Artificial Intelligence in Building Retrofitting: Deficiencies, Capabilities, and Strategies

Development of an Artificial Intelligence Methodology that addresses the deficiencies in retrofitting practices and achieves decarbonization and net-zero objectives by integrating AI capabilities and decarbonization strategies with practical implementation in design and construction management, based on insights from case studies and one-on-one interviews.

Turner & Townsend

Delft University of Technology
Faculty of Architecture
and the Built Environment

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[Front page: AI generated (source) and photoshopped]

PREFACE

It has been a privilege to write this thesis as part of my Master's in Architecture in the Management in the Built Environment track at the Technical University Delft (TU Delft). My journey began two years ago after completing my pre-master here, following my studies at college. I sought to deepen my understanding and capabilities in managing the complexities of the built environment, a field that has always captivated me. These past years have been both challenging and meaningful, and they have provided countless opportunities for personal and academic growth.

With AI rapidly evolving and becoming an integral part of many industries, its application in the built environment is still in its infancy, making it both exciting and challenging to explore. I vividly remember my supervisors cautioning me about the intricacies of working with such advanced and emerging technologies. However, this only fueled my curiosity and determination to embrace the challenge. I recognized the immense potential AI holds in transforming sustainable practices and how it could revolutionize retrofitting by optimizing energy efficiency, reducing emissions, and paving the way toward net-zero buildings. Rather than focusing on AI as merely a new technology, my research aims to provide a comprehensive guide for how AI can effectively integrate decarbonization strategies. By creating a roadmap for success, I hope to offer practical insights that help stakeholders navigate the complexities of AI, making it a valuable tool for decarbonization and achieving net-zero building objectives in the built environment.

This thesis represents the culmination of my efforts over the past year. It has been a remarkable learning experience, during which I've had the opportunity to further refine my research skills and expand my understanding of the critical role technology plays in achieving net-zero building objectives. I am deeply grateful for the guidance and encouragement provided by my supervisors, Ruben Vrijhoef and Aksel Ersoy, throughout this journey. Their critical expertise and mental support have been instrumental in shaping the direction of my research.

I would also like to extend my thanks to my graduation company Turner & Townsend Amsterdam for offering global resources and connecting me with the right people to bring this thesis to life. Their support, along with the insights gained from many conversations, has enriched my research experience.

Lastly, I am also deeply grateful to the participants who contributed to this research. Their willingness to dedicate time and share valuable insights has been essential to the completion of this work. I hope that this thesis will serve as a valuable contribution to the ongoing efforts to integrate AI-driven solutions in decarbonization strategies and retrofitting in the built environment.

Sincerely,

Po Au Xu (Kai)

Rotterdam
January, 2025

ABSTRACT

The built environment is responsible for nearly 40% of global greenhouse gas emissions, highlighting its critical role in addressing climate change. Retrofitting existing buildings has emerged as a key strategy for achieving net-zero carbon objectives, focusing on reducing both operational and embodied carbon emissions. However, retrofitting practices face challenges such as fragmented data systems, limited real-time monitoring, and inadequate stakeholder collaboration. Artificial Intelligence (AI) presents transformative potential to address these challenges by optimizing energy performance, streamlining decision-making processes, and improving retrofitting outcomes. This research investigates how AI can integrate decarbonization strategies into building retrofitting to achieve net-zero objectives, addressing the main research question: How can AI methodologies integrate decarbonization strategies in building retrofitting to achieve net-zero building objectives in design and construction management? The hypothesis of this research posits that AI-driven technologies, such as machine learning, can effectively optimize retrofitting practices by addressing deficiencies in current methods, improving decision-making processes, and enabling energy performance optimization to achieve net-zero outcomes. A review of the literature reveals eight critical retrofit measures and highlights significant gaps in current practices, such as the lack of standardized methodologies and the late-stage assessment of carbon impacts. Furthermore, the review emphasizes the potential of Artificial Intelligence (AI) and its subsets—such as machine learning, neural networks, and deep learning—to optimize retrofitting by enabling predictive analytics, energy modeling, and improved decision-making processes. To test this hypothesis and address these gaps, a qualitative, deductive methodology is adopted, combining semi-structured interviews with industry experts and a case study analysis to uncover actionable insights. The findings reveal that AI subsets, such as machine learning and neural networks, can enhance predictive maintenance, unify fragmented data, and enable dynamic adjustments in retrofitting processes. Nonetheless, barriers such as data quality, algorithmic biases, and resistance to technological change persist, requiring phased implementation and enhanced stakeholder collaboration for successful adoption. The study synthesizes these findings by linking identified deficiencies in retrofitting with specific AI-driven solutions, demonstrating how tailored AI applications can address both embodied and operational carbon challenges. This research develops an AI methodology for integrating AI to improve decarbonization strategies to address real-world deficiencies in retrofitting practices, optimize energy efficiency, reduce carbon emissions, and enhance stakeholder collaboration, ultimately contributing to achieving net-zero building objectives.

