



Kaunas University of Technology
Faculty of Civil Engineering and Architecture

Applying Life Cycle Assessment to Evaluate the Sustainability of Infrastructure Projects

Master's Final Degree Project

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Kaunas, 2026



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Master's Final Degree Project
Sustainable and Energy Efficient Buildings (6211EX006)

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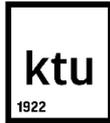
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Summary

The construction and infrastructure sector has a significant environmental impact due to high resource consumption and greenhouse gas emissions. This Master's thesis explores how Life Cycle Analysis (LCA), Circular Economy (CE) principles, and Digital Twin (DT) technologies can be combined to improve the sustainability of infrastructure projects. The aim of the study is to evaluate how digital and circular approaches can reduce environmental impacts throughout the infrastructure life cycle. The research is based on a literature review and a quantitative case study of the A5 highway overpass near Kaunas. The case study uses BIM-based data, and *One Click LCA* software to assess different design scenarios in accordance with ISO 14040/44 and EN 15804 standards. Several scenarios are analysed, ranging from a baseline design with conventional materials to more sustainable alternatives incorporating low-carbon materials, improved transport logistics, and circular design strategies. The results show that material production stages are the main source of carbon emissions. Replacing conventional concrete and steel with low-carbon and recycled alternatives achieved the greatest reduction in Global Warming Potential, while transport optimization provided smaller but additional benefits. The fully circular design scenario resulted in the highest overall emission reduction. The study also highlights the role of Digital Twin technologies in supporting circular infrastructure through real-time data monitoring and predictive maintenance. Although challenges remain, the integration of LCA, CE, and DT offers a practical pathway toward low-carbon and resource-efficient infrastructure development.

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Santrauka

Statybos ir infrastruktūros sektorius daro didelį poveikį aplinkai dėl intensyvaus išteklių suvartojimo ir šiltnamio efektą sukeliančių dujų (ŠESD) emisijų. Šiame magistro darbe nagrinėjama, kaip gyvavimo ciklo analizė (LCA), žiedinės ekonomikos (ŽE) principai ir skaitmeninio dvynio (SD) technologijos gali būti derinamos siekiant pagerinti infrastruktūros projektų tvarumą. Tyrimo tikslas - įvertinti, kaip skaitmeniniai ir su žiedine ekonomika susiję sprendimai gali sumažinti poveikį aplinkai viso infrastruktūros projekto gyvavimo ciklo metu. Tyrimas grindžiamas literatūros apžvalga ir kiekybiniu atvejo tyrimu: A5 magistralinio kelio viaduko netoli Kauno projektu. Atvejo tyrime naudojami BIM pagrindu sukurti duomenys ir „One Click LCA“ programinė įranga, vertinant skirtingus projektavimo scenarijus pagal ISO 14040/44 ir EN 15804 standartus. Analizuojami keli scenarijai: nuo bazinio dizaino su įprastinėmis medžiagomis iki tvaresnių alternatyvų, taikančių mažesnę anglies pėdsaką turinčias medžiagas, optimizuotą transporto logistiką ir žiedinio projektavimo strategijas. Rezultatai rodo, kad didžiausias anglies dioksido emisijų šaltinis yra medžiagų gamybos etapai. Įprastinio betono ir plieno keitimas mažo anglies pėdsako bei perdirbtomis alternatyvomis lėmė didžiausią visuotinio atšilimo potencialo (VAP) (angl. k. GWP – Global Warming Potential) sumažėjimą, o transporto optimizavimas suteikė nedidelę papildomą naudą. Visiškai žiedinio projektavimo scenarijus užtikrino didžiausią bendrą emisijų sumažinimą. Tyrime taip pat pabrėžiamas skaitmeninio dvynio technologijų vaidmuo, palaikant žiedinę infrastruktūrą per realaus laiko duomenų stebėseną ir prognozuojamąją priežiūrą. Nors išlieka tam tikrų iššūkių, LCA, ŽE ir SD integracija siūlo praktišką kelią link mažo anglies pėdsako ir išteklius taupančios infrastruktūros plėtros.

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List of abbreviations and terms

Abbreviations:

CE – Circular Economy

DT – Digital Twin(s)

LCA – Life Cycle Analysis

Prof. – professor.

Introduction

The construction and infrastructure sectors account for 50% of total raw material use and nearly 39% of global CO₂ emissions [1]. As the industry faces increasing sustainability challenges, the transition from a linear to a circular economy (CE) model becomes critical to reducing waste, conserving resources, and extending the lifespan of infrastructure. However, the industry's complex, long-lived projects and lack of practical experience in circularity limit the adoption of CE principles, particularly concerning the physical quality and resilience of reused or recovered materials [1].

The importance of Life Cycle Analysis (LCA) is growing as a tool for assessing the environmental impacts of construction materials and practices across their entire life cycle. LCA offers a holistic view of sustainability, taking into account economic, social, and environmental aspects from material extraction to disposal. Recent advancements, such as the integration of Building Information Modelling (BIM) with LCA tools like BIMToSimaPro, improve the accuracy and efficiency of assessing building materials' environmental impacts and help make informed decisions regarding material reuse and waste reduction [2]. The use of LCA in prefabricated buildings and other construction projects is key to promoting circularity by enabling the tracking of embodied carbon and identifying opportunities for material recovery and reuse [3].

The primary objective of this research is to demonstrate how the integration of BIM and LCA methodologies can enhance life cycle impact assessments in infrastructure projects, supporting circular economy strategies and improving decision-making for sustainability. The tasks include the following:

1. Conducting a thorough literature review
2. Acquiring data from literature as well as BIM data for the company project
3. Executing LCA analysis in accordance with relevant standards
4. Interpretation and analysis of results as well as drawing conclusions.

This study focuses on the application of LCA in a real-world infrastructure project and investigates how digital tools can support the evaluation of different design and material scenarios. A case study approach is employed to assess the environmental performance of a transport infrastructure asset using BIM-based data and *One Click LCA* software, in accordance with internationally recognized standards. By comparing conventional design solutions with alternative scenarios incorporating circular economy principles, the research illustrates the potential of digital life cycle assessment to identify environmental hotspots and support low-carbon decision-making.

Furthermore, the study explores the emerging role of digital twins as an extension of BIM–LCA integration, highlighting their potential to enable continuous monitoring, data-driven optimization, and long-term sustainability management of infrastructure assets. By addressing current limitations in data integration and practical implementation, this research aims to contribute to both academic knowledge and professional practice. The findings provide insights into how the combined use of LCA, circular economy strategies, and digital technologies can support the transition toward more sustainable, resource-efficient, and resilient infrastructure development.

1. Literature Overview

This chapter provides a literature review on circular economy principles in infrastructure projects and the role of digital twins in applying these principles to circular economy practices.

1.1. Circular Economy

Currently, there are over a hundred definitions of the Circular Economy, reflecting the diverse interpretations of its principles and applications among stakeholders and governments worldwide. Despite this variation, a common objective unites them: to increase resource efficiency while promoting economic growth without exhausting natural resources. This widely accepted definition, originally proposed by the Ellen MacArthur Foundation (EMF), is frequently cited in the literature [1].

Frequent misconceptions state that CE is an advanced recycling strategy, and consequently this notion has become a significant obstacle for the shift from linear to circular concepts. Policies to help clarify these misconceptions, proposing more accurate circularity indicators that focus on the design stage and initial factors to be addressed in of end-of-life stage would facilitate an integrated and seamless transformation [4].

When discussing circular economy principles, it is important to understand what circular economy processes look like within the construction industry. In literature, achieving circular economy is also defined as „closing the loop“ which indicates that circularity can be achieved by redesigning the life cycle of buildings. Figure 1 illustrates how International Organization for Standardization (ISO) defines the life cycle stages within construction sector [5].

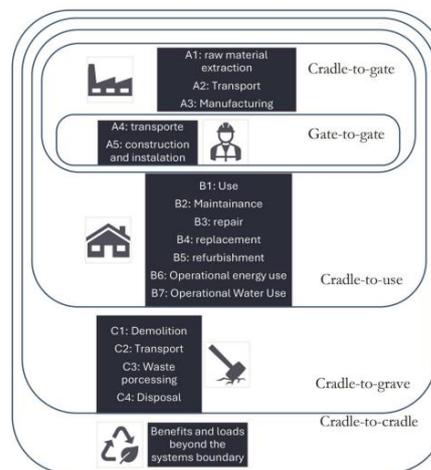


Fig. 1. Life Cycle Stages based on ISO standards [5]

Stages A1, A2, A3 are known as the „Product stage“ and includes raw material extraction, transport and manufacturing, followed by A4-A5 „Construction process stage“ involving transport to site, construction and installation process. Stages B1 through B7, defined as the „Use stage“, encompasses use, maintenance, repair, refurbishment and replacement of buildings, as well as operational energy and water use. Stages C1-C4 are the „End-of-life stage“ including deconstruction, demolition, transport to waste management facilities, waste processing and disposal. Stage D closes the circular loop and is known as „Supplementary information beyond the life cycle“ and includes benefits and financial returns beyond the building’s life cycle that can be achieved through reuse, recovery and recycling practices [5]. A more detailed graph of LCA Assessment phases is pictured n

figure 2 below. It highlights how material passports and sensors improve traceability, energy efficiency, durability, and maintenance during use, while enabling reuse, selective dismantling, and closed-loop material cycles at end of life.

