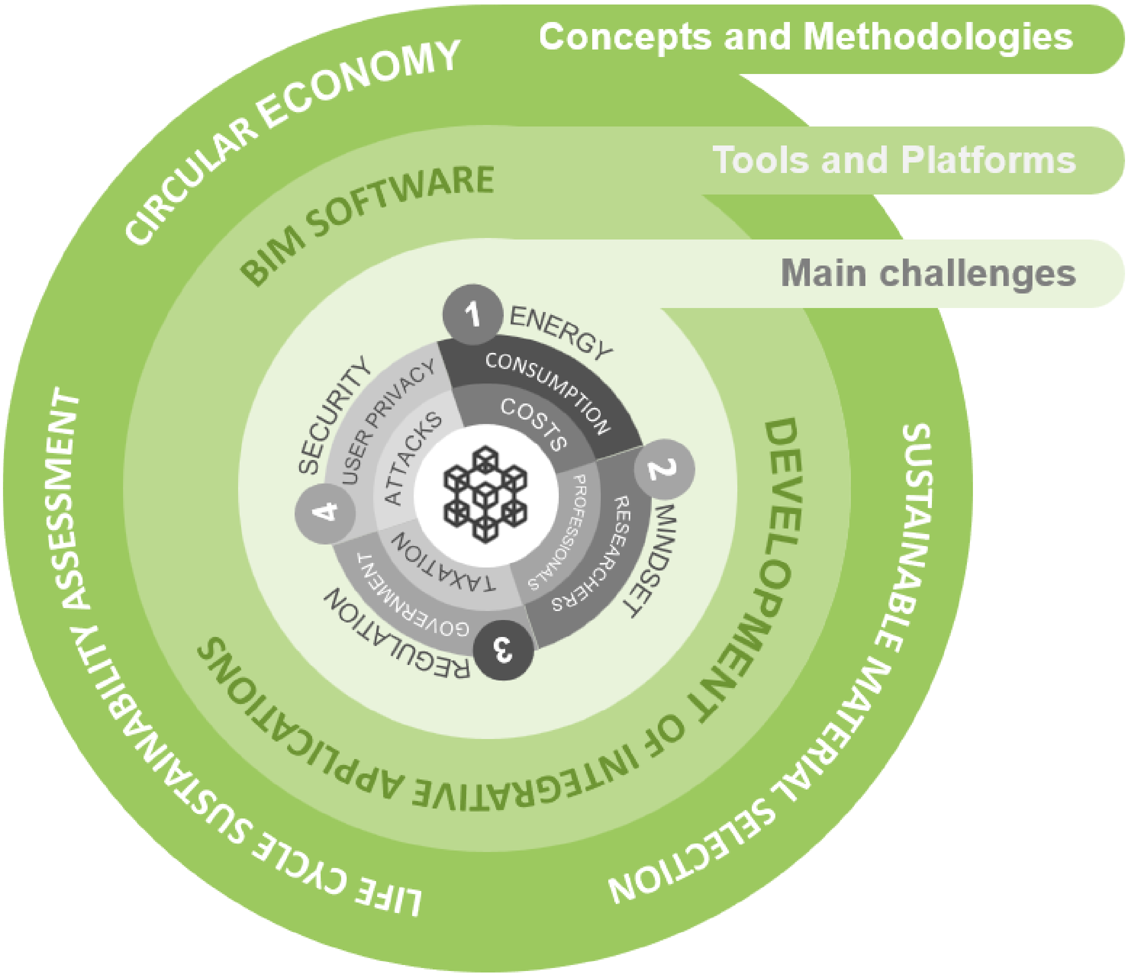

Figure 7.8 - Framework of the challenges and future exploratory directions of blockchain to achieve a sustainable built environment

Finally, the last proposed step would be to carry out studies based on concepts and methodologies proven beneficial for sustainability in buildings, using the Blockchain-based platforms developed in the previous step. It is necessary to consider a sustainable selection of materials, through which the positive and negative impacts of each material are taken into account from environmental, social and economic perspectives. When materials are chosen based on their incorporated energy and the impacts they cause, much more advanced levels of sustainability are achieved in construction. In addition, as there will be complete integration between BIM and blockchain, the control of the building materials database can be done directly in the 3D model based on BIM. It is also essential to implement methodologies such as Life Cycle Sustainability Assessment and the circular economy concept so that the impacts generated throughout the construction life cycle can be minimised.

Nevertheless, it is essential to point out that the possibilities for applying blockchain are numerous and directly depend on advances in research in this regard. Both the construction industry and real estate can benefit enormously in the coming years from this information technology. A clear example is the use of blockchain to increase the transparency and reliability of data in an Environmental Product Declaration (EPD). When applied to buildings, EPDs are used by real estate developers, architects, and engineers to provide a documentation basis of the building materials used (Rangelov et al., 2021). The reliability of the results presented in an EPD is directly linked to the data monitoring, and with blockchain, all transactions and data will be recorded in a scalable and tamper-proof way. In addition, when it comes to common legal issues experienced in the construction industry, DLT presents a viable means of tackling traceability of data back to its origin to identify the information sources (C. Z. Li et al., 2021). This will reduce the costs of legal cases involved, help minimise construction delays and facilitate stakeholders in thoroughly understanding the construction processes.

7.5 CONCLUSION FOR CHAPTER 7

Blockchain technology has widely been discussed in the literature, especially in the finance area. For other sectors, such as construction, the application of this technology is still immature and has developed mainly at the theoretical level, lacking practical applications. This article sought to identify themes from the literature based on studies conducted in various fields. Extensions of these applications for potential uses of blockchain technology to achieve sustainability in the built environment were then discussed. This is a critical discussion, given that the construction industry is responsible for generating an excessive amount of negative impacts on the environment and impacting many socio-economic issues worldwide. A key characteristic of the construction industry is its lack in the use of information technologies though it can benefit immensely from the use of blockchain.

From the comprehensive literature review, the main areas of knowledge that are the most advanced in applying blockchain to achieve sustainability were identified: supply chain, smart city, commerce, smart power grids, cryptocurrency, and agri-food sector. Then, articles related to the construction industry and the built environment were reviewed and analysed, highlighting the six most discussed objectives in this industry on applying blockchain: BIM security, construction management, contract management, real estate, payment automation, and smart city. Based on this perception and after the examination of 90 papers to provide a full picture of where and how blockchain can be applied, it was possible to conduct an in-depth discussion of what the next research steps should be in order for blockchain to become a valuable tool to achieve a sustainable built environment.

Among the articles found regarding the use of blockchain in the construction industry and the built environment, only 42 articles presented case studies to prove the effectiveness of this application. This represents 14,9% (42 of 282 documents) of the articles found in the literature search process, emphasising that blockchain technology is still much discussed conceptually for construction projects. Furthermore, most of the case studies presented did not cover different aspects of construction projects and their impacts, presenting punctual and unrepresentative discussions.

In order to illustrate the next research steps, this paper presented a conceptual framework regarding the main challenges, tools and platforms to be used, and concepts and methodologies to be integrated with blockchain. One limitation of this study is that the division of the literature and the steps suggested in the conceptual framework proposed are based on the authors' interpretation and, therefore, may present a subjective bias. It is hoped that this study will encourage research on blockchain applications for achieving a sustainable construction industry among academics, industry professionals, sustainability certification institutes and commercial companies. This study's future direction is to explore the development of a blockchain platform based on the proposed conceptual framework and apply it in a case study, thus proving its effectiveness for building projects.

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8 IMPROVING SUSTAINABILITY THROUGH DIGITAL TWIN AND BLOCKCHAIN: AN ANALYSIS OF PREFABRICATED MODULAR CONSTRUCTION

This chapter is published as a Book Chapter.

FIGUEIREDO, Karoline et al. Improving Sustainability in the Built Environment through a BIM-based Integration of Digital Twin and Blockchain: An Analysis of Prefabricated Modular Construction. In: **Cognitive Digital Twins for Smart Lifecycle Management of Built Environment and Infrastructure.** CRC Press. p. 101-122, 2023.

Abstract: As one of the largest industries globally, the construction industry plays a crucial role in sustainability, given its significant environmental, social, and economic impacts. The use of digital twin offers a possible avenue for enhancing the sustainability of this industry by improving the decision-making process of building projects. However, a major challenge facing construction projects is the often-collaborative work involved, which comprises different professionals, such as regulators, architects, engineers, and contractors. As a result, confidentiality, traceability, and security issues may arise as obstacles to the implementation of new decision-making systems. Recently, a solution that has been gaining significant attention is the use of a decentralised and auditable database integrated with the digital twin application. This is made possible through blockchain technology. In this context, this chapter aims to analyse the potential of digital twin in improving the sustainability decision-making in the built environment via integration with blockchain. The framework discussed uses the Building Information Modelling (BIM) methodology as a primary data source to develop a building digital twin, with emphasis on the sustainability assessment of prefabricated modular construction. The digital twin is examined for its benefits in terms of sustainability decision-making throughout the construction lifecycle, ensuring that the assessment is not tampered with due to blockchain application.

Keywords:
Digital Twin; Blockchain; BIM; Sustainable Construction.

8.1 INTRODUCTION

Sustainability can be understood as a development that meets the present needs in order to reconcile environmental, economic, and social aspects without compromising future generations (Holden et al., 2014). The sustainability of the built environment has been the target of many recent studies in the field. This is related to the ever-increasing nature of the construction industry, with a direct impact on the environment, significant consumption of freshwater resources worldwide (Mannan and Al-Ghamdi, 2020) and being one of the biggest consumers of fossil energy (Ritzen et al., 2016). Furthermore, considering that sustainability is a concept based on three different pillars (i.e., environmental, social, and economic), it is essential to note that construction contributes enormously to the global gross domestic product (GDP) and the global employment of labour (Saka et al., 2021). In this context, a great effort has been applied to find robust methodologies and technologies to benefit the sustainability assessment within the built environment.

A commonly utilised methodology in the construction scenario is Building Information Modelling (BIM). It refers to a working methodology based on a digital representation and information exchange, incorporating all stakeholders and facilitating data access along the project's life cycle (Kubicki et al., 2019). A BIM model thus consists of a three-dimensional digital model containing both geometric and semantic data of building materials and components. BIM guarantees the centralisation of all information and improves decision-making in construction projects (Nowak et al., 2016).

BIM has also been utilised to achieve sustainability in the construction industry. BIM can be used as a powerful tool to compare different construction materials and construction methods regarding the environmental impacts generated (Soust-Verdaguer et al., 2020). Besides, the BIM model can be used to perform simulations to minimise the energy consumed in a building (Gao et al., 2019) and improve the indoor thermal comfort for end-users (Seghier et al., 2022). It is also possible to use BIM's analytical and simulation tools to assess schedule performance and achieve life-cycle cost savings (al Hattab, 2021).

A challenging problem that arises in this domain is that the current state of BIM only provides static data of the built environment and is not compatible with the Internet of Things (IoT) integration (Boje et al., 2020). The IoT implementation in the built environment is essential to carry out accurate building sustainability assessments since IoT allows the digital building model to be updated in real-time, thus assessing the performance of what-if scenarios (Hunhevicz et al., 2022). However, BIM is generally applied during the early design stages to ensure the facility will satisfy the requirements imposed for the project without updating real-time information. The building static data, representing the time-invariant attributes and parameters, are undoubtedly relevant for sustainability assessment (Yuan et al., 2021). Yet, in order to comprehensively assess the sustainability of built assets, it is also essential to consider several time-dependent factors, such as impacts of seasonal variation, changes in the users' behaviour, the climate condition and the evolution of the physical structure over time.

Recently, the use of digital twins has been proposed to solve this problem. Conceptually, a Digital Twin (DT) is a virtual representation of an object or a system, serving as the real-time digital counterpart of the physical asset during its lifecycle (Kuo et al., 2021). By dynamically integrating data and information, a DT can improve the design of new assets and the understanding of existing asset conditions (IET - Institution of Engineering and Technology, 2019). This concept is applicable in different industries, including the construction industry. From the construction perspective, DT can be understood as an innovative methodology to enhance existing construction processes by utilising cyber-physical synchronicity (Boje et al., 2020).

Despite having different purposes and characteristics, the BIM and digital twin concepts go hand in hand. BIM is seen by several researchers as the starting point for the DT implementation in the built environment, as a BIM model can be a primary source of data for developing a building digital twin (Boje et al., 2020). Therefore, several papers in the literature discuss the application of BIM-based DT to assess a building lifecycle and its impacts. Different concepts and methods are integrated into the analyses in these studies, such as simulation (Pan and Zhang, 2021), process mining (Lin and Wu, 2021), IoT (Jiang et al., 2021), and Artificial Intelligence (Rafsanjani and Nabizadeh, 2021).

Unfortunately, this data aggregation can generate a security risk since the analysis comprises multiple parties and sources. Therefore, confidentiality, traceability, and security issues may arise as obstacles during a BIM-based digital twin development for an asset/facility. In this context, the blockchain application provides a plausible avenue for dealing with these issues. Blockchain is a Distributed Ledger Technology (DLT) that represents a database with interconnected blocks of data cryptographically protected against tampering (Sanka et al., 2021). Regarding the construction industry, blockchain can offer a tamper-proof solution throughout the information supervision of building processes (Li et al., 2021).

This chapter elaborates on viable ways to integrate a BIM-based digital twin with blockchain technology, focusing on the sustainability assessment of prefabricated modular construction as an example. Modular construction can deliver life-cycle cost benefits and minimise environmental impacts, in addition to reducing health and safety incidents (Hammad et al., 2019). The proposed framework intends to critically discuss how this integration can benefit sustainability in the built environment and contribute to the advancement of research in this field. To achieve this, the book chapter is divided as follows: some background knowledge is presented in Section 2. Section 3 explains the research methods, discussing the proposed framework based on prefabricated modular construction. The discussions of the study are presented in Section 4. Finally, concluding remarks are presented in Section 5.

8.2 BACKGROUND

Before defining the framework of this study, it is crucial to present a summarised overview of the methodologies and technologies to be used, namely digital twin, BIM, and blockchain. Therefore, this section presents the general concepts associated with these subjects and the role that they can play in the built environment. With these concepts well established, the proposed framework will be presented in Section 3.

8.2.1 Digital Twin

A digital twin can be understood as a set of realistic models that simulates the physical asset with its real-time properties, condition and behaviour across the entire lifecycle (Haag and Anderl, 2018). Utilising a digital twin is a crucial step in representing physical assets in a corresponding virtual environment (Lu and Brilakis, 2019). This concept has been used in different sectors and industries, such as manufacturing (Li et al., 2022), healthcare (Thiong'o and Rutka, 2022), and retail (Shoji et al., 2022). Regarding the construction industry, the advantages of using a building digital twin range from real-time data visualisation to continuous monitoring of assets and the development of self-learning capabilities (Ramos et al., 2022).

A building digital twin can be used from the beginning of the design project throughout the entire life cycle of the physical building. During the operation phase of the building, physical and digital assets coexist and feed each other with data and information. **Figure 8.1** represents the components of a building digital twin, corresponding to the digital building, the physical building, and the data that connects both assets. The physical building collects real-time data through IoT devices and sensors to be processed in the digital building model. In turn, the digital model is used to predict data that can be used to improve the building's operational efficiency.

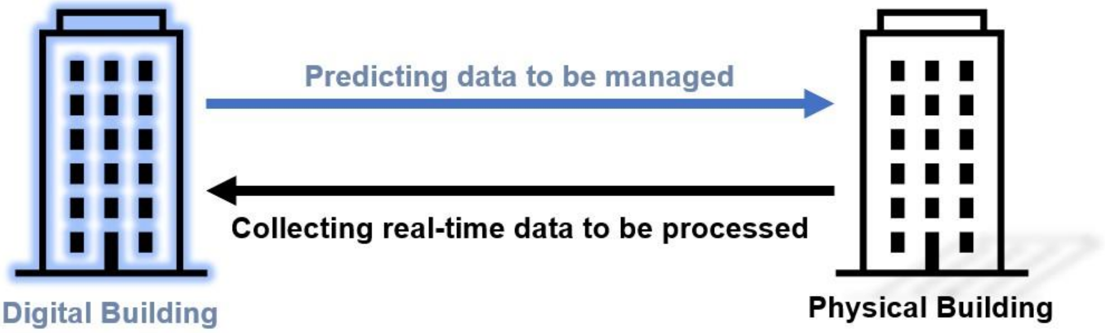

Figure 8.1 - Components of a building digital twin

Regarding prefabricated modular construction, digital twins can be implemented to guarantee accuracy, completeness, and correctness during assembly (Tran et al., 2021). For example, Jiang et al. (Jiang et al., 2022) proposed a real-time supervision service to continuously monitor the construction process on a real-time basis, with a robotic testbed demonstration for reengineered on-site assembly in prefabricated construction. However, compared to other assets to be represented via a digital twin, a building requires a high degree of detail since an entire building is composed of different systems and components with an extended lifespan. Many difficulties can arise in analysing the building's life cycles owing to the broad number of data to be considered (Kamali et al., 2018). In this context, this research proposes an integration of concepts to benefit the creation of a building digital twin for sustainability purposes. These concepts will be further explored below.

8.2.2 Building Information Modeling (BIM)

BIM is an effective methodology that centralises building information and can benefit the phases of planning, designing, constructing, managing, and recycling during the life-cycle of buildings (Alirezaei et al., 2016). The advantages of using BIM are numerous, as this methodology can simplify the design process in several ways, upsurging the accessibility of design information to stakeholders and minimising the communication failures (Ahmad and Thaheem, 2017). Besides, BIM allows the teamwork to efficiently manage their decisions during a project based on a wide range of information about materials, operation and maintenance instructions (Motalebi et al., 2022).

The 3D model generated in a BIM-based tool is a parametric and data-rich representation of the facility (Gao et al., 2019). With BIM, stakeholders have all the necessary project information centralised, which facilitates performing computer simulations to reduce costs, detect design errors, and track building timelines. Besides, evidence suggests that BIM is a crucial methodology to achieve a smart and sustainable built environment. In the literature, BIM is utilised in several case studies to attain different sustainable goals, such as thermal optimisation (Liu et al., 2020) and the minimisation of energy consumption (El Sayary and Omar, 2021), water consumption (Nguyen et al., 2021) and environmental impacts generation (Santos et al., 2020). Therefore, this methodology has been used to enhance the sustainable decision-making process of building projects, especially during the early design stages (Chen and Pan, 2016).

8.2.2.1 Level of Development (LOD)

A three-dimensional model generated in a BIM-based tool contains a wide range of information linked to it. In addition to graphical information such as volume, height, width, and length, the digital model also supports non-graphical information such as manufacturer, thermal data, and prices of materials and components. As the amount of data to be inserted depends on the phase and objective of each project, the Level of Development (LOD) concept arises to assist in the classification of a BIM model.

LOD is a classification system based on recognising that the data model evolves progressively throughout the design process (Dupuis et al., 2017). This definition has proved to be very important since a construction project normally involves different parties, and it is essential that everyone understands the building elements' maturity at each particular stage (Abualdenien and Borrmann, 2020). The LOD specification works as an agreement on which information is available at each stage, in addition to determining the purpose of the BIM model and its expected deliverables (Beetz et al., 2018). The BIM digital model describes the building geometry approximatively, using an acceptable quality representation based on the specific required LOD (Lu and Brilakis, 2019).

In order to specify and articulate the content and reliability of BIM models at various stages in the design and construction processes, the literature presents five progressively detailed levels from LOD 100 to LOD 500 (Tam et al., 2022). The LOD 100 can be related to the concept design, where the elements are represented only symbolically or schematically (Sanchez et al., 2021). In the following levels, geometric and non-geometric information can be added to the model. It is possible to associate LOD 200 and LOD 300 with the design process, the former being a schematic design and the latter representing a detailed design

(BIMForum, 2015). In turn, a BIM model with LOD 400 is detailed with enough information for fabrication, assembly, and installation (Sanchez et al., 2021). Finally, LOD 500 refers to a detailed as-built BIM model (D'Angelo et al., 2022).

8.2.2.2 Industry Foundation Classes (IFC)

When using the BIM methodology as a tool to aid in project decision-making, it is often necessary to use different BIM-based computational tools in an integrated manner. In this context, the OpenBIM concept emerges as an initiative from the buildingSMART International (bSI) organisation to disseminate the use of an open data model, allowing interoperability between BIM tools from different owners (buildingSMART International, n.d.). As a manifestation of the openBIM concept, the IFC schema arises.

The Industry Foundation Classes (IFC) data model is a standardised and digital way to describe the built environment's data, including buildings and civil infrastructure (ISO, 2018). IFC provides software-agnostic data interoperability in the Architecture, Engineering, and Construction (AEC) industry, since this model data allows sharing and exchange between heterogeneous BIM tools (Oostwegel et al., 2022). The IFC schema codifies the identity, semantics, attributes and relationships of objects, abstract concepts, processes and people involved in a project.

Although IFC schema has proved to be an excellent solution for BIM data representation and exchange, the growing amount of information relying on semantic web technologies in the construction industry has forced a breakthrough in this domain. Therefore, a connecting point between semantic web technologies and the IFC standard was developed, named ifcOWL. This is a Web Ontology Language (OWL) for IFC that intends to exploit data distribution, extensibility of the data model, querying, and reasoning (Pauwels and Terkaj, 2016). While the IFC data is expressed as a schema in the EXPRESS data specification language (ISO, 2004), ifcOWL adopts an OWL profile for specifying building information, which brings essential improvements in terms of performance (Pauwels et al., 2017).

Ontology representations of the IFC schema have been a robust backbone for challenging interoperability requirements in the BIM scenario (Venugopal et al., 2015). An ontology can better structure the interoperability of BIM-based tools as it delivers a formal and consistent taxonomy and classification framework. Regarding the use of BIM as the starting point for the DT implementation, it is considered that DT becomes entirely dependent on ifcOWL models, ensuring a robust and knowledge-oriented semantic data storage, which can be exploited by AI technologies (Boje et al., 2020).

8.2.3 BLOCKCHAIN

Blockchain is an innovative information technology that guarantees decentralisation, security, auditability, and smart execution during its application. A blockchain comprises consecutively linked blocks, each containing a pointer to the previous block, a timestamp, and a compilation of information (Estevam et al., 2021). The way blockchain is structured guarantees that data tampering is easily identified (Saxena et al., 2021). Besides, regarding the decentralisation characteristic, blockchain excludes the need for a trusted third party to validate transactions, creating a delegation of authority among network contributors that improves the service trust (Hewa et al., 2021).

In the blockchain domain, the broadcasts of the transactions are collected into blocks, which are then hashed and receive a timestamp (Lemieux, 2016). The name hash is used to identify a cryptographic function intended to encode data to form a unique, fixed-length string (Tsiatsis et al., 2019). The cryptographic functions within a blockchain guarantee the data authenticity and allow the signature of electronic documents (Lemieux, 2016), being practically impossible to carry out the opposite process and get the original data from an already formed hash. In turn, the timestamp serves as proof that the data must have existed at that time in order to get into the specific hash (Nakamoto, 2008).

A blockchain can also store a smart contract, representing an agreement between parties in the form of computer code (Wu et al., 2022). A smart contract can automatically self-execute processes based on the satisfaction of preset conditions (Kuhle et al., 2021), and it can be used as a possible solution to the slow, expensive and fragile transactions associated with the built environment (Chaveesuk et al., 2020). Unfortunately, research shows that the construction sector is classified as one of the sectors that least adopt information technology (McKinsey & Company, 2016). The full implementation of blockchain in building projects needs to be increasingly discussed among researchers and professionals. Among the currently existing blockchain platforms in the market, two of them can be applied in the construction domain: Ethereum and Hyperledger Fabric (Yang et al., 2020).

A discussion gaining strength in the literature is about integrating BIM and Blockchain. This integration can overcome several problems associated with the construction project lifecycle since BIM itself is not concerned with confidentiality, traceability, non-repudiation, provenance tracking, and data ownership (Nawari and Ravindran, 2019). A blockchain platform can mitigate project delays generated due to discrepancies in the BIM models or conflicts among the interested parties (San et al., 2019). Nevertheless, technical barriers are associated with this integration, such as the need for greater computational power to add a BIM model to a blockchain (Nawari, 2021).

8.3 MATERIALS AND METHODS

The construction sector significantly impacts the three pillars of sustainability (Kamali and Hewage, 2017), and therefore, there is a growing search for sustainable practices in this area. Generating a sustainable building involves looking at one that produces less environmental waste, improves societal influences, avoids the utilisation of natural resources indiscriminately, and is economically viable throughout its life cycle.

The use of the prefabricated modular construction method appears to be a viable solution for enhancing the sustainability of the construction industry. It has been reported that prefabricated construction reduces the construction time and the generation of environmental impacts during the construction phase (Navaratnam et al., 2021), in addition to being considered an economical construction approach (Navaratnam et al., 2019). However, for this method to effectively achieve sustainability, it is necessary to carefully optimise building material choice and improve design, manufacturing, logistics, and assembly processes (Bertram et al., 2019).

The framework proposed here addresses the integration of a BIM-based digital twin and blockchain technology for the purpose of ensuring sustainability goals. Modular construction is used as the case example to demonstrate the framework's applicability. In this proposal, BIM serves as the primary data source for developing the building digital twin, while blockchain ensures transparency and security in transactions involving multiple stakeholders. Also, the purpose of the framework proposed is to consider the impacts generated throughout the whole life cycle of a building. It is believed that only by adopting a life-cycle perspective would it be possible to meet the requirements of a sustainable built environment, given that a life-cycle approach comprehensively addresses the impacts of materials and components used, fabrication and construction practices, and waste management.

8.3.1 BUILDING LIFE CYCLE

The building digital twin concept is mainly related to using devices and sensors to collect real-time data, thus especially considering the operational phase of the building. Nonetheless, when the life-cycle approach is inserted into the assessment, the practitioners must consider the design, construction, operation, demolition, and waste treatment stages. In this context, the building digital twin evolves according to the complexity and sophistication required for each stage. With the aid of information technologies, it becomes doable to consider data from the extraction of the raw materials to the waste treatment stage in order to evaluate all the significant impacts generated by building materials and components. **Figure 8.2** presents the entire life cycle of a building that could benefit from integrating BIM, digital twin and blockchain technology.

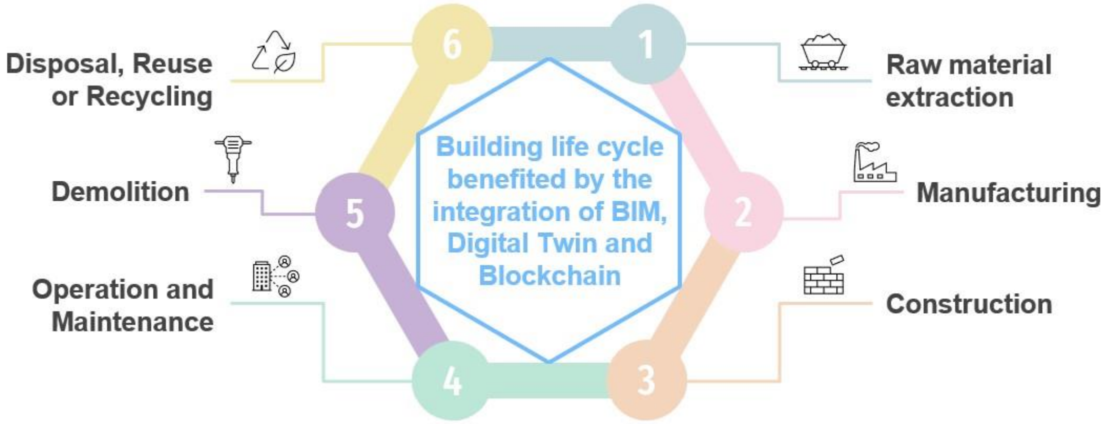

Figure 8.2 - Stages of the building life cycle

Regarding the development of new building projects, the design phase must be used to compare different materials and construction methods so that design choices are conscious and efficient to achieve sustainable goals. In this context, integrating an information technology like blockchain improves the tracking of materials and their impacts throughout their life cycles. Besides, blockchain has proven to positively influence waste management, placing accountability on every member of the chain rather than just on the manufacturer (Gopalakrishnan et al., 2021).

8.3.2 Integrated framework for the project design stage

Based on what has been mentioned so far, it is suggested that the building digital twin be generated from a BIM model with LOD 300. With this level of detail of the construction components and already knowing information about the climate and the position of the building on the ground, it is possible to carry out different types of sustainability assessments. As this study focuses on the prefabricated construction method, it is essential to point out that a large part of the prefabricated components worldwide uses high carbon-intensive construction materials such as concrete and steel (Navaratnam et al., 2021). Therefore, the first step of the proposed integration serves as a possibility for finding alternative sustainable building materials.

During the project design stage, the building digital twin can be used as a descriptive tool, for collecting and visualising data, and as an informative tool, for converting data into information for generating project insights (Seaton et al., 2022). Ideally, a comprehensive digital twin could be developed at this stage, using real-time data about impacts caused through raw materials extraction and transportation, for example, to improve the choice of materials and components and achieve better sustainability outcomes.

With the help of the IFC format and the ifcOWL ontology, it is possible to export the building models to different computational tools to perform various building analyses. With a building model, it is possible to benefit the decision-making process in several ways: testing different materials regarding their environmental, social, and economic impacts, thus improving the building materials choice (Figueiredo et al., 2021); evaluating the annual energy consumption to achieve energy-efficient buildings (González et al., 2021); and analysing adequate interior thermal comfort of the building, minimising the cooling load rate (Seghier et al., 2022). The proposal here is to use a BIM-based digital twin during the early design phases to benefit the decision-making process by focusing on sustainability.

From the simulation results, possible changes will be suggested to the 3D digital model. The idea is to use blockchain to record all these design changes since there is no chronological record of the modifications done in a traditional BIM model. Without the aid of information technology, the revision of the project would occur by updating and replacing the existing data (Kiu et al., 2020). Therefore, the synchronisation of design records through blockchain seems very beneficial. Besides, as this design phase can involve several professionals, it is suggested to use blockchain technology through its smart contracts in order to ensure transparency and security in transactions. In turn, in order to not oblige all stakeholders to significantly change their work processes or have extensive knowledge about blockchain, the proposal is to use a blockchain platform as a robust backbone system behind the interface layer of commonly used applications (Yang et al., 2020).

Figure 8.3 illustrates the integration proposal between a building digital twin and blockchain. It is also worth mentioning the importance of considering data on the life cycle of construction materials in the sustainability assessments carried out. Blockchain can be used directly in this task, as this technology can reduce data uncertainty, decrease the data collection time and ensure perfect traceability of data sources (Kouhizadeh and Sarkis, 2018).

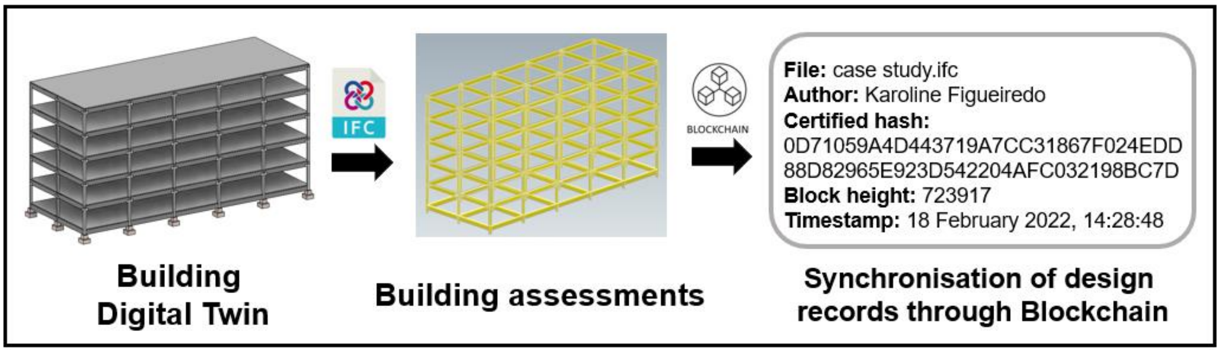

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Figure 8.3 - First steps to integrate Digital Twin and Blockchain

8.3.3 Proposal for the fabrication and assembly stages

Blockchain utilisation is again encouraged in the fabrication and assembly stages. The difference is that, from the fabrication and assembly stages, it becomes necessary to increase the level of development of the digital building model, now corresponding to LOD 400. Traditionally, stakeholders raised concerns about the absence of systematic records of inspection and operations during the fabrication stage (Wu et al., 2022). Utilising a digital fabrication drawing production with the synchronisation of data records will enable higher transparency and better collaboration opportunities.

Using information from the factory, it is possible to develop a digital fabrication model in real-time. The idea here is to include data about the materials' quality inspection into the digital model so that the digital prototype could be used to ensure minimal chances of flaws during the assembly stage. This whole process becomes accessible due to the BIM characteristic of centralising information in the 3D digital model, in addition to the parametric modelling. Therefore, using the BIM methodology as a preliminary step in developing a building digital twin makes the process more effective, given that BIM is currently considered the best tool for authoring static data for construction specifications and documentation.

The use of DTs during fabrication and assembly stages is still little discussed in the literature since the current state of the art of digital twinning in construction relies on as-built data collection (Rausch et al., 2021). Nevertheless, DTs offer great promise as quality control tools throughout fabrication and assembly, and this idea can be used to improve sustainability in the processes. A DT can be fed with scan data from the building components, which will assist professionals during the building assembly to match parts, find clamp positions and select the optimal joining sequence (Söderberg et al., 2017). But it is also possible to conduct construction simulation, safety planning and virtual job site planning from the digital twin model, which can guarantee worker safety and minimise material waste, directly affecting the three pillars of sustainability.