KEYWORDS – Artificial Intelligence (AI), Decarbonization, Net-Zero Buildings, Retrofitting, Machine Learning, Construction Management, Embodied Carbon, Operational Carbon

EXECUTIVE SUMMARY

Introduction

The built environment and construction sector face an urgent obligation to reduce carbon emissions to align with the goals of the Paris Agreement. As nearly 40% of global greenhouse gas emissions originate from this sector, achieving net-zero carbon emissions through retrofitting has emerged as a pivotal strategy. Net-zero buildings are defined as those that balance operational and embodied carbon emissions throughout their lifecycle. While progress has been made in reducing operational carbon, embodied carbon reduction continues to lag significantly. Retrofitting existing buildings, which constitute a large share of the current global building stock, presents a unique and critical challenge due to their age and complexity. Artificial Intelligence (AI) offers promising capabilities to optimize decarbonization strategies by addressing these challenges, enhancing energy efficiency, and supporting decision-making processes in design and construction management. However, the integration of AI in retrofitting is still in its emerging phase, with notable barriers including data accessibility, technological readiness, and stakeholder adoption.

Research objectives

This research explores how AI can integrate decarbonization strategies in retrofitting existing buildings to achieve net-zero building objectives in the context of design and construction management. The developed roadmap aims to optimize decarbonization strategies while balancing environmental quality and cost-effectiveness. The objectives include exploring the opportunities and limitations of AI applications in retrofitting processes, understanding how AI can optimize decision-making in sustainability, and examining how AI-driven frameworks can contribute to the broader goal of zero-emission buildings. This research aims to set the groundwork for leveraging AI in transforming the built environment toward decarbonization, and link deficiencies in existing practices with actionable AI-driven solutions.

Literature

The literature review provides the theoretical foundation for understanding building retrofitting, AI integration, and design and construction management in the context of achieving net-zero objectives. It highlights eight key retrofit measures for reducing embodied and operational carbon, such as insulation upgrades, renewable energy integration, and advanced building management systems. The review also examines the potential of AI subsets—such as machine learning, deep learning, and neural networks—to enhance retrofitting processes by enabling predictive maintenance, data-driven decision-making, and energy optimization. Additionally, it identifies significant gaps in current research, including the late-stage assessment of carbon impacts and the lack of standardized AI methodologies in retrofitting. These gaps underscore the need for early intervention and tailored AI strategies to address the dual challenges of operational and embodied carbon reduction.

Methodology

A qualitative, deductive research approach was employed, combining semi-structured interviews and case studies to provide rich, context-specific insights. The study draws on expert knowledge from professionals at the forefront of AI applications and retrofitting, alongside best practices from the construction industry. Data were analyzed using ATLAS.ti to uncover patterns, barriers, and opportunities. Expert panel validation was conducted to refine findings and ensure methodological robustness. This approach bridges theoretical understanding with practical applications, offering a multidisciplinary perspective on AI integration in retrofitting.

Findings

The findings highlight that AI can significantly enhance retrofitting outcomes by optimizing energy efficiency, improving building performance, and reducing embodied and operational carbon emissions. AI tools such as machine learning and neural networks enable the analysis of complex datasets, facilitating data-driven decisions for retrofitting projects. Challenges identified include the lack of comprehensive data for older building stock, regulatory hurdles, and high upfront costs associated with retrofitting. The study underscores the need for stakeholder collaboration, phased implementation strategies, and the integration of AI-driven tools across the retrofitting lifecycle. Key success factors include setting clear carbon reduction targets, leveraging real-time data for performance monitoring, and fostering industry-wide digitalization.