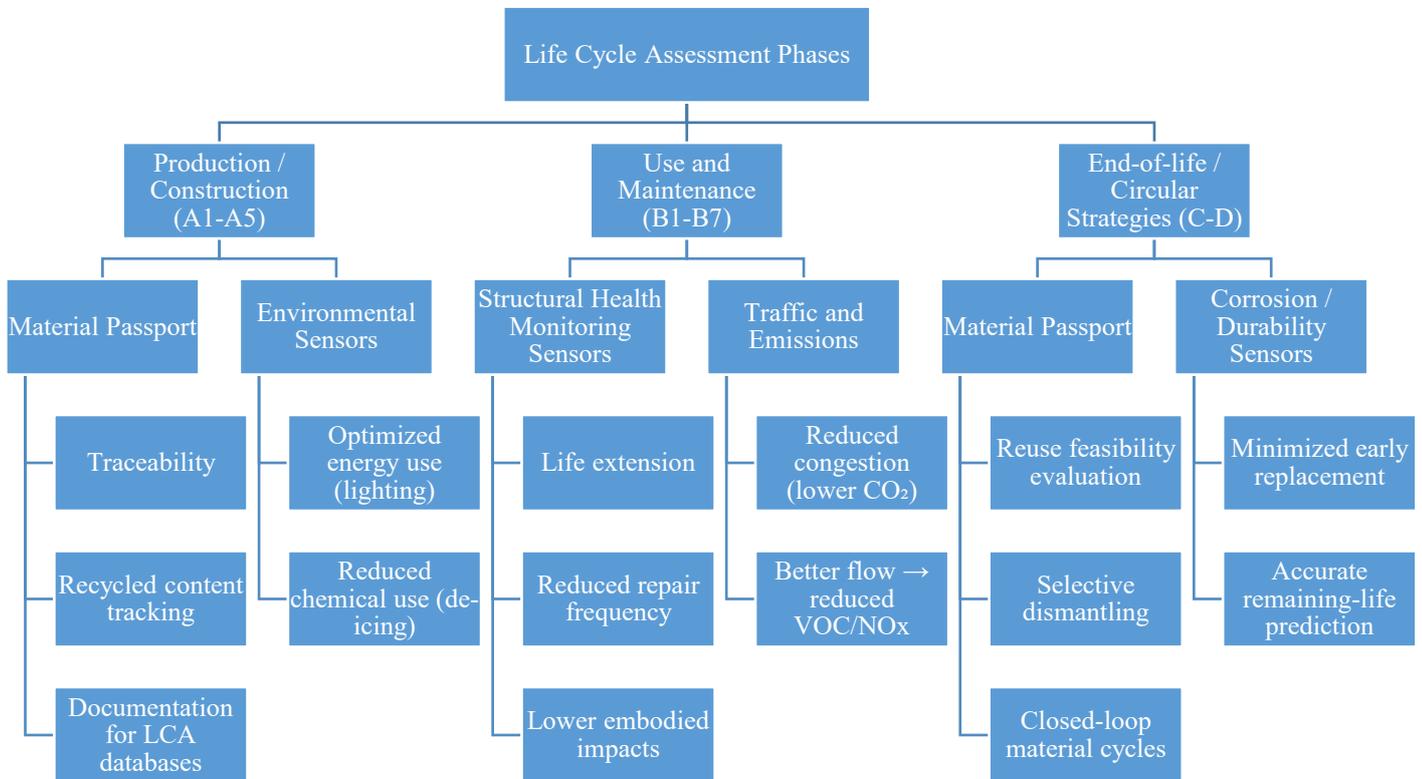


Fig. 2. Life Cycle Assessment Phases and Impact Improvements [created by author]

1.2. Resource and Waste Management

Demographic forecasts suggest that the global urban population is expected to approach 4.3 billion in the near term, reflecting a significant trend toward urbanization, as well as increasing the generation of municipal solid waste up to 1.42 kg/capita/day, equivalent to 2.2 billion tons yearly. Urbanization is projected to increase not only solid waste volumes but also complicate the management of other urban waste streams, with implications across all environmental domains. The numbers mentioned above underscore a significant issue, given the growing complexity associated with achieving efficient and sustainable waste management systems [6].

Increasing resource effectiveness and reducing waste throughout the life can be achieved through numerous practices, including modular or prefabricated construction, choosing sustainable materials, and using digital technologies to support circularity [7][8][9]. The construction industry is the sector that consumes the most resources and raw materials for its processes. The industry is also responsible for 40 % of waste generated worldwide as well as for using 3,000 million tonnes of natural resources annually [10]. Waste materials have had an increased popularity as substitutes or additives for certain construction materials. For sustainable development, it is essential that the generated tunnel spoil, as well as other manufacturing by-products and waste material, are not regarded as waste, but as a recyclable material with potential benefits to social, economic, and environmental sustainability [9]. In a study carried out in Ghana, mine rock waste is repurposed as a material for road pavement. Samples collected from three gold mining waste disposal sites are subjected to laboratory analysis to

assess their physical, mechanical, geotechnical, geometrical, and durability characteristics. After the research, if all legal requirements regarding mine rock waste are met, the waste materials can be legally and efficiently used in construction [11]. This means that waste generated can be incorporated into manufacturing processes and reduce the load of landfills. In other cases, waste marble fines are used as an aggregate to improve the soil conditions on project sites, making the soil more workable by reducing its plasticity, improving the soil's strength and reducing its permeability [12]. In another study, a cement gravel column is utilized as a part of the testing procedure to explore the viability of integrating stone dust, a waste product, into cement structures [14]. This allows for reducing waste generation and contributing to circularity practices. One of the byproducts of geothermal energy production is silica grout, which is extracted from geothermal fluids. This innovative material advances the field of soil stabilization and aligns with overarching efforts to mitigate the construction industry's carbon emissions, contributing to international sustainability goals and promoting the shift toward environmentally responsible construction methods [8]. A study in Thailand assesses the feasibility of repurposing dam sediments, chemically stabilized with eucalyptus wood ash (EA) and cement, as a sustainable alternative for road construction materials, contributing to resource efficiency and environmental conservation by increasing waste utilization in infrastructure development. The innovation of this approach is rooted in improving eucalyptus ash, a biomass-derived waste material, as a stabilizing agent, offering an economically efficient and environmentally sustainable alternative to conventional stabilization methods [13]. Biochar is a stable, carbon-rich byproduct of biomass pyrolysis (a thermochemical process conducted in limited oxygen conditions) and has gained attention for addressing environmental and agricultural issues, due to its highly porous architecture and extensive surface area. It can help enhance plant growth and minimize nutrient leaching, and consequently improve the quality of soil water. The research underlines that source-specific biochar products can effectively immobilize the contaminants in the soil which can be applicable on construction sites, as well as with further advancements biochar may help in agricultural environmental protection [15]. Stone dust is a voluminous solid waste generated as a by-product of stone aggregate processing and is typically disposed of in landfills. Emerging research indicates that its incorporation as a fine aggregate in concrete mixtures not only reduces environmental burdens but also enhances material circularity in the built environment [14].

Material Passports (MPs) play a crucial role in promoting circular economy principles and improving resource efficiency within the construction industry, which is known for its significant environmental impact. By providing detailed documentation and traceability of materials across a building's life cycle, MPs support informed strategies for reuse, recycling, and minimizing waste, ultimately reducing the sector's ecological footprint [7]. Based on literature research, there are numerous ways to increase resource effectiveness and reduce construction waste, however, notably, most of the studies identify including a waste product into the manufacturing process as a material substitute to be the best practice.

1.3. Prefabrication and Modularity of Buildings

Modularity and prefabrication are conceptually aligned, as both approaches emphasize the standardization and off-site fabrication of building components to enhance construction efficiency and adaptability. There is a connection between these two concepts, and the circular economy framework [16]. An example of prefabricated buildings as a solution to advance towards circular economy is illustrated in Figure 3. It shows that to close the loop, the deconstruction stage of the buildings should be immediately followed by a new (or continued) life cycle, meaning the materials and components left after the deconstruction should be used as raw materials or recycled to be reused [16]. The difference between conventional buildings and prefabricated ones is that, in the case of

prefabrication, there is an extra stage in the life cycle for off-site fabrication followed by transportation from the manufacturing plant to the construction site [16].

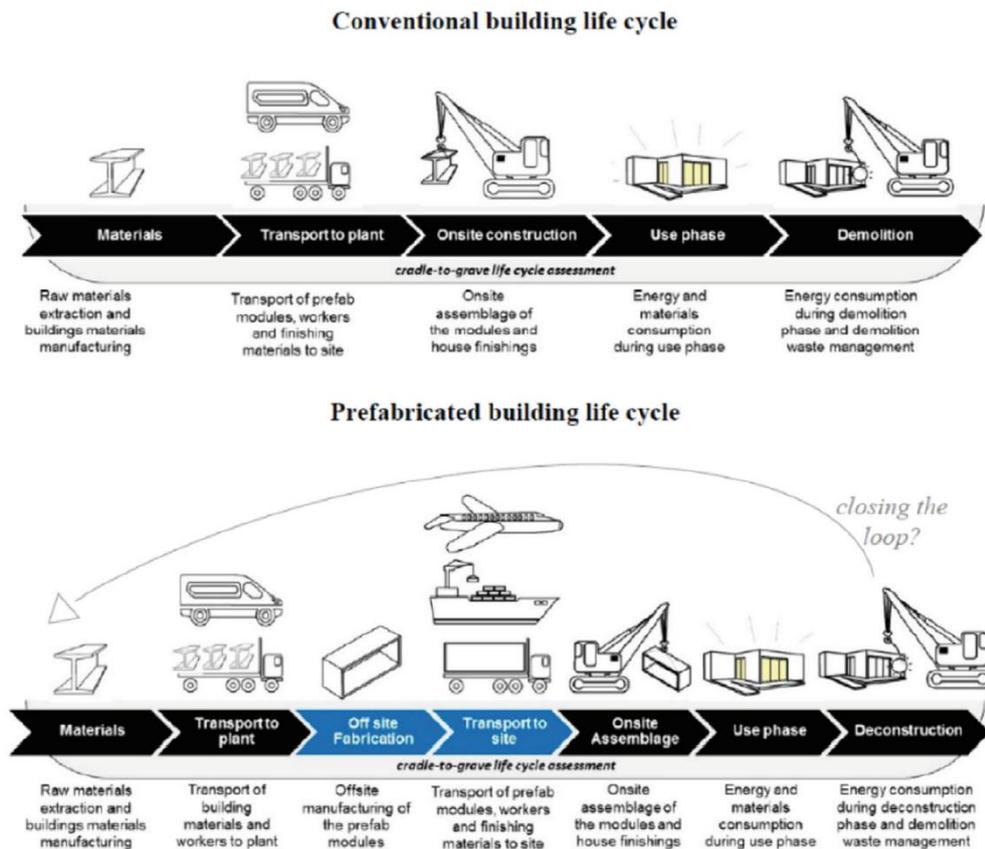


Fig. 3. Life Cycle of a conventional building and of a prefabricated building [21]

While most popular construction materials for modular or prefabricated buildings are steel and wood, followed by concrete, recently the increased use of recycled plastic has been noted in both literature and practice. Moreover, more nature-based solutions like vertical greening systems (VGS), vegetated surfaces in the building envelope that may or may not be attached to the façade, have been introduced to facilitate circular economy principles by enhancing material reutilization and maintaining associated functional performance [16]. Although a substantial amount of research is focused on assessing the impact of theoretical foundations and practical approaches of circularity on various aspects within the built environment, there is a significant research gap, especially on building components and systems (BC&S). This approach aims to determine the impact of each building system on circularity, emphasizing those with the highest relevance [10]. Integrating design strategies like modularity and accessible infrastructure enhances building maintenance, streamlining repairs and upgrades, and thereby increasing the longevity of both the structure and its components [10]. Prefabricated buildings (PB) demonstrate significant potential to facilitate the low-carbon transition within the construction sector [17]. Key advantages of prefabrication include reductions in environmental impact, cost, material consumption, waste generation, and construction time, alongside improvements in quality. However, challenges persist in cultural acceptance, technical implementation, and market readiness, often requiring substantial initial investments [16]. It is important to examine the unique features of component assemblies that form each system at a detailed level since at the component assembly level, a detailed understanding of individual system characteristics is essential [10]. Accurately accounting for carbon emission sources and their temporal patterns during PB project delivery is paramount, requiring the establishment of effective assessment and monitoring platforms. The integration of carbon emission data within BIM frameworks is key to

facilitating robust carbon footprint calculations and supporting environmental performance assessments [17].