On the other hand, the inherent characteristics of the prefabricated modular construction method suggest the involvement of more participants than in conventional construction since manufacturers represent additional parties (Yin et al., 2019). The literature shows that blockchain can enable the establishment of more efficient connections with partners and stakeholders and provide innovative solutions for the challenges faced by external professionals through a dynamic perspective on value creation (Wan et al., 2022). Based on the above, the benefits of the proposed integration are summarised in **Figure 8.4**.

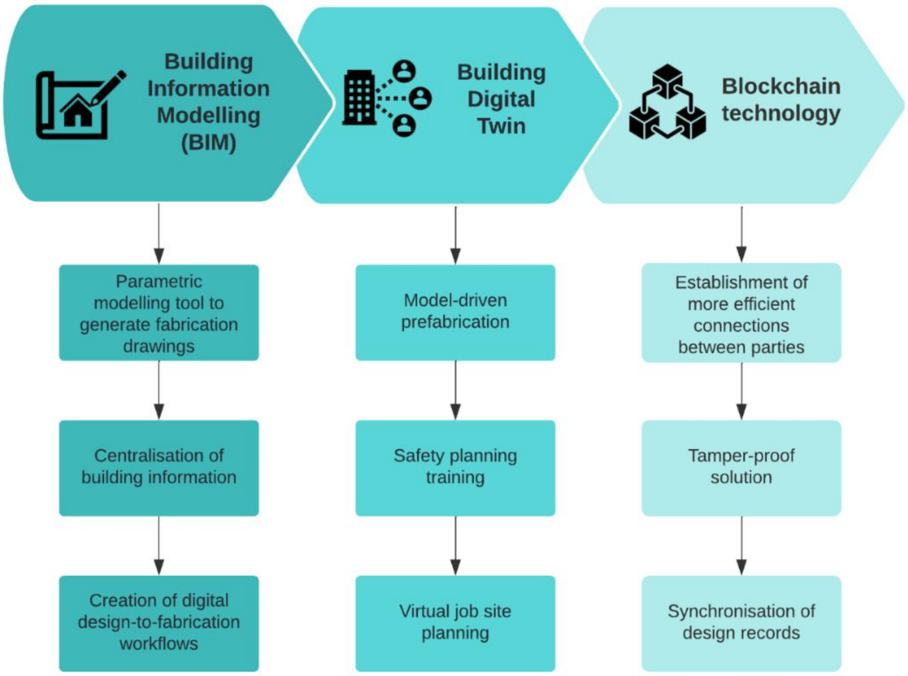


Figure 8.4 - Advantages of integrating concepts during the fabrication and assembly stages

8.3.4 Framework for the operational and maintenance stages

After the assembly stage, the digital BIM model can be updated based on LOD 500. With the help of IoT and using devices and sensors to collect real-time data, the building digital twin can be updated with dynamic and static data from multiple sources. Therefore, the dynamic digital model updates will provide a better understanding of the building performance, enabling the decision-makers to achieve a sustainable smart building. The sustainability certification experts can also make good use of the building twin, updating the digital model in accordance with established procedures (Tagliabue et al., 2021).

Indeed, this process also needs to be a tamper-proof solution, ensuring security and transparency between the parties involved. Then, it is recommended that blockchain technology be applied throughout the entire process. **Figure 8.5** presents the idea of dividing the framework into three steps, corresponding to the different levels of development (LOD) used during the integration process.

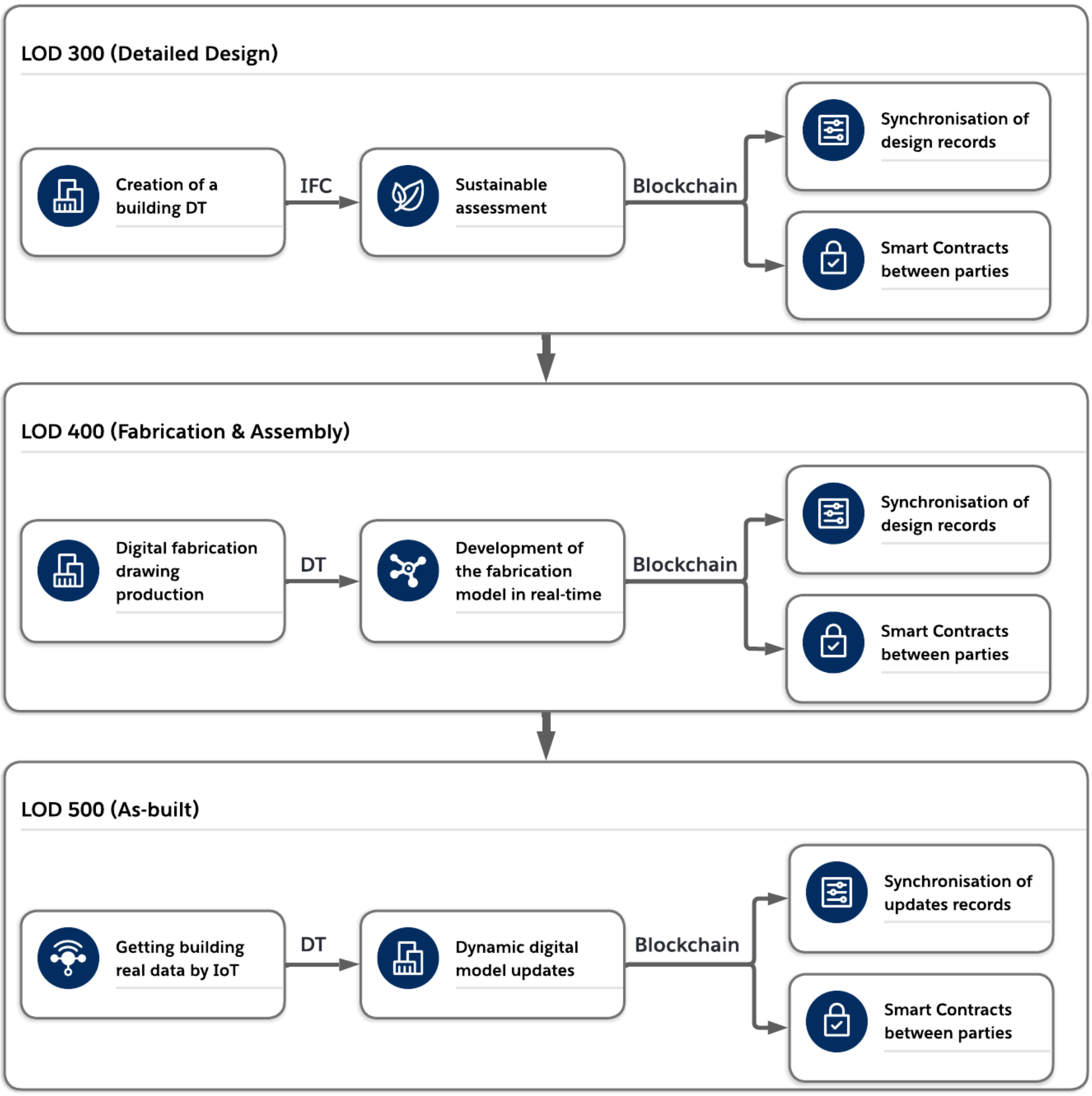


Figure 8.5 - Framework to integrate BIM, digital twin and blockchain across various stages of the building life cycle.

8.3.5 Proposal for designing a semantic BIM-based digital twin integrated with blockchain

From all that has been exposed so far, it is suggested the creation of a platform for integrating BIM, DT, and blockchain regarding the application in building projects. **Figure 8.6** presents the semantic architecture for the integrated framework. Three different layers are created (i.e., database layer, logic layer, and the user interface) for the platform to be operable. Simulation data will be generated from the BIM-based digital twin models. Then, these three-dimensional models need to be fed back with information with every change, while everything must be recorded on a blockchain. During the design, fabrication and assembly, and operation stages, all documentation generated must be stored on the blockchain so that data reliability and traceability are guaranteed.

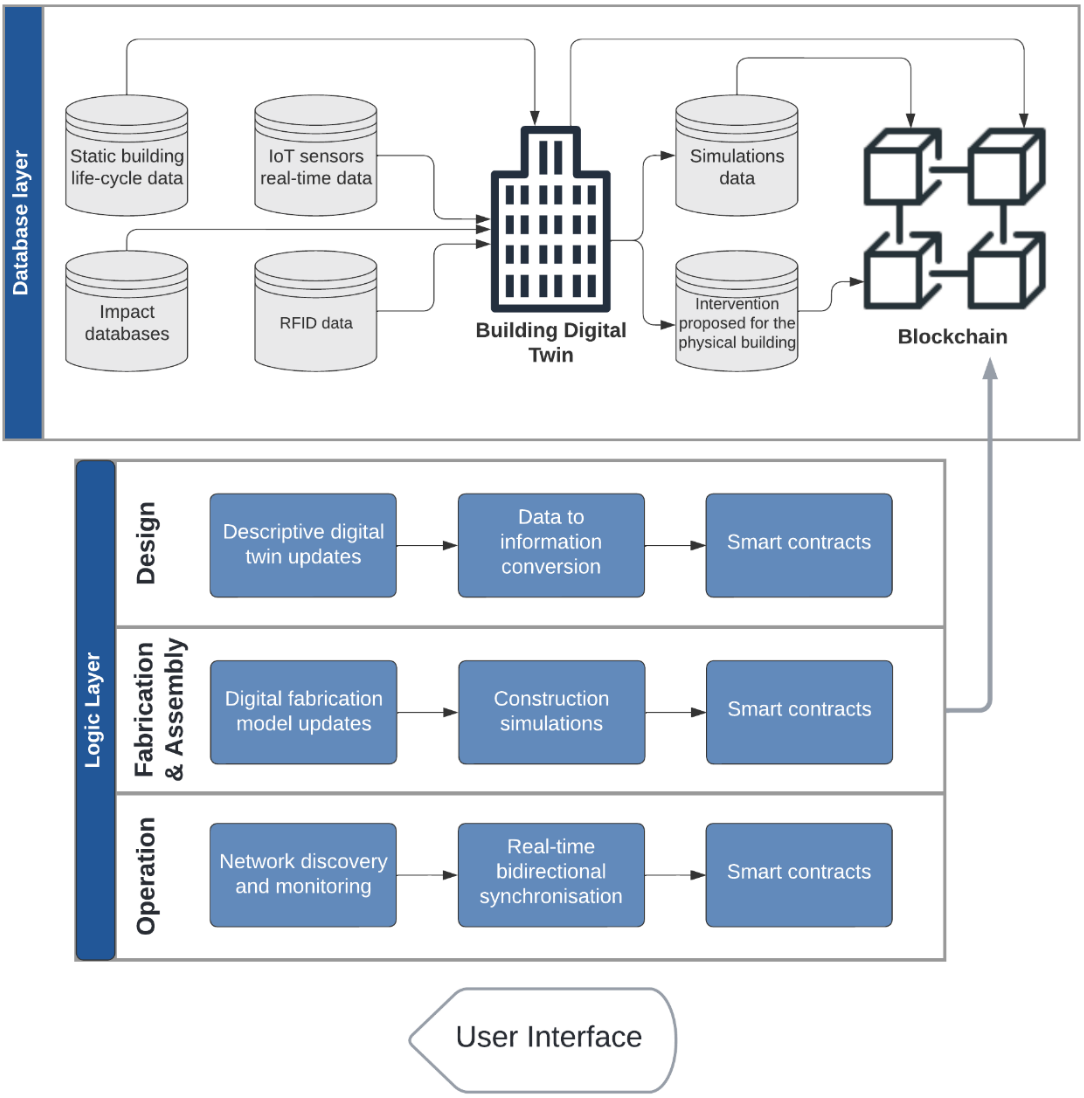
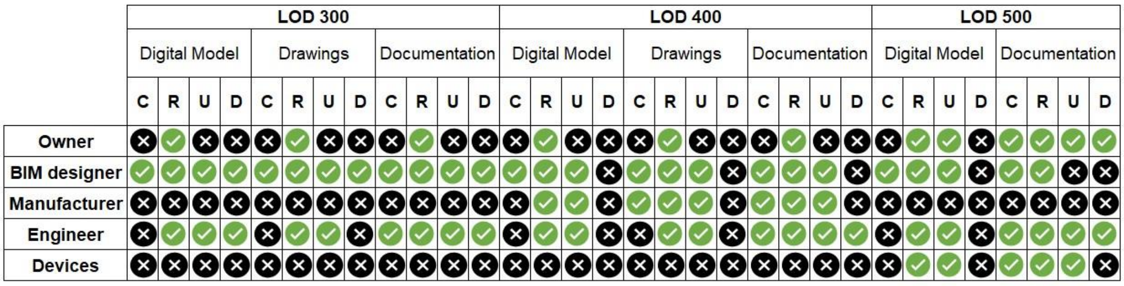


Figure 8.6 - Proposed semantic architecture for the integrated framework

The database layer consists of the 3-D BIM models and all data to be inserted and generated. Simulations can be developed throughout the entire project lifecycle, either to benefit decision-making of which materials and methods should be used to achieve sustainable standards or to optimise the use of building systems throughout the operation phase. During the operation phase, sensors and devices collect real-time data from the physical asset. The building digital twin can be calibrated to accept data from numerous data streams, such as video devices, accelerometers, laser scanners, Radio Frequency Identification (RFID) devices, and displacement sensors (Seaton et al., 2022). Therefore, new simulations can be performed based on real-time data, and all information generated must be recorded in a blockchain.

The logic layer needs to be divided into the three project phases as the permissions of each entity will be different in each step. For example, the manufacturer does not need permission to modify any files (i.e., digital model, drawings, and documentation) generated during the design and operation stages. However, this entity needs some permission during fabrication and assembly when the BIM-based digital twin is based on LOD 400. In this context, it is necessary to precisely define a role mapping with permissions defined for each entity. It is illustrated in **Figure 8.7**.



	LOD 300												LOD 400												LOD 500							
	Digital Model				Drawings				Documentation				Digital Model				Drawings				Documentation				Digital Model				Documentation			
	C	R	U	D	C	R	U	D	C	R	U	D	C	R	U	D	C	R	U	D	C	R	U	D	C	R	U	D	C	R	U	D
Owner	✗	✓	✗	✗	✗	✓	✗	✗	✗	✓	✗	✗	✗	✓	✗	✗	✗	✓	✗	✗	✗	✓	✗	✗	✗	✓	✓	✗	✓	✓	✓	✓
BIM designer	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✗	✗
Manufacturer	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗
Engineer	✗	✓	✓	✓	✗	✓	✓	✗	✓	✓	✓	✓	✗	✓	✓	✗	✗	✓	✓	✗	✓	✓	✓	✓	✗	✓	✓	✗	✓	✓	✓	✓
Devices	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✗	✓	✓	✓	✗

Permissions: C = Create; R = Read; U = Update; D = Delete.

Figure 8.7 - An example of a role mapping with permissions defined for each entity

8.4 DISCUSSION

This chapter intends to start a discussion on how digital twin and blockchain technology can be integrated to assist designers, manufacturers, engineers, and architects in developing more sustainable building projects, considering the three pillars of sustainability (i.e., environmental, social and economic), and using the prefabricated modular construction method. The main achievements, including contributions to the field, are related to the proposal for designing a semantic BIM-based digital twin platform to improve design, manufacturing, logistics, and assembly processes. Besides, as the proposed platform is based on blockchain technology, it will consist of a tamper-proof solution for a building sustainability assessment. Thus, this research sheds light on the sustainable benefits that building assessment tools offer to the built environment, also assisting in analysing the entire building life cycle.

Unfortunately, as the framework is proposed, a considerable manual effort is required for practitioners to manually update the digital model during the design and fabrication stages. This problem will persist as long as the three-dimensional modelling is done in BIM tools currently available on the market since they do not use domain ontology. Indeed, some BIM applications support the IFC standard but do not adequately export the IoT information, focusing on the physical object and not considering its behaviour.

Another critical issue to be pointed out is that building models may require greater computational power to be added to a blockchain, which can create technical barriers to the implementation of the proposed framework. Besides, the performance of this integrative framework can face many cultural and organisational challenges, given that the construction industry delays the adoption of process and technology advancements. Therefore, the application in real projects of what has been discussed so far and the dissemination of this integration directly depend on advances in research in this regard.

The following steps of this research refer to the practical development of this platform, with the validation of its use through application in a case study. However, it is worth mentioning that the platform in its current state already represents an advance for research in this area, as it presents a feasible solution to minimise errors and achieve greater sustainability in prefabricated modular construction.

8.5 CONCLUSION FOR CHAPTER 8

A semantic architecture for the integrated framework was proposed in this chapter, with an example of how practitioners could develop a role mapping with permissions defined for each entity. The proposal uses the Building Information Modelling (BIM) methodology as a primary data source to establish a building digital twin, focusing on the sustainability assessment of prefabricated modular construction. The digital twin is examined for its benefits in terms of sustainability decision-making throughout the construction lifecycle, ensuring that the evaluation is not tampered with due to blockchain application.

Several challenges are associated with the proposal discussed. It is essential to note that a life-cycle sustainability assessment of a built asset, considering the three pillars of sustainability jointly, is very challenging as it requires a comprehensive understanding of uncertainties and processing a large amount of data. As such, several technical barriers can appear during the integration of digital twin and blockchain and the development of the proposed platform. Nonetheless, more research needs to be conducted to explore the links between environment, society, and economy, realistically quantifying the impacts generated by the construction industry and encouraging the creation of a more sustainable and smarter built environment.

Future studies will focus on three main aspects: (i) the practical development of this platform, with the validation of its use through application in a building case study; (ii) improvement of the platform in order to minimise manual and repetitive work related to 3D-BIM models; (iii) investigation about the integration of the Life Cycle Sustainability Assessment (LCSA) methodology into this platform, so that it will be possible to analyse environmental, social and economic impacts based on the whole life-cycle of the building.

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9 INTEGRATING DIGITAL TWIN AND BLOCKCHAIN FOR DYNAMIC BUILDING LIFE CYCLE SUSTAINABILITY ASSESSMENT

This chapter is submitted as an original research article.

FIGUEIREDO, Karoline et al. Integrating Digital Twin and Blockchain for Dynamic Building Life Cycle Sustainability Assessment.

Abstract: The Life Cycle Sustainability Assessment (LCSA) methodology represents a possible solution to meet the requirements of a sustainable built environment by adopting a lifecycle perspective and simultaneously accounting for all sustainability pillars. Nevertheless, the LCSA application is typically focused on the early design stages of a building and does not consider real-time information, representing a static LCSA approach. Therefore, based on the results derived from a systematic literature review on this subject, this paper proposes a comprehensive framework that demonstrates how the integration of LCSA with Digital Twin and Blockchain can enhance building sustainability. A platform based on Smart Contracts is presented to facilitate the integration of these technologies. A case study is also conducted to validate the framework's applicability and showcase its benefits in achieving sustainable outcomes in the built environment. This research contributes to improving dynamic impact assessments and achieving sustainability, thus fostering sustainable practices in construction projects.

Keywords:
BIM; Blockchain; Digital Twin; Dynamic Analysis; Life Cycle Sustainability Assessment; Sustainable Construction.

9.1 INTRODUCTION

Life Cycle Sustainability Assessment (LCSA) emerged as a thorough methodology based on the life cycle thinking approach. This approach takes into account the fact that all phases of a product's life cycle have an impact on the environment and have socio-economic repercussions. All these issues, in turn, need to be assessed in order to achieve sustainability [1]. The LCSA methodology is the result of combining three key processes: i) Life Cycle Assessment (LCA), related to the environmental pillar of sustainability; ii) Life Cycle Costing

(LCC), associated with the economic pillar; and iii) Social Life Cycle Assessment (S-LCA), linked to the social pillar.

In recent years, researchers have started emphasizing the importance of incorporating dynamic aspects into building sustainability assessments, which involves considering time-dependent factors and real-time impact scores to assess the impacts across different time horizons [2]. This topic still receives little attention in the literature, particularly when it comes to research that validates this concept in building case studies. Considering the specific application of LCA, thus assessing only environmental aspects, some efforts have already been presented in the literature with the aim of transforming this application into a dynamic LCA. This emerging field, Dynamic Life Cycle Assessment (DLCA), aims to provide a more comprehensive and accurate understanding of the environmental implications over time.

Yet, while the concept of DLCA holds significant potential for advancing the understanding of the dynamic nature of environmental impacts, there is a notable gap in the literature regarding the standardization of this application and the extrapolation to a dynamic LCSA, considering the three pillars of sustainability. In this context, tools and technology that facilitate the life-cycle data collection and real-time data visualization needed to produce in-depth conclusions during the building sustainability assessment seem pertinent.

Building Information Modeling (BIM) might be one of the most apparent solutions in this regard. BIM is a widely used methodology in the construction industry and refers to a working procedure based on a digital representation of the facility. Besides, BIM incorporates all stakeholders into the workflow and facilitates data access along the project's life cycle [3]. Therefore, a BIM model consists of a 3-D digital model containing both geometric and semantic data of building elements. However, the current state of BIM lacks semantic completeness in managing dynamic data and is considered incompatible with the Internet of Things (IoT) integration, a tough challenge currently discussed in the literature [4].

In order to deal with this issue, research has focused on synchronizing the cyber-physical bi-directional data flow between the digital model and the existing building, making use of the Digital Twin (DT) paradigm. Conceptually, a DT is a virtual representation of an object or system, serving as the real-time digital counterpart of the asset during its life cycle [5]. From the construction standpoint, several DT applications have been investigated under the BIM field, understanding a construction DT as a digital prototype with increased detail and precision and using the BIM model as the primary data source to develop the DT [4].

Unfortunately, this data aggregation throughout the facility’s life cycle can generate a security risk due to the presence of multiple parties and sources. Traceability, confidentiality, and security issues may arise as obstacles while developing a construction DT. From this perspective, applying blockchain technology can provide a plausible avenue for dealing with these issues. Blockchain is nowadays the most prominent Distributed Ledger Technology (DLT) in the market [6]. DLT is a transaction system that runs on a distributed peer-to-peer (P2P) network and does not require a central authority to arbitrate such transactions [7]. In turn, a blockchain is a DLT that represents a database with interconnected blocks of data cryptographically protected against tampering [8], in which the data integrity is reached through the process of hashing [7]. Regarding the projects associated with the built environment, blockchain can offer a tamper-proof solution throughout the information supervision of built assets [9].

In this vein, one of the critical objectives of this research is to explore how the knowledge gained from the individual application of LCSA, DT, and blockchain can be harmonized into an integrative solution for dynamic building assessments. Despite significant advancements in each of these domains, there is still a critical need to bridge the gap between theory and practical implementation within the construction industry. Therefore, this study begins with a systematic literature review, presenting a comprehensive bibliometric analysis and defining the state-of-the-art of LCSA, DT and blockchain in construction. Particularly, this paper intends to answer the following research questions (RQ):

(RQ1) Is it feasible to extrapolate the discussion on Building LCSA, typically focused exclusively on the early design stages and not considering real-time information, via applying different levels of Digital Twins throughout the entire life cycle of the building and creating a dynamic approach?

(RQ2) How does integrating blockchain and Digital Twin contribute to enhancing the precision, reliability, and comprehensiveness of dynamic sustainability assessments in the built environment, particularly regarding ensuring data security and user privacy?

Based on the conclusions derived from the systematic review, an integrative framework is proposed to showcase how this integration can enhance sustainability in construction and advance research in this field. A proof of concept is then presented to validate the framework and showcase its applicability, highlighting the innovative potential of combining LCSA, DT, and blockchain within the construction industry. By analyzing the challenges encountered in the framework application, a platform based on Smart Contracts is also proposed to integrate the technologies, with a semantic architecture being illustrated.

9.2 RESEARCH METHODS

This study systematically explores LCSA, DT, and blockchain within the construction industry, aiming to culminate in an integrative framework. The research methods, illustrated in **Figure 9.1**, span three distinct phases: systematic literature review, framework development and proof of concept.

The study starts with a systematic literature review based on the PRISMA guidelines [10] to achieve the findings needed to answer the research questions posed herein. In this phase, a scientific evolution analysis is proposed based on a bibliometric and text data mining exploration to grasp the progression of the concepts over time. Then, a meticulous examination to delineate the current state-of-the-art in LCSA, DT, and blockchain within the construction industry is carried out, serving as the foundation for the subsequent phases.

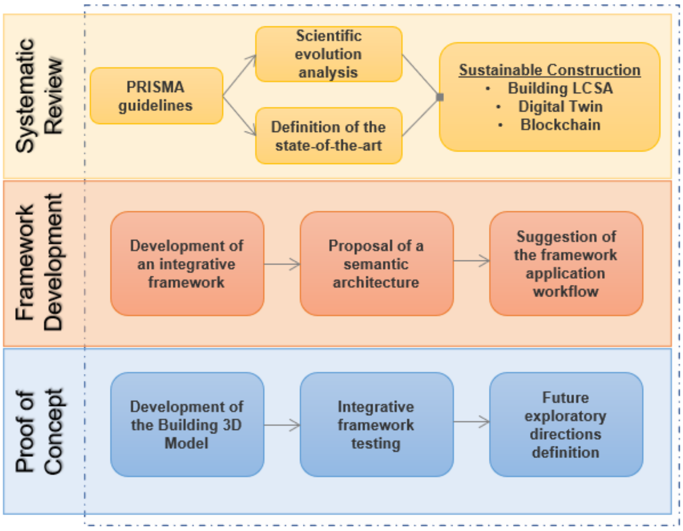

Figure 9.1 - Research methods proposed for this study

Scopus was chosen as the preferred search database. The study intends to provide quantitative and qualitative assessments of the research trends and key publications in the field, in addition to identifying existing gaps in the literature. Firstly, the search considered LCSA, DT, and blockchain being used together. After that, the study was conducted by searching for the chosen keywords related to each concept separately in article titles and abstracts. The keywords were combined with logical operators AND, OR, and NOT. The data was collected in September 2023. **Table 9.1** shows the different interactions carried out in this study.

The first key objective of the review was to evaluate current research trends and establish the status of LCSA, DT and blockchain within the context of sustainable construction. Therefore, all interactions presented in **Table 9.1** contained critical terms related to sustainability. Then, the documents were screened and filtered, considering the overall relevance of the papers. Relevance criteria involved the inclusion of journal articles and review articles while excluding books, book chapters, and conference papers. Furthermore, to maintain uniformity in language, the search was restricted to documents in English. **Figure 9.2** illustrates the steps of the systematic literature review conducted in this study based on the PRISMA guidelines.

Table 9.1 - Keywords used in each interaction of the literature review search

Interactions in *Scopus* and *Web of Science* databases	**Keywords used**
First interaction	("Building" OR “Construction”) AND ("LCSA" OR "Life Cycle Sustainability Assessment" OR "TBL" OR “Triple bottom line” OR (“Environmental” AND “Economic” AND “Social”)) AND ("Digital Twin" OR “data-driven simulation” OR “cyber-physical”) AND ("Blockchain" OR “Distributed Ledger Technology” OR “DLT”)
Second interaction	("Building" OR “Construction”) AND ("LCSA" OR "Life Cycle Sustainability Assessment" OR "TBL" OR “Triple bottom line” OR (“Environmental” AND “Economic” AND “Social”))
Third interaction	("Building" OR “Construction”) AND ("Digital Twin" OR “data-driven simulation” OR “cyber-physical”) AND (“Sustainable” OR “Sustainability”)
Fourth interaction	("Building" OR “Construction”) AND ("Blockchain" OR “Distributed Ledger Technology” OR “DLT”) AND (“Sustainable” OR “Sustainability”)

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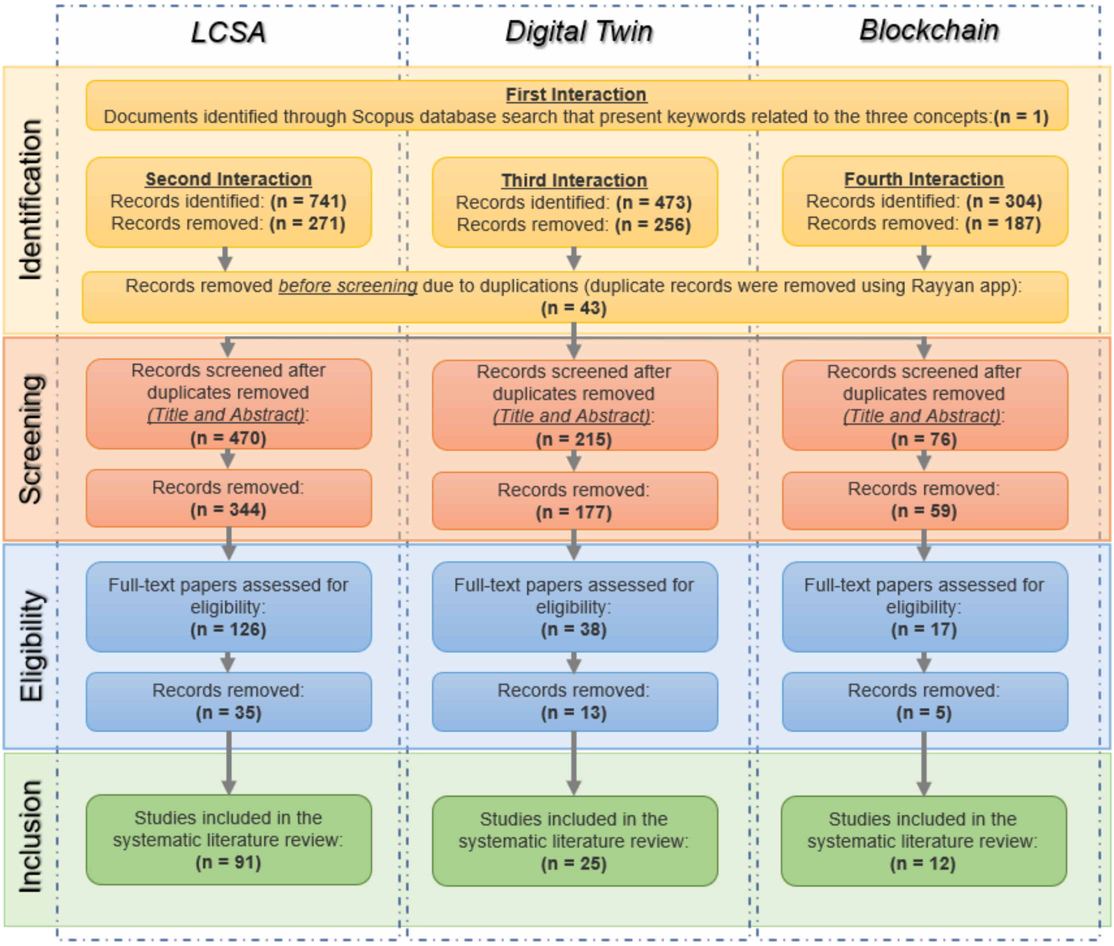


Figure 9.2 - PRISMA-based diagram for the systematic literature review conducted in this study

The culmination of the systematic review sets the stage for the second phase of the methodology proposed in this study, related to the framework development. In this phase, a comprehensive framework is proposed to seamlessly integrate LCSA, DT, and blockchain within the construction domain. In the context of this study, the integration proposed is a multifaceted endeavor. To ensure that this integration is both practical and comprehensive, the framework is designed to provide a structured and all-encompassing approach, allowing practitioners to consider every critical facet of these broad concepts.

The final phase is related to the Proof of Concept of the framework developed herein. This phase will start with creating a 3D model that emulates real-world construction scenarios, enabling practical testing of the framework. The main goal is to use rigorous testing to assess the framework's effectiveness, potential for enhancing sustainability, and adaptability to diverse scenarios. Ultimately, the discussion of this study’s results intends to consider a forward-looking perspective, identifying areas for future exploration, refinement, and innovation. All these phases will be discussed in the following sections of this paper.

9.3 LITERATURE REVIEW

9.3.1 Scientific evolution analysis

A bibliometric analysis was conducted (i) separately on each approach (LCSA, DT, blockchain) and (ii) accumulatively via the use of these concepts together in the same study. The decision to search for studies that include at least one of the three approaches is due to the understanding that the advancements in each topic can be extrapolated and combined to achieve the objectives of this paper. The results of this analysis are used to show the current research stage on these concepts.

The papers filtered in the literature search were classified via a bibliometric analysis using text data mining and clustering. For this, the authors utilized specialized software, namely VOSViewer (version 1.6.18), developed by researchers from Leiden University in Sweden [11]. VOSviewer uses the VOS mapping technique to construct a bibliometric map, where VOS stands for Visualisation of Similarities [12]. The maps created based on the co-occurrence of terms among the papers found in the second, third, and fourth interactions, related to applying the methodologies with a sustainability focus, are shown respectively in **Figures 9.3, 9.4, and 9.5**. The distance between two keywords in these figures indicates their relatedness. The closer two terms are located, the stronger their relatedness.