Chapter 4 identifies several critical deficiencies in current retrofitting practices that hinder progress toward achieving net-zero building objectives. A lack of integration between existing building systems and retrofitting technologies creates inefficiencies, particularly in managing energy performance and operational carbon reduction. The data required for informed decision-making is often incomplete or fragmented, limiting the ability to assess retrofitting outcomes effectively. Additionally, there are significant challenges in balancing cost-effectiveness with sustainability goals, as financial constraints often take precedence over long-term environmental benefits. Stakeholder collaboration is another identified deficiency, with siloed communication between design teams, contractors, and building owners delaying progress and reducing the overall effectiveness of retrofitting projects. Lastly, a notable gap exists in real-time performance monitoring and feedback systems, which impedes the ability to adjust strategies dynamically during the retrofitting process.

Chapter 5 examines the potential of AI to address these deficiencies through expert insights. AI demonstrates significant promise in areas such as predictive maintenance, energy performance optimization, and decision-making enhancement. Machine learning and neural networks, for example, enable the analysis of large datasets to uncover patterns, predict energy needs, and identify inefficiencies in building systems. Experts agree that AI can help integrate fragmented data sources, creating a more comprehensive understanding of building performance and supporting dynamic decision-making processes. AI tools, such as real-time sensors and automation systems, can address deficiencies in monitoring by providing continuous feedback and actionable insights, enabling more efficient retrofitting outcomes.

However, the chapter also highlights what AI cannot yet achieve. Experts emphasize that AI solutions are heavily dependent on data quality, availability, and structure, which remain inconsistent across retrofitting projects. In particular, older buildings often lack the necessary baseline data for AI models to function effectively. Additionally, algorithmic biases and a lack of standardization in AI applications pose risks to accuracy and reliability. Another challenge lies in stakeholder adoption, as the construction sector is traditionally resistant to technological change, further slowing the integration of AI-driven solutions.

Experts suggest that for AI to succeed, certain conditions must change. Improved data collection and management processes are critical, particularly in the early stages of retrofitting projects. Encouraging collaboration across the supply chain can ensure that all stakeholders are aligned on goals and data sharing, which is essential for AI adoption. The phased implementation of AI tools, starting with smaller pilot projects before scaling up, is also recommended to minimize risks and build confidence among stakeholders. Finally, experts advocate for the development of industry-wide standards and guidelines to ensure that AI applications are both reliable and scalable.

Chapter 6 synthesizes the deficiencies identified in chapter 4 with the potential solutions outlined in chapter 5. For example, the lack of real-time performance monitoring can be addressed through AI-enabled sensor technologies, which provide continuous data on building energy use and operational efficiency. Similarly, the challenge of fragmented data integration aligns with AI's capability to process and analyze diverse datasets, creating a unified platform for decision-making. In cases of high operational carbon emissions, machine learning algorithms can be employed to model energy optimization scenarios and predict the most effective retrofitting strategies. This synthesis illustrates how AI subsets can be tailored to specific deficiencies, offering a clear roadmap for integrating AI into retrofitting processes.

Discussion
This research contributes to addressing the practical and theoretical gaps in integrating AI with decarbonization strategies for retrofitting. The findings emphasize that AI can bridge the gap between sustainability objectives and current retrofitting practices by providing actionable insights and optimizing resource use. However, the challenges of data accessibility, regulatory compliance, and stakeholder adoption remain significant. AI's transformative potential lies in its ability to adapt to diverse project contexts, streamline decision-making processes, and align retrofitting outcomes with net-zero goals. The study also introduces new perspectives on the role of construction management practices in enabling AI-driven retrofitting strategies.

Conclusion
This research concludes that AI has the potential to resolve critical deficiencies in retrofitting practices, particularly in areas such as energy optimization, data-driven decision-making, and real-time monitoring. By aligning identified deficiencies with specific AI subsets, the study provides a structured approach to integrating AI into retrofitting projects. While challenges remain, AI's adaptability and data-driven capabilities offer significant opportunities for advancing sustainable building practices.

Furthermore, this research also emphasizes that AI is not a standalone solution but rather a complementary tool that enhances human decision-making and fosters collaboration among stakeholders. By integrating AI into retrofitting practices, the built environment can transition toward more sustainable and efficient operations, ultimately contributing to global decarbonization efforts and the goals of the Paris Agreement.