1.4. Material Recovery and Reuse

In order to achieve a circular economy, it is essential for construction companies to recover as many materials and building parts as possible to further reuse them and move from a linear economy model towards circularity. Several examples of deconstruction and material recovery are presented further. The global decommissioning of wind turbines introduces complex waste management issues, particularly regarding composite blade materials. The study applies life cycle analysis (LCA) to compare the environmental outcomes of four major disposal strategies: landfilling, mechanical recycling, pyrolysis, and solvolysis, all in the context of Australia's move toward sustainable energy systems. The LCA-based evaluation explains the influence of the energy transition on the environmental effectiveness of various disposal techniques, providing critical insights for the advancement of sustainable waste management approaches [18].

When it comes to the reuse of materials from older or unusable buildings, an audit of the “donor” building is required, with the construction date to be specified in the accompanying records. The issue of steel product reuse and recycling has garnered increasing scholarly focus. In developed countries, steel recycling rates reach approximately 93–95%; however, reuse accounts for a significantly smaller proportion, limited to 4–5%, primarily through prolonging the service life of structural components. The issue with reusing metal building products is ensuring their material properties through testing and verification, and research in this area is rather limited [3]. Among prefabricated construction materials, steel displays higher embodied environmental impacts but is highly recyclable and reusable. Timber contributes biogenic carbon storage and provides significant reuse opportunities while concrete presents challenges related to transport and assembly. The discussion also encompasses the renovation of prefabricated buildings and the incorporation of prefabricated components into renovation projects [16].

1.5. Designing for Longevity

Traditionally understood as a specified waste management framework, the Circular Economy has been reframed as a tool for comprehensive economic development. Municipalities can make use of the ability to stimulate innovation, support job creation, and improve the adaptability of regions by integrating the Circular Economy principles and practices into local policies. This outlook goes hand in hand with the existing school of thought that underscores the transformative potential of the CE while also carrying on the conversation by demonstrating how integrated, cross-sectoral approaches can secure stakeholder engagement [19]. The findings of the case study suggest that successful implementation of CE strategies depends on prioritizing those with high circularity potential, minimal cost, and low technical complexity. Furthermore, opportunities exist to strengthen market interest and drive technological innovation. The integration of CE principles into architectural and construction practices contributes to a more sustainable, resilient, and health-conscious built environment [1].

Additionally, the adoption of circular economy principles across all stages of the building life cycle and infrastructure projects remains a critical challenge within the industry due to limited hands-on experience and practical knowledge. Shifting towards a circular economy framework requires organizations to develop targeted skills and deepen their knowledge base. The cross-disciplinary integration, and long and intricate life cycles in infrastructure projects, as opposed to products with shorter life cycles, restrict the practical applicability of circularity principles. This complexity contributes to delays in adopting circular economy practices. Moreover, industry professionals

experience difficulties in verifying the quality of reused, recycled, or refurbished materials throughout design and construction processes, resulting in uncertainty over their long-term performance and limiting their integration [1]. The occurrence of recent severe seismic hazards highlights the imperative need for upgrading existing structures built before the enforcement of modern seismic design standards. In response, a comprehensive life-cycle sustainability assessment framework has been proposed for evaluating multiple seismic retrofit alternatives for reinforced concrete (RC) frame structures in earthquake-sensitive regions. The framework integrates environmental, economic, and social criteria with seismic resilience and functionality to guide the selection of the most suitable retrofit approach [20]. The application of greening systems, particularly green roofs and green walls, is increasingly recognized as essential for advancing urban sustainability and energy efficiency. These nature-based solutions play a significant role in enhancing thermal performance and reducing energy consumption in buildings. The complexity of enhancing thermal efficiency through greening systems arises from their diverse designs and the variability inherent in their physical and thermal characteristics [21].

Designing for longevity through circular economy principles requires integrated, life-cycle-based approaches that balance sustainability, resilience, and innovation, while overcoming practical, technical, and knowledge-related barriers in complex building and infrastructure projects.

1.6. The role of Digital Twins in Circular Economy

The shift from a linear to a circular economy model requires innovative systems and solutions to optimize resource management, waste management, maintenance and repairs of buildings and infrastructure. The Fourth Industrial Revolution (also referred to as Industry 4.0), defined by the integration of advanced digital technologies and intelligent systems, offers a transformative opportunity to advance sustainable business practices. Leveraging Industry 4.0 technologies (artificial intelligence, the Industrial IoT, blockchain, digital twins, big data analytics, advanced robotics, additive manufacturing) can facilitate the development of industrial systems that align with environmental stewardship, social equity, and economic resilience [22].

In pursuit of the European Union’s climate neutrality target for 2050, the European Commission has prioritized the “twin transitions,” which refer to two closely linked but separate concepts: Digital Twins and Green Twins. The twin transition, encompassing both digital and green transformations and their integration, is increasingly acknowledged as a critical pathway toward a sustainable and resilient future. These interconnected transitions seek to decarbonize the economy through the deployment of advanced digital technologies. [23]. Figure 4 shows the overlap between digital and green transition based on related policies and while both transitions are crucial, this section goes more in depth on Digital Twin transformations within the built environment.



Fig. 4. A policy-oriented agenda for twin transition [23]

Despite growing policy initiatives aimed at advancing the twin transitions agenda and achieving a net-zero society by 2050, companies and governmental organizations continue to encounter significant challenges. These encompass challenges such as the capital-intensive nature of digital infrastructure upgrades, gaps in expertise and training, and regulatory ambiguity. Furthermore, reconciling the rapid pace of technological innovation with the slower adoption of sustainable practices, as well as managing data privacy concerns and system interoperability, hinder effective convergence of digital and sustainability initiatives. There is a clear lack of a well-defined sequence of action to help move towards the twin transition. These deficiencies emphasize the interdependence of effective twin transition implementation and the necessity for comprehensive future studies [23].

1.7. Data Integration and Real-Time Monitoring

Amid rapid urban growth, intensifying resource depletion, and ecological decline, there is a critical imperative for innovative urban development strategies. To address these challenges, sustainable smart cities are increasingly implementing state-of-the-art technologies such as Generative Artificial Intelligence (GenAI), Foundation Models (FMs), and Urban Digital Twin (UDT) frameworks, thereby transforming conventional urban planning and design processes [24]. By integrating vast datasets and advanced algorithms, these technologies facilitate predictive insights and dynamic urban system management, advancing sustainability goals. [24].



Fig. 5. Sustainable Development Goals 11, 12 and 13 [1,2]

In pursuit of Sustainable Development Goals 11 (Sustainable Cities and Communities), 12, 13 (Fig. 4), cities are increasingly prioritizing efficient waste management as a central strategy for environmental and social resilience. Proper waste collection, sorting, and recycling not only mitigate ecological harm but also serve as foundational actions in reducing greenhouse gas emissions [25]. Within this context, Material Passports (MPs) are emerging as valuable tools for enhancing material circularity in the construction and demolition sectors. Yet, existing limitations, such as fragmented data systems and insufficient real-time monitoring, impede their widespread effectiveness. Integrating advanced technologies like Artificial Intelligence (AI) can address these shortcomings by automating data flows, supporting real-time updates, and enabling platform interoperability, thereby unlocking the full potential of MPs to contribute meaningfully to circular and climate-conscious urban systems [7]. Given the escalating severity of environmental challenges, including the growing volume of waste and its contribution to climate change, there is a critical need for innovative and scalable

solutions applicable across diverse urban and regional contexts. The integration of artificial intelligence in waste management offers a pathway to modernizing existing infrastructure while supporting sustainable urban development through enhanced operational efficiency and reduced environmental impacts [25]. Search engines (e.g., Google) and social media platforms (e.g., X, Meta) offer promising avenues for mitigating the data availability gap, particularly within the urban context. The integration of digital software, simulation models, and big data represents a pivotal advancement in urban analytics, addressing the limitations that have historically impeded the accuracy and applicability of digital models. Crucially, big data is defined not merely by its volume but by its continuous evolution, driven by real-time, multifaceted data streams and the rapid development of data-processing technologies. As stated, “Big data is more than just a massive collection of information; it is a dynamic entity in constant flux, shaped by the relentless generation and flow of data from diverse sources in real-time” [2]. AI has been increasingly explored as a means to optimize municipal waste management processes and contribute to the attainment of globally and locally defined environmental goals. Recent studies highlight the potential of AI to enhance operational efficiency, inform decision-making, and support sustainability, especially by outlining frameworks tailored for implementation in waste systems within developing regions [25]. Scholarly discourse on AI-driven waste management highlights the synergistic potential of integrating Internet of Things (IoT) technologies. The deployment of IoT-enabled sensors, in conjunction with AI algorithms, supports dynamic real-time tracking of waste levels, thereby optimizing collection routes and improving system efficiency [25]. Findings of a study carried out in Yogyakarta, Indonesia underscore that the integration of advanced technological solutions with community-based initiatives demonstrate measurable improvements in the efficiency of waste management systems. Moreover, targeted educational programs and culturally sensitive communication strategies tailored to local practices enhance public participation and foster more sustainable waste management behaviours. These outcomes reinforce the critical role of sustained learning and adaptive management in enabling urban planning frameworks to address emerging and evolving urban issues in a dynamic manner. The integration of technological advancements with active citizen participation is deemed fundamental to the long-term viability and effectiveness of smart city strategies [26]. Although existing building energy simulation models incorporate reactive, predictive, and preventative maintenance strategies, there is a growing need for these models to evolve by integrating emerging energy assets required to support energy-neutral and climate-resilient building designs [27].

1.8. Prognosis and Preventive Care for Longevity

Artificial intelligence is instrumental in optimizing operational performance across systems and processes while advancing environmental sustainability by reducing landfill disposal, increasing recycling rates, and lowering greenhouse gas emissions. Consequently, the integration of AI into waste management can be contributory to achieving sustainable development objectives [25]. Within urban infrastructure, sewer pipelines are fundamental to safeguarding environmental integrity and ensuring system resilience. Failures in these systems may lead to substantial ecological degradation and increased asset management expenditures, therefore, predictive analytics and pre-emptive intervention strategies are crucial. However, existing literature reveals that the development of digital lifespan prediction models is still emerging, with most of the research concentrating on concrete and PVC sewer pipes. Improving these advanced technologies is critical for strengthening hazard detection capabilities and optimizing urban infrastructure resource allocation [28].