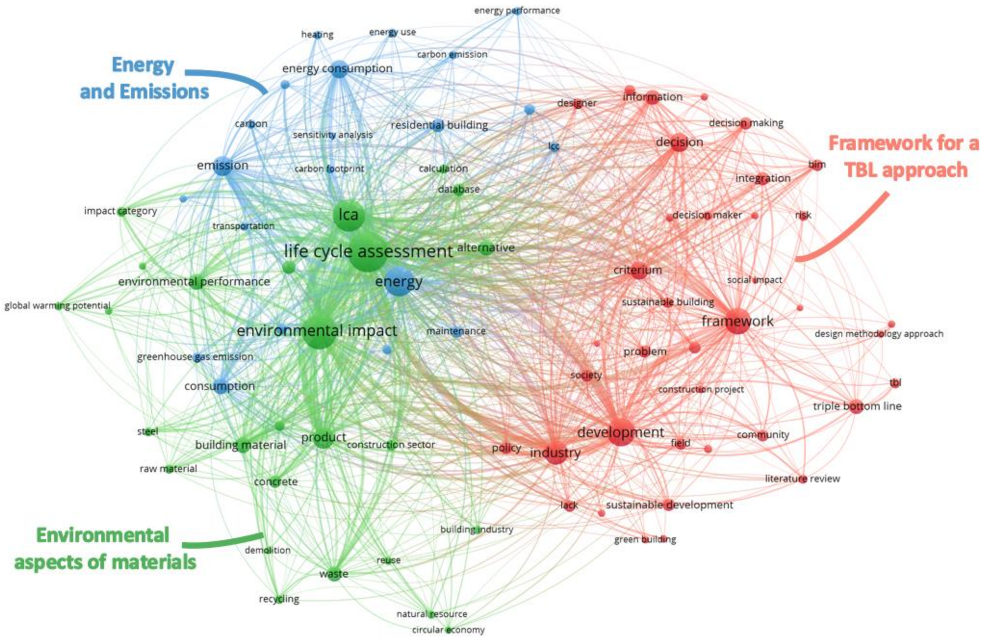


Figure 9.3 - A map based on the co-occurrence of terms in scientific papers related to Building LCSA, divided into three clusters.

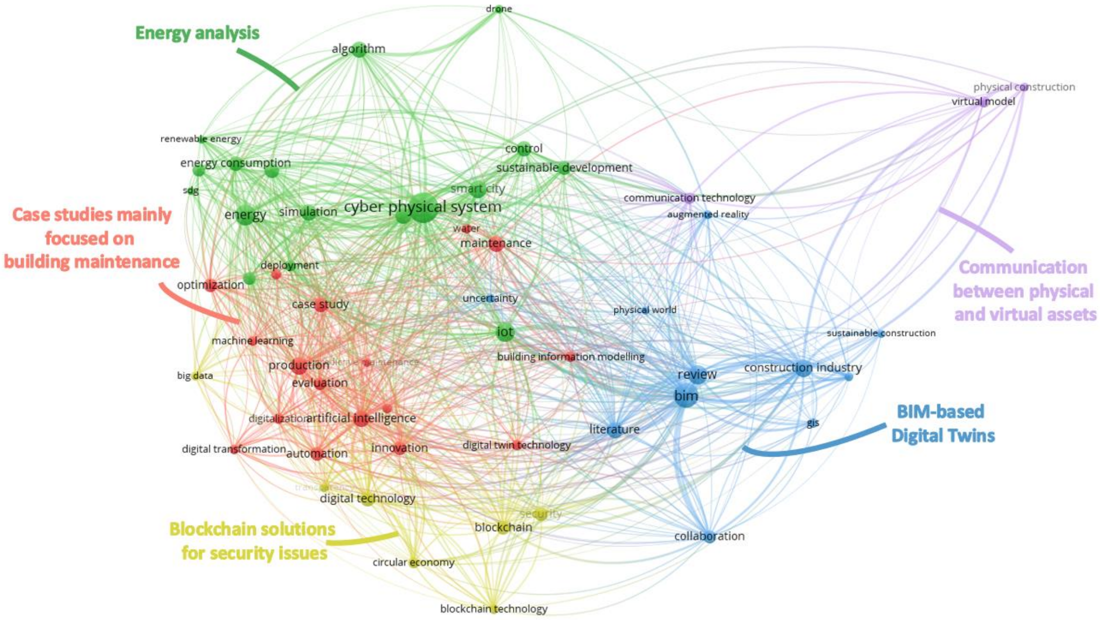


Figure 9.4 - A map based on the co-occurrence of terms in scientific papers related to Building Digital Twin, divided into five clusters.

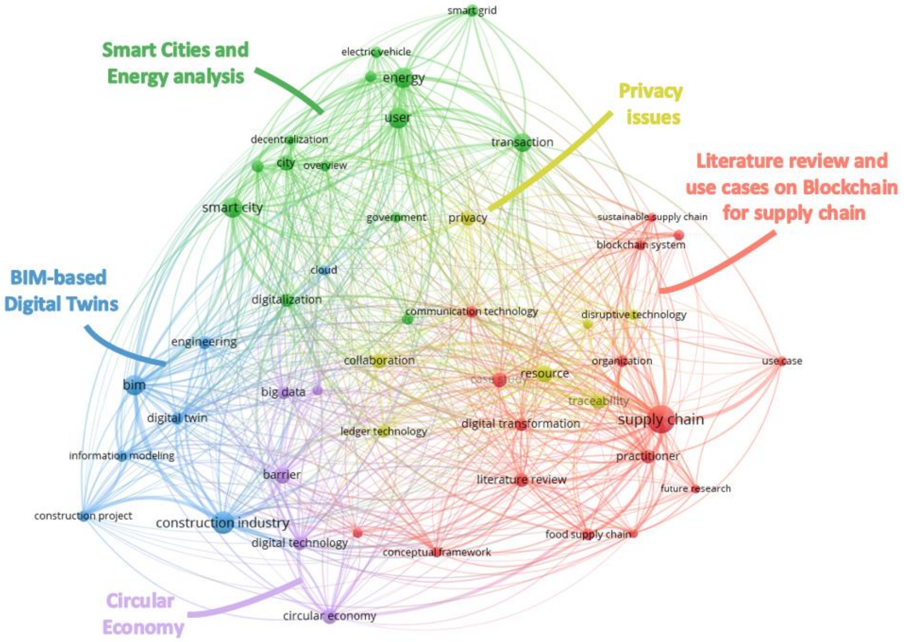


Figure 9.5 - A map based on the co-occurrence of terms in scientific papers related to Blockchain applied in the construction industry, divided into five clusters.

Although many articles mention the application of LCSA, it is essential to note that many of these publications tend to be limited in scope, predominantly addressing environmental assessments without fully encompassing all three pillars of sustainability, as indicated by the green cluster in **Figure 9.3**. Besides, several publications focus on energy analysis and carbon emission, as shown in the blue cluster. Finally, papers that delve deeper into a triple-bottom-line approach typically emerge from literature review searches or the development of conceptual frameworks. This approach aims to mitigate the ongoing challenges of harmonizing LCA, LCC, and S-LCA. This specific focus can be observed within the red cluster.

In turn, an evident correlation with the BIM methodology emerges regarding the use of DT in the construction industry. Many papers utilize a BIM-based DT model in their analyses, as evidenced in the blue cluster in **Figure 9.4**. Also, it was possible to derive two critical areas of DT application in the construction industry. On the one hand, numerous publications concentrate on applying DTs for energy analysis, showcasing their relevance to sustainability outcomes. On the other hand, another significant cluster underscores the adoption of DTs for building maintenance, emphasizing their role in optimizing facility operations. This application is closely linked to information and control systems, which are crucial for leveraging DTs to enhance the sustainability of physical facilities. Notably, some articles have begun to address this need by discussing the integration of BIM-based DTs with blockchain, highlighted in the yellow cluster.

Ultimately, **Figure 9.5** is related to the application of blockchain in the construction industry. Notably, many papers in this interaction also involve the application of BIM-based DTs, reaffirming the potential benefits of this integration in construction projects, as shown in blue. Besides, four more clusters were identified as the key research areas on using blockchain to advance sustainability: smart cities and energy analysis; supply chain, particularly in terms of transparency and traceability; circular economy; and the use of blockchain to solve privacy issues, acknowledging the importance of data security and user confidentiality.

9.3.2 Definition of the state-of-the-art of LCSA, Digital Twin, and Blockchain in construction

After conducting a scientific evolution analysis, the documents were filtered for further careful investigation. This step aimed to find the most relevant works to assist in developing an integrative framework. The most significant articles for each topic that have been reviewed are discussed in the following subsections.

9.3.2.1 Life Cycle Sustainability Assessment

The Life Cycle Sustainability Assessment (LCSA) is an interdisciplinary framework that simultaneously evaluates the impacts associated with products and processes from an environmental, social, and economic perspective [13]. The techniques that form the LCSA framework (i.e., LCA, LCC, and S-LCA) follow the same methodological structure based on the ISO 14040 standard. This methodological structure is divided into four stages: Goal and Scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation [14].

Although the three life-cycle methodologies have similarities, significant differences in each technique have been identified in the literature [15]. For instance, not all the economic and social indicators can be estimated as a function of the functional unit of the study, resulting in a significant drawback in the interpretation stage [16]. In this vein, numerous issues concerning the complete application of LCSA remain unanswered in the literature, and many studies continue to execute only a portion of the evaluation. This is primarily due to the varying maturity levels of the three sustainability pillars, which impedes the widespread adoption of LCSA.

Regarding the use of LCSA as a decision-making technique in the construction industry, researchers have applied this methodology mainly during the early stages of a building design

[15,17–19]. A recent study introduced an innovative LCSA model designed for integration into the design phase of new building projects and energy refurbishments for existing buildings [20]. The authors further developed a novel formulation and weighting method to derive a final LCSA index, facilitating a holistic assessment of design scenarios and considering the three pillars of sustainability. The study also innovatively integrates Machine Learning (ML) techniques into the optimization process, enhancing the efficiency of design assessments while upholding their precision.

Nevertheless, when considering using this methodology in different stages of the building's life cycle, a new challenge emerges related to the need for more temporal information in the assessments. Notably, the current LCSA methods take a stagnant approach that fails to consider dynamic factors during the building life cycle, such as material deterioration, varying energy consumption, and technology up-gradation, resulting in inaccurate sustainability assessments [21]. In this context, the data inventory can be considered the most sensitive and challenging step of an LCSA application since it leads to the creation of a model that should represent, as accurately as possible, all the exchanges between the distinct phases of a process [22]. So far, the need for more impact data sources adapted to the specific requirements of a building project has been seen in the literature [15]. Besides, it has been noted that impact assessments are typically based on data from historical series, which hinders the use of LCSA for rapid corrective actions on a project.

Therefore, it becomes necessary to consider a dynamic LCSA approach in which a dynamic life cycle inventory (D-LCI) is considered, along with time-dependent characterization factors, to assess the impacts by considering real-time impact scores for any time horizon [23]. This topic still receives little attention in the literature, particularly when it comes to research that validates this concept in building case studies. However, considering the specific application of LCA, thus assessing only environmental aspects, some efforts were already presented in the literature with the aim of transforming this application into a dynamic LCA.

For example, Ferrari et al. [24] proposed the integration of the life cycle inventory (LCI) stage with the Enterprise Resource Planning (ERP) system to overcome some limitations in LCA inventory data. The authors highlighted that many companies already have part of the primary inventory data in an ERP system, thus making it possible to dynamize LCA applications by exploiting the data collected by ERP. This idea was discussed with a focus on manufacturing companies and implemented in a case study related to the environmental monitoring needs of a ceramic tile manufacturer.

Recent works started to discuss a dynamic LCA approach in the construction domain but with specific and limited goals. Ramon et al. [25] analyzed the operational phase in building LCA assessments by employing a dynamic energy consumption and electricity mix approach and integrating future climate model data and dynamic energy simulations. In turn, Apostolopoulos et al. [26] evaluated a set of energy-efficient retrofit measures in a residential case study in Greece. In this study, carbon emissions, primary energy needs, and lifecycle costs were analyzed. The authors considered that a Dynamic-LCA approach was implemented due to the use of a specific building energy variable, incorporating time-dependent features in the context of temporal and spatial variations.

In a notable case study centered in Quebec, Canada, the authors investigated the increasing utilization of wood in non-residential buildings through LCA [27]. This study compared a conventional static LCA, which adopts fixed time horizons for assessing environmental impacts, with a dynamic approach using the DynCO2 tool. The findings underline the importance of considering both short-term and long-term consequences, as conventional static LCAs may provide incomplete insights, especially when dealing with elementary flows with varying values. Still, this study did not apply a dynamic life-cycle inventory. The analysis was considered dynamic due to the use of a dynamic characterization method during the LCIA phase.

Other recent publications presented different frameworks for a dynamic LCSA application but with limited advances in this field. Francis and Thomas [21] developed a methodological framework that allows practitioners to set desired values for material use, material replacement alternatives, energy mix, and water recycling percentage to evaluate the building impacts of the selected combination of values. It can be observed that the authors considered more environmental indicators as compared to economic and social ones. Besides, the framework continues to resemble the traditional LCSA application, allowing the comparison of several alternatives from manual changes in the system.

Another point that deserves attention is that although the number of lifecycle approaches is constantly growing in construction, the number of Environmental-LCA applications is still much more significant than LCC and S-LCA studies. Besides, previous thorough literature reviews have revealed that most investigations over the last 20 years focus on the impacts generated during the extraction and manufacturing stages of building materials and components, moderately or infrequently considering the other building life cycle stages specified in international standards (i.e., construction installation, use, maintenance, repair, demolition, processing, disposal, recycling, etc.) [28]. It reveals another research gap that needs to be solved in the literature.

In light of the above, it becomes evident that the foundational realm of LCA, which has evolved in tandem with D-LCA and LCSA [21], must undergo further expansion to accommodate the dynamic influences and intricate interrelationships among the three sustainability pillars. This evolution can undoubtedly contribute to the progression and maturation of research in this domain, fostering a more holistic understanding of sustainability in construction and the built environment.

9.3.2.2 Digital Twin (DT)

A DT represents a collection of realistic models that intend to simulate the physical asset's real-time attributes, conditions, and behavior throughout its existence [29]. Particularly, communication between virtual models and physical assets in bi-directional coordination allows for changes in one environment to be reflected in the other and vice versa. This idea has been employed in various sectors and businesses, including construction. Unlike BIM, which focuses on centralizing data and information and is typically used as a single digital shadow [30], a building DT can provide timely optimization suggestions by mirroring the building's lifecycle and current status [31]. In this context, DTs of constructed assets can present different complexity levels from design to handover, depending on the availability of data and the model's sophistication [32].

Several contributions of using DT in the construction sector are discussed in the literature, such as the real-time building's remote monitoring and management and the maintenance and planning estimation [33]. A building DT is considered a contextual model of an entire building, bringing together third-party data and resulting in a dynamic digital replica that can be used to solve a wide range of issues [34]. The benefits of using a building DT vary from real-time data visualization to continuous asset monitoring and the development of self-learning capabilities [35]. However, a closer look at the literature reveals some gaps and shortcomings. Although the DT concept already provides solutions to current problems in building projects, research on this subject continues mainly at a theoretical level. Several articles that apply a building DT in a case study upgraded existing modules of a BIM model to a DT system without considering real-time data, thus only partially realizing a building DT [31].

Besides, the literature shows that the use of virtual models as a platform for continuously tracking building components during the operation and maintenance phases is underutilized despite the opportunities for building monitoring and control [36]. Previous methods for integrating virtual models and physical construction have primarily focused on resource and activity monitoring during the construction stage, as well as documentation of the as-built.

State-of-the-art literature on DT proves that the proliferation of the concept associated with the built environment and the construction industry has not been primarily driven by the need to achieve sustainable outcomes in this sector, with limited applications regarding sustainability assessments based on a triple-bottom-line approach. Notably, a recent study with a hybrid approach involving literature review, expert interviews, and modeling techniques stated that the relationship between DT and sustainable success remains insufficiently studied in the literature regarding the building and construction sectors [37]. There are several barriers to implementing DT in this context, such as interoperability issues, difficulty in protecting intellectual property, data uncertainties, connectivity, and cultural inertia.

However, as the demand for sustainable practices grows, research has started to pivot in this direction. Several studies have begun to outline specific goals for employing BIM-based DTs to achieve sustainability within construction. For instance, some efforts have focused on maximizing the recycling and reuse of demolition waste [38], while others have explored the development of Zero Energy Districts [39]. These studies represent critical steps toward integrating DT technology with sustainability principles, aligning the construction industry with the broader sustainability agenda.

Nonetheless, it is observed that the application intended to improve the LCSA methodology via DT implementation is still briefly addressed in the literature. Tagliabue et al. [40] have discussed the application of a BIM-based DT for sustainability assessments. Still, their case study primarily pertained to the design and operational phases, with a particular focus on energy efficiency. As a result, it did not encompass all sustainability pillars or consider the full array of parameters associated with sustainable construction. This gap between DT and comprehensive LCSA integration in the context of the construction industry points to an avenue for further research and innovation.

9.3.2.3 Blockchain

Blockchain is an innovative information technology that ensures decentralization, auditability, security, and smart execution in a process. At its core, a blockchain comprises consecutively linked blocks, each containing a pointer to the previous block, a timestamp, and a collection of data [41], and this structure guarantees that any data tampering is easily identified [42]. Briefly, the blockchain process collects the broadcasts of transactions into blocks, which are then hashed and receive a timestamp [43]. Hash is the name used to identify a cryptographic function that encodes data to create a unique and fixed-length string in the chain [44].

Due to these cryptographic functions, it is practically impossible to carry out the opposite process and get the original data from an already-formed hash, which ensures data authenticity and security [43]. Furthermore, the timestamp created in this process provides reliable evidence that the data must have existed at that moment to get into that specific hash [45], thus further enhancing the security and auditability of the blockchain. In turn, blockchain excludes the need for a trusted third party to validate transactions due to its decentralization characteristic, resulting in a delegation of authority among network contributors that improves the service trust [46].

In the blockchain domain, smart contracts play a pivotal role. They are used as agreements between parties expressed in the form of computer code [47]. A smart contract can automatically self-execute processes based on satisfying preset conditions [48], in addition to determining the content, norms, rights, and obligations of each member of the chain [49]. When considering applying blockchain technology to projects associated with the built environment, smart contracts seem to be a possible solution to the slow, fragile, and expensive transactions observed in this context [50].

Unfortunately, it is noteworthy that the construction industry has historically lagged behind in adopting information technology within its processes [51]. Consequently, the application of blockchain technology in the construction sector remains predominantly a theoretical discussion. Despite its theoretical underpinnings, the potential for blockchain to revolutionize the construction industry by streamlining transactions and enhancing security cannot be underestimated. It is essential to recognize that the adoption of blockchain in the construction industry faces challenges related to technical expertise, interoperability, and cost [52]. However, as the technology matures and awareness grows, more practical applications are expected to emerge, fostering a profound transformation in the built environment.

9.3.3 Preliminary Integration Attempts Presented in the Literature

The systematic review of the literature revealed a scarcity of studies that effectively leverage DTs to enhance all three pillars of sustainability from a life-cycle perspective. Moreover, the practical application of blockchain technology in construction projects remains theoretical mainly, with limited case studies available within the construction industry. However, some preliminary integration attempts presented in the literature are worth analyzing.

Previous studies have emphasized the benefits of integrating BIM and blockchain [53–55]. While highly effective in managing project information, the BIM methodology lacks certain features such as confidentiality, traceability, provenance tracking, non-repudiation, and data ownership. In this vein, by integrating BIM and blockchain, various challenges inherent to the construction project lifecycle can be addressed [56]. For example, a blockchain platform can alleviate project delays resulting from BIM model discrepancies or stakeholder conflicts [57]. Nonetheless, several technical barriers are linked to this proposal, such as the necessity for greater computational power to add a BIM model to a blockchain [58].

Considering a BIM model as the primary data source for constructing a building DT, it becomes evident that integrating blockchain technology into DT is a logical next step. Several frameworks have been proposed to satisfactorily apply this integration, some focusing on project management [59] and others on manufacturing systems [60]. In the construction industry context, two prominent blockchain platforms available in the market, Ethereum and Hyperledger Fabric, can be harnessed for this purpose [61].

In turn, the integration of BIM and Environmental LCA has gained substantial traction in the literature, and different ‘LCA Profiles’ have emerged, establishing associations between LCA processes and construction materials or components, often represented as BIM objects [62]. BIM's role in this context is linked to an information aggregator and context provider, offering a rich dataset to support the LCA analysis. Therefore, LCA tools and plug-ins are pivotal in connecting the information sourced from BIM with the corresponding LCA processes within the databases [63]. Still, while promising, recent studies have shown that this integration has sometimes led to inaccurate results within the current designers' workflow [64,65]. This conclusion underscores the critical need for analysis tools that seamlessly align with the dynamic nature of a building project.

In a parallel vein, exploring synergies between LCSA and BIM-based DTs promises to revolutionize sustainability practices in the construction industry. As discussed in a recent study by Boje et al. [62], a fully monitored construction project could help track events in real time and provide inputs for a dynamic sustainability assessment, but this lies in the scope of a DT model and not a BIM model. Therefore, the authors introduced a streamlined LCSA of an office building with a limited scope to showcase the complementary roles of BIM and DT. However, it is essential to note that the utilization of BIM and DT in this case study was primarily restricted to environmental LCA during modules A1, A2, A3 (product stages), B6 (operational energy), and B7 (operational water). This limited application did not fully address the potential of LCSA-DT integration, leaving room for further exploration and development in this evolving field.

Regarding the use of blockchain, Zhao et al. [59] highlighted a significant challenge concerning the current levels of blockchain technology employed in the literature, which may not meet the requirements for DTs applied in construction management. Several drawbacks arise, such as high latency and performance loss due to the large amount of transaction data associated with a construction project. To address this, the authors proposed a framework to enhance collaboration and communication among project stakeholders, mainly when internet connections are unstable, focusing specifically on project management.

Moreover, integrating blockchain technology in life-cycle approaches can significantly enhance data reliability and trustworthiness, enabling better tracking of a building's life-cycle performance. For example, when combined with IoT sensors for automatically collecting data, blockchain can track a product and record its footprint along its entire value chain [66]. Additionally, all inventory data can be stored, processed, and validated on a blockchain platform [67], potentially improving the quality of LCSA inventories and enhancing the sustainability decision-making process for construction projects.

9.4 FRAMEWORK DEVELOPMENT

This section introduces the integrative framework presented in this work, as illustrated in **Figure 9.6**. The framework's primary focus lies in integrating a building DT with blockchain technology to enhance the application of the LCSA methodology in the construction industry, thereby advancing sustainability goals. The proposed framework emphasizes the dynamic nature of LCSA, to be conducted across different phases of a building's life cycle with real-time data derived from a digital building twin. It is also essential to recognize that the digital building model's complexity will evolve, adapting to the available data at different stages of the building's existence. By incorporating blockchain technology, the framework not only ensures the integrity, traceability, and transparency of data but also revolutionizes the collaboration and data exchange processes among diverse stakeholders.

Many researchers advocate for applying life cycle techniques during the building design stage, recognizing the significant influence of stakeholders in these early phases, which diminishes as the project approaches completion. However, this application is inherently hindered by the dearth of data available at the inception of the project life cycle. The workflow articulated in this study presents a dynamic approach, enabling LCSA to be executed throughout various building phases, supported by additional technologies. This innovative approach treats LCSA as an iterative process that evolves alongside the physical building. In this context, the LCSA results in the pre-construction phase play a pivotal role in enhancing design decisions. Subsequently, the digital model continuously evolves by assimilating real-time data, allowing for ongoing LCSAs that support the building's construction, renovation, and maintenance.

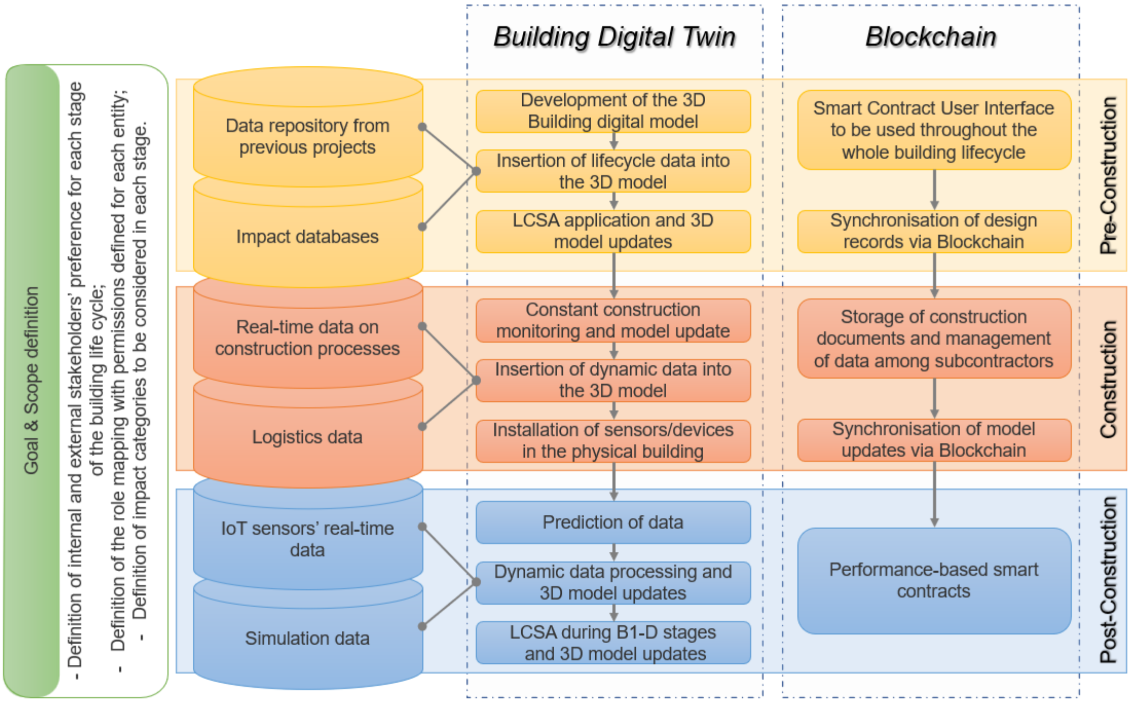


Figure 9.6 - The integration framework proposed in this study

In contrast to conventional LCSA with its fixed time horizon, the proposed framework proposes a dynamic LCSA approach adaptable to different stages of the building's life cycle. While retaining the fundamental methodological structure based on the ISO 14040 standard, it emphasizes the importance of clearly and accurately defining the goal and scope of LCSA at each building stage. This encompasses elements like functional unit, system boundary, target audience, assumptions, and limitations, ensuring that the selected impact categories align with the specific sustainability objectives of each building stage.

The digital model is established and constantly updated in the pre-construction phase as design decisions are made. This descriptive DT, driven by 3D-BIM models, incorporates detailed information about construction materials, aiding in the early-stage conceptualization and sustainable material choices. During construction, real-time data is collected and seamlessly integrated into the digital model, establishing a bidirectional connection between the digital and physical assets. This synchronization empowers the utilization of real-time data in LCSA, elevating the quality of decision-making and creating a construction data repository for future projects. Furthermore, it facilitates construction simulations, virtual job site planning, and safety planning, enhancing sustainability across all three pillars.

In the post-construction phase, the DT model receives updates encompassing static data from various sources, including impact databases and data repositories from prior projects. These updates are complemented by dynamic data IoT sensors. Integrating artificial intelligence (AI) and machine learning is also encouraged, driving building assessments to a level of autonomy and connectivity, significantly reducing human intervention while maintaining sustainability goals. The DT's role in decision-making spans various domains, from material selection to energy efficiency and thermal comfort.

The digital twin's role in decision-making is extensive, offering benefits in material selection, energy efficiency, and thermal comfort. While its application during pre-construction and construction stages remains an emerging topic, the framework envisions using digital twins as quality control tools in design, fabrication, and assembly processes, thus improving sustainability outcomes.

The framework also proposes using blockchain technology to record all design changes, addressing the long-standing challenge of absent chronological records in traditional building models. Blockchain synchronization promises transparency, security, and streamlined collaboration among diverse professionals in the construction project. Smart contracts within blockchain technology guarantee transaction security without imposing extensive knowledge or workflow alterations on stakeholders. This innovative approach delivers benefits across all stages of a building's life cycle, addressing concerns associated with inspection records and operations during fabrication.

By employing blockchain for digital fabrication drawing production, real-time data synchronization, and data record tracking, transparency and collaboration within the construction process are significantly enhanced. Furthermore, blockchain technology can establish efficient connections among professionals and offer innovative solutions to external stakeholders, culminating in heightened value creation.

Finally, the LCSA interpretation step should assist the stakeholders in the decision-making process related to each stage of the building life cycle. The decision-makers must be able to select the optimum sustainable choice for the building based on the three pillars of sustainability. In these terms, utilizing multi-criteria decision-making (MCDM) methods to facilitate the decision and performing a Sensitivity Analysis during interpretation is encouraged, as it allows the LCSA practitioner to compare all possibilities highlighted as suitable for the building during the previous LCSA steps.

9.4.1 Demonstration of the proposed framework for Proof of Concept

A case study is examined to validate the applicability of the proposed framework. It was considered a building of typical architecture in the southeast of Brazil to present a discussion representative of the Brazilian construction industry. The analyzed building is a 17-unit residential building composed of 6 stories (ground floor, four floors, and a roof) in Rio de Janeiro, Brazil. The baseline 3D model was modeled in Autodesk Revit 2023, with data integrated and extracted using Dynamo as the visual programming language. The whole process was developed on the Microsoft Windows 11 operating system, using an Intel core i7 processor at 2.3 GHz and 32GB of RAM.

This case study serves as a vital component in developing and validating the integrative framework. The primary objective of this case study is not to comprehensively apply the entire framework across all stages of a building's life cycle. Instead, the focus is on testing and validating specific aspects, primarily within the pre-construction phase, using available tools in the market. The rationale behind this approach is to understand the practical challenges, feasibility, and functionality of integrating LCSA, DT, and blockchain technologies within the critical context of a construction project. Focusing on the pre-construction phase, where significant sustainability decisions are made, materials and methods are selected, and the foundation for a building's life cycle is laid, this case study allows for a targeted assessment of the framework's effectiveness. Ultimately, it acknowledges that while the ultimate goal is to apply the framework across all stages of a building's life cycle, a phased approach to validation is crucial.

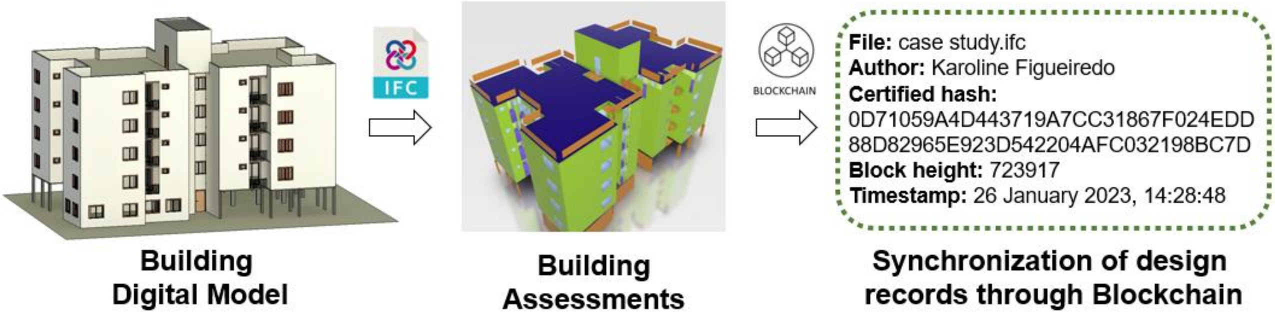
The process begins with developing a detailed 3D model using specialized Autodesk Revit software. This BIM model acts as the primary data source, creating the foundational DT while offering a comprehensive building representation. It includes physical attributes, materials, systems, and design elements. Subsequently, a BIM-based DT is crafted to provide a real-time virtual replica of the physical building. This DT serves as the dynamic element in the process, continuously engaging with the actual building throughout its lifecycle.

With the insertion of lifecycle data in the 3D building model, the first LCSA application occurs, following all recommendations proposed by ISO 14040 and 14044 standards. The

LCSA scope during the pre-construction stage is to determine the best building elements and methods among a pre-defined list, considering environmental, economic, and social impacts. In this study, the functional unit of the study corresponds to all architectural materials and assemblies for the whole building, including all materials required for manufacturing and use, such as sealants, adhesives, coatings, and finishing. Besides, the definition of the functional unit considers that it is related to a multi-family residential building with a service life of 60 years. In this work, a 1% cut-off factor by mass was considered to determine which materials to exclude from the assessment.

Furthermore, a cradle-to-grave system boundary is adopted in this study, in which the following stages are considered: extraction of raw materials, transportation, fabrication, construction, operation, and end of life. For the end-of-life phase, it is assumed that the building would be imploded, and the assessment would include the relevant material collection and landfilling rates. The same system boundary is adopted for environmental, economic, and social evaluations to guarantee that the harmonization of the three approaches occurs satisfactorily.

Ultimately, to enable seamless data transfer and to export the building model to different computational tools to perform various building analyses, it is suggested to make use of the Industry Foundation Classes (IFC) data model, a standardized and digital way to describe the built environment's data [68], providing software-agnostic data interoperability in the Architecture, Engineering, and Construction (AEC) industry [69]. Remarkably, in this case study, it is proposed that the final IFC models are exported to the ACCA software to use the *usBIM.blockchain* application, which allows practitioners to register any document uploaded to the platform on a public blockchain. The steps taken are represented in **Figure 9.7**.