Recommendations future research
Future research should explore the evolving role of AI in retrofitting, focusing on developing advanced tools for data collection, processing, and decision support. Investigating strategies for overcoming financial and regulatory barriers will be essential for scaling AI adoption. Additionally, further studies are needed to assess the long-term impacts of AI-driven retrofitting on stakeholder engagement and industry practices. The findings also highlight the importance of fostering cross-disciplinary collaboration to ensure the successful implementation of AI methodologies in the built environment. The research concludes that AI methodologies, represented by the author's recommendation development of the AIR0 Guidelines and DCM FRAIM Framework, offer a structured and scalable approach to achieving net-zero objectives in retrofitting. By addressing embodied and operational carbon reduction through AI tools. The integration of AI provides a clear pathway to overcoming barriers in retrofitting and achieving sustainable building practices.

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CHAPTER 1

INTRODUCTION

1 | INTRODUCTION

1.1 Research context

In an era where our climate evolves more rapidly than anticipated.
Where challenges arise and solutions are innovated.
We stand at a crossroads, a moment debated.
Seeking harmony with nature, a future unabated.

- Po Au Xu

The escalating physical consequences of a changing climate are becoming more evident as communities face storms, floods, fires, extreme heat, and other risks, as stated by Boland et al. (2022). In the face of a significant challenge, the world is compelled to combat climate change and reduce greenhouse gas (GHG) emissions, aiming to limit the rise of global temperatures (IEA, 2021). The built environment is considered one of the most promising emissions reduction sectors and is responsible for almost 40% of global energy and GHG emissions (Janda et al., 2021; Ohene et al., 2022). Therefore, reducing energy use and GHG emissions from the built environment is critical. In the realm of the built environment, as described by Boland et al. (2022), the consideration of climate change was once a relatively peripheral corner. But the landscape has transformed, and what was once on the outskirts has now taken center stage in the real estate players' considerations (Boland et al., 2022). Amid this shift, the World Green Building Council calls for a significant and ambitious transformation towards a completely zero-carbon built environment (Attia, 2018). This vision aligns seamlessly with the global commitment established in the Paris Agreement, where nations collectively agreed to achieve net-zero emissions (United Nations, n.d.). The built environment, a critical player in this collective effort, now shoulders the responsibility of the dual goal set by the World Green Building Council. First, all new buildings must operate at net zero carbon from 2030, and second, 100% of buildings must operate at zero carbon by 2050 (Attia, 2018; World Green Building Council, 2022). Aligned with the World Green Building Council's two-fold mandate for the constructed environment, as outlined by Attia (2018) and the World Green Building Council (2022), recent studies by Petkov et al. (2023) emphasize two pivotal challenges. These challenges are crucial in the broader pursuit of decarbonization and achieving net-zero emissions. The first challenge is ensuring that new buildings are efficient, resilient, and energetically renewable while constructed with low-CO2 footprint materials. The second challenge is addressing the aging existing building stock of developed economies, such as Europe's, where 90% of buildings are still expected to stand in 2050 (Petkov et al., 2023). While there is considerable focus dedicated to new building development, although challenging, it is often well-understood and integrated early into the development process. As shown in Table 1, there are clear distinctions in focus areas and components between new buildings and existing buildings for net zero achievements. Constructing new buildings allows for integrating design features that focus on reducing embodied carbon and taking design decisions for optimizing operational carbon emissions from the initial phases of development, emphasizing emission reduction during construction and beyond.to achieve net-zero emissions for these existing structures. Recognizing this challenge, it is essential to explore innovative solutions that can speed up and optimize the transition of the existing building stock towards net-zero emissions.This underscores the transformative potential of AI in reshaping our approach to sustainability in the built environment, whether by assisting or revolutionizing innovative strategies to achieve our goal of zero carbon emissions.

However, the real elephant in the room is how to reduce carbon emissions from our existing building stock (Max Fordham LLP, n.d.). As stated by Ruparathna et al. (2016), "New buildings are only a small percentage of the national building stock. Therefore, improving the existing buildings provides the greatest opportunity for sustainable development." The existing building stock needs key priority in retrofitting to a zero-carbon level to achieve the built environment decarbonization targets for 2030 and 2050 (IEA, 2022). The main concern is that the existing building stock is challenging since at least 40% of the building floor area in developed economies was built before 1980, and 80% of the buildings with us today will still be in use in 2050 (IEA, 2022; Max Fordham LLP, n.d). Along with the complex areas and components in Table 1.0, it becomes evident that retrofitting existing buildings presents a unique set of challenges due to the complexities involved in striving to achieve net-zero emissions for these existing structures. Recognizing this challenge, it is essential to explore innovative solutions that can speed up and optimize the transition of the existing building stock towards net-zero emissions.