A major challenge in sustainability modelling is the limited availability of data, which affects the accuracy of system dynamics (SD) models. Amid the accelerating digital transformation and the proliferation of big data, Sustainable Development models are experiencing a paradigm shift [6].

Urban areas have become complex data-driven ecosystems, with real-time data emerging from myriad of sources such as social networks and interconnected IoT infrastructure. In recent years, the proliferation of infrastructure data from diverse sources has provided an increasingly detailed representation of urban life. Urban infrastructure such as streetlights and weather stations, equipped with embedded sensors, continuously generate high-frequency data at a scale of billions of points per second, offering real-time insights into traffic dynamics, environmental conditions, and public space usage. This complex and heterogeneous and evolving data landscape offers significant potential to improve urban planning, streamline resource management, enhance public services, and boost the overall quality of life in cities [6].

Structural resilience is another critical factor in infrastructure longevity. During their operational lifespan, bridges are exposed to a range of loading conditions such as service loads, seismic activity, and environmental forces that can potentially undermine their structural integrity. As these structures are high-value, critical and expensive assets, there is an emphasis on using increasingly innovative structural health monitoring (SHM) techniques to guarantee their safety and longevity [7]. The effective integration and optimization of new energy technologies, such as solar PV panels and energy storage batteries, are critical for advancing financial sustainability and operational resilience. These assets demand careful planning to safeguard building energy systems from unfavourable climatic events and grid instabilities. Therefore, contemporary energy optimization frameworks prioritize both optimal investment allocation and resilience enhancement to ensure system reliability [27].

1.9. Life Cycle Analysis and Optimization using Digital Twins

Life Cycle Assessment (LCA) is established as a critical methodology for assessing the environmental consequences of products and systems across all stages of their life cycle, from initial raw material acquisition to production, operation, and end-of-life management [31]. Recent advancements emphasize the integration of LCA with automated data processing tools and AI, particularly ensemble learning models, with the goal to enhance the accuracy and sustainability of decision-making in infrastructure and manufacturing contexts [30]. For example, Vlasenko et al. [30] demonstrate a machine learning–assisted framework capable of predicting the reuse potential of steel structures in the final phase of a building’s life cycle (Stage D), showing that data-driven decision support tools can reduce uncertainty and enable more effective circular practices. Such innovations highlight the shift toward dynamic and responsive life cycle modelling, where reuse, recovery, and material substitution are not just theoretical options but operationally feasible with high predictive confidence [30, 31].

An integrative framework has been introduced to align sustainability models with product life cycle assessment (PLCA), underscoring the critical need for a multidimensional approach that includes economic, social, and environmental considerations. It provides guidance on optimal sustainable practices throughout the entire product life cycle, from resource extraction to final disposal. Associated studies examine fundamental questions concerning the deployment of sustainable strategies, focusing on social and financial viability and potential barriers to implementation, thereby facilitating business development that is economically robust, environmentally responsible, and socially equitable across the product life cycle [26]. One notable progression in LCA methodologies is the introduction of BIMToSimaPro, a software tool engineered to automate the integration of Building Information Modelling (BIM) data into LCA processes. Its practical applicability is demonstrated by a case study on a prefabricated building in Hong Kong, wherein results are compared with those obtained via traditional LCA techniques. This innovative tool can help improve the accuracy of LCA in the lifetime of buildings [2]. An important development within LCA is the

emergence of digital tools that enable construction sector professionals to make strategic, evidence-based decisions concerning the reuse of building materials. The accuracy of the integrated model and its compatibility with existing tools and methodologies demonstrate substantial improvements in the management of material reuse, such as steel, particularly during the building's end-of-life phase (life cycle stage D) [3]. The complete waste life cycle, including generation, collection, transportation, treatment, and disposal, can be understood as an interconnected system driven by feedback mechanisms at each step [6]. Beyond material reuse, urban energy consumption presents a major sustainability challenge, as cities constitute roughly 75% of the total global primary energy consumption. The increasing energy demand of urban environments poses sustainability concerns, necessitating more efficient management strategies to mitigate carbon footprint. Achieving sustainability requires addressing multifaceted challenges in energy management, particularly through the optimization of efficiency and the control of pollution. Digital modelling serves as a strategic approach to address these complexities [6].

In parallel, the concept of digital twins (the virtual representations of physical systems updated in real time) offers transformative potential in life cycle optimization [31]. By integrating real-world data from sensors, automated systems, and environmental monitoring platforms, digital twins can continuously inform and adjust sustainability models over the course of a building's or infrastructure asset's use phase [29]. Petersen et al. [29] illustrated how automation and system-level data integration in agricultural settings supported continuous optimization of resource use and performance outputs, an approach that is increasingly transferable to construction and urban infrastructure applications. Moreover, a recent study proposed a framework for holistic sustainability assessment that merges environmental, economic, and social indicators, arguing that dynamic life cycle feedback systems, such as those enabled by digital twins, are essential for achieving regional circular economy goals. Together, these developments demonstrate that integrating LCA with digital twin systems not only enables real-time environmental impact tracking but also supports proactive, system-wide sustainability optimization [29, 30, 31].

The literature review critically examines the application of circular economy (CE) principles within infrastructure projects, with particular emphasis on the enabling role of digital twin technologies. Key areas include resource and waste management, modular and prefabricated construction, material recovery and reuse, and design strategies aimed at extending building lifespans. The review synthesizes a wide array of studies demonstrating innovative uses of secondary materials, such as mine waste, biochar, and stone dust in construction practices. Furthermore, it underscores the growing relevance of tools such as Material Passports and Building Information Modelling (BIM) in supporting material traceability and enhancing life cycle performance. Digital twins are presented as a pivotal advancement, offering real-time data integration and system-level insights that can facilitate dynamic sustainability optimization across the built environment.

1.10. Literature Overview Conclusions

Despite the growing academic interest, the review identifies a clear research gap: there is limited practical implementation of digital twins in life cycle assessment (LCA) and circular economy strategies within infrastructure projects. While theoretical models and conceptual frameworks are well-established, real-world integration remains underdeveloped. To address this, the planned research will explore how digital twins can be practically applied to enhance LCA and support circular decision-making in infrastructure development. This study aims to provide insights for linking digital innovation with sustainability goals, contributing to the advancement of the twin transition in the built environment.

The reviewed literature highlights that the transition from linear to circular models in infrastructure projects is both urgent and complex. While CE principles are widely acknowledged as essential for reducing resource consumption, minimizing waste, and extending the life of infrastructure assets, their practical implementation remains inconsistent and fragmented. Common strategies like the use of secondary raw materials, modular and prefabricated construction, and material recovery and reuse demonstrate clear environmental and economic benefits, yet challenges persist in ensuring quality assurance, scalability, and market acceptance.

Digital twin technologies emerge as a critical enabler of CE practices, offering real-time monitoring, predictive modelling, and life cycle optimization. When integrated with LCA, BIM and Material Passports, digital twins provide a dynamic framework for tracking material flows, enhancing transparency, and supporting evidence-based decision-making. These tools can bridge existing knowledge and practice gaps, fostering greater adoption of circular practices in the construction sector.

Nevertheless, the literature points to unresolved issues, including high upfront costs, regulatory ambiguities, and technical barriers that limit broader application of both CE principles and digital twins. There is also a lack of comprehensive frameworks to guide the “twin transition” of digitalization and sustainability, particularly in infrastructure projects with long and complex life cycles.

Overall, the integration of CE and digital twin approaches holds significant promise for advancing sustainable infrastructure. By combining resource efficiency with digital intelligence, future projects can move toward truly circular models that not only reduce environmental burdens but also enhance resilience, adaptability, and long-term economic value.

2. Methodology

This study adopts a qualitative-quantitative hybrid research design to explore the integration of Life Cycle Analysis (LCA), Circular Economy (CE) principles, and Digital Twin (DT) technologies in infrastructure projects. The goal of the research is to investigate how digital tools like *One Click LCA* can quantify environmental impacts and how these insights can support circular decision-making throughout the life cycle of infrastructure assets. A case study approach is employed to ground the research in real-world scenarios, enabling an in-depth assessment of selected infrastructure projects modelled with digital twin environments and subjected to LCA via *One Click LCA* software. The research also includes a theoretical component, reviewing academic literature and policy frameworks to contextualize the findings and identify synergies between CE and DT through LCA.

2.1. Research Design

The research design of this study is structured to explore the intersection of Life Cycle Analysis (LCA), Circular Economy (CE), and Digital Twin (DT) technologies in infrastructure projects. The study employs a mixed-methods design. The goal is to assess how digital modelling and circular design strategies can optimize sustainability outcomes throughout the infrastructure life cycle. The flow chart below outlines each stage of the research process, including literature review, data collection, life cycle assessment, interpretation and integration of findings, and final conclusions.

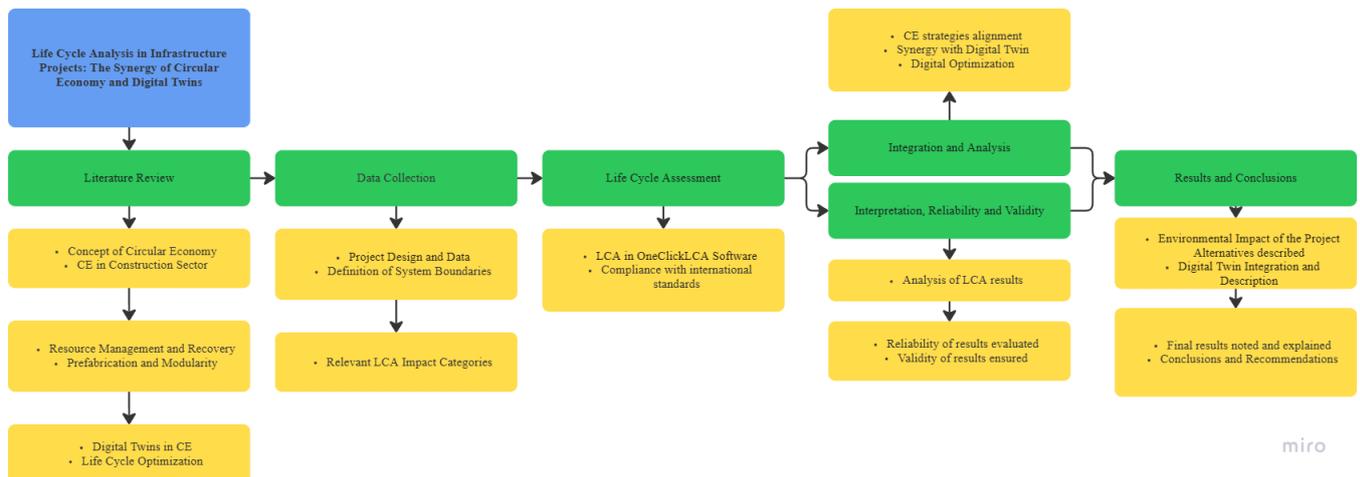


Fig. 6. Research Design Flowchart

2.2. Research Methods

The research design ensures a multi-layered and interdisciplinary approach that bridges theory and practice by integrating LCA modelling, circular economy (CE) strategies, and digital infrastructure tools. By combining qualitative and quantitative methods, the study captures both conceptual frameworks and practical applications. The systematic workflow, grounded in standardized datasets, internationally accepted methodologies, and academic rigor, is designed to ensure transparency, reproducibility, and scientific validity. Overall, the approach aims to generate actionable and transferable insights that support more sustainable and resource-efficient infrastructure development.