File: case study.ifc
Author: Karoline Figueiredo
Certified hash:
0D71059A4D443719A7CC31867F024EDD
88D82965E923D542204AFC032198BC7D
Block height: 723917
Timestamp: 26 January 2023, 14:28:48

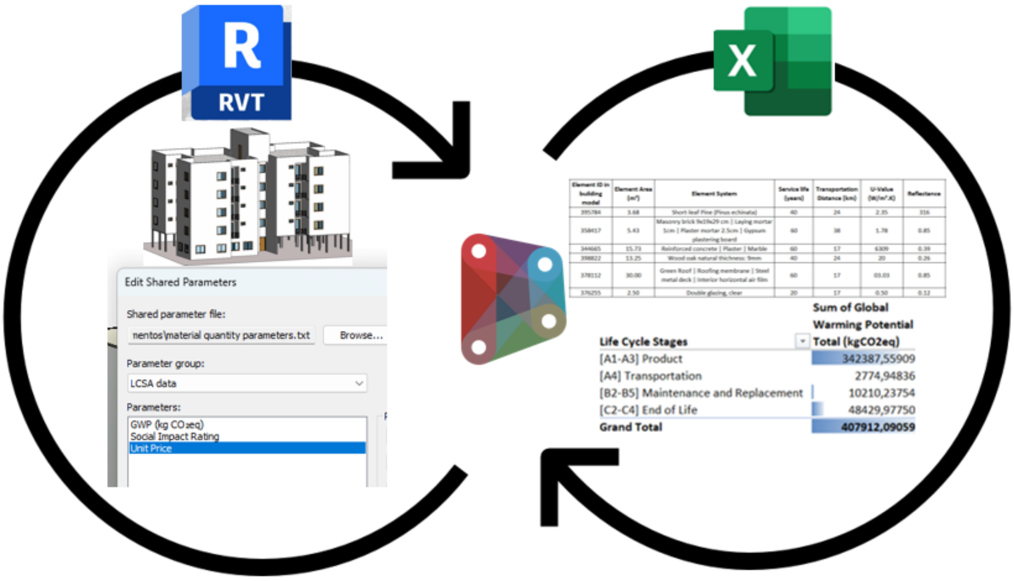
Figure 9.7 - First steps applied in the case study

On the one hand, some papers suggest exporting the Bill of Quantities (BoQ) from the BIM software to a specific tool related to life cycle approaches or using plug-ins and add-ons to conduct the LCSA calculation in the BIM tool [63]. On the other hand, some researchers encourage the inclusion of environmental, social, and economic data within the BIM model using different data sources [19]. This last approach is the most supported here since it represents the evolution of the building's digital model with the centralization of more data and information, thus allowing the growth of the building’s digital shadow in BIM into a building's DT in the following stages of the building life cycle. Therefore, the modeling process of this case study incorporated an efficient data integration method. Building materials' properties and additional data were seamlessly integrated into Autodesk Revit using a custom Dynamo script. This approach augmented the existing dataset, enhancing the depth and accuracy of information associated with building elements.

In the context of the pre-construction stage, specific impact categories were meticulously selected to evaluate the building's sustainability from a holistic perspective. The Global Warming Potential (GWP), measured in kg CO_2 eq., was chosen as the environmental impact category, addressing the carbon footprint of the building materials and processes. The economic assessment focused on the building's life-cycle cost, encompassing aspects related to the cost-effectiveness of materials and construction methods. In parallel, the social assessment emphasized the well-being of workers and local communities, adopting the "Social Impact Rating" category. This rating category is considered a multifaceted approach, encompassing ethical labor practices, local sourcing, sustainable production methods, and community engagement—acknowledging the importance of social responsibility in construction projects.

An extensive inventory database was established in Microsoft Excel to support the data integration and augmentation process. This database was comprised of the most frequently employed construction materials and building systems within the Brazilian construction sector. It drew upon data derived from previous projects conducted by a construction company in the state of Rio de Janeiro. The database contained a comprehensive array of information, including properties of materials, cost data, and regional availability.

The gathering process was underpinned by the construction company's extensive experience in real-world projects, ensuring that the data reflected practical, on-the-ground considerations. Moreover, this wealth of data enabled the computation of final values to be inserted into the new parameters in Autodesk Revit, facilitating the quantification of environmental, economic, and social aspects within the building's life cycle. Utilizing this industry-derived data not only enhanced the accuracy of the assessments but also underscored the relevance of the study's findings to real-world construction practices. The summary of this process is provided in **Figure 9.8**, offering a succinct representation of the new parameters created in the 3D model and the database's content while maintaining the discussion's brevity.



Shared parameter file: nentos\material quantity parameters.txt

Parameter group: LCSA data

Parameters:
GWP (kg CO₂eq)
Social Impact Rating
Unit Price

Life Cycle Stages	Sum of Global Warming Potential Total (kgCO2eq)
[A1-A3] Product	342387,55909
[A4] Transportation	2774,94836
[B2-B5] Maintenance and Replacement	10210,23754
[C2-C4] End of Life	48429,97750
Grand Total	**407912,09059**

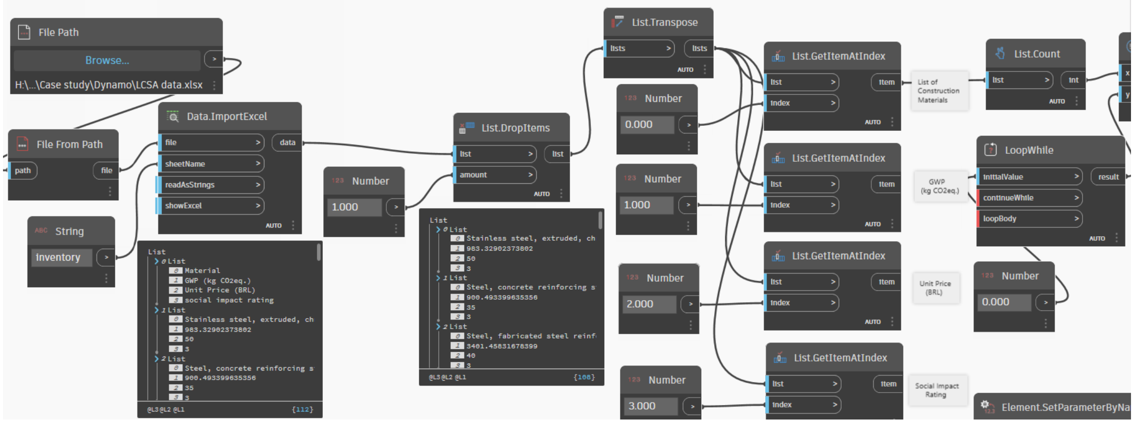
Figure 9.8 - The process of integrating the inventory database with the building model

It is important to highlight that the traditional architectural design process in BIM often involves manual exploration and iteration of design alternatives, which can be time-consuming and limit the exploration of diverse possibilities. This proposal encourages using visual programming languages, such as Dynamo, that offer a promising approach to automate and optimize this process by leveraging computational tools.

Therefore, in order to facilitate the analysis of various design iterations and their corresponding environmental, economic, and social impacts, a systematic approach was adopted. Firstly, Dynamo, a visual programming language, was employed to establish a connection between the inventory database stored in Excel sheets and the Revit environment. This integration allowed for the seamless transfer of vital material information from the database to the Revit model, enriching each building element with detailed data.

Secondly, a script was developed to update the baseline 3D model in Revit and generate alternative design options for key building elements. This script enabled the variation of parameters such as door types, window types, external wall configurations, and slab types, resulting in the creation of 24 distinct alternatives for the building construction. By systematically altering these elements, the script facilitated the exploration of diverse design possibilities, each with its unique set of environmental, economic, and social implications.

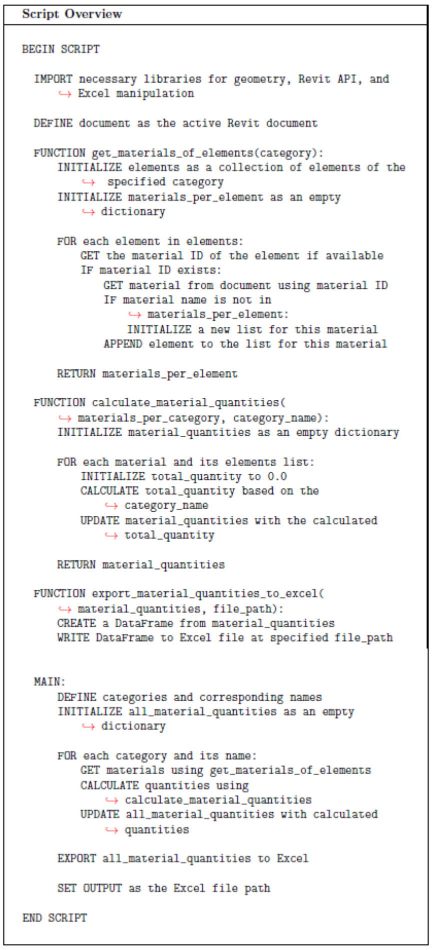
A snapshot of the Dynamo code utilized in this case study is presented in **Figure 9.9**, providing insight into the technical implementation of the data integration process. Furthermore, to streamline the analysis of each design iteration, a Python code was developed to collect data from the material takeoff of every solution. This Python script extracted essential data points from the Revit model and exported them to an Excel spreadsheet for further analysis. The script overview is detailed in **Figure 9.10**, outlining the key functions and procedures involved in the data collection process.



```
List
 > 0 List
     0 Material
     1 GWP (kg CO2eq.)
     2 Unit Price (BRL)
     3 social impact rating
 > 1 List
     0 Stainless steel, extruded, ch
     1 983.32902373802
     2 50
     3 3
 > 2 List
     0 Steel, concrete reinforcing s
     1 900.493399635356
     2 35
     3 3
@L3 @L2 @L1                    {112}
```

```
List
 > 0 List
     0 Stainless steel, extruded, ch
     1 983.32902373802
     2 50
     3 3
 > 1 List
     0 Steel, concrete reinforcing s
     1 900.493399635356
     2 35
     3 3
 > 2 List
     0 Steel, fabricated steel reinf
     1 3401.45831678399
     2 40
     3 3
@L3 @L2 @L1                    {108}
```

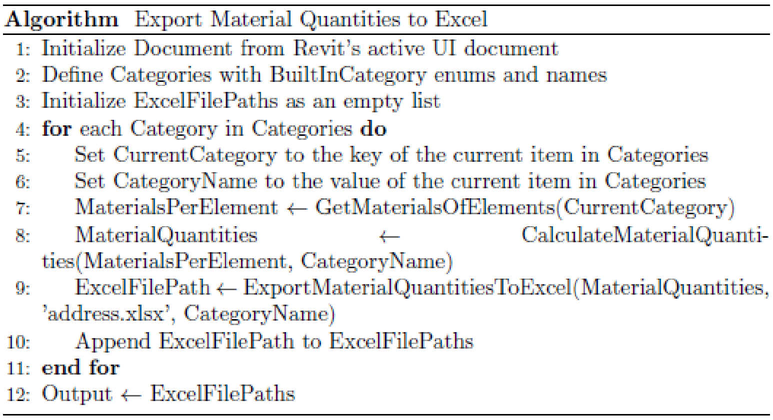
Figure 9.9 - Part of the Dynamo code used in this case study



```
Script Overview

BEGIN SCRIPT

  IMPORT necessary libraries for geometry, Revit API, and
    ↪ Excel manipulation

  DEFINE document as the active Revit document

  FUNCTION get_materials_of_elements(category):
      INITIALIZE elements as a collection of elements of the
        ↪ specified category
      INITIALIZE materials_per_element as an empty
        ↪ dictionary

      FOR each element in elements:
          GET the material ID of the element if available
          IF material ID exists:
              GET material from document using material ID
              IF material name is not in
                ↪ materials_per_element:
                  INITIALIZE a new list for this material
              APPEND element to the list for this material

      RETURN materials_per_element

  FUNCTION calculate_material_quantities(
    ↪ materials_per_category, category_name):
      INITIALIZE material_quantities as an empty dictionary

      FOR each material and its elements list:
          INITIALIZE total_quantity to 0.0
          CALCULATE total_quantity based on the
            ↪ category_name
          UPDATE material_quantities with the calculated
            ↪ total_quantity

      RETURN material_quantities

  FUNCTION export_material_quantities_to_excel(
    ↪ material_quantities, file_path):
      CREATE a DataFrame from material_quantities
      WRITE DataFrame to Excel file at specified file_path


  MAIN:
      DEFINE categories and corresponding names
      INITIALIZE all_material_quantities as an empty
        ↪ dictionary

      FOR each category and its name:
          GET materials using get_materials_of_elements
          CALCULATE quantities using
            ↪ calculate_material_quantities
          UPDATE all_material_quantities with calculated
            ↪ quantities

      EXPORT all_material_quantities to Excel

      SET OUTPUT as the Excel file path

END SCRIPT
```

Figure 9.10 – Script Overview

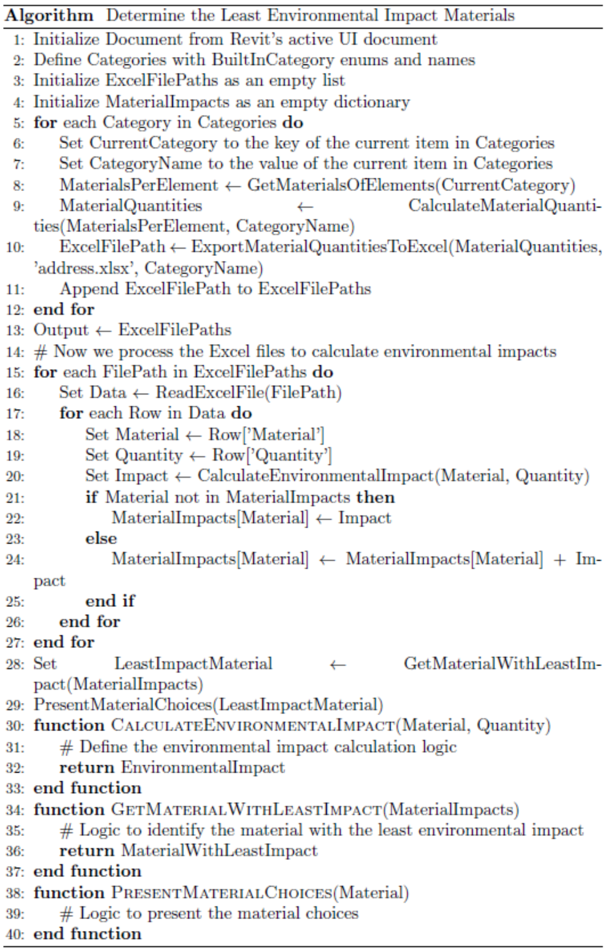
Subsequently, the exported data was subjected to rigorous evaluation and assessment to quantify the environmental, economic, and social impacts associated with each design alternative. **Figures 9.11 and 9.12** delineate the algorithms employed to export material quantities to Excel and determine the least environmental impact materials, respectively. These algorithms provided a structured framework for analyzing the collected data and deriving meaningful insights into the sustainability implications of various design choices.



```
Algorithm Export Material Quantities to Excel
Initialize Document from Revit's active UI document
Define Categories with BuiltInCategory enums and names
Initialize ExcelFilePaths as an empty list
for each Category in Categories do
    Set CurrentCategory to the key of the current item in Categories
    Set CategoryName to the value of the current item in Categories
    MaterialsPerElement ← GetMaterialsOfElements(CurrentCategory)
    MaterialQuantities ← CalculateMaterialQuantities(MaterialsPerElement, CategoryName)
    ExcelFilePath ← ExportMaterialQuantitiesToExcel(MaterialQuantities, 'address.xlsx', CategoryName)
    Append ExcelFilePath to ExcelFilePaths
end for
Output ← ExcelFilePaths
```

Figure 9.11- Algorithm to Export Material Quantities to Excel

By leveraging computational tools and scripting techniques, this approach facilitated a systematic exploration of design alternatives and their corresponding sustainability outcomes. Moreover, it underscored the importance of integrating data-driven decision-making processes within the architectural design workflow, paving the way for more informed and sustainable design practices in the construction industry.



```
Algorithm Determine the Least Environmental Impact Materials
Initialize Document from Revit's active UI document
Define Categories with BuiltInCategory enums and names
Initialize ExcelFilePaths as an empty list
Initialize MaterialImpacts as an empty dictionary
for each Category in Categories do
    Set CurrentCategory to the key of the current item in Categories
    Set CategoryName to the value of the current item in Categories
    MaterialsPerElement ← GetMaterialsOfElements(CurrentCategory)
    MaterialQuantities ← CalculateMaterialQuantities(MaterialsPerElement, CategoryName)
    ExcelFilePath ← ExportMaterialQuantitiesToExcel(MaterialQuantities, 'address.xlsx', CategoryName)
    Append ExcelFilePath to ExcelFilePaths
end for
Output ← ExcelFilePaths
# Now we process the Excel files to calculate environmental impacts
for each FilePath in ExcelFilePaths do
    Set Data ← ReadExcelFile(FilePath)
    for each Row in Data do
        Set Material ← Row['Material']
        Set Quantity ← Row['Quantity']
        Set Impact ← CalculateEnvironmentalImpact(Material, Quantity)
        if Material not in MaterialImpacts then
            MaterialImpacts[Material] ← Impact
        else
            MaterialImpacts[Material] ← MaterialImpacts[Material] + Impact
        end if
    end for
end for
Set LeastImpactMaterial ← GetMaterialWithLeastImpact(MaterialImpacts)
PresentMaterialChoices(LeastImpactMaterial)
function CALCULATEENVIRONMENTALIMPACT(Material, Quantity)
    # Define the environmental impact calculation logic
    return EnvironmentalImpact
end function
function GETMATERIALWITHLEASTIMPACT(MaterialImpacts)
    # Logic to identify the material with the least environmental impact
    return MaterialWithLeastImpact
end function
function PRESENTMATERIALCHOICES(Material)
    # Logic to present the material choices
end function
```

Figure 9.12 - Algorithm to Determine the Least Environmental Impact Materials

9.5 RESULTS AND DISCUSSION

This work intends to prove that integrating LCSA, DT, and blockchain creates a powerful Decision Support System (DSS) to be applied in the built environment. This DSS facilitates data-driven decision-making by providing stakeholders with real-time insights, allowing them to optimize design choices, material selections, and operational strategies throughout the building life cycle. Besides, this solution empowers stakeholders to make more informed and sustainable decisions, fostering a more efficient and environmentally conscious building industry. In order to thoroughly discuss the findings of this work, this section will be divided into three parts, as presented below.

9.5.1 Research Questions and Their Implications

From the investigation conducted, key findings emerge related to a dynamic approach to achieving sustainability in the construction industry. It is understood that this industry still lacks an integrated and systematized methodology for assessing the triple-bottom-line sustainability of building projects, considering the impacts generated from the extraction of raw materials to the building end-of-life phase and benefiting the decision-making process throughout the whole building lifecycle. In addition, there is still a need to develop more guidelines related to the social and economic impacts generated by construction so that the sustainability assessment encompasses the three pillars comprehensively. This is a significant research gap, directly affecting the achievement of more sustainable buildings.

In this context, the proposed framework adds to a growing corpus of research showing the steps to be taken to create an iterative and dynamic building sustainability assessment. This addresses RQ1 by offering a strategy to extrapolate the discussion on BIM-LCSA integration, usually focused exclusively on the early design stages of a building project. The workflow proposed in this study demonstrates the possibility of applying LCSA during different building phases with the aid of a building DT. From centralizing data and information in the same digital model and adopting a project management methodology focused on achieving sustainable goals, it will become much easier to carry out dynamic life cycle assessments at different stages of the building's life cycle.

It is proposed that the LCSA results in the pre-construction phase improve design decisions and that, later, the digital model continues to be fed with real-time data so that new LCSAs can be applied and assist in the construction, renovation, and maintenance of the building. It is also expected that practitioners consider the future of individual elements and components since their impacts can be calculated and analyzed by integrating LCSA and BIM-based DT. Deconstruction practices should be tested and compared to benefit decision-making during the building's end of life. These possibilities address RQ1 by proposing different levels of DTs throughout the entire building life cycle and creating a dynamic approach to improve building decisions.

In turn, one primary application that a BIM-based DT can play a significant role in is ensuring that the sustainability assessment of a building takes into account temporal information. As implemented in conventional LCSA, using fixed time horizons may limit the availability of crucial data, leading to less realistic sustainability assessments. Addressing RQ2, the proposed framework offers a dynamic LCSA approach that can be applied at various stages of the building's life cycle. By harnessing the power of DT and blockchain, sustainability assessments are enabled to continuously access and utilize real-time data without creating security and transparency issues. This seamless integration ensures that LCSAs remain current and adaptable, providing stakeholders with an up-to-date understanding of the building's environmental, economic, and social impacts throughout its entire life span.

Moreover, incorporating blockchain technology further enhances the credibility and transparency of data sources, fostering trust and reliability in the sustainability evaluation process. Blockchain's decentralized and immutable nature ensures the synchronization of design records across all stages of the building's life cycle, safeguarding data integrity and preventing discrepancies that may arise from multiple stakeholders' contributions. Consequently, this synergistic utilization of DT and blockchain empowers stakeholders to make informed decisions, optimize sustainability outcomes, and drive transformative change in the construction industry.

9.5.2 Case Study Results and Challenges

Demonstrating the proposed framework via a building case study provides the reader with greater insight into how the proposed development can be leveraged to support relevant queries for various stages of a building life cycle. This building case study was tested with a focus on the building design stage, providing an opportunity to validate the effectiveness of integrating different technologies to achieve sustainability in the construction industry. Moreover, this integrative approach lays the foundation for extending real-time sustainability evaluations to subsequent phases of the building's life cycle, offering the potential to enhance decision-making processes and sustainability outcomes throughout the entire building's lifespan.

The analysis of 24 different building design alternatives was conducted, starting with the baseline solution. The presentation of results was then organized according to the sustainability indicators evaluated, followed by an interpretation of the findings and their alignment with the proposed framework. All results were normalized to standardize the data and ensure that each criterion carries equal weight in this multi-criteria analysis. Besides, each alternative was represented by a unique combination of construction elements from a pre-selected list. For example, the baseline solution is considered the first combination, represented by "d1 w1 e1 s1," where "d1" refers to door type 1, "w1" refers to window type 1, "e1" refers to external wall type 1, and "s1" refers to slab type 1. The LCSA result summary related to the baseline 3D model is presented in **Table 9.2**, while the comparison among the different alternatives is visually shown in **Figure 9.13**.

Table 9.2 - Life Cycle Impact Assessment result summary

Sustainability Dimension	Impact categories	Total
Environmental	Global Warming Potential (kg CO_2eq)	716,327
Economic	Life-cycle cost (Brazilian Real - BRL)	18,952,789
Social	Social Impact Rating	3.784

Notably, it is essential to emphasize that while the social indicator is intended to be maximized in this study, other indicators reflect negative impacts and are aimed to be minimized. To facilitate a consistent comparison, the inverse of the social indicator was employed as the final indicator throughout the analysis. This approach guarantees the uniform minimization of all indicators considered in this study.

In this case study, the primary objective was not to determine the single most suitable solution for the building, as this would necessitate assigning specific weights to each criterion during the MCDM analysis [17]. The relative importance of these criteria varies based on project-specific factors and the preferences of stakeholders, aligning with the proposed integrative framework that stresses the significance of incorporating stakeholder preferences to achieve optimal and context-specific decisions.

Nonetheless, while the case study was focused on the building design stage, the authors recognize the importance of testing the framework during the operational phase of an actual building. As part of the ongoing research, the authors are actively collecting data from a physical building where a 3D-BIM model developed in the design stage will continue to be utilized throughout the building operational phase. By integrating real-time data collected from IoT sensors during the operational stage, it is aimed to validate the framework's performance over the entire building life cycle.

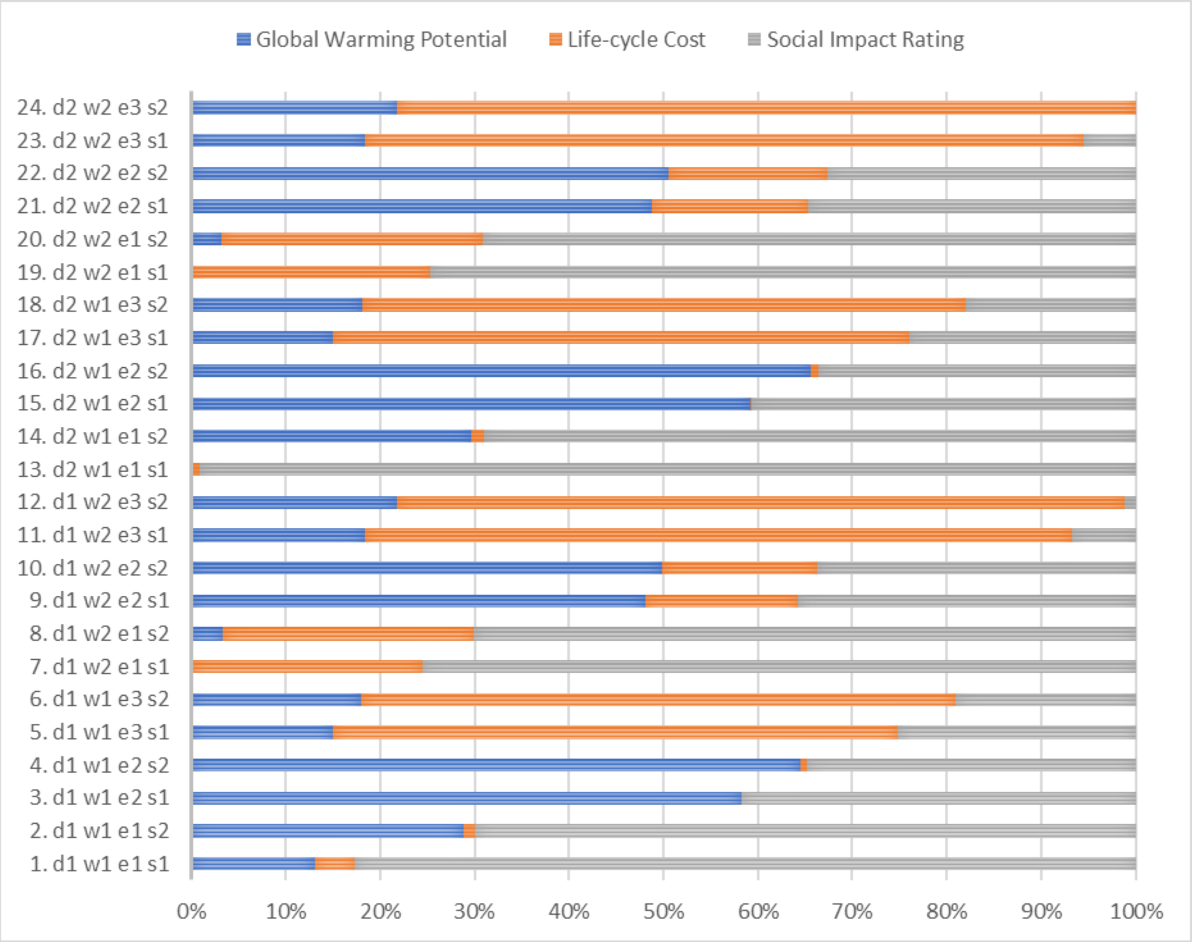


Figure 9.13 - Comparison of impact categories for 24 building design combinations

While exploring the feasibility of integrating different technologies in the construction industry, it is essential to acknowledge the challenges inherent in employing available market tools. One of the most significant issues is the interoperability challenge, where various devices and platforms often struggle to communicate effectively with one another, hindering the seamless flow of information and data. Additionally, these tools may not inherently support the diverse requirements of sustainability assessments in different building life cycle phases. Recognizing these obstacles, this paper underscores the necessity of developing a novel platform that can bridge the existing gaps, fostering a more integrated, efficient, and robust ecosystem for comprehensive sustainability assessments.

9.5.3 The Role of a Semantic Platform and Future Development

In order to facilitate the entire implementation of the integrative framework, it is suggested the creation of a platform for integrating the concepts, with a Smart Contract user interface to be used throughout the whole building life cycle. This platform aims to address interoperability concerns and ensure the effective utilization of digital twins, blockchain technology, and real-time data for enhancing sustainability across the building life cycle.

Figure 9.14 presents the semantic architecture for this platform. Three different layers are proposed here (i.e., the database layer, the logic layer, and the user interface) to allow the platform to be operable. The database layer consists of the 3-D building models and all data to be inserted and generated. Simulations should be carried out throughout the entire project lifecycle, either to benefit decision-making of which components and methods to use or to optimize the use of building systems during the operational building stage.

Sensors and devices should collect real-time data from the physical building. In contrast, the building model should be calibrated to accept data from numerous data streams, such as video devices, laser scanners, accelerometers, Radio Frequency Identification (RFID) devices, or displacement sensors [32]. In this way, up-to-date simulations can be performed based on real-time data, and all data generated must be recorded in the blockchain platform. The logic layer may be divided into building phases as the stakeholders and processes involved can differ. Ultimately, the user interface is based on Smart Contracts to protect all data exchange throughout the building life cycle and guarantee data reliability and traceability.

Besides, the team should choose a blockchain platform that aligns with the project requirements. In this decision, it is fundamental to consider factors such as scalability, data privacy, consensus mechanism, and smart contract capabilities. Then, designing and deploying smart contracts that define how the data will be stored, accessed, and managed becomes necessary. These smart contracts will dictate the logic governing interactions with the data.

In turn, the proposed framework also suggests that the practitioner define the role mapping with permissions for each entity at this stage. For example, a specific entity may need permission to modify any file (i.e., building 3D models, 2D drawings, documents, and reports) generated during the design stages. However, this entity may not need permission during fabrication and assembly. In this context, it is necessary to precisely define a role mapping with permissions defined for each entity, which will directly affect the logic layer of the proposed platform. It is illustrated in **Figure 9.15**.

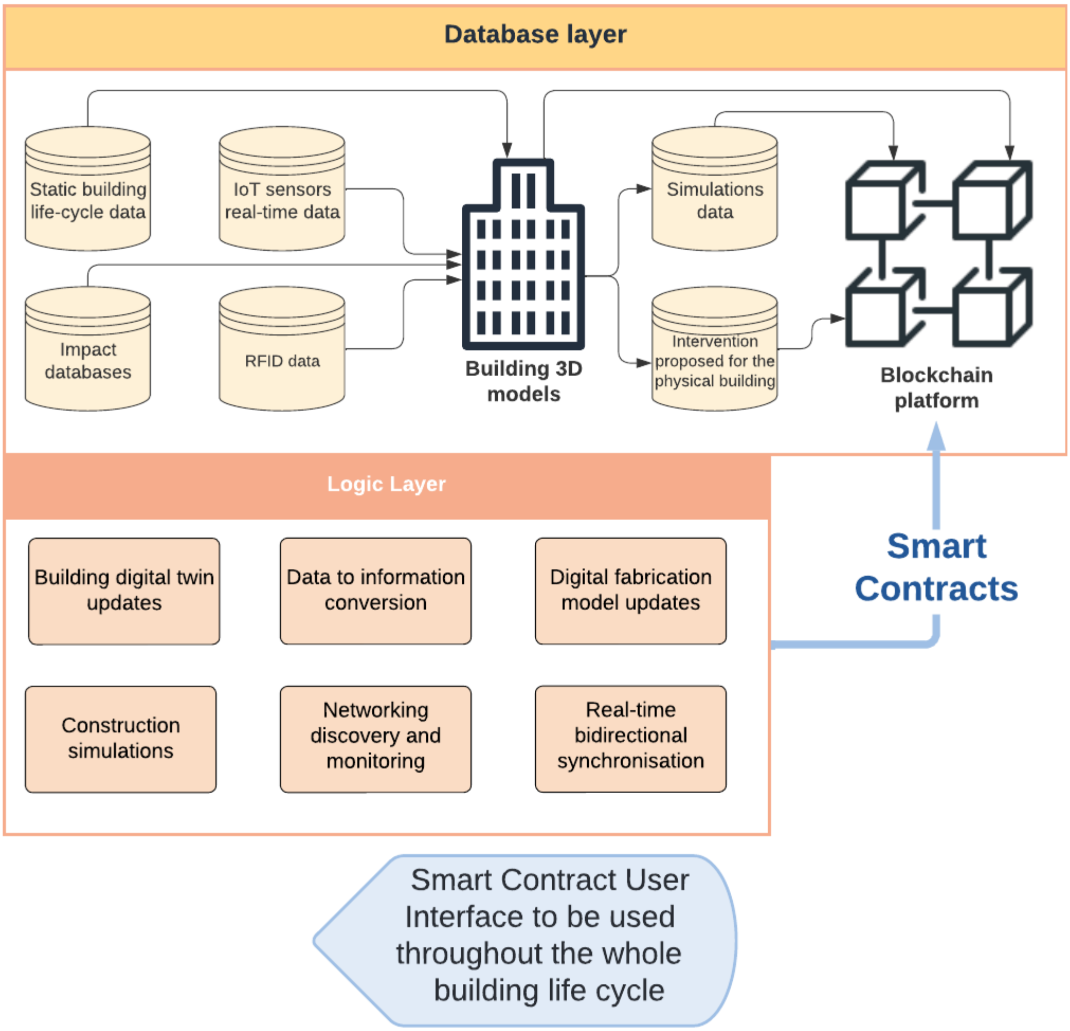
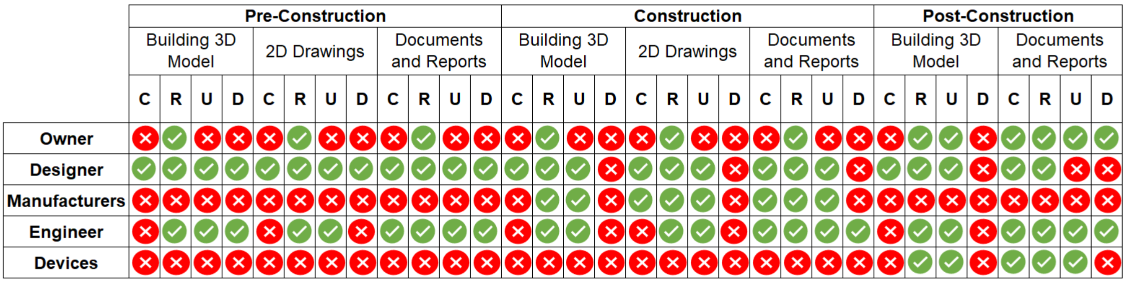


Figure 9.14 - Proposed semantic architecture for the integrated framework



	Pre-Construction												Construction												Post-Construction							
	Building 3D Model				2D Drawings				Documents and Reports				Building 3D Model				2D Drawings				Documents and Reports				Building 3D Model				Documents and Reports			
	C	R	U	D	C	R	U	D	C	R	U	D	C	R	U	D	C	R	U	D	C	R	U	D	C	R	U	D	C	R	U	D
Owner	✗	✓	✗	✗	✗	✓	✗	✗	✗	✓	✗	✗	✗	✓	✗	✗	✗	✓	✗	✗	✗	✓	✗	✗	✗	✓	✓	✗	✓	✓	✓	✓
Designer	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✗	✗
Manufacturers	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗
Engineer	✗	✓	✓	✓	✗	✓	✓	✗	✓	✓	✓	✓	✗	✓	✓	✗	✗	✓	✓	✗	✓	✓	✓	✓	✗	✓	✓	✗	✓	✓	✓	✓
Devices	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✗	✓	✓	✓	✗

Permissions: C = Create; R = Read; U = Update; D = Delete.