Therefore, artificial intelligence (AI) emerges as a transformative force, offering technologies that can enable and accelerate the shift towards a zero-carbon built environment (Conway, 2018; Viriato, 2019). The use of AI relies on algorithms, data processing, and pattern recognition to simulate certain human cognition and problem-solving aspects (Mora-Esperanza, 2004; Conway, 2018; Abioye et al., 2021). In essence, according to Conway (2018), artificial intelligence involves learning from the past to predict the future, leveraging "big data". Building upon this concept, Tekouabou et al. (2023) highlight that the use of AI holds the potential to support the integration of new methods of analyzing historical data, thereby enhancing future decision-making. This underscores the transformative potential of AI in reshaping our approach to sustainability in the built environment, whether by assisting or revolutionizing innovative strategies to achieve our goal of zero carbon emissions.

Difference areas & components	New building (new development)	Existing building (retrofitting process)
Key Phase(s)	Especially in the early design phase and the whole building lifecycle from design and construction to operation and end/beyond of the life cycle (Roberts et al., 2020; UK Green Building Council, 2019).	Operational phase: refurbishment of expanding the life cycle and using existing materials beyond the life-cycle (Hill et al., n.d.; UK Green Building Council, 2019).
Challenges	Short-term vs long-term for developers & investors (stakeholders) Combination of one-sized fits all and tailor-made approach based on building/site demand and supply (Petkov et al., 2023) Knowledge & large data collection and application into new buildings.	Building energy performance Feasibility and cost-effective (Shaikh et al., 2017) Tailor-made existing buildings require a standardized approach for building retrofit (Petkov et al., 2023; UK Green Building Council, 2022). And data collection for application in retrofitting buildings. Institutional real estate owners of these existing buildings (Petkov et al., 2023)
State of the building	New condition	Building year (age of the building) and condition, performance, approach
Data collection	Site analyze and optimizing the buildings floorplan for energy performance/ effective design (UK Green Building Council, 2020	Understanding the original use of the building through the collection of metered data. Building 's context opportunities and constraints. Underperformance risk (technical and financial underperformance metrics) (UK Green Building Council, 2022).
(Energy) Demand management	Balance the embodied-operational carbon for the whole lifecycle through the design process. By changing occupant building behavior, optimizing building performance, and improving as an infinite loop. (Hill et al., n.d; UK Green Building Council, 2020)	Reducing operation demand and optimize the performance needs. (UK Green Building Council, 2024).
Materials and circular use for embodied-operational carbon	-Implementing reuse materials, -Lifecycle data of new materials and equipment into the material choice (Material passport) (UK Green Building Council, 2020)	- Existing material used, - Material passport (Hill et al., n.d; UK Green Building Council, 2022).
Design	Passive design in the (early) design phase; wall/insulation massing, facades, floors to create a embodied-operational balance for the whole lifecycle carbon. Natural or mixed ventilation, shading, maintain occupant behavior. Renewable energy sources in the operational phase management. (UK Green Building Council, 2020)	-The condition of the existing building and the retrofit approach. Implementing passive components to lower the embodied carbon. Renewable energy sources in the operational phase management. (Hill et al., n.d; UK Green Building Council, 2022).
Minimise waste	Mostly offsite prefabrication and on-site installation of components (Hill et al., n.d; UK Green Building Council, 2020)	If possible offsite prefabrication, but on-site prefabrication/installation in existing buildings process (Hill et al., n.d).
Repurposing	More carbon emission of embodied carbon by new buildings (Hill et al., n.d; UK Green Building Council, 2022).	Refurbishment of building = transform & reuse of existing building (Hill et al., n.d; UK Green Building Council, 2022).
Installation & systems	Taken into the process in an (early) design phase = minimize operational carbon and effective use of the building. (Attia et al., 2013; UK Green Building Council, 2020) Integrating the use of renewable energy sources / electric systems (solar, wind, hydrogen, geothermal, biomass, heat pumps, and other types of renewable energies.) (Hassan et al., 2023; Building Council, 2022).	Generally, switching from the existing fossil fuels supply (oil and gas) to a renewable energy source / electric system (solar, wind, hydrogen, geothermal, biomass, heat pumps, and other types of renewable energies) in the operational phase after analyzing the performance for the retrofitting approach. (Hassan et al., 2023; Building Council, 2022).
Onsite renewables (energy performance)	Calculate the supply and demand of the site & building for lifecycle cost and carbon assessment for the needed performance of renewables. (UK Green Building Council, 2020)	Feasibility of onsite renewables (solar photovoltaic (PV) panels) Calculate the supply and demand of the site & existing buildings for lifecycle cost and carbon assessment. (Hill et al., n.d; UK Green Building Council, 2022).
Monitoring & performance verification	To ensure low carbon benefits are realized, measurement, recording and evaluation of data should take place to verify the effectiveness of the initial measures of the new development. Key Performance Indicators (KPI) to ensure building operation remains as intended at design (set at the start of the project) (UK Green Building Council, 2022). Maintain effective operation. (Hill et al., n.d; UK Green Building Council, 2020)	To ensure low carbon benefits are realized, measurement, recording and evaluation of data should take place to verify the effectiveness of the retrofit measures. Key Performance Indicators (KPI) to ensure building operation remains as intended at design (set at the start of the project) (UK Green Building Council, 2022). Maintain effective operation. (Hill et al., n.d)