2.2.1. Qualitative research

A systematic literature review is conducted to establish the theoretical and contextual foundation of the study. The reviewed literature is used to define and clearly distinguish the key concepts of circular economy (CE), digital twins (DT), and life cycle assessment (LCA). In addition, it helps identify current applications of circular strategies within the construction and infrastructure sector, including resource efficiency, material reuse, prefabrication, and design for disassembly. The review also

examines the role of digital technologies in environmental monitoring, data integration, and the implementation of circularity principles. Furthermore, existing LCA tools are analysed, with particular attention given to their compatibility with digital data sources and their potential integration with digital modelling environments.

2.2.2. Case Study Method

A case study approach is used to ground the research in real-world infrastructure practice. and to demonstrate the practical relevance of the proposed methodology. The selected case involves a transport infrastructure project, specifically a highway overpass, which incorporates elements of digital modelling and sustainability-oriented design considerations.

The case study is provided by one of the largest transport infrastructure engineering companies in Lithuania, Tyrens Lietuva. A visual representation of the case study project is presented in the figure below.



Fig. A5 road overpass project near Kaunas city (source: *Tyrens Lietuva*)

The project consists of a multi-level highway overpass designed to manage high traffic volumes through grade-separated ramps and bridge structures. Key elements include curved entry and exit ramps, reinforced embankments, bridge decks supported by piers, and integrated systems such as lighting, drainage, and safety barriers. The green areas shown in the figure represent landscaped slopes and earthworks, which contribute to structural stability, erosion control, and the reduction of environmental impacts.

2.2.3. Quantitative Research

The core analytical component of the study is a quantitative life cycle assessment (LCA) conducted using One Click LCA software. This method enables a detailed evaluation of the environmental impacts associated with the infrastructure project across its life cycle. The assessment follows

internationally recognized standards, ensuring methodological consistency and credibility, particularly:

- ISO 14040/14044 (LCA principles and framework),
- EN 15804 (Environmental Product Declarations for construction products),
- EN 15978 (assessment of environmental performance of buildings and infrastructure over the life cycle).

The LCA analysis includes several methodological elements and system boundary choices, which are summarized in the table below, along with the specific assumptions and parameters defined for the purposes of this research study.

Table 1. LCA Analysis elements

LCA Analysis Element	Description	Current Study
Functional Unit Definition	Ensures that comparisons between different products or systems are made on a consistent basis.	Consistency is ensured for the entire project; no volumes of materials are changed.
System Boundaries	Based on geographical, temporal, technological scopes (cradle-to-grave or cradle-to-cradle)	Project is based in Lithuania, cradle-to-cradle.
Material Data	Importing material data from BIM or other databases to be used in the software calculations	Accessed from <i>Tyrens Lietuva</i> and <i>One Click LCA</i> software database
Impact Categories	Selecting relevant environmental impact categories (e.g., Global Warming Potential, resource depletion, water use).	Global Warming Potential (GWP) in CO ₂ e
Assessment and Interpretation	Performing impact assessment and interpreting results through hotspot analysis and scenario modelling	Comparison of results based on GWP and the different environmental impact across scenarios.

2.2.4. Integration and Cross-Analysis

To assess the synergy between CE strategies and digital modelling, the study applies integrative methods:

- Scenario Comparison: Assessing environmental impacts under linear vs. circular design strategies.
- Digital Twin Evaluation: Analysing how real-time data, predictive modelling, and asset performance monitoring contribute to sustainability.
- Cross-referencing with Literature: Comparing modelled results with academic and industry benchmarks.

This integrated analysis provides a comprehensive and holistic understanding of how digital technologies and circular economy practices co-evolve to enhance sustainability in infrastructure projects. By combining theoretical frameworks with practical applications, the study captures the dynamic interactions between technological innovations, resource efficiency strategies, and environmental performance outcomes, offering insights that are both actionable and academically robust.

2.3. Reliability and Validity Assessment

Ensuring the reliability and validity of research findings is a critical aspect of this study, particularly because it employs hybrid digital-analytical tools and spans multiple interdisciplinary domains, including life cycle assessment (LCA), circular economy (CE), and digital twin (DT) technologies.

Given the complexity of integrating these approaches, rigorous methodological safeguards are implemented to maintain consistency, repeatability, and accuracy of results.

To achieve this, the study incorporates several measures. These include careful selection and verification of data sources, adherence to internationally recognized standards for LCA and digital modelling, systematic documentation of assumptions and procedures, and cross-validation of results with existing literature and comparable case studies. Additionally, the use of standardized software tools, combined with expert consultation from engineers and sustainability specialists, further strengthens the credibility of the findings and ensures that the research outcomes are both robust and reproducible.

Table 2. Reliability and Validity Assessment

Assessment Type		Strategy	Description
Reliability		Standardized procedures	Life cycle assessments are conducted using <i>One Click LCA</i> , a validated tool compliant with EN 15804 and ISO 14040, ensuring methodological consistency and comparability.
		Automated data handling	BIM data integration into <i>One Click LCA</i> minimizes manual data entry errors, increasing replicability and ensuring consistent calculations using predefined life cycle datasets.
		Sensitivity analysis	Key input variables (e.g., lifespan, material origin, waste scenarios) are tested to assess result stability under variable conditions.
		Transparent documentation	All modelling assumptions, data sources, and system boundaries are recorded to support reproducibility and external auditing.
Validity	Internal	Controlled variable definitions	Definitions of life cycle stages (A1–D), circular strategies, and digital twin components are standardized to reduce interpretation ambiguity.
		Triangulation of methods	LCA outputs are analysed in conjunction with CE and DT literature to strengthen methodological triangulation.
		Error checking and cross referencing	Results are verified against benchmarks and Environmental Product Declarations (EPDs) to confirm accuracy
	Technical	Theoretical alignment	The framework aligns with established standards (ISO 14044, ISO 19650, Ellen MacArthur CE principles), ensuring conceptual soundness.
		Tool objective consistency	<i>One Click LCA</i> is selected for its alignment with both theoretical LCA objectives and practical environmental performance analysis.
	External	Case study representativeness	The selected case reflects typical transport infrastructure features (e.g., modularity, digital integration), allowing some generalization.
Method scalability		The digital BIM–LCA workflow is adaptable to other infrastructure types, enhancing its broader applicability.	

3. Results

This chapter presents the outcomes of the Life Cycle Assessment (LCA) performed using *One Click LCA* for the A5 highway overpass near Kaunas city. The analysis compares five design and implementation scenarios reflecting progressive sustainability strategies. Each scenario represents gradual integration of circular economy principles, ranging from the baseline configuration to a fully sustainable model emphasizing material reuse, recycling, and optimized logistics.

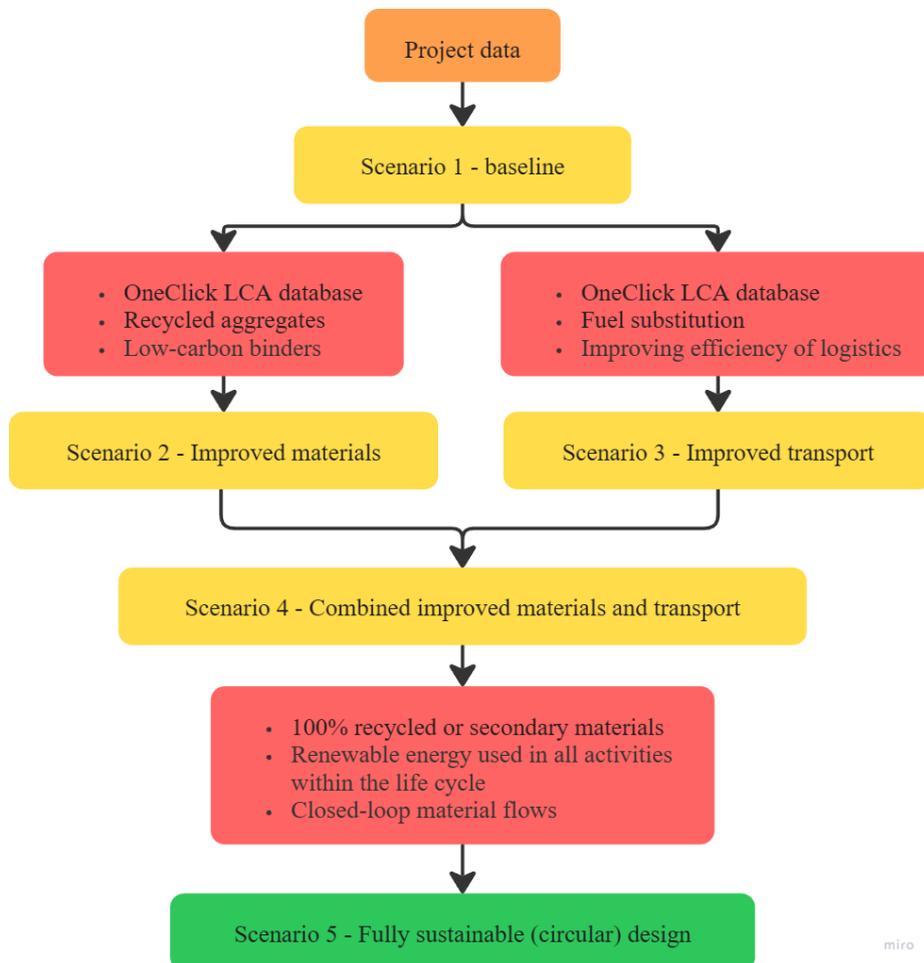


Fig. 7. Flow chart of 5 designs analysed within the scope of this research

All simulations are conducted in *One Click LCA* under the EN 15804 and ISO 14040/44 frameworks, assessing the cradle-to-grave impacts across life cycle stages (A1–D). The primary impact category analysed is Global Warming Potential (GWP) expressed in tonnes CO_{2e}. As per European Standard EN15804, this indicator accounts for GWP associated with greenhouse gas emissions and removals across all environmental media resulting from the oxidation or reduction of fossil fuels or materials containing fossil carbon, including processes such as combustion, incineration, landfilling, and other related activities. The indicator also accounts for GWP from GHG emissions as well as GHG removals.