Figure 9.15 - Proposed role mapping with permissions defined for each entity

The semantic architecture for the integrative system is an innovative proposal to guide the following steps in this ongoing research. To enhance the accuracy of this architecture, future iterations of the framework will explore the integration of IoT sensors in a physical building to collect real-time data. Besides, this architecture will be developed with a focus on scalability and its potential for broader industry adoption. The main goal is that researchers and industry stakeholders can explore this platform in various building types and construction projects, ranging from small-scale developments to large infrastructure projects. Ultimately, identifying potential challenges and opportunities will facilitate widespread acceptance and integration.

9.6 CONCLUSION FOR CHAPTER 9

This paper elaborated on viable ways to improve the LCSA application in buildings, focusing on a dynamic sustainability assessment. This need arose from the observation that relying on historical data in impact assessments is recurrent, ignoring the impact of time-related changes in building data. This simplification compromises the reliability of LCSA findings, introducing a potential bias and questioning the overall validity of sustainability assessments in the construction industry.

In this context, this paper presented a framework that integrates the LCSA methodology with DT and blockchain. On the one hand, the building DT model provides a real-time digital representation of the physical building throughout its life cycle. On the other hand, blockchain is introduced to address the critical aspects of data security, integrity, and transparent collaboration in sustainable construction practices. The integration proposed in this work, demonstrated in a building of typical architecture in the southeast of Brazil, is an earnest attempt to offer practical solutions to the challenges faced in embracing construction sustainability comprehensively.

Although research has illuminated the importance of combining different technologies to aid the application of LCSA to built assets, the integration of LCSA, DT, and blockchain in a building remains briefly addressed in the literature, as proved by the systematic review posed in this work. Combining these concepts can benefit the decision-making process of which materials and methods would be most suitable for a building, as well as the most appropriate decisions during construction and post-construction, considering the three pillars of sustainability.

The limitations of this work can be stated as follows: even though the integration of DT and blockchain in the dynamic LCSA process has shown promising results in the proposed building case study, it has laid the foundation for a dynamic LCSA approach exclusively within the building design stage. To advance the field, future research should focus on expanding the framework's capabilities and addressing any limitations encountered. Investigating innovative technologies, refining assessment methodologies, and exploring real-world applications will further solidify the proposed framework's potential for transformative change in sustainable building practices. Still, the discussion presented in this work set the stage for future research and implementation of dynamic LCSAs during buildings' pre-construction, construction, and post-construction phases. Ultimately, it is essential to highlight that the study presented in this paper is part of a larger research project on developing an application software to be used in real-world buildings.

9.7 REFERENCES FOR CHAPTER 9

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10 TOWARDS DYNAMIC LIFE CYCLE SUSTAINABILITY ASSESSMENTS: A REAL-WORLD CASE STUDY INTEGRATING DIGITAL TWIN AND BLOCKCHAIN

This chapter is submitted as an original research article.

FIGUEIREDO, Karoline et al. Towards Dynamic Life Cycle Sustainability Assessments: A Real-World Case Study Integrating Digital Twin and Blockchain.

Abstract: Sustainability in construction necessitates a triple-bottom-line approach, integrating environmental, economic, and social considerations throughout the project lifecycle. However, conventional sustainability assessments face challenges in data management and methodological standardization, in addition to being typically based on static data, compromising the reliability of findings. This paper introduces a novel framework integrating Life Cycle Sustainability Assessment (LCSA), Digital Twin, and blockchain. Developed using the Design Science Research methodology, a machine-learning-based software application is presented to facilitate dynamic sustainability assessments by leveraging real-time data from IoT sensors. This integration aims to enhance traditional sustainability assessments by harnessing the benefits of Digital Twin technology, such as real-time monitoring, predictive analysis, and scenario testing, to provide more accurate and timely insights into the sustainability performance of construction projects. Additionally, blockchain technology is utilized to ensure data integrity and transparency throughout the assessment process, addressing data security and trustworthiness concerns. A real-world case study comparing static and dynamic LCSA outcomes demonstrates the approach's efficacy. Comparative analysis reveals significant disparities in impact assessments, such as a 20.37% increase in non-renewable energy demand from static to dynamic LCSA after 12 months of real-time data collection. This approach provides critical insights into the temporal variability of sustainability impacts, underscoring the transformative potential of integrating real-time data into LCSA frameworks.

Keywords:

Blockchain; Digital Twin; Energy Performance Gap; Life Cycle Sustainability Assessment; Machine Learning.

10.1 INTRODUCTION

Sustainability, at its core, entails the creation of projects that strike a delicate balance between environmental, economic, and social considerations, with a commitment to meeting both present and future needs [1]. In the construction industry, this means prioritizing projects that consider the three pillars of sustainability and that are capable of adapting to changing conditions and meeting the needs of all stakeholders. In this vein, a triple-bottom-line (TBL) approach for construction projects is essential, where environmental, social, and economic factors are considered simultaneously to develop more sustainable built assets.

Besides, sustainability in the construction industry demands a holistic approach that considers the entire life cycle of buildings and infrastructure. Building upon the TBL framework, Life Cycle Sustainability Assessment (LCSA) emerges as a crucial tool. LCSA ensures a comprehensive examination of a built asset's impacts and benefits throughout its entire life cycle, aligning with the broader sustainability goals of considering the three sustainability dimensions together [2]. However, the integration of LCSA in construction presents several challenges, particularly in terms of data management and methodological standardization.

First, the sheer volume of data required for assessing functional and technical aspects throughout the life cycle poses a significant hurdle [3]. Moreover, the lack of standardized approaches in combining Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA) methodologies, related to environmental, economic, and social dimensions, respectively, creates gaps in the effective application of LCSA to building projects [4] Ultimately, static data is often utilized in building impact assessments, making the impact of time-related changes on the data frequently overlooked [5]. This oversight jeopardizes the reliability of LCSA findings and compromises the overall validity of sustainability assessments in the construction industry.

To address these challenges, this paper introduces a machine learning-based framework application that plays a central role in dynamically enhancing LCSA. More specifically, the development of a robust and adaptive software solution is presented, integrating a Building Information Modeling-based Digital Twin (BIM-based DT) and blockchain technology into the LCSA framework. This integration aims to revolutionize sustainability assessments in construction by offering a strategic response to the complexities posed by data management, static data reliance, and methodological standardization challenges. By combining these cutting-edge technologies, this research aims to create a dynamic, real-time, and secure framework for sustainability assessments throughout the entire life cycle of buildings.

Particularly, this paper intends to discuss the rationale behind each component of the proposed integration. Firstly, the LCSA application ensures a holistic environmental, economic, and social evaluation. Secondly, the building DT model evolves from a Building Information Model (BIM) and provides a real-time digital representation of the physical building throughout its life cycle. Lastly, blockchain is introduced to address the critical aspects of data security, integrity, and transparent collaboration in the evolving landscape of sustainable construction practices. This integration is not only conceptual; it is an earnest attempt to offer practical solutions to the challenges the construction industry faces in embracing sustainability comprehensively.

This investigation is underpinned by several hypotheses, each addressing specific facets of this integrated approach. The primary hypothesis proposes that the amalgamation of BIM, DT, and blockchain in the LCSA process will substantially elevate the precision, comprehensiveness, and reliability of sustainability assessments within the construction industry. Recent literature indicates that the utilization of BIM furnishes crucial static information at the building level, contributing to more accurate environmental assessments [6–10]. Anticipating that the DT, complementing BIM, will provide a dynamic evaluation of impacts, this paper also hypothesizes the DT's potential to offer insights beyond traditional LCSA capabilities. Additionally, blockchain integration is expected to play a pivotal role in ensuring the security, transparency, and integrity of real-time data collected, addressing confidentiality concerns commonly disregarded in building LCSAs.

In totality, the integrated approach is hypothesized to enhance not only the assessment of environmental impacts but also the evaluation of economic and social aspects, culminating in a more holistic building LCSA. Therefore, the research question (RQ) guiding this study is as follows:

(RQ) What are the roles of BIM-based DT and blockchain in facilitating a dynamic and comprehensive LCSA, and how does their integrated use contribute to sustainability in the construction industry?

While LCSA offers a comprehensive framework for evaluating building life cycles, this paper focuses primarily on energy consumption due to its critical role in overall sustainability. This decision aligns with industry imperatives to address challenges such as the Energy Performance Gap (EPG) and the growing demand for energy-efficient buildings [11]. By prioritizing energy analysis within LCSA, this study aims to tackle multifaceted challenges, including discrepancies between predicted and actual energy performance [12]. This emphasis reflects industry recognition of energy's pivotal role in environmental, economic, and social sustainability outcomes, aiming to advance practical solutions for enhancing energy efficiency in the built environment.

This paper is organized as follows: Section 2 provides the literature review, offering essential contextual information to identify the research problem and motivation. Section 3 describes the methodology used in this research, outlining the approach and techniques employed. Section 4 presents the software development proposed in this work. A real-world case study is given in Section 5 to demonstrate the software’s usability and validate this proposal. Section 6 showcases the main results obtained from the research and provides a comprehensive analysis and discussion of these findings. Finally, Section 7 presents the study's conclusion, summarizing the key findings, discussing their implications, and offering insights into potential future research directions.

10.2 LITERATURE REVIEW

This section proposes a comprehensive literature review, the synthesis of which is presented below. This review will enable the identification of existing gaps in the literature and lay the foundation for the proposed integration of concepts.

10.2.1 Life Cycle Sustainability Assessment

The LCSA methodology is an interdisciplinary framework that simultaneously evaluates the impacts associated with products and processes from an environmental, social, and economic perspective [13]. The techniques that form the LCSA framework (i.e., LCA, LCC, and S-LCA) follow the same methodological structure based on the ISO 14040 standard. This methodological structure is divided into four stages: Goal and Scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation [14].

Regarding the use of LCSA as a decision-making technique in the construction industry, researchers have applied this methodology mainly during the early stages of a building design [2,4,15,16]. A recent study introduced an innovative LCSA model designed for integration into the design phase of new building projects and energy refurbishments for existing buildings [17]. The authors further developed a novel formulation and weighting method to derive a final

LCSA index, facilitating a holistic assessment of design scenarios and considering the three pillars of sustainability. The study also innovatively integrates machine learning techniques into the optimization process, enhancing the efficiency of design assessments while upholding their precision.

Nevertheless, when considering using this methodology in different stages of the building's life cycle, a new challenge emerges related to the need for more temporal information in the assessments. Notably, the current LCSA methods take a stagnant approach that fails to consider dynamic factors during the building life cycle, such as material deterioration, varying energy consumption, and technology up-gradation, resulting in inaccurate sustainability assessments [18]. In this context, the data inventory can be considered the most sensitive and challenging step of an LCSA application since it leads to the creation of a model that should represent, as accurately as possible, all the exchanges between the distinct phases of a process [19]. So far, the need for more impact data sources adapted to the specific requirements of a building project has been seen in the literature [4]. Besides, it has been noted that impact assessments are typically based on data from historical series, which hinders the use of LCSA for rapid corrective actions on a project.

Other recent publications presented different frameworks for a dynamic LCSA application but with limited advances in this field. Francis and Thomas [18] developed a methodological framework that allows practitioners to set desired values for material use, material replacement alternatives, energy mix, and water recycling percentage to evaluate the building impacts of the selected combination of values. It can be observed that the authors considered more environmental indicators than economic and social ones. Besides, the framework continues to resemble the traditional LCSA application, allowing the comparison of several alternatives from manual changes in the system.

10.2.1.1 BIM-LCSA integration

Considering the specific application of LCA, thus assessing only environmental aspects, the integration with BIM has gained substantial traction in the literature. Different 'LCA Profiles' have emerged, establishing associations between LCA processes and construction materials or components, often represented as BIM objects [20]. BIM's role in this context is linked to an information aggregator and context provider, offering a rich dataset to support the LCA analysis. Therefore, LCA tools and plug-ins are pivotal in connecting the information sourced from BIM with the corresponding LCA processes within the databases [21]. Still, while promising, recent studies have shown that this integration has sometimes led to inaccurate results within the current designers' workflow [6,7]. This conclusion underscores the critical need for analysis tools that seamlessly align with the dynamic nature of a building project.

In turn, it is observed that the application intended to improve the LCSA methodology via BIM integration is still briefly addressed in the literature. For example, Boje et al. [20] discussed how BIM-based DT data can affect LCSA outcomes. However, the case study presented to validate the proposed framework was related to a simplified version of this integration with limited scope, argumentation, and data. Notably, the case study was focused on demonstrating the complementary roles between BIM and DT, being limited in scope to Environmental LCA.

10.2.2 Digital Twins in Construction

Unlike BIM, which focuses on centralizing data and information and is typically used as a single digital shadow [22], a building DT can provide timely optimization suggestions by mirroring the building's lifecycle and current status [23]. In this context, DTs of constructed assets can present different complexity levels from design to handover, depending on the availability of data and the model's sophistication [24].

A recent review paper [25] has highlighted that most methods for creating DTs are only effective for specific purposes and may not be suitable for other types of projects. Additionally, many of these applications begin by generating a 3D BIM model and then incorporating non-geometric information from sensors or devices in the physical world into the digital model. This additional data can include various parameters such as temperature, humidity, pressure, vibration frequency, flow rate, cost, energy consumption, and more. This data insertion guarantees the transformation of the model into a BIM-based DT representation.

For example, a recent publication presents a case study of a university building using IoT sensors integrated with the virtual BIM model with a focus on environmental aspects [26]. Throughout the process, the effectiveness and challenges of the proposed framework architecture were analyzed. However, to avoid difficulties in rendering the model for web-based viewers, the authors decided to reduce the size of the BIM model created using Autodesk Revit to 20 MB from over 500 MB. To achieve this, they performed BIM lightweight and removed all irrelevant elements of the building, such as members, floors, and redundant data. They retained only the spatial information necessary for environmental monitoring and manually deleted all unnecessary elements per the system requirements. Therefore, this DT model is not suitable for other types of analysis.

In turn, the literature shows that using virtual models as a platform for continuously tracking building components during the operation and maintenance phases is underutilized despite building monitoring and control opportunities. Previous methods for integrating virtual models and physical construction have primarily focused on resource and activity monitoring during the construction stage, as well as documentation of the as-built [27].

10.2.3 Blockchain in Construction

In the ever-evolving domain of data analysis and machine learning, the integrity and trustworthiness of data are fundamental. Traditional methods of securing data typically rely on centralized systems, which are susceptible to single points of failure and malicious alterations. Blockchain technology offers a solution to these challenges by providing a decentralized and immutable ledger system [28].

The advantages of using blockchain for this purpose are multifold. It provides immutability, ensuring that once the data is stored, it cannot be altered, which is crucial for maintaining records that may be subject to future scrutiny or auditing [29]. The decentralized nature of blockchain means that it does not rely on a central point of trust, making the data integrity mechanism robust against failures. Moreover, the transparency and trust provided by blockchain mean that all participants can verify the data independently, fostering a trustful environment [30].

When considering blockchain utilization in the construction sector, this technology is encouraged in all stages of the building life cycle. For example, professionals traditionally raised concerns about the absence of systematic records of inspection and operations during the fabrication stage [31]. Utilizing a digital fabrication drawing production with the synchronization of data records will enable higher transparency and better collaboration opportunities. Besides, using information from the factory, it is possible to develop a digital fabrication model in real-time, improving the digital building model and facilitating LCSA applications [5]. Ultimately, Blockchain can establish more efficient connections among different professionals and provide innovative solutions for the challenges faced by external stakeholders through a dynamic perspective on value creation [32].

10.3 METHODOLOGY

The methodology applied in this work is the Design Science Research (DSR) [33], structured according to Peffers et al. [34]. The methodology encompasses the following key phases: (1) problem identification and motivation, (2) definition of solution objectives, (3) artifact design and development, (4) demonstration, (5) evaluation, and (6) communication.

In previous attempts at implementing life cycle techniques in building projects, the authors encountered several limitations [2,21,35–37]. These challenges prompted a re-evaluation of the approach, leading to the exploration of innovative solutions in the literature and the market. The scrutiny revealed inherent complexities related to data management, methodological standardization, and an overreliance on static data. Importantly, it became apparent that a paradigm shift was needed to overcome these challenges and enhance the accuracy and reliability of sustainability assessments.

Furthermore, the significance of privacy and security concerns emerged, especially when dealing with real-time data collected from buildings. This concern gained prominence during attempts at LCSA applications where limitations were encountered. The privacy of occupants and the need for secure data management became central issues that conventional approaches struggled to address effectively.

In this vein, the integration of DT technology for real-time data collection and visualization, coupled with blockchain to ensure user privacy, emerged as a viable option. On the one hand, DT technology, evolving from the BIM methodology, was introduced as a dynamic solution capable of providing real-time data and a comprehensive representation of the building throughout its lifecycle. This evolution addresses limitations from previous LCSA attempts and introduces a more robust approach to building data representation. On the other hand, blockchain, known for its capabilities in ensuring data security, integrity, and transparent collaboration, emerged as a vital component in guaranteeing the confidentiality of sensitive information gathered from building occupants.

This conceptual atomization of the problem underscores the intricate challenges faced in sustainability assessments, each component representing a critical aspect that the integrated approach seeks to address. Therefore, a rigorous literature review was conducted to systematically address these challenges. This review focused on applying LCSA, DT, and blockchain concepts in the construction industry. The objective was to gain insights into the existing landscape, identify potential synergies, and understand the feasibility of integrating these concepts to enhance sustainability assessments in the construction domain. This research aims to contribute to a more robust and effective sustainability assessment framework in the construction industry by recognizing the interplay of challenges, solutions, and the need for an integrated approach.

Based on this, the identified problems in sustainability assessments in the construction industry necessitate a well-defined set of objectives for the proposed solution. The objectives of this study are twofold:

Objective 1: Enhance the precision, comprehensiveness, and reliability of sustainability assessments, focusing on addressing the dynamic aspects of building impacts and advancing the understanding of sustainability over time.

Objective 2: Address privacy and security concerns in real-time data collection in buildings.

Then, the artifact design and development step involves designing an integration process to be implemented in building projects. This solution will be demonstrated and validated through a real-world case study application. The subsequent steps involve evaluating challenges in implementing the proposed integrative framework, defining future exploratory directions, and addressing the research question posed. A visual representation of the methodology is presented in **Figure 10.1**.

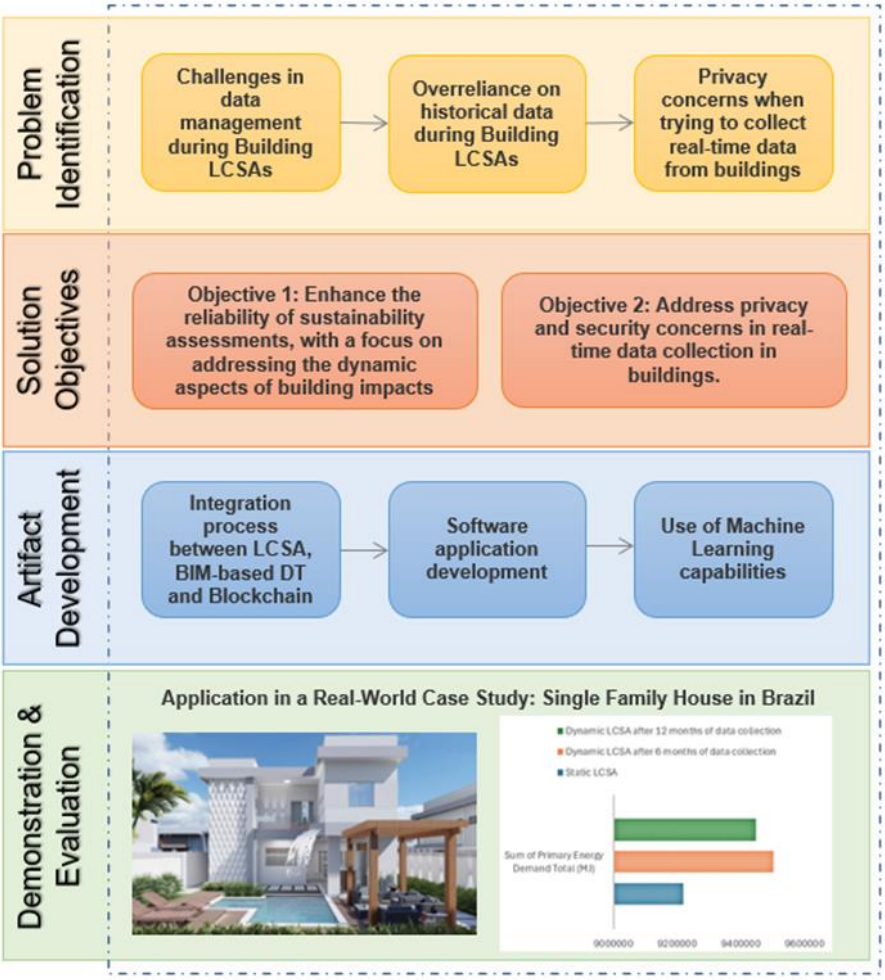


Figure 10.1 - Methodology proposed for this study

10.4 INTEGRATED FRAMEWORK

This section introduces the development of an integrated framework based on what has been discussed so far. In this study, a machine learning-based approach was developed to predict and analyze real-time energy consumption within the context of LCSA. The selection of the *RandomForestRegressor* was driven by its robustness in handling complex datasets and its ability to evolve predictions over time through an interactive user interface. The primary aim is to accurately predict unknown energy consumption values, indicated as -1 in the dataset, and to refine these predictions over time through a real-time user interface.

10.4.1 Data Collection and Preprocessing

The core of the software development lies in the collection and preprocessing of a dataset, denoted as $D = \{(x_1, y_1), (x_2, y_2), \ldots, (x_n, y_n)\}$, comprising n samples. This dataset encapsulates critical variables such as Temperature (T), Season (S), Occupants Ratio (O), Room Size (R), and Power Cost (Co) that are carefully chosen for their potential impact on energy consumption, energy cost and thermal comfort of occupants, which serves as the key impact categories in LCSA. The target variable, y, in our analysis, represents the Total Energy Consumption C. Knowing that, the target variables are get from dataset D, then it is extracted the feature matrix X and the target vector y. Also, the Energy Cost is calculated and stored in the model, considering the power distribution company's cost rating related to the period when the data was gathered.

The dataset is then divided into training and test sets, with the training set comprising $(1 - test\_size) \times n$ samples and the test set comprising $test\_size \times n$ samples. This split was important for validating the model's performance on unseen data. Finally, the RandomForestRegressor model was trained on the subset of the dataset with known energy consumption values from in-loco gathering data. The training process involved optimizing a set of hyperparameters $\theta = \{\theta_1, \theta_2, \ldots, \theta_k\}$, including 'n_estimators', 'max_depth', and 'min_samples_split'. The optimal hyperparameters θ^* were identified using 5-fold cross-validation, which facilitated the fine-tuning of the model to minimize loss.

A distinctive feature of this methodology is the incorporation of an interactive interface. This interface enables the system to update specific records of energy consumption collected from Internet of Things (IoT) sensors and devices, thereby enhancing the model's adaptability and accuracy over time, reaching a smart model. The algorithm dynamically incorporates IoT inputs into the model, re-predicting energy consumption values for records previously marked as unknown.

10.4.2 Digital Twin-Driven Model Evaluation

Post-training, the model's performance is rigorously evaluated using metrics such as Mean Squared Error (MSE), Root Mean Squared Error (RMSE), and Mean Absolute Error (MAE). These metrics not only assess the accuracy of the model but also provide essential insights into its error margins, critical for the reliability of energy consumption predictions.

Visualization techniques, encompassing scatter plots, feature importance charts, pair plots, and heatmaps, contribute to a holistic understanding of the model and the intricate relationships between diverse features. Notably, the data fueling these evaluations originates directly from strategically positioned IoT sensors within the physical building. These sensors seamlessly interface with a 3D building model, forming a robust DT. This integration ensures real-time representation and dynamic adaptation to the building's evolving conditions.

In this context, the developed algorithm represents a groundbreaking fusion of automated machine learning predictions with adaptability driven by data generated from IoT sensors. This integration not only serves as a cutting-edge tool for predicting energy consumption but also stands as an integral component within a broader LCSA framework. The building DT, through its dynamic connection with real-world data, reinforces the model's practicality and contributes significantly to the comprehensive evaluation of sustainability in building projects.

10.4.3 Blockchain-Ensured Data Integrity

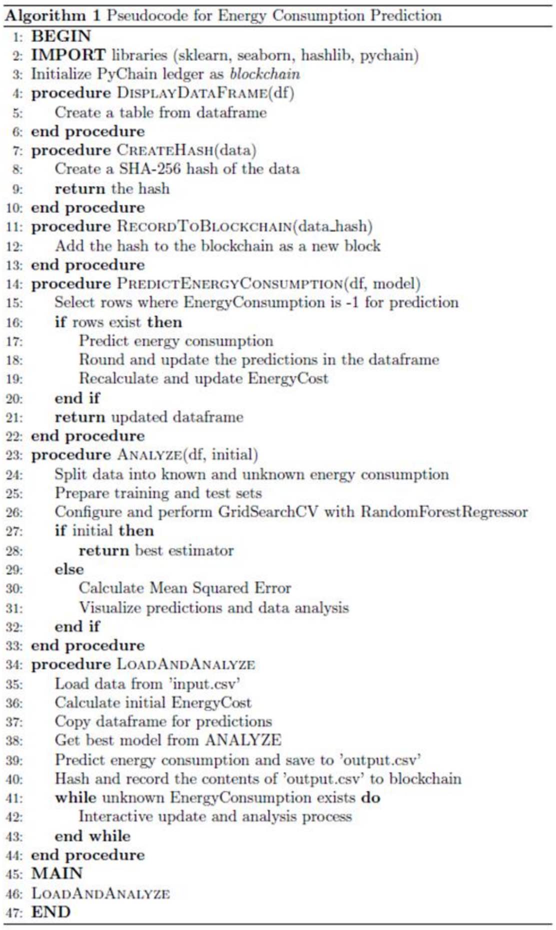
Within the Python script developed for predicting energy consumption, blockchain technology is seamlessly integrated to fortify the integrity of the gathered data. The process involves creating a cryptographic hash of the file's contents, essentially forming a compact digital fingerprint. A Python library, PyChain, is utilized to simulate blockchain behavior, although the recommendation stands for considering a more advanced network. PyChain facilitates the creation of a new block containing the file's hash, appending it to the existing chain and securely linking it to the preceding one. This interconnection guarantees that any attempt to manipulate the data becomes readily detectable, as it necessitates altering the entire chain.

Integrating blockchain technology to protect the output of a machine learning model represents an innovative approach to ensuring data integrity. In this implementation, blockchain serves as a robust tool to create an immutable record of energy consumption and energy costs, enhancing the reliability and trustworthiness of the analysis. As the technology matures and becomes more accessible, the role of blockchain in securing and verifying data will likely expand, offering a new standard for data integrity.

In the context of integrating this idea with a building DT, it is important to highlight that the data collected pertains to the daily energy use of occupants, accounting for their presence or absence from home. This level of granularity is crucial for accurate predictions. Here, blockchain plays a pivotal role in guaranteeing the privacy of occupants. Blockchain safeguards sensitive information related to occupants' daily routines, usage patterns, and home occupancy times by ensuring an immutable data record. As the technology matures, blockchain's significance in securing and verifying data, particularly in scenarios involving personal privacy, is poised to become a cornerstone in data analytics and machine learning applications.

10.4.4 Pseudocode for the Integrated Framework

Figure 10.2 presents the pseudocode outlining the integrated framework for predicting real-time energy consumption, leveraging DT, and ensuring data integrity through blockchain technology. This pseudocode emphasizes key steps, including data preprocessing, model training, real-time adaptability through an interactive interface, evaluation, visualization, DT integration, and blockchain-enabled data integrity and privacy assurance.



Algorithm 1 Pseudocode for Energy Consumption Prediction

```
BEGIN
IMPORT libraries (sklearn, seaborn, hashlib, pychain)
Initialize PyChain ledger as blockchain
procedure DisplayDataFrame(df)
    Create a table from dataframe
end procedure
procedure CreateHash(data)
    Create a SHA-256 hash of the data
    return the hash
end procedure
procedure RecordToBlockchain(data_hash)
    Add the hash to the blockchain as a new block
end procedure
procedure PredictEnergyConsumption(df, model)
    Select rows where EnergyConsumption is -1 for prediction
    if rows exist then
        Predict energy consumption
        Round and update the predictions in the dataframe
        Recalculate and update EnergyCost
    end if
    return updated dataframe
end procedure
procedure Analyze(df, initial)
    Split data into known and unknown energy consumption
    Prepare training and test sets
    Configure and perform GridSearchCV with RandomForestRegressor
    if initial then
        return best estimator
    else
        Calculate Mean Squared Error
        Visualize predictions and data analysis
    end if
end procedure
procedure LoadAndAnalyze
    Load data from 'input.csv'
    Calculate initial EnergyCost
    Copy dataframe for predictions
    Get best model from ANALYZE
    Predict energy consumption and save to 'output.csv'
    Hash and record the contents of 'output.csv' to blockchain
    while unknown EnergyConsumption exists do
        Interactive update and analysis process
    end while
end procedure
MAIN
LoadAndAnalyze
END
```

Figure 10.2 - Pseudocode of the software application proposed in this study

10.5 CASE STUDY

A case study is examined to validate the practicality and efficacy of the proposed software application. The whole process was developed on the Microsoft Windows 11 operating system, using an Intel core i7 processor at 2.3 GHz and 32GB of RAM. It was considered an actual single-family house of typical architecture in the southeast region of Brazil to present a discussion representative of the Brazilian construction industry. The analyzed construction features a two-story design, with a ground floor and an upper floor, with a total built area of 230m². The project was developed in April 2020, and the baseline 3D model was modeled in Autodesk Revit 2021. The construction stage lasted from May 2020 to August 2021, situated in Campos dos Goytacazes - RJ, Brazil, 21°45'02.2" S 41°21'31.4" W. **Figure 10.3** displays some orthographic views of this project, along with a rendered image and the 3D model in Revit. The model was developed based on the Level of Development (LOD) 400, using graphical representation of components, with detailed information on fabrication, assembly and installation.

During the later design stage, a static LCSA was performed using the 3D BIM model, considering a building service life of 60 years. The analysis employed a cradle-to-grave system boundary, encompassing product manufacturing, transportation, construction, operation and maintenance (O&M), and end-of-life phases. For the end-of-life phase, assumed to involve implosion, the analysis factored in material collection and landfilling rates. This consistent system boundary was applied across environmental, economic, and social analyses for effective harmonization.

Figure 10.3 - The case study used in this study

The environmental impact categories chosen for this study are widely discussed in the literature and are related to building energy consumption. This consumption is divided into Primary Energy Demand (PED), Non-renewable Energy Demand (NED), and Renewable Energy Demand (RED). For the economic analysis, the impact category is the life-cycle cost associated with the energy usage for lighting and HVAC, considering all building phases within the system boundary of this study. Finally, the social analysis focuses on Indoor Air Quality (IAQ) as a crucial dimension of occupant well-being and satisfaction. A comprehensive checklist was developed to assess various factors influencing IAQ during the building's life cycle. This checklist encompasses ventilation systems, natural ventilation, material choices, maintenance practices, air filtration, humidity control, and compliance with standards.

This assessment, based on the static BIM model, provided insights into the environmental, economic, and social dimensions associated with the building life cycle. Having established the baseline with the static LCSA and after constructing this house, the Revit model was upgraded to Revit 2024, a more contemporary software version. This update was accompanied by a meticulous data integration and extraction process using Dynamo, a visual programming language recognized for its versatility and efficiency in architectural and construction contexts. The 3D model was augmented with additional as-built data to transform it into a comprehensive DT of the house. This integration and extraction were essential for ensuring the continued relevance and accuracy of the digital representation of the structure, enabling extensive analysis and assessment within the scope of the study.

The installation of sensors in the house was carried out with the owner's explicit consent. The sensors were installed to monitor various aspects of the house's environment, including temperature, humidity, and air quality, among others. However, it was made clear that the privacy of the occupant data must be fully guaranteed. This means that any data collected will be treated with the utmost confidentiality and will not be shared with any third party without the explicit consent of the occupant. Additionally, measures have been put in place to ensure that the data collected is only used for the intended purpose and is not misused in any way.

Leveraging this real-time data, the developed software played a pivotal role in estimating energy consumption, energy cost, and IAQ. The integration of machine learning algorithms, including the *RandomForestRegressor*, allowed for accurate predictions and adaptability based on the dynamic input from the installed IoT sensors. The Random Forest algorithm is a versatile machine learning model employed in our work to enhance the accuracy of predictions. Its significance comes from its collective method, which utilizes multiple decision trees to make predictions based on various subsets of the dataset, ensuring robustness against overfitting and improving prediction reliability.

In our framework, *RandomForestRegressor* is instrumental for interpreting the real-time data collected from IoT sensors, enabling the framework to adapt its predictions dynamically as new data is received. This continuous learning aspect is crucial for maintaining the precision of sustainability assessments and facilitating intelligent decision-making in the management of building systems. By leveraging the Random Forest model, we ensure that our framework remains sensitive to the evolving patterns and trends in the data, supporting a sustainable and responsive building environment and enhancing the ongoing dynamic method proposed.

This relationship between real-time data from the sensors and the framework's predictive capabilities not only facilitated precise estimations but also contributed to the overall dynamic adaptability and responsiveness of the model. Ultimately, using blockchain ensures occupant privacy as agreed with the owner. In this way, the proposed application can be utilized to maximize the utility of the collected data for improving the sustainability assessment framework within the broader context of the DT, blockchain, and LCSA integration.

10.6 RESULTS AND DISCUSSION

This section first presents the findings from the static LCSA based on a 3D BIM. It is followed by an analysis of the dynamic LCSA outcomes derived from the evolved DT, which provides insights into the transformative potential of real-time data integration from IoT sensors. A comparative analysis then illustrates the discrepancies and enhancements between the static and dynamic approaches. Finally, a discussion is presented about the roles of BIM-based DT and blockchain in fostering a dynamic and comprehensive LCSA, answering the research question posed in the Introduction section.

10.6.1 Static LCSA Findings

In order to carry out the static LCSA, an energy model was created using Autodesk Revit, which was derived from the house's 3D BIM model. This model, structured according to the Green Building XML schema (gbXML), encompasses the primary heat transfer pathways within the building. The gbXML schema is specifically designed to streamline the transfer of building data from BIM platforms to environmental analysis tools [2]. Utilizing this model, the annual energy consumption of the building was estimated, considering the energy used by both HVAC and lighting systems.

This work adopted the TRACI 2.1 characterization scheme to classify and understand environmental impacts. The TRACI methodology characterizes impact categories at the midpoint level by drawing cause-effect chains to identify the point at which each category is characterized [38]. In this study, the Tally® application was used to match each material in the 3D BIM model in Autodesk Revit with the GaBi database materials, allowing for an automated exchange process [39]. Besides, the estimated annual energy use calculated through the energy model was added to the Tally® application to consider this data in the environmental impact calculations.

The reference unit used in this study was the full collection of processes and materials required to construct a single-family house, which is quantified according to the given goal and scope of the assessment over the entire life of the building. For example, Figure 4 presents data obtained from Tally to analyze material mass and non-renewable energy demand across each life cycle stage. The total energy calculation encompasses all stages of the design options studied, including material manufacturing, transportation, maintenance, replacement, and eventual end-of-life considerations.

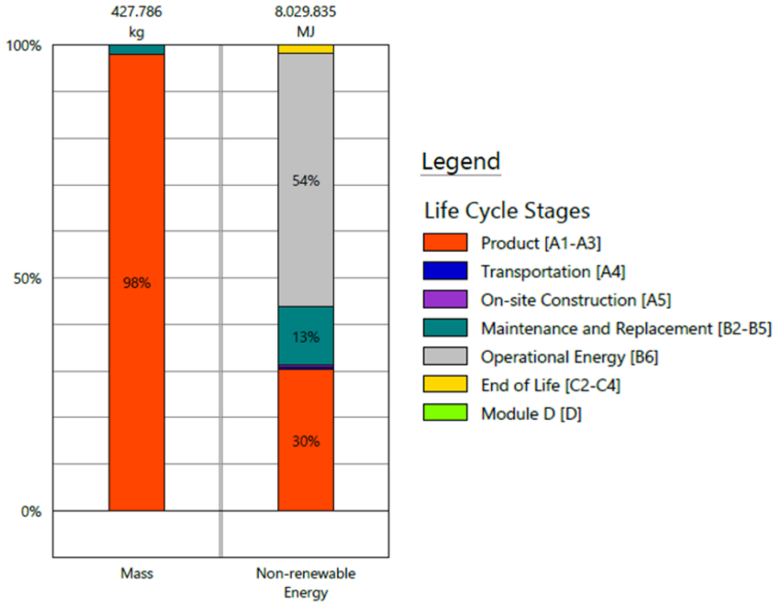


Figure 10.4 - Static data obtained during the design stage of the case study

10.6.2 Dynamic LCSA Outcomes

The dynamic LCSA, facilitated by advanced machine learning techniques integrating DT and blockchain technologies, revealed a significant shift in the building's energy consumption profile. The real-time data, sourced from IoT sensors installed in the house, provided insights into the actual energy usage, diverging from the initial predictions of the static LCSA. This dynamic approach offered an accurate reflection of the building's energy consumption, accounting for variables like occupant behavior, environmental conditions, and material performance over time.

The integration of the *RandomForestRegressor* algorithm within the software application played a critical role in dynamically predicting and adjusting the energy consumption values. The software's ability to iteratively learn and adapt to real-time data led to a more nuanced understanding of the building's energy dynamics, surpassing the static LCSA's capabilities. **Figure 10.5** presents a pair plot, a graphical matrix that illustrates the relationship between multiple variables in the dataset.

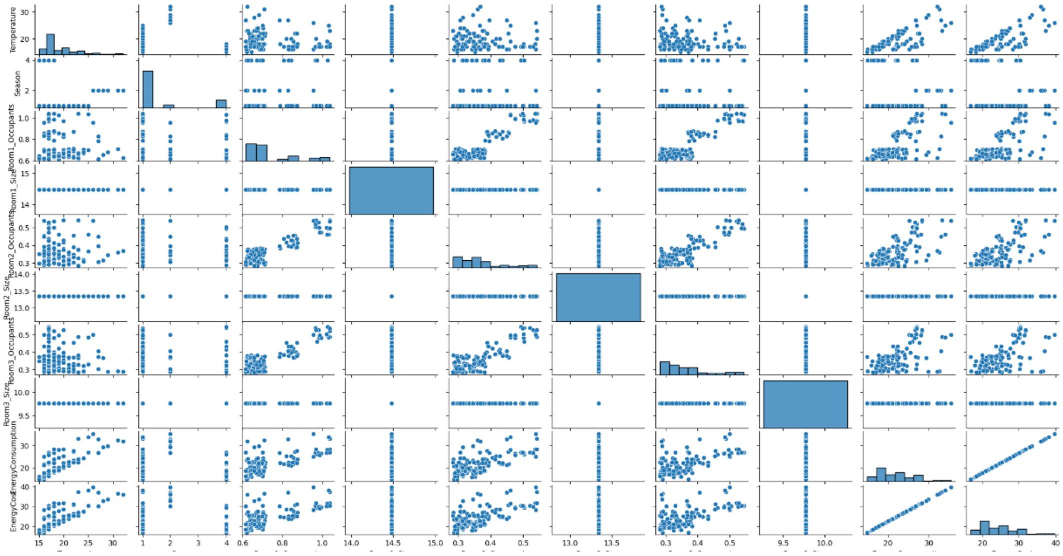


Figure 10.5 - Pair plot of building energy consumption dynamic data

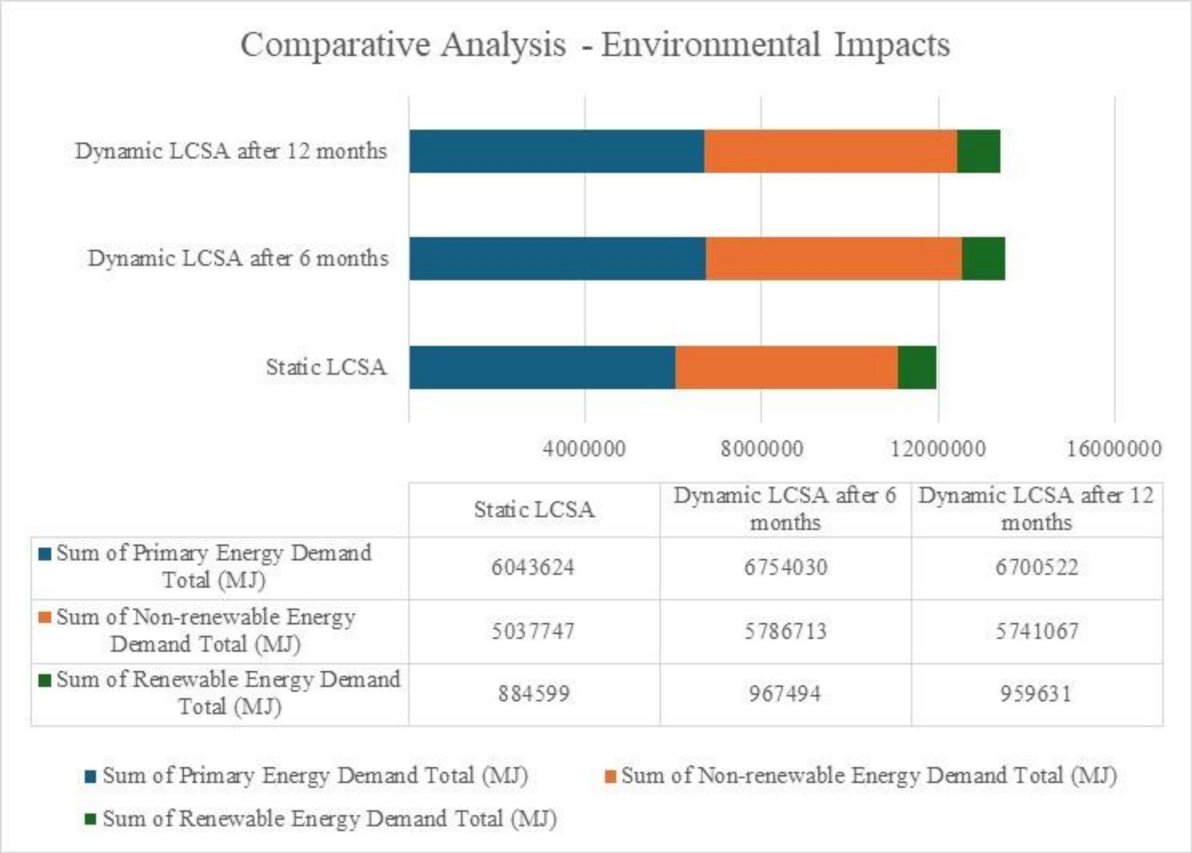
On the diagonal, histograms reveal the distribution of each individual variable, providing insight into their individual characteristics, being the spread and central tendency. Off-diagonal scatter plots compare the interactions between pairs of variables, which in this case study, highlight the trends and potential outliers, which are the constant variables (Room Size). These visual relationships are crucial for identifying how variables influence each other and were essential to step in exploratory data analysis. The box plots adjacent to the histograms offer a view of each variable's distribution, median, and outliers. For this study, the occupancy ratio and temperature showed a strong correlation with the proposed model.

10.6.3 Comparative Analysis

The comparative analysis reveals fluctuations in the environmental impacts across different stages of the building's life cycle. Notably, the static LCSA performed during the design stage offers a baseline understanding of energy demands. However, as seen in the dynamic LCSAs conducted after 6 and 12 months, variations emerge due to real-time adaptations and changes in occupant behavior and energy consumption patterns.

The developed algorithm, utilizing automated machine learning predictions with IoT-driven adaptability, stands as a novel and flexible tool. Importantly, it is a foundational component in the broader LCSA framework, enriching the dynamic and comprehensive assessment of sustainability in building projects. In this context, the primary objective here was to rigorously compare the findings of the static LCSA based on the initial 3D BIM model with the outcomes of the dynamic LCSA utilizing the augmented DT.

As shown in **Figure 10.6**, the increments in all three types of Energy Demand suggest that the building undergoes alterations that impact its energy efficiency over time. This reinforces the significance of dynamic assessments, as they consider evolving conditions, ensuring a more accurate representation of the building's sustainability profile. Moreover, it is crucial to recognize that these disparities will likely amplify over time. The dynamic LCSA approach, facilitated by the BIM-based DT, allows for continuous updates based on the building's actual performance and usage patterns. This ongoing adaptability becomes increasingly pertinent as unforeseen alterations occur throughout the building's life cycle, which was not accounted for during the initial design stage.



	Static LCSA	Dynamic LCSA after 6 months	Dynamic LCSA after 12 months
■ Sum of Primary Energy Demand Total (MJ)	6043624	6754030	6700522
■ Sum of Non-renewable Energy Demand Total (MJ)	5037747	5786713	5741067
■ Sum of Renewable Energy Demand Total (MJ)	884599	967494	959631

Figure 10.6 - Comparative Analysis between Static and Dynamic LCSAs

Ultimately, the software's ability to perform dynamic LCSAs not only captures the present state of sustainability impacts but also positions itself as a valuable tool for predicting and managing future sustainability considerations. As the building evolves, the software can continue to provide insights, offering a proactive approach to sustainable construction practices.

This aligns seamlessly with the primary goal of this study – to enhance the comprehensiveness and accuracy of sustainability assessments throughout the entire life cycle of buildings.

Although our discussion primarily focuses on environmental aspects, it is imperative to acknowledge the potential for incorporating economic and social factors within the same framework. While real-time data collection over 12 months allows for robust environmental analysis, observing tangible changes in economic and social factors may take longer. However, the inherent adaptability of this dynamic LCSA approach, facilitated by the BIM-based DT and blockchain, provides a foundation for incorporating economic and social considerations in future decision-making processes.

As the building's lifecycle progresses, ongoing updates based on actual performance and usage patterns enable stakeholders to monitor economic indicators, such as operational costs and return on investment, as well as social factors, including occupant satisfaction. Recognizing that these disparities are likely to amplify over time underscores the importance of adopting a holistic approach that considers the interconnectedness of environmental, economic, and social dimensions in sustainability assessments.

10.6.4 Insights on the Integration of DT and Blockchain into the LCSA framework

Applying LCSA in the construction industry is not without its obstacles, both in research and practice; managing a vast amount of data is necessary when considering all functional and technical requirements of a built asset throughout its life cycle [2]. In this vein, the integration of BIM-based DT and blockchain technologies within the LCSA framework signifies a paradigm shift in sustainable construction practices.

Particularly, a critical aspect of our study involves the data's origin from IoT sensors, intricately connected to a 3D building model as a building DT. This ensures that predictions are firmly rooted in real-time conditions. By anchoring LCSA in real-world data, the framework contributes to the dynamic and comprehensive evaluation of sustainability in building projects, furthering the objectives of this research. Besides, the software's focus on energy consumption, a pivotal impact category spanning environmental, economic, and social dimensions, contributes to the dynamic and comprehensive evaluation of sustainability in building projects. It is understood that, over time, the DT implementation will become even more vital, accommodating unforeseen changes throughout the building's life cycle that were not considered in the static LCSA during the design stage.

The developed algorithm, combining automated machine learning predictions with IoT-driven adaptability, represents a novel and flexible tool for predicting energy consumption. Importantly, this tool serves as a foundational component in the broader LCSA scheme, contributing to the dynamic and comprehensive assessment of sustainability in building projects. By focusing on energy consumption as a critical impact category, the software ensures that LCSA encompasses environmental, economic, and social dimensions, thus addressing the research question posed in this paper.

Ultimately, the integration of blockchain technology addresses critical aspects of data security, integrity, and transparent collaboration within the LCSA framework. Blockchain's immutability safeguards the integrity of the data collected from IoT sensors, ensuring that predictions and assessments are transmitted as trustworthy information. While blockchain introduces performance and scalability considerations, its role in securing and verifying real-time data, especially concerning privacy-sensitive information, is crucial. As blockchain technology matures, its potential to become a cornerstone in data analytics and machine learning applications, particularly in scenarios involving personal privacy, is evident.

10.7 CONCLUSION FOR CHAPTER 10

This study aimed to address the challenges that hinder sustainability assessments in the construction industry. These challenges include the lack of standardized approaches, reliance on static data, and the significant amount of data required for life cycle assessments. Particularly, the use of static data can lead to a lack of consideration for changes over time, which can impact the reliability of LCSA findings. Therefore, this paper elaborated on integrating key concepts, namely DT and blockchain, to address the challenges the construction industry faces in embracing sustainability comprehensively.

Based on the Design Science Research methodology, the exploration proposed culminated in developing an advanced software application tailored for application in diverse building projects. This is a machine learning-based software application that integrates BIM-based DT and blockchain technology into the LCSA framework. LCSA provides a holistic evaluation of the environmental, economic, and social dimensions of buildings. The BIM-based DT model provides a real-time digital representation of the physical building throughout its life cycle. Finally, blockchain addresses critical aspects of data security, integrity, and user privacy, a cornerstone in sustainable construction practices. This integration aims to create a dynamic, real-time, and secure framework for sustainability assessments across the entire life cycle of buildings.

In turn, the comparative analysis between static and dynamic LCSAs conducted in this study aimed to showcase the transformative potential of the integrated technologies. By transitioning from a static to a dynamic approach, the research illustrated improvements, discrepancies, and nuanced insights gained. The outcomes of this comparative study contribute essential knowledge to sustainable construction practices, underscoring the effectiveness of the proposed framework in enhancing the comprehensiveness and accuracy of sustainability assessments in building projects.

Demonstrated through a real-world case study on a typical Brazilian structure, this integration represents a great effort to provide practical solutions to the challenges faced in construction sustainability. Notably, the sum of non-renewable and renewable energy demand increased by 20.37% and 19.70%, respectively, from the static LCSA to the dynamic LCSA calculated after 12 months of real-time data collection. These outcomes underscore the effectiveness of the proposed framework in enhancing the comprehensiveness and accuracy of sustainability assessments in building projects.

While acknowledging the promising results of integrating DT and blockchain to achieve a dynamic LCSA process, a number of limitations remain to be addressed. The specificity of the case study, while providing valuable insights and validating the proposed framework, necessitates caution in extrapolating the results universally. Future research should focus on diversifying case studies to fortify the robustness and applicability of the integrated approach across varied construction projects. This acknowledgment emphasizes the need for continuous exploration and refinement in pursuing sustainable construction practices.

Besides, while blockchain enhances data integrity, considerations must be acknowledged. Blockchain can introduce performance and scalability issues, primarily when implemented on a large scale. The added layer of complexity means that developers and users must understand how to interact with and maintain the blockchain. Additionally, as a relatively new technology, it may not always be the best solution and should be applied carefully, considering the specific use cases and requirements. Therefore, through rigorous exploration and analysis, future research aims to illuminate the transformative potential of these integrated technologies and their collective impact on sustainability practices in the construction sector.

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11 CONCLUSIONS

This thesis has comprehensively explored enhancing the Life Cycle Sustainability Assessment (LCSA) of buildings through innovative model-based approaches and data-driven solutions. The overarching objective was to bridge critical research gaps, specifically addressing limitations associated with the application of LCSAs in early design stages that often rely on static and historical data. This research endeavors to propel the field forward by introducing dynamic and real-time adaptability to sustainability assessments, overcoming the constraints posed by conventional retrospective methodologies.

The four specific objectives (SO) outlined in this thesis have been meticulously addressed, contributing novel insights to the scientific community. First, the investigation into current trends in Building LCSA, particularly focusing on its implementation during the design phase, has been a cornerstone of this research. Chapters 2, 3, and 4 have significantly refined sustainability assessments during the early design stage of buildings, addressing challenges and paving the way for more accurate assessments. This foundational work has set the stage for the subsequent objectives.

Particularly in Chapter 3, an innovative framework that integrates LCSA, BIM, and MCDA was presented to determine the most sustainable choice of materials for construction projects. Our findings demonstrated that while previous studies have adopted individual approaches, none have yet implemented them simultaneously to improve material choice sustainability comprehensively. Through a case study of a residential building, we applied the developed framework and observed significant variations in key sustainability indicators, such as global warming potential, energy costs for lighting and HVAC systems, and Fair Wage Potential. These variations underscored the importance of adopting a holistic approach to material selection. However, certain limitations, such as modeling assumptions and data availability constraints, were acknowledged, highlighting the need for continued exploration and refinement in Building LCSA.

In the following chapters, therefore, the focus shifted toward exploring the role of other technologies in solving the limitations encountered in traditional LCSA applications. Chapters 5 and 6 provided insights into the potential of Digital Twin technology to facilitate real-time data visualization and decision-making processes, thereby improving the overall sustainability performance of buildings. By integrating Digital Twin technology, we demonstrated the feasibility of enhancing sustainability assessments beyond the design phase, extending its applicability to other life cycle stages.

However, some points should be highlighted. Based on a literature review search, Chapter 5 discussed the issue of the misuse of the term "Digital Twin," with some publications failing to utilize real-time data or establish a genuine connection with the physical asset, thus representing only a digital shadow rather than a genuine Digital Twin. It is imperative to distinguish between BIM and Digital Twin, as a pure BIM model typically involves only static data related to the building. However, leveraging a 3-D BIM model can significantly ease the creation of a Digital Twin by providing existing geometric and semantic information. Therefore, this thesis proposes using a BIM-based Digital Twin to enhance the triple-bottom-line sustainability framework in the built environment.

Based on this discussion, Chapter 6 emphasizes the significance of integrating a BIM-based digital twin with LCSA methodology for sustainable building assessments. This integration is proposed as an iterative process, spanning from the early design stage to the building's end of life. The proposed integration enhances decision-making processes regarding material selection, construction methods, and post-construction considerations, aligning with sustainability pillars. Additionally, the framework enables continuous monitoring and improvement of built assets through real-time analyses.

However, challenges such as understanding uncertainties and managing large datasets may arise, warranting further research. It became clear that to leverage Digital Twins for improving sustainable outcomes, the application of information and control systems, along with the adoption of new organizational structures, is vital. The proposal to integrate BIM-based Digital Twins with Blockchain arises in this context. This integration can offer tamper-proof solutions for information supervision in building processes, but deeper discussions are still needed in this domain.

In this context, based on a comprehensive literature review, Chapter 7 highlights the current state of Blockchain technology in the construction industry and its potential for achieving sustainability in the built environment. Despite widespread discussion in the literature, practical applications of Blockchain in construction remain limited, with most developments occurring at a theoretical level. This chapter aimed to bridge this gap by identifying key themes and discussing potential applications of Blockchain technology in construction, emphasizing its importance in addressing environmental and socio-economic challenges.

The literature review revealed that only a small percentage of articles presented case studies demonstrating the effectiveness of Blockchain in construction projects, indicating a need for more empirical research in this area. Additionally, the identified case studies often lacked comprehensive coverage of different aspects of construction projects, highlighting the need for more representative discussions. To guide the continuity of the research, a conceptual framework was proposed, outlining key challenges, tools, platforms, and methodologies to be integrated with Blockchain.

In addition to the discussions presented in Chapter 7, the exploration of Blockchain technology in Chapter 8 further extends the potential of enhancing sustainability assessments in building projects. The main achievement is the proposal for a semantic BIM-based digital twin platform aimed at enhancing design, manufacturing, logistics, and assembly processes while providing a tamper-proof solution via Blockchain. However, it is essential to note that while Blockchain offers promising solutions, its integration into building sustainability assessments presents its own set of challenges and complexities. Ensuring data security, scalability, and interoperability with existing systems are crucial considerations that must be addressed in future research endeavors.

Based on what has been pointed out so far, the thesis culminates in the comprehensive integration of LCSA, DT, and Blockchain technologies, offering practical solutions to sustainability challenges in building projects. Chapter 9 demonstrated the proposed framework in a building case study in southeast Brazil, which showed promising results. However, it is essential to acknowledge the limitations of this first trial, which was focused primarily on the building design stage.

Chapter 10 expanded the framework's capabilities, refined the assessment methodologies, and explored a real-world application to solidify its potential further. Through a comparative analysis between static and dynamic LCSAs, this final paper used machine learning to demonstrate the transformative potential of integrated technologies, showcasing improvements and nuanced insights gained. However, while acknowledging promising results, the study recognizes limitations, such as the specificity of the case study and potential performance and scalability issues with Blockchain. Therefore, future research should focus on diversifying case studies, refining the integrated approach, and carefully considering the applicability of Blockchain technology in sustainable construction practices.

Overall, integrating innovative technologies such as BIM-based Digital Twins and Blockchain holds immense potential to revolutionize sustainability assessments in building projects. By bridging critical research gaps and addressing limitations associated with traditional LCSA methodologies, these advancements pave the way for more accurate, real-time, and transparent sustainability assessments throughout the entire building life cycle.

Ultimately, the resolution of the identified problems and challenges through the course of these papers underscores the practical applicability of the proposed frameworks. The advancements made in each specific objective of this thesis collectively contribute to a paradigm shift in the approach to sustainability assessments, focusing on adaptability, transparency, and reliability.

This thesis, therefore, not only fills existing research gaps but also offers practical solutions that can significantly impact the decision-making processes in building projects, aligning them more closely with evolving sustainability needs. These contributions are aimed at shaping the trajectory of sustainable practices in the construction industry, opening avenues for further research and innovation in the dynamic field of building sustainability. Yet, continued collaboration between academia, industry stakeholders, and policymakers is essential to drive further innovation and adoption of these technologies, ultimately fostering a smarter, more sustainable built environment.

11.1 MAIN CONTRIBUTIONS

The main contributions of this thesis, aimed at proposing innovative solutions for sustainable building practices, can be summarized as follows:

- **Improvement in Building Material Selection:** Through the development of an innovative framework that integrates LCSA, BIM, and MCDA, the thesis facilitates holistic material choices during the early design stage of buildings. This framework enhances decision-making processes regarding material selection, construction methods, and post-construction considerations, aligning with the triple-bottom-line sustainability framework.

- **Advancements in Dynamic LCSA:** This thesis introduces dynamic and real-time adaptability to the LCSA methodology, overcoming limitations associated with static and historical data reliance. By integrating advanced technologies such as Digital Twin and Blockchain, the thesis aims to revolutionize sustainability assessments in building projects.

- **Exploration of Digital Twin Technology:** The thesis explores the potential of Digital Twin technology to facilitate real-time data visualization and decision-making processes, extending its applicability beyond the design phase to other life cycle stages of buildings. By leveraging 3-D BIM models and ensuring genuine connections with physical assets, the thesis proposes the use of BIM-based Digital Twins to enhance sustainability assessments in the built environment.

- **Investigation into Blockchain Technology:** Through a comprehensive review of Blockchain technology's potential applications in the construction industry, the thesis highlights its significance in achieving sustainability goals. The thesis identifies key themes and proposes conceptual frameworks to guide future research and implementation efforts.

- **Decision-Making Empowerment:** This research contributes to improving decision-making processes in construction projects by leveraging advanced technologies. The integration of BIM, Digital Twins, and Blockchain offers opportunities for more informed, secure, and efficient decision-making, particularly in areas such as material selection and construction methods.

- **Addressing Industry Challenges:** The thesis recognizes and addresses challenges within the construction industry, such as the need for standardized approaches, reliance on historical data, and the processing of large amounts of data for life cycle assessments. The proposed solutions aim to overcome these challenges and revolutionize sustainability assessments.

- **Practical Implementation:** While rooted in theoretical discussions, the thesis emphasizes the practical implementation of integrated technologies. The proposed frameworks and software applications provide practical tools for industry professionals to apply in real-world construction projects.

- **Emphasis on Sustainability Pillars:** Throughout the thesis, there is a consistent emphasis on the triple-bottom-line sustainability approach, considering environmental, social, and economic aspects. The integration of technologies aims to ensure a balanced consideration of these pillars in construction decision-making.

- **Contributions to Smart Construction Practices:** The research significantly contributes to the ongoing transformation of the construction industry toward smarter and more sustainable practices. The proposed frameworks and integrated technologies pave the way for a paradigm shift in how sustainability is assessed and achieved in building projects.

Finally, the thesis recognizes that the integrated technologies and frameworks presented are not exhaustive solutions. It is essential to emphasize the need for continuous improvement, refinement, and adaptation as technology evolves and as real-world applications uncover additional challenges and opportunities. Acknowledging the limitations and challenges, the thesis outlines clear directions for future research. It calls for continued exploration, refinement, and validation of integrated technologies in diverse building projects.

11.2 LIMITATIONS AND FURTHER RESEARCH

This thesis has made significant contributions to the field of sustainable building practices; however, certain limitations should be acknowledged, and avenues for further research should be explored. The primary limitation of this research lies in its reliance on case studies and theoretical frameworks, which may limit the generalizability of the findings. While case studies offer valuable insights into specific contexts, they may not fully capture the diversity of challenges and opportunities in different geographical and temporal settings.

Furthermore, although efforts were made to validate proposed solutions through case studies and simulations, future research should explore the scalability and generalizability of the proposed frameworks across diverse building typologies, geographical regions, and cultural contexts. Comparative studies and meta-analyses could provide valuable insights into the effectiveness and adaptability of integrated technologies in different settings.

Additionally, despite the contributions made in this thesis, several avenues for further research remain unexplored, presenting opportunities for future researchers to build upon this work. These potential research topics include:

- **Longitudinal Impact Studies:** Conduct longitudinal studies to track the long-term impacts of sustainability initiatives implemented in buildings. This includes assessing the environmental, economic, and social performance of buildings over extended periods to understand how sustainable practices evolve over time and their lasting effects on building performance.

- **Cultural and Contextual Adaptation:** Investigating how cultural and contextual factors influence the adoption and effectiveness of sustainability frameworks in different regions and communities is crucial. Understanding socio-cultural norms, economic conditions, and regulatory environments can provide insights into decision-making processes in sustainable construction practices.

- **Technological Innovations and Emerging Trends:** With rapid advancements in technology, exploring the integration of emerging technologies such as artificial intelligence and advanced sensing technologies into sustainability assessments is important. Investigating their potential applications in optimizing building performance and enhancing decision-making processes could lead to innovative solutions for sustainable construction practices.

- **Resilience and Adaptation Strategies:** Researching resilience and adaptation strategies in the face of climate change and environmental stressors is essential. Identifying strategies to enhance the resilience of buildings and infrastructure to climate-related risks while ensuring long-term sustainability is critical.

- **Policy and Regulatory Frameworks:** Examining the role of policy and regulatory frameworks in promoting sustainable building practices is also necessary. Future studies could assess the effectiveness of existing policies and regulations in incentivizing sustainable design, construction, and operation of buildings, as well as identify barriers to their implementation and enforcement.

By addressing these research topics, future researchers can further advance our understanding of sustainable building practices and contribute to the ongoing transformation of the construction industry toward a more resilient, equitable, and sustainable future.

APPENDIX A – BIBLIOGRAPHIC PRODUCTION

A1. RESEARCH PRODUCTS

Table A.1 presents a summary of all research products, showing the corresponding chapters of this thesis and whether personal contributions led to first authorship.

Table A.0.1 - Summary of bibliographic production derived from the present research

Research Line	Appendix/ Front Page	Product Type	Thesis Chapter	First Author	Reference Number
Investigate current trends in Building LCSA and enhance its implementation during the building design phase.	B	Book Chapter	02	Yes	[1]
	C	Book Chapter	02	Yes	[2]
	D	Scientific Article	03	Yes	[3]
	E	Scientific Article	04		[4]
	F	Book Publication	-		[5]
	G	Book Chapter	-	Yes	[6]
	H	Book Chapter	-	Yes	[7]
	I	Book Chapter	-	Yes	[8]
	J	Book Chapter	-	Yes	[9]
	K	Book Chapter	-		[10]
	L	Book Chapter	-	Yes	[11]
Investigate the role of Digital Twins in enhancing the triple-bottom-line sustainability framework in the built environment.	N	Conference Paper	05	Yes	[12]
	O	Conference Paper	06	Yes	[13]
Examine how Blockchain technology can increase the reliability of data obtained from building sustainability assessments.	P	Scientific Article	07	Yes	[14]
		Book Chapter	08	Yes	[15]
Explore practical ways of combining LCSA, Digital Twin, and Blockchain to improve decision-making in building projects related to sustainability goals.	Submitted	Scientific Article	09	Yes	-
	Submitted	Scientific Article	10	Yes	-

Table A.0.1 - Summary of bibliographic production derived from the present research, Continued.