3.1. Scenario 1: Baseline

The baseline model represents the current developed design of the A5 overpass, created by *Tyrens Lietuva* for their client, using chosen conventional construction materials, provided in the original design as well as predetermined transportation logistics, provided by the company. Material data is

imported directly from BIM models provided by *Tyrens Lietuva*, with *One Click LCA* used to quantify the embodied carbon associated with each component.

The baseline composition primarily includes standard ready-mix concrete (C30/37, C40/50, C35/45) with 10 % recycled cement binder, conventional steel reinforcement (S235–S355, 15% recycled content), and asphalt mixtures. Transport assumptions are based on internally verified technical characteristics and datapoints from *One Click LCA* software database and include conventional diesel-fuelled cargo trucks and concrete mixer trucks.

Table 3. Baseline scenario: main contributors to GWP (A1–A3) (Source: *One Click LCA* baseline model)

Rank	Material	Description	GWP (A1–A3) [t CO ₂ e]	Share of total [%]
1	Ready-mix concrete, C30/37	10% recycled cement binder	347	36.9%
2	Precast concrete beam, rectangular	0% recycled binders	244	26.0%
3	Precast concrete foundation	C30/37, 2400 kg/m ³	183	19.4%
4	Precast concrete beam	0% recycled binders	135	14.3%
5	Steel sheets, 15% recycled content	S235–S355	13	1.4%
6	Asphalt mixture	5% bitumen–aggregate ratio	6.2	0.3%
...	Other materials (sealants, gravel, EPS insulation, etc.)	NA	NA	<1%

Figure 8 shows the contribution of different resource types to the GWP in the A2 life cycle stage. Structural concrete for beams, columns, and piles is the dominant source of emissions, accounting for 57.2%, followed by ready-mix concrete for external walls and floors at 39.6%. All other materials contribute only marginally: structural steel represents 2.0%, while asphalt, sealants, sand, gravel, stones, concrete slabs, and EPS insulation each account for 0.6% or less. Overall, the chart highlights that concrete-related materials are responsible for nearly the entire GWP impact in this stage.

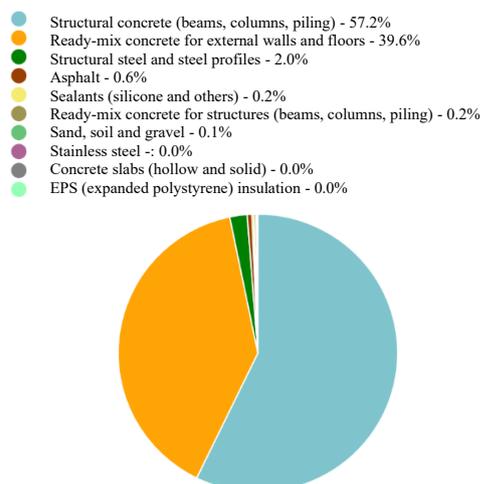


Fig. 8. GWP contributions based on resource types (*One Click LCA* output)

The baseline results indicate that concrete dominates the embodied carbon profile, accounting for over half of total emissions, primarily due to high clinker content in cement and energy-intensive precast manufacturing. Steel components contribute marginally to GWP, reflecting their relatively small mass compared to concrete, though with high unit emissions per kilogram.

3.2. Scenario 2: Improved Materials

In this scenario, conventional materials are replaced with low-carbon and high recycled-content alternatives using the *One Click LCA* database and manual selection of materials with lower environmental impact. Selection criteria prioritized:

- $\geq 30\%$ recycled aggregate content for concrete mixes
- $\geq 20\%$ supplementary cementitious materials (SCMs), such as fly ash or GGBS
- $\geq 60\%$ recycled content for steel components

Table 4. Substituted materials in the improved materials scenario (Source: *One Click LCA* sustainable materials library, 2025)

Original Material	Replacement	Key improvement	GWP Change [t CO ₂ e]
Ready-mix concrete C30/37	C30/37 (GGBS 20%)	Reduced clinker	-94
Precast concrete beam	Recycled concrete aggregate (30%)	Secondary aggregates	-64
Steel sheets (15% recycled)	Recycled steel (100%)	Increased circular content	-8.2
Asphalt mixture	RAP 30% + bio-binder	Lower bitumen footprint	-3.7

In comparison to the baseline scenario, precast concrete foundations are not replaced by any other material since the initial choice was the most sustainable one within the database.

The comparative analysis revealed a substantial reduction in Global Warming Potential (GWP) between the second scenario and the baseline case: a decrease of approximately 21%, from 1,023,712 kg CO₂e to 808,018 kg CO₂e. This reduction in GWP can be primarily attributed to the reduced clinker intensity in cementitious materials and the increased incorporation of recycled aggregates. Such results are consistent with contemporary research demonstrating that the substitution of Portland cement with supplementary cementitious materials (SCMs), such as fly ash, slag, or silica fume, can lower embodied carbon emissions by 20–40%, depending on the specific binder composition [14, 26].

The selection of alternative materials aligns with Circular Economy principles by closing resource loops through the reutilization of industrial by-products and recycled aggregates. The integration of a digital Life Cycle Assessment (LCA) model within a Building Information Modelling (BIM) framework further strengthens this approach by enabling traceable and data-driven monitoring of the embodied environmental impacts associated with these materials. Moreover, by embedding LCA capabilities within a Digital Twin environment, it becomes possible to quantify, simulate, and visualize the environmental benefits of circular design interventions in near real time. This integration not only enhances decision-making during the design and construction phases but also supports continuous performance evaluation across the assets or material's entire life cycle [14, 26].

3.3. Scenario 3: Improved Transport

This scenario retains baseline materials but optimizes the A4 transport stage, emphasizing logistics efficiency and fuel substitution. The modelling assumptions include:

- Average transport distance reduced by 30% through local sourcing
- Introduction of biodiesel-powered delivery vehicles

Table 5. Transport optimization parameters

Parameter	Baseline	Improved transport	Source
Average transport distance	40 -470 km	25-330 km	Hypothetical
Fuel type	Diesel	biodiesel (B100) from (RME)	LCA model input
Load factor	50-70%	100%	Assumed
Total emissions	1 023 712 kg CO ₂ e	779 431 kg CO ₂ e	Output

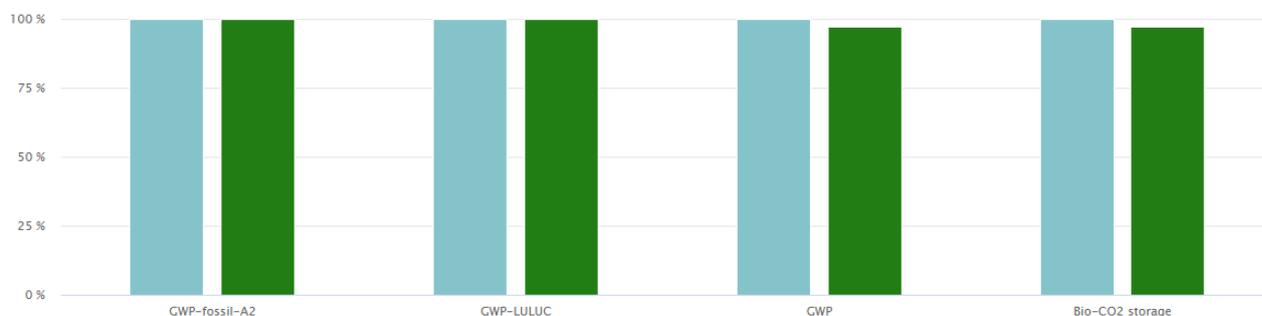


Fig. 9. GWP comparison of infrastructure carbon: baseline scenario vs improved transport (*One Click LCA* output)

Although transport generally represents a smaller share of total embodied emissions (<10%), optimization significantly reduces cumulative emissions and enhances supply chain resilience. In this case, the reduction is 2.77% of total carbon, when implementing 30% distance reduction and biodiesel (B100) from rapeseed methyl ester (RME) for all cargo, including dumper trucks, concrete mixer trucks and trailers. Similar research confirms that localization of material supply chains can reduce transport-related CO₂e by 10–15% in infrastructure projects [9].

From a Digital Twin perspective, real-time data integration could further enhance transport optimization by linking supplier logistics data with the LCA model. This enables predictive route optimization and CO₂ impact tracking, consistent with CE goals of resource efficiency and system transparency [11].

3.4. Scenario 4: Combined Improved Materials and Transport

This scenario integrates both low-carbon materials and optimized logistics (Scenarios 2 and 3 mentioned above). It represents a practically achievable intermediate solution for infrastructure stakeholders, including both development companies as well as clients and users.

The *One Click LCA* simulation shows cumulative benefits across all life cycle stages (A1–A5), with especially notable improvements in the production and transport phases compared to baseline scenario (Scenario 1).

Table 6. Aggregated GWP results for Scenarios 1 and 4

Scenario	A1–A3 (Production)	A4 (Transport)	A5 (Construction)	Total GWP [t CO ₂ e]
Baseline	910	72	38	1020
Scenario 4	690	48	32	770

This scenario indicates synergistic effects between material circularity and transport optimization. The compounded reduction in emissions supports earlier research emphasizing multi-dimensional circular strategies as more effective than isolated interventions [15, 32].

3.5. Scenario 5: Fully Sustainable (Circular) Design

The final scenario portrays further improvement of Scenario 4 and incorporates circularity-enhanced design, combining material substitution, optimized logistics, reuse of structural components, and recycled end-of-life material reintegration (Stage D).

Improvements towards circularity include:

- Integration of Material Passports for traceability
- Use of prefabricated modular components enabling future disassembly
- Reuse of steel and precast concrete elements in secondary applications
- Circular asphalt incorporating recycled content and low-temperature mixing
- Inclusion of renewable energy-powered construction processes
-

Figure 10 presents the distribution of Global Warming Potential (GWP) across the life-cycle stages for the A2 module. The results indicate that the A1–A3 product stage is the dominant contributor, accounting for 89.8% of total emissions. Smaller contributions originate from A4 transport (4.7%), C1–C4 end-of-life processes (2.6%), and C2 waste transport (2.3%). The A5 construction process and B4–B5 material replacement have negligible impacts at 0.2% and 0.4%, respectively. Overall, the figure shows that nearly all emissions are embedded upstream in the production of materials rather than during transport, construction, or end-of-life stages.