Investigate current trends in the Construction Industry ***(co-authorship works)***	**Q**	**Scientific Article**	**-**	**[16]**
	R	Conference Paper	-	[17]
	S	Scientific Article	-	[18]
	T	Scientific Article	-	[19]
	U	Scientific Article	-	[20]
	V	Scientific Article	-	[21]

A2. REFERENCES FOR APPENDIX A

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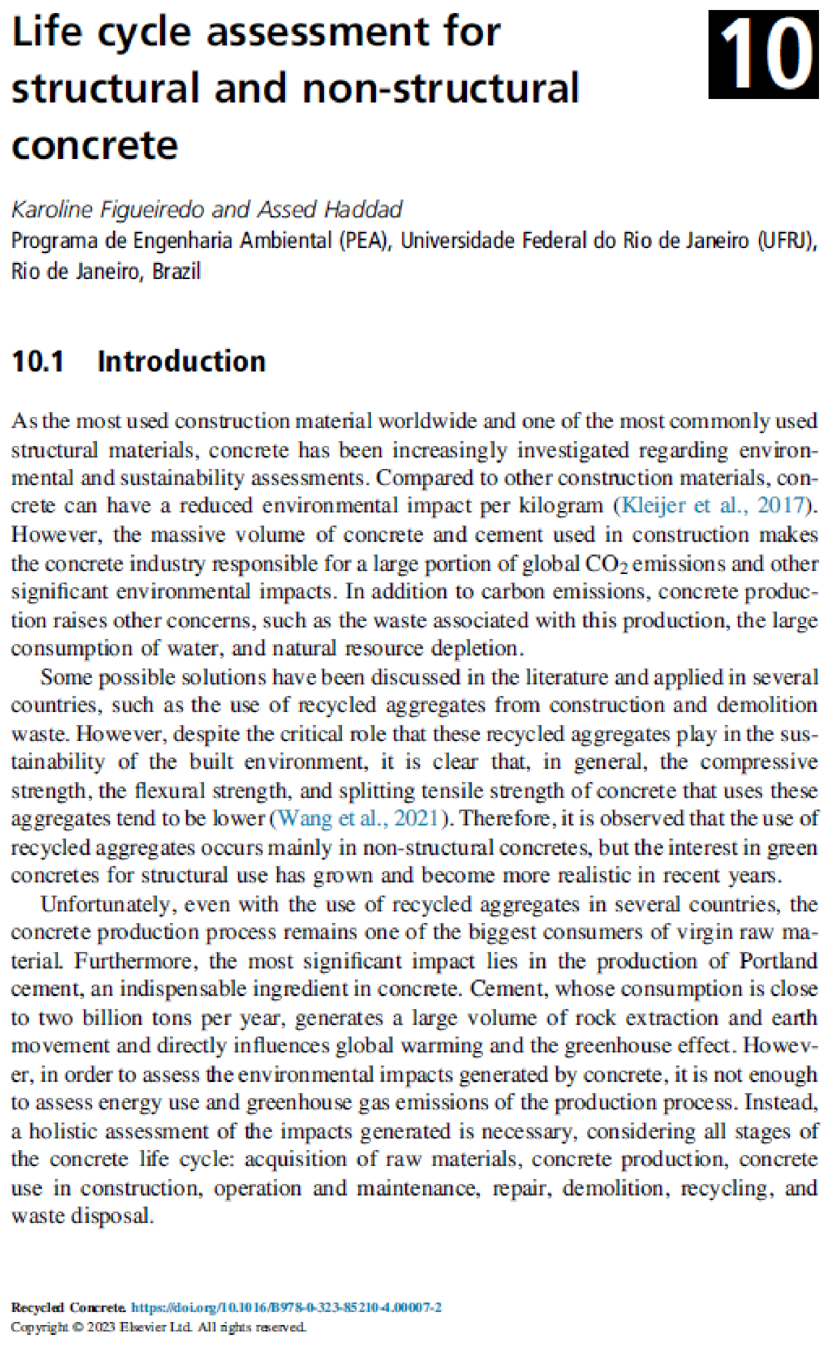
APPENDIX B – BOOK CHAPTER ON LCA APPLICATION

FIGUEIREDO, Karoline and HADDAD, Assed. Life Cycle Assessment for Structural and Non-structural Concrete. In: **Recycled Concrete: Technologies and Performance**. Woodhead Publishing Series in Civil and Structural Engineering, 2023. p. 309-335.



Life cycle assessment for structural and non-structural concrete

10

Karoline Figueiredo and Assed Haddad
Programa de Engenharia Ambiental (PEA), Universidade Federal do Rio de Janeiro (UFRJ),
Rio de Janeiro, Brazil

10.1 Introduction

As the most used construction material worldwide and one of the most commonly used structural materials, concrete has been increasingly investigated regarding environmental and sustainability assessments. Compared to other construction materials, concrete can have a reduced environmental impact per kilogram (Kleijer et al., 2017). However, the massive volume of concrete and cement used in construction makes the concrete industry responsible for a large portion of global CO_2 emissions and other significant environmental impacts. In addition to carbon emissions, concrete production raises other concerns, such as the waste associated with this production, the large consumption of water, and natural resource depletion.

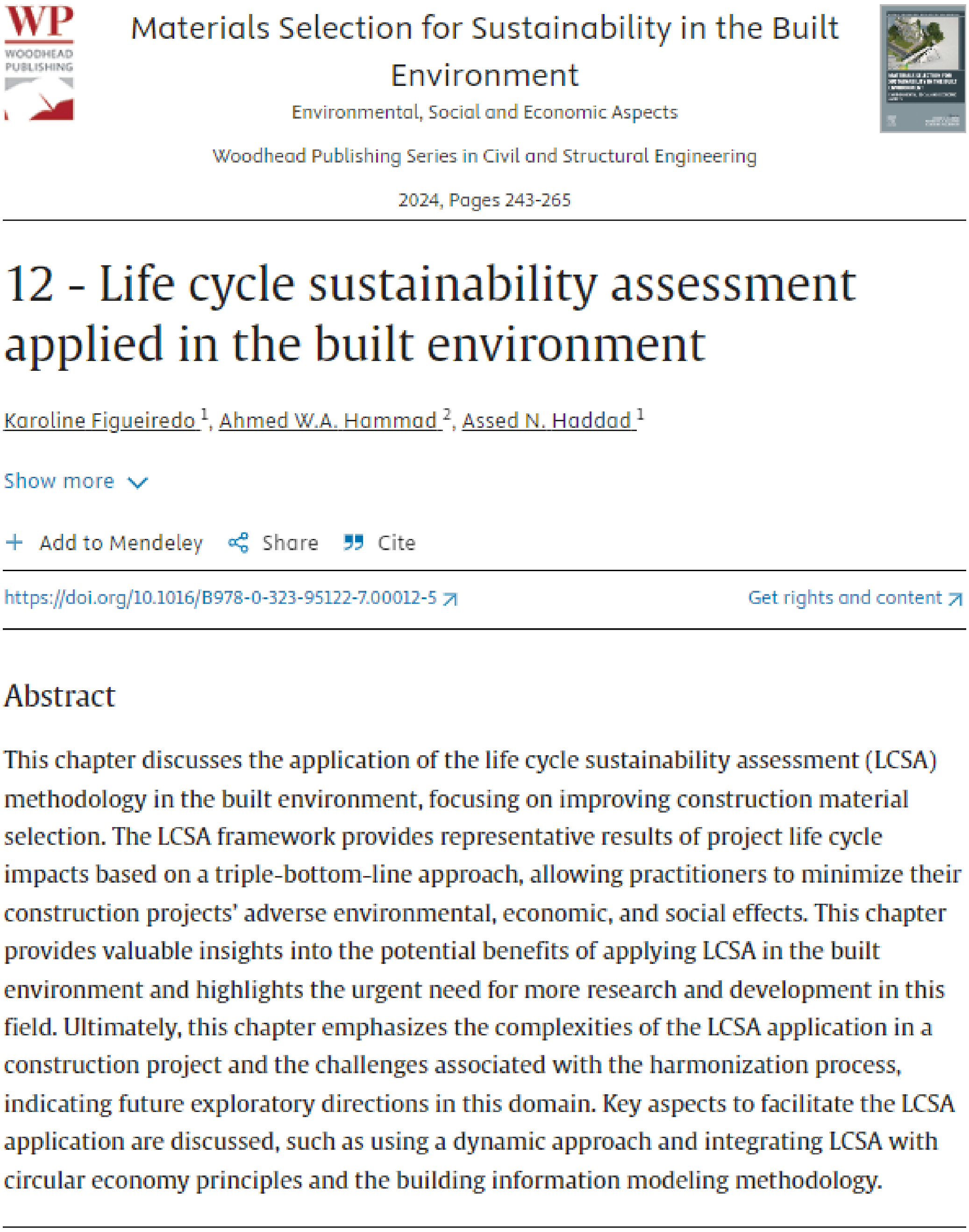
Some possible solutions have been discussed in the literature and applied in several countries, such as the use of recycled aggregates from construction and demolition waste. However, despite the critical role that these recycled aggregates play in the sustainability of the built environment, it is clear that, in general, the compressive strength, the flexural strength, and splitting tensile strength of concrete that uses these aggregates tend to be lower (Wang et al., 2021). Therefore, it is observed that the use of recycled aggregates occurs mainly in non-structural concretes, but the interest in green concretes for structural use has grown and become more realistic in recent years.

Unfortunately, even with the use of recycled aggregates in several countries, the concrete production process remains one of the biggest consumers of virgin raw material. Furthermore, the most significant impact lies in the production of Portland cement, an indispensable ingredient in concrete. Cement, whose consumption is close to two billion tons per year, generates a large volume of rock extraction and earth movement and directly influences global warming and the greenhouse effect. However, in order to assess the environmental impacts generated by concrete, it is not enough to assess energy use and greenhouse gas emissions of the production process. Instead, a holistic assessment of the impacts generated is necessary, considering all stages of the concrete life cycle: acquisition of raw materials, concrete production, concrete use in construction, operation and maintenance, repair, demolition, recycling, and waste disposal.

Recycled Concrete. https://doi.org/10.1016/B978-0-323-85210-4.00007-2

APPENDIX C – BOOK CHAPTER ON LCSA APPLICATION

FIGUEIREDO, Karoline et al. Life Cycle Sustainability Assessment applied in the Built Environment. In: **Materials Selection for Sustainability in the Built Environment: Environmental, Social and Economic Aspects**. Woodhead Publishing, Elsevier, 2024.



Materials Selection for Sustainability in the Built Environment
Environmental, Social and Economic Aspects
Woodhead Publishing Series in Civil and Structural Engineering
2024, Pages 243-265

12 - Life cycle sustainability assessment applied in the built environment

Karoline Figueiredo [1], Ahmed W.A. Hammad [2], Assed N. Haddad [1]

Show more

https://doi.org/10.1016/B978-0-323-95122-7.00012-5

Abstract

This chapter discusses the application of the life cycle sustainability assessment (LCSA) methodology in the built environment, focusing on improving construction material selection. The LCSA framework provides representative results of project life cycle impacts based on a triple-bottom-line approach, allowing practitioners to minimize their construction projects' adverse environmental, economic, and social effects. This chapter provides valuable insights into the potential benefits of applying LCSA in the built environment and highlights the urgent need for more research and development in this field. Ultimately, this chapter emphasizes the complexities of the LCSA application in a construction project and the challenges associated with the harmonization process, indicating future exploratory directions in this domain. Key aspects to facilitate the LCSA application are discussed, such as using a dynamic approach and integrating LCSA with circular economy principles and the building information modeling methodology.

APPENDIX D – SCIENTIFIC ARTICLE ON LCSA APPLICATION

FIGUEIREDO, Karoline et al. Sustainable material choice for construction projects: A Life Cycle Sustainability Assessment framework based on BIM and Fuzzy-AHP. **Building and Environment**, v. 196, p. 107805, 2021.

Building and Environment 196 (2021) 107805

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Sustainable material choice for construction projects: A Life Cycle Sustainability Assessment framework based on BIM and Fuzzy-AHP

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ARTICLE INFO

Keywords:
Life cycle sustainability assessment
Multi-criteria decision analysis
Building information modeling
Sustainable buildings
Fuzzy analytic hierarchy process

ABSTRACT

Construction professionals and researchers are increasingly looking for sustainable solutions for buildings in a bid to reduce some of the negative impacts associated with the sector. A common misconception is to consider sustainability as only concerning environmental issues, without regard for the interaction between a triple bottom line framework that is comprised of social, economic, and environmental factors. Material choice is known to impact building sustainability directly since the use of certain materials can dramatically alter the footprint generated over the life cycle of the building. However, the construction industry is not yet equipped with approaches that simultaneously account for all three aspects of sustainability when it comes to deciding on materials to adopt. This paper proposes a decision-making framework for construction professionals and researchers involving the integration of Life Cycle Sustainability Assessment (LCSA), Multi-Criteria Decision Analysis (MCDA), and Building Information Modeling (BIM) to choose suitable materials for buildings. The framework is built based on a literature review of relevant papers to identify critical factors and challenges to implementing this integration. The Fuzzy Analytic Hierarchy Process was chosen as the MCDA method within the proposed framework, given that the problem of material choice often contains subjectivity, uncertainty, and ambiguity, which is best solved with fuzzy logic. A residential building was adopted as a case study to validate the proposed framework, and the LCSA method is applied, covering the construction, operation, and end-of-life phases of the building.

1. Introduction

The construction industry is responsible for the significant consumption of natural resources, along with the generation of large amounts of waste [1]. In the last decade, researchers have attempted to study alternative materials, technologies, and design concepts that are less damaging to the environment. However, sustainability is not only concerned with environmental issues, as it involves an interaction between a triple bottom line framework comprised of social, economic, and environmental factors. In addition, several stakeholders are involved in a construction project, leading to the generation of various information from different parties and thus increasing uncertainty revolving around the decisions made [2]. Thus, there is a need for tools and technologies that facilitate a comprehensive analysis of a building and which cover all dimensionalities of sustainability.

Many decisions are made across the design, construction, and operation phases of a construction project. Such decisions can impact multiple aspects of a project. Hence, it is crucial to understand how such impacts reflect on several factors, including economic, environmental, and social ones. There are several examples in which a decision in the construction field impacts multiple criteria: the process to determine the best energy retrofit decision for a building, defining the impacts of different retrofit scenarios [3]; the equipment selection for construction projects [4]; and the definition of the construction system productivity [5]. One method to handle the simultaneous criteria that need to be evaluated before a decision is made is through multi-criteria decision analysis (MCDA), whereby concerns about various conflicting criteria can be formally incorporated into the decision-making process [6].

Of particular relevance in this study is the selection of suitable materials for building projects, which is a task that is linked to multiple criteria that require analysis and interpretation concurrently. Material selection in projects is traditionally based on satisfying technical

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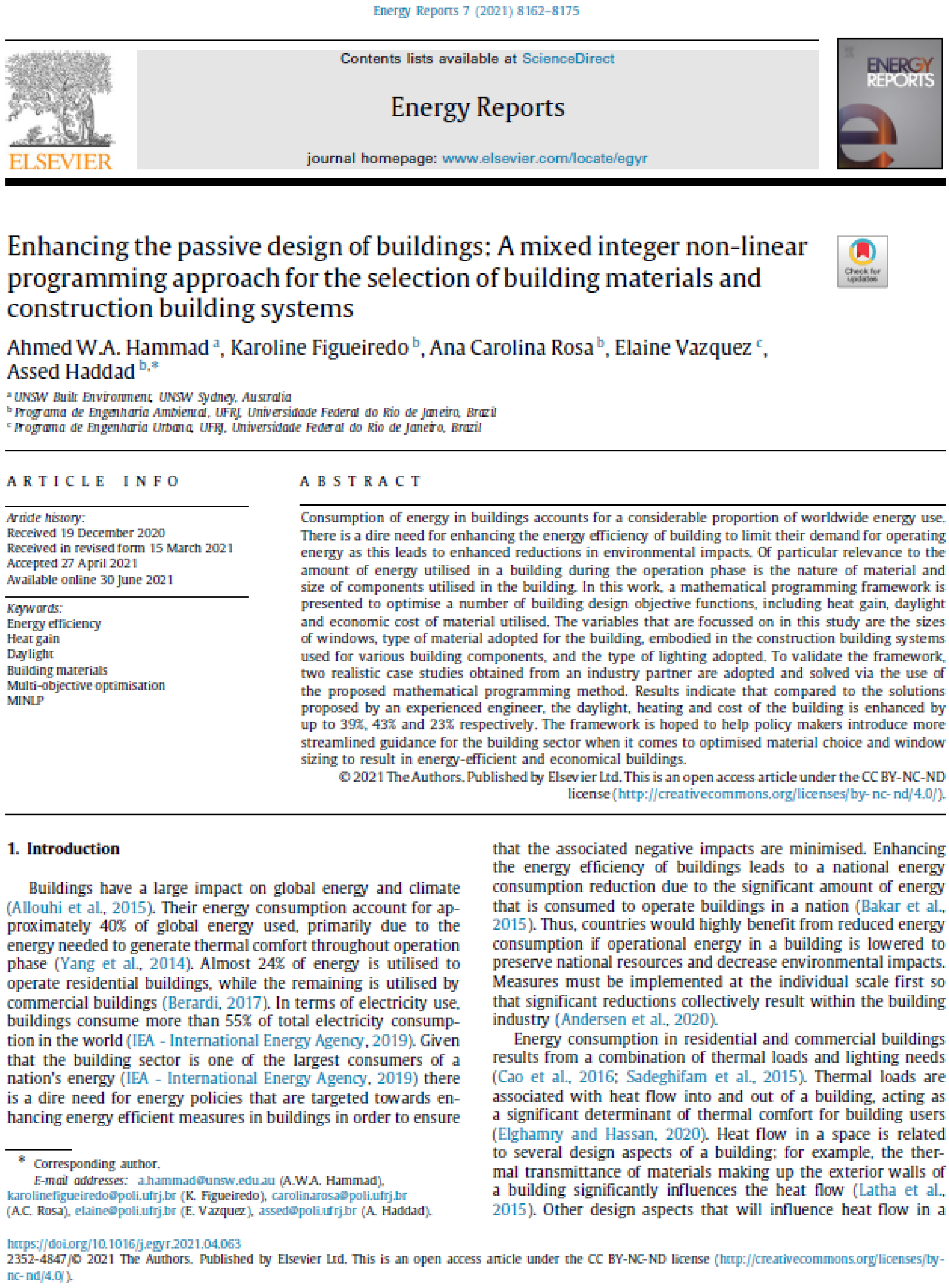
APPENDIX E – SCIENTIFIC ARTICLE ON MATERIAL SELECTION

HAMMAD, Ahmed, FIGUEIREDO, Karoline et al. Enhancing the passive design of buildings: A mixed integer non-linear programming approach for the selection of building materials and construction building systems. **Energy Reports**, v. 7, p. 8162–8175, 2021.



Energy Reports 7 (2021) 8162–8175

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journal homepage: www.elsevier.com/locate/egyr

Enhancing the passive design of buildings: A mixed integer non-linear programming approach for the selection of building materials and construction building systems

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ABSTRACT

Consumption of energy in buildings accounts for a considerable proportion of worldwide energy use. There is a dire need for enhancing the energy efficiency of building to limit their demand for operating energy as this leads to enhanced reductions in environmental impacts. Of particular relevance to the amount of energy utilised in a building during the operation phase is the nature of material and size of components utilised in the building. In this work, a mathematical programming framework is presented to optimise a number of building design objective functions, including heat gain, daylight and economic cost of material utilised. The variables that are focussed on in this study are the sizes of windows, type of material adopted for the building, embodied in the construction building systems used for various building components, and the type of lighting adopted. To validate the framework, two realistic case studies obtained from an industry partner are adopted and solved via the use of the proposed mathematical programming method. Results indicate that compared to the solutions proposed by an experienced engineer, the daylight, heating and cost of the building is enhanced by up to 39%, 43% and 23% respectively. The framework is hoped to help policy makers introduce more streamlined guidance for the building sector when it comes to optimised material choice and window sizing to result in energy-efficient and economical buildings.

1. Introduction

Buildings have a large impact on global energy and climate (Allouhi et al., 2015). Their energy consumption account for approximately 40% of global energy used, primarily due to the energy needed to generate thermal comfort throughout operation phase (Yang et al., 2014). Almost 24% of energy is utilised to operate residential buildings, while the remaining is utilised by commercial buildings (Berardi, 2017). In terms of electricity use, buildings consume more than 55% of total electricity consumption in the world (IEA - International Energy Agency, 2019). Given that the building sector is one of the largest consumers of a nation's energy (IEA - International Energy Agency, 2019) there is a dire need for energy policies that are targeted towards enhancing energy efficient measures in buildings in order to ensure that the associated negative impacts are minimised. Enhancing the energy efficiency of buildings leads to a national energy consumption reduction due to the significant amount of energy that is consumed to operate buildings in a nation (Bakar et al., 2015). Thus, countries would highly benefit from reduced energy consumption if operational energy in a building is lowered to preserve national resources and decrease environmental impacts. Measures must be implemented at the individual scale first so that significant reductions collectively result within the building industry (Andersen et al., 2020).

Energy consumption in residential and commercial buildings results from a combination of thermal loads and lighting needs (Cao et al., 2016; Sadeghifam et al., 2015). Thermal loads are associated with heat flow into and out of a building, acting as a significant determinant of thermal comfort for building users (Elghamry and Hassan, 2020). Heat flow in a space is related to several design aspects of a building; for example, the thermal transmittance of materials making up the exterior walls of a building significantly influences the heat flow (Latha et al., 2015). Other design aspects that will influence heat flow in a

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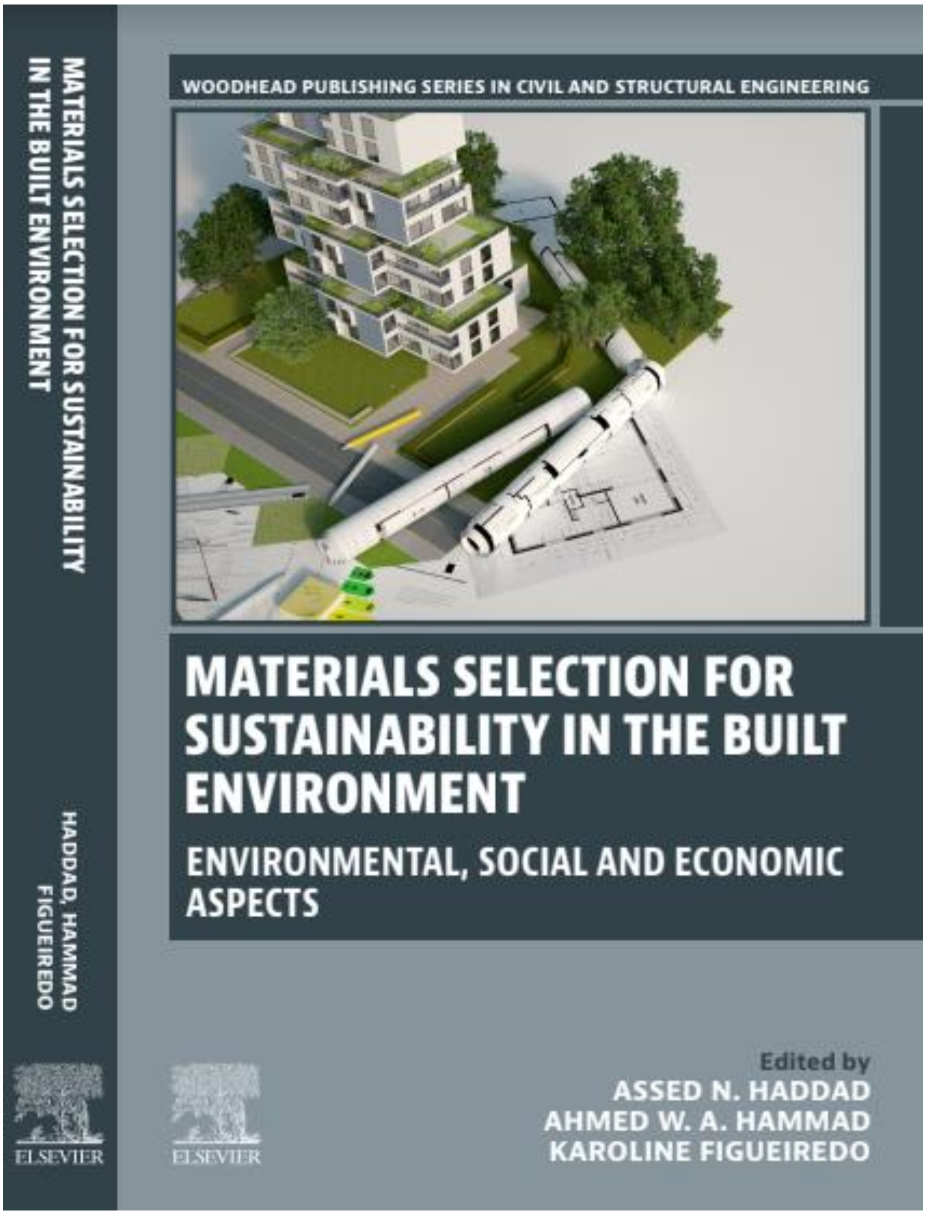
APPENDIX F – BOOK PUBLICATION

Materials Selection for Sustainability in the Built Environment: Environmental, Social and Economic Aspects. Editors: Assed N. Haddad, Ahmed W.A. Hammad, Karoline Figueiredo. Paperback ISBN: 9780323951227, Elsevier, 2024.



MATERIALS SELECTION FOR SUSTAINABILITY IN THE BUILT ENVIRONMENT

HADDAD, HAMMAD
FIGUEIREDO

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MATERIALS SELECTION FOR SUSTAINABILITY IN THE BUILT ENVIRONMENT

ENVIRONMENTAL, SOCIAL AND ECONOMIC ASPECTS

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APPENDIX G – BOOK CHAPTER

FIGUEIREDO, Karoline et al. Introduction. In: **Materials Selection for Sustainability in the Built Environment: Environmental, Social and Economic Aspects**. Woodhead Publishing, Elsevier, 2024.

WP WOODHEAD PUBLISHING

Materials Selection for Sustainability in the Built Environment

Environmental, Social and Economic Aspects

Woodhead Publishing Series in Civil and Structural Engineering

2024, Pages 1-13

1 - Introduction

Karoline Figueiredo [1], Ahmed W.A. Hammad [2], Assed N. Haddad [1]

https://doi.org/10.1016/B978-0-323-95122-7.00001-0

Abstract

The first chapter of this book offers a thorough introduction to its scope, objectives, and structure. It delves into the increasing significance of sustainability in the built environment and the importance of material selection practices that take into account environmental, social, and economic factors. The chapter then outlines the book's key themes, such as sustainable material selection criteria, the use of machine learning and mathematical programming, life cycle sustainability assessment, circular economy principles, and stakeholder engagement. It also emphasizes the interdisciplinary approach of the book that brings together experts from different fields to provide a complete view of sustainable material selection in the built environment. In summary, this book is an essential resource for professionals, researchers, and students in the fields of architecture, engineering, and materials science who seek to advance sustainable practices.

APPENDIX H – BOOK CHAPTER

FIGUEIREDO, Karoline et al. Standards and legal regulations regarding sustainable construction. In: **Materials Selection for Sustainability in the Built Environment: Environmental, Social and Economic Aspects**. Woodhead Publishing, Elsevier, 2024.

Materials Selection for Sustainability in the Built Environment
Environmental, Social and Economic Aspects
Woodhead Publishing Series in Civil and Structural Engineering
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6 - Standards and legal regulations regarding sustainable construction

Karoline Figueiredo [1], Mohammad K. Najjar [1], Ahmed W.A. Hammad [2], Assed N. Haddad [1]

https://doi.org/10.1016/B978-0-323-95122-7.00006-X

Abstract

In recent years, the construction industry has made sustainable practices a top priority to reduce its impact on the environment. Standards and regulations play a vital role in promoting sustainable construction, but there is still room for improvement. To keep building certification systems up to date, new indicators and approaches should be explored. This chapter discusses various guidelines for sustainable construction, including building codes, green building ratings, and international frameworks. It also emphasizes the importance of auditing building certification systems. In summary, the chapter highlights the need for comprehensive policies that address social, economic, and environmental aspects using a triple-bottom-line approach. Achieving this will require a collaborative effort from all stakeholders. Ultimately, the chapter discusses integrating building rating systems with other concepts, such as building information modeling and lifecycle techniques, presenting not only its advantages but also some misconceptions that hinder a comprehensive and accurate application of rating systems.

APPENDIX I – BOOK CHAPTER

FIGUEIREDO, Karoline et al. Introductory Overview. In: **Materials Selection for Sustainability in the Built Environment: Environmental, Social and Economic Aspects**. Woodhead Publishing, Elsevier, 2024.

Materials Selection for Sustainability in the Built Environment
Environmental, Social and Economic Aspects
Woodhead Publishing Series in Civil and Structural Engineering
2024, Pages 133-135

7 - Introductory overview

Karoline Figueiredo[1], Mohammad K. Najjar[1], Ahmed W.A. Hammad[2], Assed N. Haddad[1]

https://doi.org/10.1016/B978-0-323-95122-7.00007-1

Abstract

This chapter serves as the introductory overview for Section 2 of this book, providing readers with a comprehensive understanding of commonly used construction materials and their pivotal role in shaping a sustainable built environment. Through an exploration of concrete, cementitious materials, wood, and glass, this section not only highlights their unique properties but also examines their diverse impacts, underscoring the critical importance of informed material choices. By delving into the properties and consequences associated with these materials, this section equips readers with the knowledge needed to make conscientious decisions in construction projects. Furthermore, it offers valuable insights into the latest technological advancements in building materials, recognizing their profound influence on the construction industry. This foundational knowledge is intended to catalyze future progress and innovation in the field, with a focus on promoting environmentally, economically, and socially responsible construction practices.

APPENDIX J – BOOK CHAPTER

FIGUEIREDO, Karoline et al. Concluding Overview: Advancements in Building Materials Technology. In: **Materials Selection for Sustainability in the Built Environment: Environmental, Social and Economic Aspects**. Woodhead Publishing, Elsevier, 2024.

Materials Selection for Sustainability in the Built Environment
Environmental, Social and Economic Aspects
Woodhead Publishing Series in Civil and Structural Engineering
2024, Pages 227-240

11 - Concluding overview: advancements in building materials technology

Karoline Figueiredo [1], Ahmed W.A. Hammad [2], Assed N. Haddad [1]

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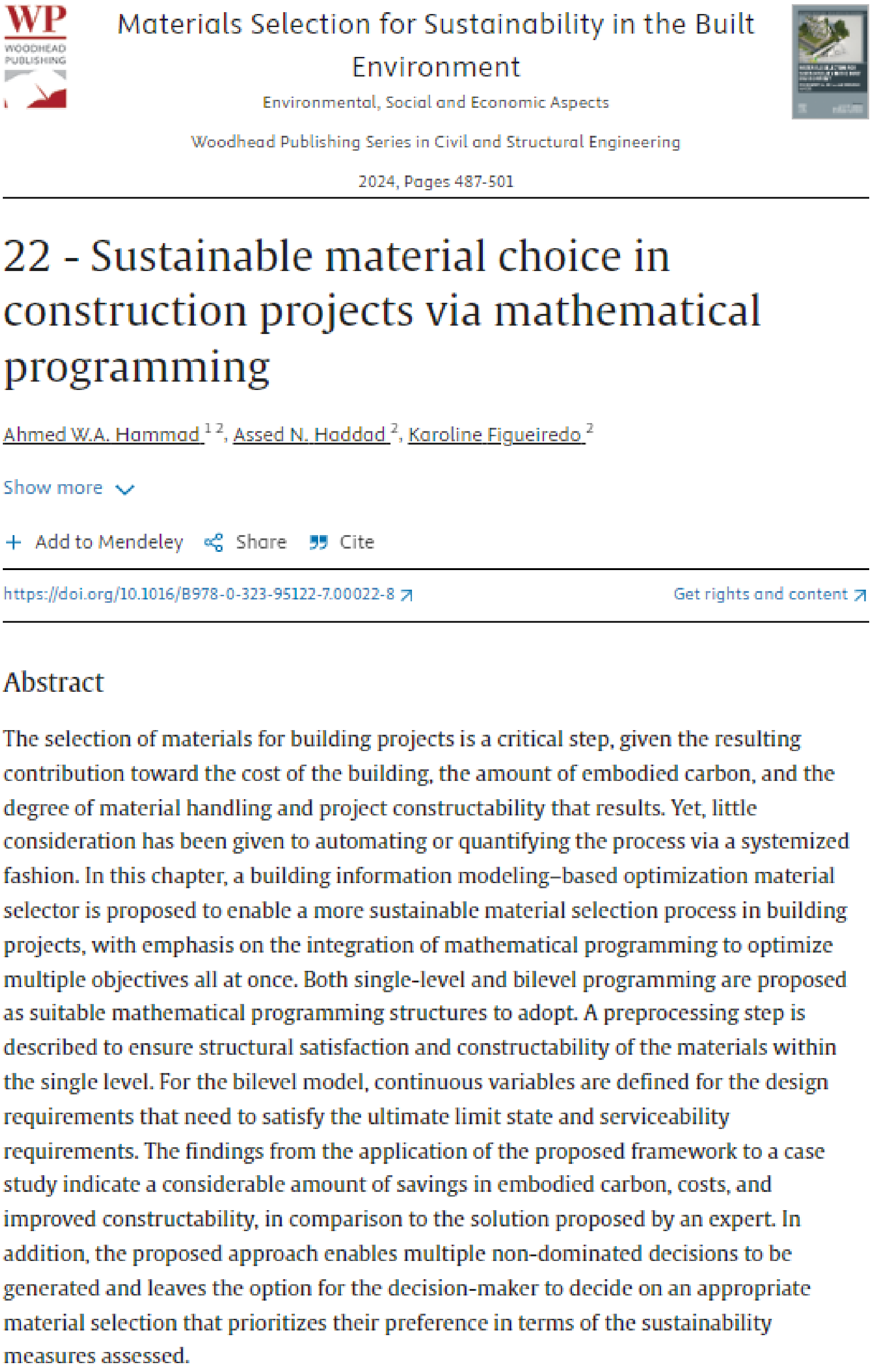
Abstract

This chapter serves as a concluding overview of the second section in this book while also introducing innovative solutions to foster a sustainable built environment through enhanced construction materials. This chapter delves into the revolutionary concepts of material-based computational design, additive manufacturing (also called 3D printing), and multi-material 4D printing. By exploring these cutting-edge techniques, the chapter highlights their potential to revolutionize the construction industry and pave the way for more efficient, cost-effective, and sustainable building practices. Additionally, the chapter explores the promising application of bioplastics in construction, shedding light on their viability as eco-friendly alternatives. This comprehensive overview offers readers valuable insights into the advancements in building materials technology and their significant impact on the construction industry, providing a foundation for future progress in the field.

APPENDIX K – BOOK CHAPTER

HAMMAD, AHMED et al. Sustainable Material Choice in Construction Projects via Mathematical Programming. In: **Materials Selection for Sustainability in the Built Environment: Environmental, Social and Economic Aspects**. Woodhead Publishing, Elsevier, 2024.



Materials Selection for Sustainability in the Built Environment
Environmental, Social and Economic Aspects
Woodhead Publishing Series in Civil and Structural Engineering
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22 - Sustainable material choice in construction projects via mathematical programming

Ahmed W.A. Hammad [1] [2], Assed N. Haddad [2], Karoline Figueiredo [2]

https://doi.org/10.1016/B978-0-323-95122-7.00022-8

Abstract

The selection of materials for building projects is a critical step, given the resulting contribution toward the cost of the building, the amount of embodied carbon, and the degree of material handling and project constructability that results. Yet, little consideration has been given to automating or quantifying the process via a systemized fashion. In this chapter, a building information modeling–based optimization material selector is proposed to enable a more sustainable material selection process in building projects, with emphasis on the integration of mathematical programming to optimize multiple objectives all at once. Both single-level and bilevel programming are proposed as suitable mathematical programming structures to adopt. A preprocessing step is described to ensure structural satisfaction and constructability of the materials within the single level. For the bilevel model, continuous variables are defined for the design requirements that need to satisfy the ultimate limit state and serviceability requirements. The findings from the application of the proposed framework to a case study indicate a considerable amount of savings in embodied carbon, costs, and improved constructability, in comparison to the solution proposed by an expert. In addition, the proposed approach enables multiple non-dominated decisions to be generated and leaves the option for the decision-maker to decide on an appropriate material selection that prioritizes their preference in terms of the sustainability measures assessed.

APPENDIX L – BOOK CHAPTER

FIGUEIREDO, Karoline et al. Concluding Remarks: Future Directions and Emerging Trends in Sustainable Material Selection for the Built Environment. In: **Materials Selection for Sustainability in the Built Environment: Environmental, Social and Economic Aspects**. Woodhead Publishing, Elsevier, 2024.

Materials Selection for Sustainability in the Built Environment
Environmental, Social and Economic Aspects
Woodhead Publishing Series in Civil and Structural Engineering
2024, Pages 503-516

23 - Concluding remarks: future directions and emerging trends in sustainable material selection for the built environment

Karoline Figueiredo [1], Ahmed W.A. Hammad [2], Assed N. Haddad [1]

https://doi.org/10.1016/B978-0-323-95122-7.00023-X

Abstract

The final chapter of this book explores future directions and emerging trends in sustainable materials selection. It serves as a concluding reflection on the book's themes, highlighting critical areas of development and providing insights into the evolving landscape of sustainability in the built environment. This chapter will present the following topics: evolving materials and technologies, Circular Economy (CE) and resource efficiency, Design for Deconstruction (DfD), Integrated Design (ID) and collaboration, data-driven decision-making, and social and cultural considerations. This comprehensive exploration not only concludes the book on a forward-looking note but also provides readers with a deeper understanding of sustainable materials' dynamic and crucial role in creating a greener and more responsible world.

APPENDIX M – CONFERENCE PAPER ON DIGITAL TWIN

FIGUEIREDO, Karoline et al. Examining the Use of BIM-Based Digital Twins in Construction: Analysis of Key Themes to Achieve a Sustainable Built Environment. In: International Symposium on Advancement of Construction Management and Real Estate. Singapore: Springer Nature Singapore, 2022. p. 1462-1474.

Examining the Use of BIM-Based Digital Twins in Construction: Analysis of Key Themes to Achieve a Sustainable Built Environment

Karoline Figueiredo[1], Vivian W. Y. Tam[2](✉), and Assed Haddad[1]

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Abstract. Pursuing more sustainable construction projects has become a global priority. The construction industry is responsible for the massive use of freshwater resources and fossil fuels and several other environmental impacts, in addition to considerably affecting the gross domestic product (GDP) worldwide. In this vein, it is crucial to find strategies to develop a sustainable built environment based on a triple-bottom-line (TBL) strategy, concurrently considering environmental, social, and economic factors. The application of BIM-based Digital Twins seems to offer a tenable solution for overcoming the challenges related to achieving sustainability in the construction and real estate sectors. This concept is associated with developing a digital counterpart of the facility to assist the decision-making process throughout its life cycle, using real-time data and an actual connection between the 3D digital model and the physical asset. A BIM-based Digital Twin can be advantageous for a single building or an entire city and is, therefore, often related to the development of smart cities. This study's novelty is presenting a structured literature review that defines the most recent developments in BIM-based Digital Twin applications for the real estate and construction sectors regarding sustainability goals. Based on this literature review, the authors present a discussion of how the knowledge acquired so far can be diffused into the built environment.

Keywords: Sustainable Construction · Real Estate · Building Information Modelling (BIM) · Digital Twin

1 Introduction

The Digital Twin concept has been discussed in many industries and sectors for years. In the construction and real estate sectors, this concept still presents divergences in its definition and application. A Digital Twin is generally understood as a series of accurate digital models representing a physical asset's real-time characteristics, state, and behaviour during its entire lifespan [1]. Regarding the application of this concept

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https://doi.org/10.1007/978-981-99-3626-7_113

APPENDIX N – CONFERENCE PAPER ON DIGITAL TWIN AND LCSA

FIGUEIREDO, Karoline et al. Improving decision-making of building projects towards a smart and sustainable future via the integration of life cycle sustainability assessment and BIM-based digital twin. In: **The 45th Australasian Universities Building Education Association Conference**. 2022. p. 985-994.

Improving Decision-making of Building Projects towards a Smart and Sustainable Future via the Integration of Life Cycle Sustainability Assessment and BIM-based Digital Twin

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Abstract:
Buildings play a critical role in sustainability due to the massive environmental, social, and economic impacts generated throughout their life cycles. Although the search for sustainability is growing globally, developing sustainable building projects continues to be a challenging task linked to multiple criteria. The Life Cycle Sustainability Assessment (LCSA) methodology appears as a possible solution to meet the requirements of a sustainable built environment by adopting a lifecycle perspective and simultaneously accounting for all sustainability pillars. Nevertheless, compared to other assets, a building sustainability assessment requires extensive data processing. In this context, integrating LCSA and BIM-based Digital Twin from the early design stages of building projects, when it is possible to ensure maximum control over project decisions, to the building's end-of-life seems appropriate. A building Digital Twin can improve real-time data visualisation and develop self-learning building capabilities. Besides, the digital model can facilitate the simulations and data collection required to generate detailed results on impacts during sustainability assessments. Therefore, this study aims to extrapolate the discussion on integrating BIM and LCSA by adding the Digital Twin concept throughout the whole building's life cycle and inserting real-time data, thus transforming the application into a dynamic LCSA. To this end, this study proposes a conceptual framework with the steps to integrate LCSA and BIM-based Digital Twin throughout the entire building lifecycle to improve the design, fabrication, construction, operation and deconstruction processes. The advantages and challenges of using these concepts to achieve a smart and sustainable construction industry are discussed.

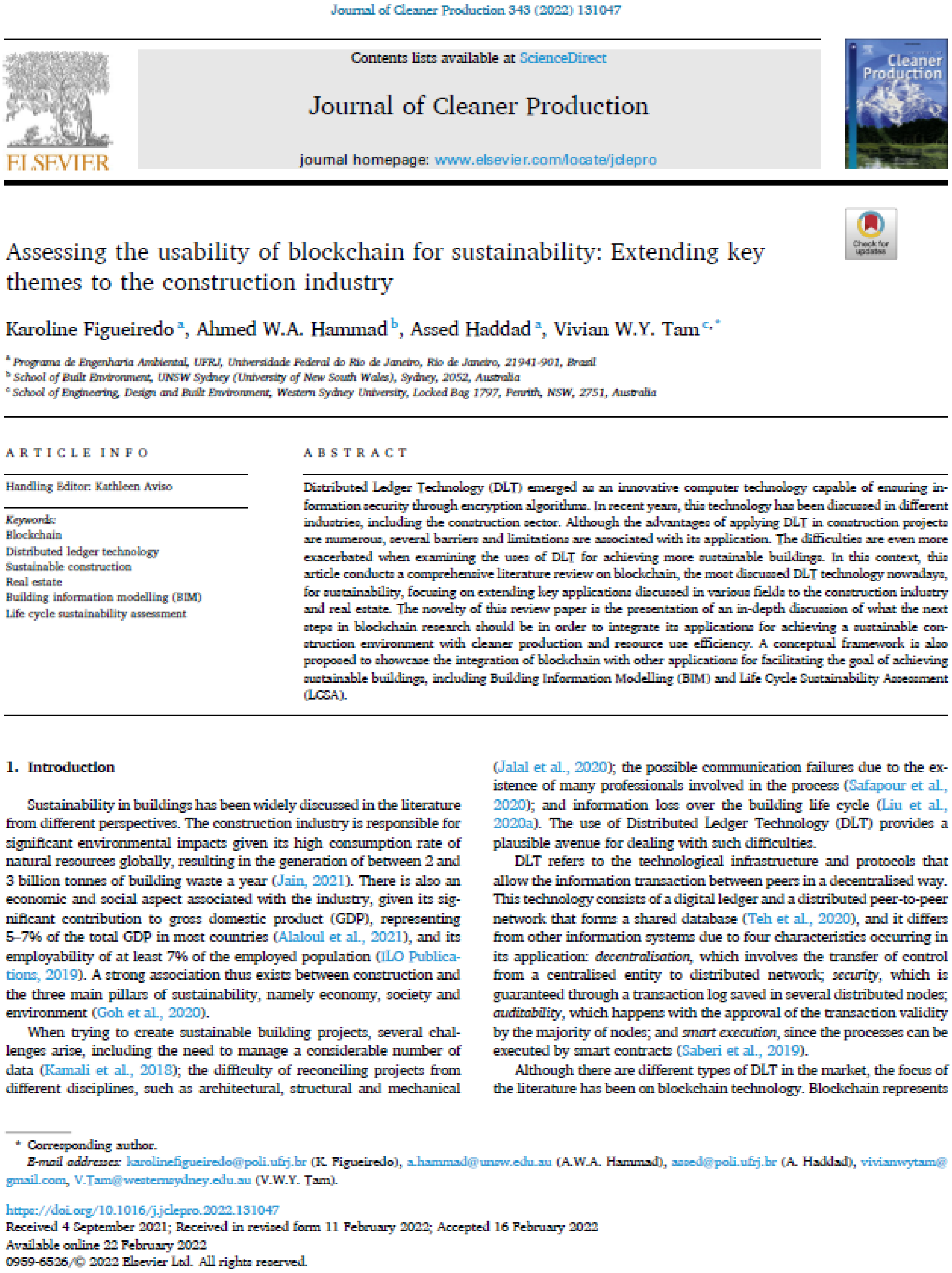
Keywords:
BIM, Decision-making, Digital Twin, Life Cycle Sustainability Assessment, Sustainable Construction.

1 Introduction

Seeking more sustainable projects in construction has become a primary goal worldwide. The importance of this becomes clear when analysing the massive number of environmental impacts the construction industry generates annually, with significant consumption of freshwater resources (Mannan and Al-Ghamdi, 2020) and fossil energy (Gao *et al.*, 2022). Moreover, this industry is responsible for influencing multiple social and economic aspects, directly contributing to the global employment of labour (Saka *et al.*, 2021) and the global gross domestic product (GDP) (Fu *et al.*, 2022). As a result, it is critical to look for ways to create more sustainable construction projects based on a triple-bottom-line (TBL) strategy, simultaneously considering environmental, social, and economic aspects.

APPENDIX O – SCIENTIFIC ARTICLE ON BLOCKCHAIN

FIGUEIREDO, Karoline et al. Assessing the usability of blockchain for sustainability: Extending key themes to the construction industry. **Journal of Cleaner Production**, v. 343, p. 131047, 2022.



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Assessing the usability of blockchain for sustainability: Extending key themes to the construction industry

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ABSTRACT

Distributed Ledger Technology (DLT) emerged as an innovative computer technology capable of ensuring information security through encryption algorithms. In recent years, this technology has been discussed in different industries, including the construction sector. Although the advantages of applying DLT in construction projects are numerous, several barriers and limitations are associated with its application. The difficulties are even more exacerbated when examining the uses of DLT for achieving more sustainable buildings. In this context, this article conducts a comprehensive literature review on blockchain, the most discussed DLT technology nowadays, for sustainability, focusing on extending key applications discussed in various fields to the construction industry and real estate. The novelty of this review paper is the presentation of an in-depth discussion of what the next steps in blockchain research should be in order to integrate its applications for achieving a sustainable construction environment with cleaner production and resource use efficiency. A conceptual framework is also proposed to showcase the integration of blockchain with other applications for facilitating the goal of achieving sustainable buildings, including Building Information Modelling (BIM) and Life Cycle Sustainability Assessment (LCSA).

1. Introduction

Sustainability in buildings has been widely discussed in the literature from different perspectives. The construction industry is responsible for significant environmental impacts given its high consumption rate of natural resources globally, resulting in the generation of between 2 and 3 billion tonnes of building waste a year (Jain, 2021). There is also an economic and social aspect associated with the industry, given its significant contribution to gross domestic product (GDP), representing 5–7% of the total GDP in most countries (Alaloul et al., 2021), and its employability of at least 7% of the employed population (ILO Publications, 2019). A strong association thus exists between construction and the three main pillars of sustainability, namely economy, society and environment (Goh et al., 2020).

When trying to create sustainable building projects, several challenges arise, including the need to manage a considerable number of data (Kamali et al., 2018); the difficulty of reconciling projects from different disciplines, such as architectural, structural and mechanical (Jalal et al., 2020); the possible communication failures due to the existence of many professionals involved in the process (Safapour et al., 2020); and information loss over the building life cycle (Liu et al., 2020a). The use of Distributed Ledger Technology (DLT) provides a plausible avenue for dealing with such difficulties.

DLT refers to the technological infrastructure and protocols that allow the information transaction between peers in a decentralised way. This technology consists of a digital ledger and a distributed peer-to-peer network that forms a shared database (Teh et al., 2020), and it differs from other information systems due to four characteristics occurring in its application: *decentralisation*, which involves the transfer of control from a centralised entity to distributed network; *security*, which is guaranteed through a transaction log saved in several distributed nodes; *auditability*, which happens with the approval of the transaction validity by the majority of nodes; and *smart execution*, since the processes can be executed by smart contracts (Saberi et al., 2019).

Although there are different types of DLT in the market, the focus of the literature has been on blockchain technology. Blockchain represents

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APPENDIX P – BOOK CHAPTER ON DIGITAL TWIN AND BLOCKCHAIN

FIGUEIREDO, Karoline et al. Improving Sustainability in the Built Environment through a BIM-based Integration of Digital Twin and Blockchain: An Analysis of Prefabricated Modular Construction. In: **Cognitive Digital Twins for Smart Lifecycle Management of Built Environment and Infrastructure**. CRC Press. p. 101-122.

Chapter

Improving Sustainability in the Built Environment through a BIM-based Integration of Digital Twin and Blockchain

An Analysis of Prefabricated Modular Construction

By Karoline Figueiredo, Ahmed W.A. Hammad, Assed Haddad

Book Cognitive Digital Twins for Smart Lifecycle Management of Built Environment and Infrastructure

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ABSTRACT

As one of the largest industries globally, and given its significant environmental, social, and economic impacts, construction plays a crucial role in sustainability. The use of digital twins offers a possible avenue for enhancing the sustainability of this sector by improving the sustainable decision-making process. However, the challenge is that it is necessary to consider that construction processes are often collaborative and comprise different professionals, such as regulators, architects, engineers, and contractors. As a result, confidentiality, traceability, and security issues may arise as obstacles. Therefore, creating a decentralised and auditable database integrated with the digital twin application is crucial, and it is possible through blockchain technology. In this context, this chapter aims to analyse the potential of digital twins in improving sustainability in the built environment, integrating this concept into the blockchain. The investigation uses the Building Information Modelling (BIM) methodology as a primary data source to develop a building digital twin, focusing on the sustainability assessment of prefabricated modular construction. The digital twin is examined for its benefits in terms of sustainability decision-making throughout the construction lifecycle, ensuring that the assessment is not tampered with due to blockchain application.

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Next Chapter >

APPENDIX Q – SCIENTIFIC ARTICLE ON LCSA

FILHO, Marcus et al. Sustainability Assessment of a Low-income Building: A BIM-LCSA-FAHP-based Analysis. **Buildings**, v. 12, 2022.

buildings

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Article

Sustainability Assessment of a Low-income Building: A BIM-LCSA-FAHP-based Analysis

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Abstract: The construction industry is one of the most significant consumers of environmental resources worldwide. Faced with the need to produce new buildings, but without further burdening the environment, attempts to improve social, economic, and environmental indicators have turned attention to building construction in recent decades. The objective of this research is to develop a novel framework to assess the most sustainable choice of materials applied to the construction of low-income buildings, according to the three pillars of the Triple Bottom Line (TBL). A BIM-LCSA-FAHP-based model was proposed with the creation of nine different scenarios, where the materials of the structure (precast concrete, cast-in-place concrete, and structural masonry), painting (PVA water-based and acrylic), and roofing (ceramic and fiber cement tiles) varied. The proposed procedure consists of the elaboration of a 3D Building Information Modeling (BIM) model, for which the parameters described above were evaluated according to the Life Cycle Sustainability Assessment (LCSA)-TBL-based criteria, divided into ten sub-criteria, that includes: (1) environmental (acidification, eutrophication, global warming, ozone depletion, smog formation, primary energy, non-renewable energy, and mass total), (2) economic (construction cost) and (3) socio-political issues (community impact). Finally, the Fuzzy Analytical Hierarchy Process (AHP) was used as a multi-criteria decision-making technique that helps in aggregating and classifying the impacts of each scenario in a sustainability index (SI). Regarding the best option for low-income construction, the results indicated that precast concrete when combined with acrylic paint and fiber cement tiles (scenario 3) proved to be the most advantageous and achieved first place in the sustainability index (SI) developed in this work. This methodology is replicable for different construction typologies and several categories of materials, making it a robust decision-aiding tool for engineers, architects, and decision makers.

Keywords: triple bottom line; life cycle sustainability assessment; building information modeling; multicriteria decision making; fuzzy analytic hierarchy process; sustainability index; sustainable building

Citation: Filho, M.V.A.P.M.; da Costa, B.B.F.; Najjar, M.; Figueiredo, K.V.; de Mendonça, M.B.; Haddad, A.N. Sustainability Assessment of a Low-Income Building: A BIM-LCSA-FAHP-Based Analysis. *Buildings* **2022**, 12, 181. https://doi.org/10.3390/buildings12020181

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1. Introduction

The construction industry is one of the most significant consumers of environmental resources worldwide [1,2], and one of the biggest industries responsible for giving rise to large amounts of waste [3]. The construction sector uses 30–40% of all-natural resources and primary energy over its lifespan, accounting for 30% of global greenhouse gas (GHG) emissions and representing about 6% of the world's Gross Domestic Product (GDP) [4,5].

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APPENDIX R – CONFERENCE PAPER ON BIM

CARNEIRO, Luã et al. BIM Methodology applied to Facility Management: Development of an Integrated Tool to benefit the Building Operation. **IEEE**, 2021.

2021 Third International Sustainability and Resilience Conference: Climate Change

BIM Methodology applied to Facility Management: development of an integrated tool to benefit the building operation

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Abstract — The Building Information Modeling (BIM) methodology applied to Facility Management (FM) has proven to be a great facilitator for professionals. However, this integration is still a little-explored topic in the construction sector. This is because there is still a significant obstacle in construction related to interoperability between systems, making it difficult to centralize information related to the building's operational phase. Thus, the application of BIM for FM is still experimental, with few practical studies on this subject being presented in the literature. In this context, this article aims to introduce a new tool called BIMBoard: a new way to present data exported from BIM projects, with practicality, speed, and efficiency, allowing all the stakeholders to access information and reporting of a building. In its first version, the BIMBoard tool enables practitioners to generate work orders for a particular element, centralizing data and benefiting the decision-making process during the building's operation phase. The future direction of this study is to add more capabilities to BIMBoard, connecting the program to the internet, thus allowing to extract information that is not possible only with BIM-based software.

Keywords— BIM, Facility management, Interoperability, Integration

I. INTRODUCTION

Building Information Modeling (BIM) is an IT-enabled approach that involves applying and maintaining a complete digital representation of all building information for different phases of the project lifecycle in the form of a data repository [1] According to [2], BIM represents the centralization of information about the entire building and a complete set of design documents stored in an integrated database, which leads the methodology to be accepted as an interesting process for construction projects. This technology can improve the efficiency and effectiveness of delivering a project from inception to operation/maintenance [3]. Besides, this methodology can also be used for deconstruction planning [4], which makes BIM worthwhile throughout the lifecycle of a building. BIM, together with advanced technologies, optimizes the efficiency of workflows. Thus, there is a need for innovative tools that help represent the data, making BIM not a mere data storage place but enabling access to all types of raw data analysis that BIM can perform. This study points to the possibility of centralizing data in spreadsheets that can generate dynamic dashboards that facilitate data storage and manipulation.

II. BACKGROUND

A. BIM dimensions

There is no single satisfactory definition of what BIM is. Instead, it needs to be analyzed as a multidimensional, historically evolving, a complex phenomenon [5]. In addition to the methodology definition, the BIM dimensions concept is widely discussed in the literature, referring to the levels of information inserted in the digital model. According to [6], 3D to 7D BIM dimensions are already disseminated, but many others need to be added for BIM to fulfill its potential.

The first dimension to be considered in this methodology is the 3D since the BIM proposes the creation of three-dimensional digital prototypes of the building. Therefore, 3D BIM can be regarded as the ubiquitous dimension in the design and constuction fields [6]. While the CAD methodology already supports the representation of construction elements in terms of their attributes and geometric relationships in three dimensions, the 3D BIM dimension goes beyond. The BIM methodology provides collaboration technologies and solutions that allow practitioners to increase modeling productivity and minimize compatibility errors.

In turn, BIM 4D involves linking a time schedule to a 3D model to improve construction planning techniques [7],[8]. According to [8], the benefits of applying the method include winning work at the tender stage, construction method planning, timescale communication, design interrogation, resource management, workspace planning, ID hazards, and safety planning. The 5th dimension, on the other hand, refers to data collection aimed at creating a budget for all stages of the project. This dimension is essential for a proper cost analysis for different solutions in project production. Thus, BIM 5D contributes to greater cost management competition

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APPENDIX S – SCIENTIFIC ARTICLE ON ENERGY ANALYSIS

ARRUDA, Roberto et al. Cost-benefit Analysis of Solar Energy Integration in Buildings: A Case Study of Affordable Housing in Brazil. **Frontiers in Built Environment**, v. 9, 2023.

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Cost-benefit analysis of solar energy integration in buildings: a case study of affordable housing in Brazil

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Introduction: The construction sector plays a pivotal role in global natural resource consumption, underscoring the urgency of promoting energy efficiency in buildings. With the escalating demand for renewable energy, solar power has gained significant traction. This study focuses on conducting a comprehensive cost-benefit analysis of solar energy integration in residential buildings.

Methods: The approach involves a novel comparison between photovoltaic panels and Solar Heating Systems (SHS) based on both environmental and financial considerations. To evaluate the practical implications, a case study was undertaken on an affordable housing complex in Brazil. Three distinct models were simulated for analysis: Model 1, featuring a grid-connected photovoltaic project with zero energy balance; Model 2, incorporating a grid-connected photovoltaic project with two solar panels generating 340 W each; and Model 3, integrating an SHS.

Results: The findings reveal the technical and economic feasibility of all proposed models. Model 1 stands out with superior performance in terms of estimated energy generation, energy savings, and annual reduction of CO_2 emissions. On the other hand, Model 3 excels in the financial analysis, indicating its viability from a cost perspective.

Discussion: This research contributes to informed decision-making processes regarding the utilization of photovoltaic panels and SHS, thereby fostering energy efficiency and sustainability in buildings. The nuanced comparison of environmental and financial aspects provides valuable insights for stakeholders in the construction and renewable energy sectors. The identified strengths and trade-offs of each model enable a more holistic understanding of the implications of solar energy integration in residential buildings.

KEYWORDS
energy efficiency, renewable energy, cost-benefit analysis, photovoltaic panels, solar heating systems, environmental sustainability

APPENDIX T – SCIENTIFIC ARTICLE ON SMART CITY

Kasznar, Ana Paula et al. Multiple Dimensions of Smart Cities' Infrastructure: A Review. **Buildings**, v. 11, 2021.

buildings MDPI

Review

Multiple Dimensions of Smart Cities' Infrastructure: A Review

Ana Paula P. Kasznar [1], Ahmed W. A. Hammad [2], Mohammad Najjar [3,*], Eduardo Linhares Qualharini [4], Karoline Figueiredo [4], Carlos Alberto Pereira Soares [5] and Assed N. Haddad [4,*]

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Abstract: In recent years, there has been significant focus on smart cities, on how they operate and develop, and on their technical and social challenges. The importance of infrastructure as a major pillar of support in cities, in addition to the rapid developments in smart city research, necessitate an up-to-date review of smart cities' infrastructure issues and challenges. Traditionally, a majority of studies have focused on traffic control and management, transport network design, smart grid initiatives, IoT (Internet of Things) integration, big data, land use development, and how urbanization processes impact land use in the long run. The work presented herein proposes a novel review framework that analyzes how smart city infrastructure is related to the urbanization process while presenting developments in IoT sensor networks, big data analysis of the generated information, and green construction. A classification framework was proposed to give insights on new initiatives regarding smart city infrastructure through answering the following questions: (i) What are the various dimensions on which smart city infrastructure research focuses? (ii) What are the themes and classes associated with these dimensions? (iii) What are the main shortcomings in current approaches, and what would be a good research agenda for the future? A bibliometric analysis was conducted, presenting cluster maps that can be used to understand different research trends and refine further searches. A bibliographic analysis was then followed, presenting a review of the most relevant studies over the last five years. The method proposed serves to stress where future research into understanding smart systems, their implementation and functionality would be best directed. This research concluded that future research on the topic should conceptualize smart cities as an emergent socio-techno phenomenon.

Keywords: smart city; infrastructure; urban systems; sustainability; e-governance; IoT

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Citation: Kasznar, A.P.P.; Hammad, A.W.A.; Najjar, M.; Linhares Qualharini, E.; Figueiredo, K.; Soares, C.A.P.; Haddad, A.N. Multiple Dimensions of Smart Cities' Infrastructure: A Review. *Buildings* **2021**, *11*, 73. https://doi.org/10.3390/buildings11020073

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1. Introduction

The year 2008 was a turning point for cities: the Earth's population became more urban than rural. Nowadays, more than half of the world's population—approximately 3.3 billion—lives in urban areas, increasingly in highly dense cities. By 2030, it is expected that the number of people living in urban areas will reach 5 billion. With the rapid increase in the urban population worldwide, cities are facing various challenges [1]. One of many challenges is the addition of new infrastructure, along with the need to operate and maintain existing infrastructure worldwide. New demand for resilient infrastructure opens the way for governments, in a combined effort with research and citizen input, to build smart cities that promote equity, education, health, and a better quality of life for everybody [2]. A smart city is defined as a city that is guided—through the Internet of Things (IoT)—in collecting data that is then interpreted and analyzed to efficiently and sustainably manage

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APPENDIX U – SCIENTIFIC ARTICLE ON ENERGY EFFICIENCY

Najjar, Mohammad et al. Influence of Ventilation Openings on the Energy Efficiency of Metal Frame Modular Constructions in Brazil Using BIM. **Eng**, v. 4, 2023.

eng

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Article

Influence of Ventilation Openings on the Energy Efficiency of Metal Frame Modular Constructions in Brazil Using BIM

Mohammad K. Najjar [1,2,*], **Luis Otávio Cocito De Araujo** [1], **Olubimbola Oladimeji** [3], **Mohammad Khalas** [4], **Karoline V. Figueiredo** [2], **Dieter Boer** [5], **Carlos A. P. Soares** [6] **and Assed Haddad** [1,2]

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Abstract: Construction projects demand a higher amount of energy predominantly for heating, ventilation, and illumination purposes. Modular construction has come into the limelight in recent years as a construction method that uses sustainable building materials and optimizes energy efficiency. Ventilation openings in buildings are designed to facilitate air circulation by naturally driven ventilation and could aid in reducing energy consumption in construction projects. However, a knowledge gap makes it difficult to propose the best dimensions of ventilation openings in buildings. Hence, the aim of this work is to empower the decision-making process in terms of proposing the best ventilation opening dimensions toward sustainable energy use and management in buildings. A novel framework is presented herein to evaluate the impact and propose the best dimensions of ventilation openings for metal frame modular construction in Brazil, using building information modeling. The ventilation openings were constructed and their dimensions evaluated in eight Brazilian cities, based on the bioclimatic zone (BioZ) classification indicated in ABNT NBR 15220: Curitiba (1st BioZ); Rio Negro (2nd BioZ); São Paulo (3rd BioZ); Brasilia (4th BioZ); Campos (5th BioZ); Paranaibe (6th BioZ); Goiás (7th BioZ); and Rio de Janeiro (8th BioZ). The study results show that the energy consumption of the same building model would vary based on the dimensions of ventilation openings for each BioZ in Brazil. For instance, modeling the same modular construction unit in the city of Rio Negro could consume around 50% of the energy compared to the same unit constructed in the city of Rio de Janeiro, using the small opening sizes based on the smallest dimensions of the ventilation openings. Similarly, modeling the construction unit in Curitiba, São Paulo, Brasilia, Campos, Paranaiba, and Goiás could reduce energy consumption by around 40%, 34%, 36%, 18%, 20%, and 16%, respectively, compared to constructing the same building in the city of Rio de Janeiro, using the small opening sizes based on the smallest dimensions of the ventilation openings. This work could help practitioners and professionals in modular construction projects to design the best dimensions of the ventilation openings based on each BioZ towards increasing energy efficiency and sustainability.

Keywords: modular construction; building information modeling; ventilation openings; energy efficiency

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Citation: Najjar, M.K.; De Araujo, L.O.C.; Oladimeji, O.; Khalas, M.; Figueiredo, K.V.; Boer, D.; Soares, C.A.P.; Haddad, A. Influence of Ventilation Openings on the Energy Efficiency of Metal Frame Modular Constructions in Brazil Using BIM. *Eng* **2023**, *4*, 1635–1654. https://doi.org/10.3390/eng4020093

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1. Introduction

The construction sector requires the use of various equipment and appliances over its lifespan to extract raw materials, and for fabrication, transportation, construction, operations, and demolition [1]. Hence, this sector has high energy demands and is known as

APPENDIX V – SCIENTIFIC ARTICLE ON CONCRETE

Silva, Leandro et al. A Comprehensive Review of Stone Dust in Concrete: Mechanical Behavior, Durability, and Environmental Performance. **Buildings**, v. 4, 2023.

buildings MDPI

Review

A Comprehensive Review of Stone Dust in Concrete: Mechanical Behavior, Durability, and Environmental Performance

Leandro S. Silva [1], **Mayara Amario** [1,*], **Carina M. Stolz** [2], **Karoline V. Figueiredo** [1] **and Assed N. Haddad** [1]

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Abstract: The escalating demand for natural resources within the construction industry is progressing upward. At the same time, however, there is a great concern regarding the depletion of these resources. This review paper emphasizes the significance of utilizing alternative aggregate materials in concrete. Particularly, it aims to explore replacing natural sand with stone dust. On the one hand, the depletion of primary sources of natural sand worldwide, combined with environmental and ecological concerns, drives the adoption of alternative aggregate materials for sustainable concrete construction. On the other hand, stone dust, a waste from the quarrying industry, offers a cost-effective and practical solution for producing concrete. This article presents a comprehensive literature review of the main trends in utilizing stone dust in recycled aggregates in the past decade and its influence on concrete properties. It addresses critical research questions regarding the physical and chemical properties of stone dust aggregates compared to natural sand; the impact of stone dust on the workability, mechanical, physical, and durability properties of recycled concrete; and the potential reduction of environmental impacts in terms of energy consumption and emissions through the replacement of natural sand with stone dust. Ultimately, this paper proposes future investigative work based on identified research gaps.

Keywords: recycled concrete; stone dust; mechanical properties; durability; embodied energy; CO_2 emissions

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1. Introduction

1.1. Overview

On a global scale, the construction industry is a significant consumer of both renewable and nonrenewable natural resources, utilizing approximately 35–40% of all raw materials. Additionally, it consumes 40% of the total energy production and approximately 15% of the world's available water while being responsible for about 35% of the world's CO_2 emissions [1]. Considering the substantial impact of the construction industry on the environment, the sustainable management of natural resources in this sector becomes imperative for a more environmentally conscious future.

Among the main raw materials, sand and gravel are widely used in the construction industry as fine and coarse concrete aggregates, respectively. They represent a significant portion of the concrete's total volume [2], with sand alone accounting for over one-third of the aggregate by volume or mass [3]. The demand for these materials is enormous, with an estimated consumption of 3.2 billion to 5.0 billion tons of sand annually for various applications such as concrete, glass, ceramics, mortar, and road construction [3,4]. By the year 2100, the amount of sand used is projected to reach 25 billion tons annually,

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