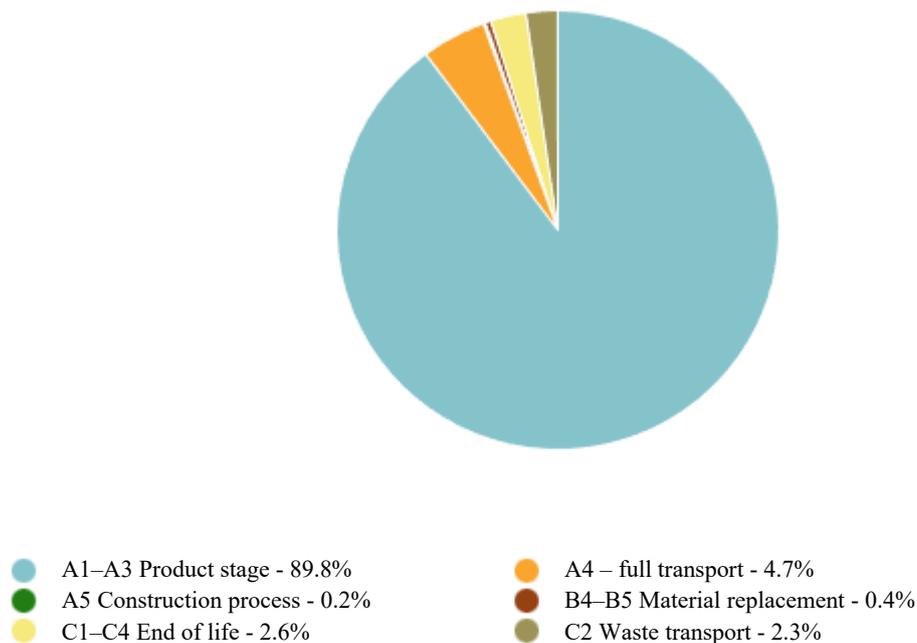


Fig. 10. GWP contributions based on Life-cycle stages (*One Click LCA* output)

Table 7 shows the GWP contributions by resource type in the A2 stage. The results are dominated by concrete: structural concrete accounts for 57.2%, and ready-mix concrete for external walls and floors adds another 39.6%. All remaining materials (structural steel, asphalt, sealants, and aggregates) each contribute 1% or less, indicating that concrete use is almost entirely responsible for the emissions in this stage.

Table 7. GWP contributions based on resource types (One Click LCA output)

Item	Value (kg CO ₂ e)	Percentage %
Ready-mix concrete for external walls and floors	210 000	60.73 %
Structural concrete (beams, columns, piling)	210 000	58.78 %
Structural steel and steel profiles	5 300	1.53 %
Asphalt	2 700	0.79 %
Sealants (silicone and others)	2 500	0.72 %
Recycled soil and aggregates	540	0.15 %
Stainless steel	440	0.13 %
Concrete slabs (hollow and solid)	160	0.05 %
Sand, soil and gravel	150	0.04 %

The fully sustainable model represents a circular infrastructure prototype, demonstrating the integration of environmental design, material circularity, and digital intelligence. Consistent with recent research, such strategies could achieve up to 40–60% total GWP reduction depending on the recovery efficiency and renewable energy integration [23, 24].

This scenario represents the fully circular life cycle, in accordance with the study’s conceptual framework integration of LCA and CE. The *One Click LCA* simulation provides quantitative sustainability metrics, while the integration with BIM and potential Digital Twin data flows creates a feedback system for monitoring material circularity and operational performance over time. Such integration demonstrates the feasibility of real-time, data-driven circular infrastructure design.

3.6. Comparative Analysis of Scenarios

The analysis reveals a consistent downward trend in GWP as circular strategies intensify. Material efficiency remains the most influential factor, followed by logistical optimization and end-of-life recovery.

The results presented in Table 7 indicate a consistent and measurable decline in GWP as the degree of circularity increases across the five scenarios. The baseline scenario exhibits the highest impact at 1,020 tonnes of CO₂, serving as the reference point for subsequent comparisons.

Table 8. Comparison of GWP reduction in five scenarios

Scenario	Estimated GWP Reduction
Scenario 1 – Baseline	1 020 tonnes CO ₂
Scenario 2 – Improved materials	~20% reduction
Scenario 3 – Improved logistics	~3% reduction
Scenario 4 – Improved materials and transport	240+ tonnes CO ₂ saved (approx. 23%)
Scenario 5 – Fully circular design	340 tonnes CO ₂ (approx. 70% reduction)

In Scenario 2, the incorporation of improved material efficiency yields an estimated 20% reduction in GWP. This demonstrates the substantial influence of material-related interventions on overall system performance. By contrast, Scenario 3, which introduces logistical optimization exclusively, results in a comparatively minor reduction of approximately 3%, indicating that transport-related measures contribute only marginally to total emission reductions when implemented in isolation.

A more pronounced improvement is observed in Scenario 4, where material enhancements are combined with optimized logistics. This integrated approach reduces emissions by over 240 tonnes of CO₂ (around 23%), representing a significantly greater impact than either measure alone. Notably,

the combined reduction is more than an order of magnitude greater than that achieved through logistical improvements alone and surpasses the effect of improved materials applied independently.

The most substantial reduction occurs in Scenario 5, which reflects a fully circular design strategy. This configuration results in an estimated 340-tonne reduction in CO₂ emissions, corresponding to an approximately 70% decrease relative to the baseline. This outcome is more than three times the reduction attributable to material improvement alone and exceeds the effect of improved logistics by more than two orders of magnitude.

Overall, the findings demonstrate that higher levels of circularity correlate strongly with reduced GWP, with material efficiency emerging as the dominant factor and comprehensive circular design providing the greatest cumulative benefit. These results are consistent with existing literature emphasizing the importance of integrating digital twin-enabled feedback loops with circular economy principles to advance infrastructure decarbonization [12, 29, 31].

3.7. Challenges and Opportunities for Sustainability and Circularity in Infrastructure Projects

3.7.1. Challenges

Data availability and interoperability. To enhance the robustness of LCA studies in the field, a decision-tree framework is proposed to support the prioritization of environmental impact indicators. This framework classifies indicators as mandatory (e.g., global warming, eutrophication, human toxicity), recommended (e.g., water depletion), or optional, based on criteria such as global relevance, agreement across established methods, regional importance, and data availability [34]. A major challenge for implementing circular and data-driven infrastructure systems lies in the lack of interoperability between BIM and LCA platforms. Current Material Passport and BIM systems rely on fragmented databases and inconsistent environmental data standards, limiting seamless data exchange [16]. In the A5 overpass case, integrating BIM data into *One Click LCA* required manual verification of material parameters. This demonstrates that without a standardized digital environment, data mismatches can distort impact assessments and reduce confidence in results. Developing shared data formats, APIs, and protocols for BIM–LCA–DT integration is therefore essential to ensure accuracy and replicability.

Economic constraints. The transition toward circular and low-carbon construction is also hindered by high upfront costs. Many regional infrastructure projects face budget limitations that discourage investment in modular systems, low-carbon materials, or digital infrastructure [7]. For example, recycled aggregates and green cement alternatives typically carry a cost premium due to limited market availability. Although life cycle savings can offset these expenses over time, short-term procurement models often prioritize lower capital costs over long-term sustainability gains. This underscores the need for life cycle costing (LCC) integration into early design stages.

Quality assurance of reused materials. To maximize resource value within a circular economy and minimize the environmental impact of waste, an approach is adopted that considers the full life cycle or circulation of materials, ensuring effective recycling [37]. Ensuring the structural integrity and performance of reused components remains a key technical obstacle. While steel structures have high theoretical recyclability, the absence of standardized testing and certification for reused materials restricts their application in infrastructure [24]. Within the A5 overpass context, introducing reclaimed steel or precast concrete elements would require additional inspection and certification procedures to verify compliance with Eurocode and Lithuanian standards. Implementing reliable digital Material Passports could mitigate this issue by documenting material provenance and mechanical properties throughout their life cycle. The availability of agricultural waste further presents opportunities for energy recovery through its use as biomass [35].

Regulatory ambiguity. To ensure comparability of results and relevance for policy-making, studies must clearly disclose these methodological choices and ensure that the defined system boundaries align with the specific goal of the LCA and whether it aims to support process optimization, climate reporting, or technology comparison [33]. Circular procurement frameworks remain inconsistent across European jurisdictions. The “twin transition” of digitalization and sustainability is slowed by the absence of clear legal and technical guidelines for circular tenders and recycled-material acceptance [20]. For public infrastructure, this regulatory gap translates into uncertainty about what qualifies as a compliant circular practice, leading to risk aversion among engineers and contractors. Stronger policy coherence under the EU Green Deal and taxonomy mechanisms is needed to align funding, compliance, and sustainability metrics.

Digital skill gaps. The widespread adoption of Digital Twins and data-driven construction requires upskilling across disciplines. The implementation of GenAI and Urban Digital Twins demands advanced capabilities in data analytics, system integration, and life cycle modelling [11]. The A5 case study reflects this challenge, as effective digital twin operation would depend on ongoing data input and real-time interpretation by skilled personnel. Without cross-disciplinary education in digital sustainability, DT-enabled circularity will remain underutilized. It is crucial to identify the knowledge gap and provide both student and professionals with means to try out LCA in the field. Special focus ought to be given to how LCA is taught and whether students encounter challenges similar to those faced by professionals in the field [35].

3.7.2. Opportunities

Digital Twin integration. Digital Twin technologies represent one of the most promising tools for achieving sustainable infrastructure. By incorporating LCA into project planning and implementation, engineers can proactively identify and address potential environmental impacts during the early design stages, resulting in more sustainable project outcomes [38]. DT systems, when linked to LCA databases, can enable predictive maintenance, dynamic impact monitoring, and continuous optimization [12]. For the A5 overpass, integrating DT capabilities with LCA data could allow real-time tracking of structural performance and embodied emissions, reducing maintenance costs while extending service life.

Material Passports (MPs). Material Passports offer a structured method for tracking the environmental and technical data of materials across their life cycle. Some studies identify MPs as key instruments for operationalizing circularity, enabling the reuse and resale of construction materials [16]. By linking MPs to Digital Twins, infrastructure operators can visualize material flows, anticipate replacement needs, and plan for future recovery by closing the resource loop envisioned in circular economy frameworks.

Modular and prefabricated systems. Modular construction techniques offer substantial opportunities to reduce waste, improve efficiency, and simplify disassembly [21]. Prefabrication allows for better material control and shorter on-site construction phases, directly contributing to CE principles. In the A5 overpass scenario, prefabricated concrete beams and modular deck components could facilitate future reuse or adaptation while reducing on-site emissions and disruption. Moreover, one study deduces some notable differences in labour and equipment needs when comparing deconstruction with traditional demolition practices. This comparison emphasizes the labour-intensive character of deconstruction, which, although demanding greater workforce involvement, enables increased material recovery rates and reduces dependence on heavy machinery [40]. Deconstructed and reused parts and materials of built projects can further ensure circularity.

AI-driven LCA optimization. AI is increasingly used to automate data handling and scenario modelling in environmental assessment. AI-integrated LCA models can streamline material selection and provide automated feedback loops for decision-makers [17]. Applying AI to infrastructure LCAs, such as the A5 case, would enhance data accuracy and shorten analysis cycles, allowing continuous updates as material or process data evolve in real time.

Policy alignment with EU Green Deal and Taxonomy. Beyond serving as an environmental assessment tool, LCA has become increasingly significant in policy making, especially within the EU, where it is being systematically embedded into regulatory frameworks and sustainability

strategies. The European Commission now endorses the Environmental Footprint (EF) method, which is based on LCA principles, as the standard approach for assessing the environmental performance of products and organizations [41]. Additionally, recent policy frameworks provide strong momentum for scaling sustainable construction. Aligning infrastructure design and procurement with the European Green Deal and EU Taxonomy criteria enables access to sustainability-linked funding mechanisms [7]. Such alignment incentivizes early adoption of CE and DT principles while creating measurable benchmarks for emissions reduction and circularity performance.

3.8. Summary of Findings

The results confirm that progressive implementation of circular economy principles, from improved material selection to complete life cycle reintegration, can substantially reduce environmental burdens in infrastructure projects. The combination of LCA, BIM, and Digital Twins provides a data-driven foundation for sustainable decision-making, while *One Click LCA* facilitates transparent quantification of benefits under different design choices.

3.9. Integration of LCA, CE, and DT Frameworks

The results of this study validate the proposed integration of Life Cycle Analysis (LCA), Circular Economy (CE), and Digital Twin (DT) frameworks in infrastructure sustainability assessment. The LCA serves as a quantitative foundation for measuring environmental impacts, while CE principles provide strategic direction toward resource efficiency, reuse, and reduced waste generation. The inclusion of DT technologies enables continuous monitoring, data feedback, and scenario adaptation.

Conclusions

1. The LCA assessment of the A5 highway overpass demonstrated that the baseline design resulted in a total GWP of 1,020 tonnes of CO₂e across life cycle stages A1–A5. The production stage (A1–A3) was the dominant contributor, accounting for 910 tonnes, or 89.2% of total emissions. Transport (A4) contributed 72 tonnes (7.1%), while construction processes (A5) contributed 38 tonnes (3.7%). These results confirm that the environmental performance of the overpass is primarily determined by material production rather than on-site activities.
2. The analysis identified concrete as the main source of embodied emissions in all scenarios. Structural concrete used in beams, columns, and piles accounted for 57.2% of emissions in the production stage, while ready-mix concrete for external walls and decks contributed an additional 39.6%. Combined, concrete materials were responsible for 96.8% of production-stage emissions. Steel, asphalt, insulation, and auxiliary materials each contributed 2.0% or less, confirming that emission reduction strategies must focus primarily on cementitious materials.
3. The improved materials scenario achieved a reduction in total GWP from 1,023,712 kilograms to 808,018 kilograms of CO₂e, corresponding to a decrease of 215,694 kilograms, or 21.1%. This reduction was achieved by using concrete with 20% supplementary cementitious materials, recycled concrete aggregates at 30%, recycled steel with 100% recycled content, and asphalt with 30% reclaimed asphalt pavement. The results demonstrate that material substitution alone can reduce embodied emissions by more than one fifth without altering the structural design.
4. The improved transport scenario reduced total emissions from 1,023,712 kilograms to 779,431 kilograms of carbon dioxide equivalent. This corresponds to a reduction of 244,281 kilograms, or 2.77% relative to the baseline. The reduction was achieved through a 30% decrease in average transport distances, full vehicle load utilization, and replacement of diesel with biodiesel derived from rapeseed methyl ester. These results confirm that transport optimization contributes to emission reduction but remains secondary compared to material-related measures.
5. Scenario 4 (combined improved materials and transport) resulted in a total GWP of 770 tonnes of CO₂e, compared to 1,020 tonnes in the baseline scenario. This represents a reduction of 250 tonnes, or 24.5%. The production stage emissions decreased from 910 tonnes to 690 tonnes, while transport emissions decreased from 72 tonnes to 48 tonnes. The results demonstrate that combining circular material strategies with optimized logistics produces a greater reduction than applying either measure independently.
6. The fully circular design scenario achieved the largest emission reduction among all evaluated options. The total reduction reached 340 tonnes of CO₂e, corresponding to an approximate 70% decrease compared to the baseline. The results confirm that comprehensive circular strategies provide substantially higher benefits than isolated interventions.

The study confirmed that the proposed integration of life cycle assessment, circular economy principles, and digital twin concepts is technically feasible and environmentally effective. Life cycle assessment provided quantitative evidence of emission reductions, circular economy strategies enabled material reuse and recycling, and digital twin integration offered the potential for continuous monitoring and future optimization of environmental performance. Manual verification of data inputs highlighted the need for improved interoperability between digital design and assessment platforms. Based on the results, it is recommended that future highway overpass projects prioritize low-clinker concrete, high recycled-content materials, and design-for-reuse principles at the early design stage. For practical implementation, infrastructure clients and designers should adopt combined material circularity and logistics optimization strategies, supported by life cycle assessment integrated into digital design environments, as this approach can reduce embodied carbon by more than two thirds compared to conventional designs.

The findings of this research have been presented in Smart Built Environment Conference at Kaunas University of Technology on 5th December 2025.

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Appendices

Appendix 1. Literature Review Protocol

Life Cycle Analysis in Infrastructure Projects: The Synergy of Circular Economy and Digital Twins

Agnė Grigaitytė

Master's Final Degree Project

Planning

1. To define the terms "Circular Economy", "Life Cycle Analysis" and "Digital Twin", and specify the connections between mentioned concepts to be included in the scope of the research.
2. To review previous studies on the impact of LCA on infrastructure projects and reducing the environmental impact within construction sector.
3. To perform LCA simulations assessing the material consumption of road development project in different scenarios.
4. To conduct a comparative analysis to determine the influence of different construction materials within the case study.
5. To evaluate the role of Digital Twins within construction sector and future prospects.

PICOC

Population: Infrastructure Project*

Intervention: Life Cycle Analysis

Comparison: Road Infrastructure Development

Outcome: Environmental Impact, Emissions Reduction

Context: Lithuania

Research Questions

How can LCA Analysis tools help reduce the environmental impact of infrastructure projects in Lithuania?

Keywords and Synonyms

Keyword	Synonyms
Emissions Reduction	Decarbonization, GHG mitigation
Environmental Impact	Ecological footprint
Infrastructure Project*	Built Environment Development
Life Cycle Analysis	Environmental performance modelling
Road Infrastructure Development	Road construction

Search String

digital AND twins AND infrastructure AND circular AND economy

Sources

Scopus (<http://www.scopus.com>)

Selection Criteria

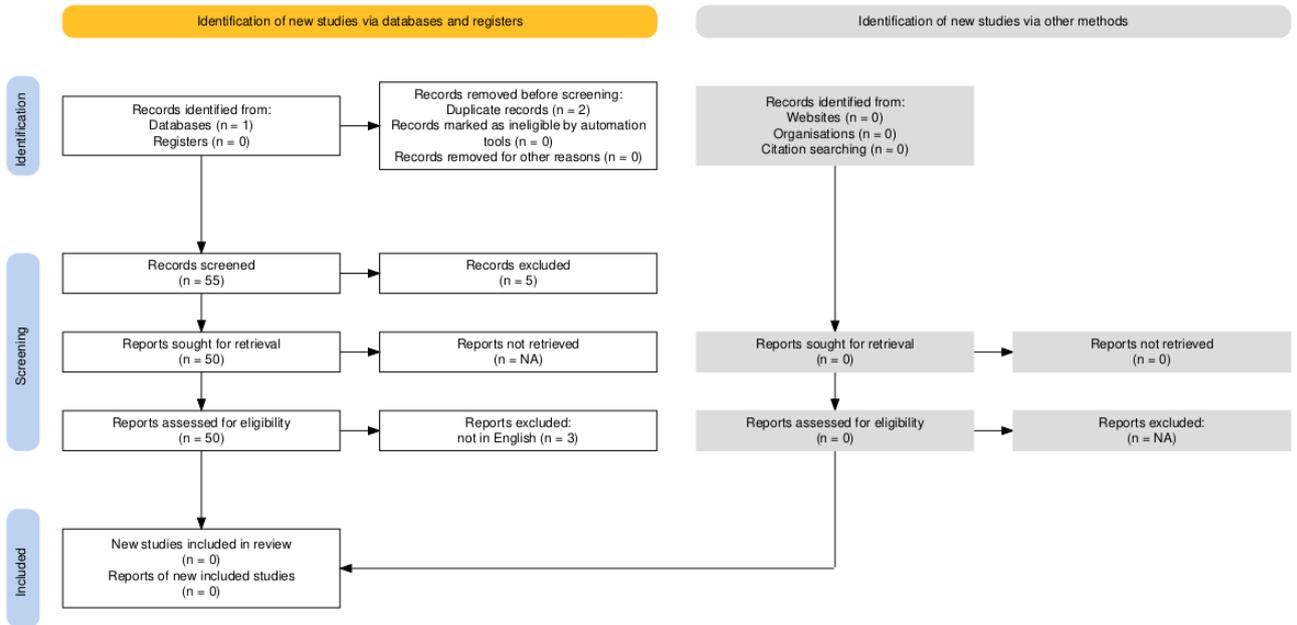
Inclusion Criteria:

contains keywords
within scope of research

Exclusion Criteria:

full text not available
not in English or Lithuanian
not peer reviewed
published before 2015

Appendix 2. Prisma Flowchart

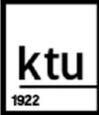


Appendix 3. Declaration of AI Usage

AI tool “Grammarly” was used to improve the grammar, spelling and coherence of the English language in this document. No content was created using this tool.

Appendix 4. Smart Built Environment Conference 2025 Certificate

STUDENT SCIENTIFIC CONFERENCE



ktu
1922

faculty of civil
engineering and
architecture

CERTIFICATE

Agnė Grigaitytė

Has participated in Student scientific conference
„SMART BUILT ENVIRONMENT“
on 5 December 2025

Delivered the presentation:
Life Cycle Analysis in Infrastructure Projects: the Synergy of
Circular Economy and Digital Twins

Dean of the Faculty of Civil
Engineering and Architecture

Prof. Dr. Andrius Jurelionis