Table 1.0: The difference areas & components between the new building and existing building for a net-zero carbon building state
(Own ill, based on sources mentioned in the table cells)

1.2 Research problem

Problem statement

Studies of Hassan et al. (2023) and Rocha et al. (2024) state that in the context of architecture, construction, and real estate, AI applications have emerged as transformative tools, enhancing efficiency, sustainability, and overall performance. As highlighted by the pressing need for decarbonization in the built environment, especially the challenge in the existing building stock. Current studies revealed through the literature review, focused on individual areas in bridging the gap between AI technologies and zero-emission buildings within the broader terms of decarbonization. These individual areas typically center on linking AI with various facets such as design and construction processes, energy performance, cost-effectiveness, high-efficiency technical systems, and material lifecycle. The existing studies tend to approach these elements as isolated components. However, it is unclear how to incorporate these isolated components into artificial intelligence for analyzing, identifying, and optimizing the decarbonization process as transformative tools while integrating these decarbonization strategies in building retrofitting. The main barriers are the availability of detailed data, insufficient knowledge available in science and practice, and the appropriateness of tools, methods, and guidelines for incorporating artificial intelligence in the zero-emission process. Therefore, there is a lack of insight into the opportunities and challenges in artificial intelligence applications to enable and accelerate zero-emission buildings. The intersection of AI methodology and the zero-emission building process is explored in this research. To conclude, while artificial intelligence is to simulate certain human cognition, the research explores the limit of more guidance, and avenues for decision-making, possibly even surpassing human intelligence in the context of net zero buildings process.

1.3 Research relevance

1.3.1 Societal

This research addresses three important interconnected areas with profound societal and scientific relevance. Firstly, examining the nexus between climate change and the built environment, it underscores the urgent need for carbon emission reduction as a major contributor to global warming. Secondly, focusing on the built environment highlights the pivotal role of retrofitting existing buildings in significant decarbonization efforts. Lastly, the research explores advanced digital technology and artificial intelligence, offering transformative opportunities for a zero-carbon built environment. Hence, interconnecting these three areas accelerates the transition, driving societal change towards sustainability, and it contributes to understanding and implementing AI in zero-emission buildings for effective decarbonization. These themes advocate for urgent action, decarbonization, and advanced technologies, forming a narrative that contributes to a more resilient and low-carbon future.

1.3.2 Scientific relevance

The scientific relevance of this research lies in its contribution to the fields of sustainable construction, decarbonization, and artificial intelligence (AI) integration. By addressing the role of retrofitting in decarbonization strategies, this study expands the understanding of how existing buildings can be transformed to meet net-zero objectives, which is a growing area of interest in both environmental engineering and urban planning disciplines. Furthermore, the integration of AI into sustainable building practices is relatively nascent and offers new possibilities for optimization in building design, energy management, and material efficiency. This research provides a foundational exploration of how AI techniques can be leveraged to improve the efficiency of retrofitting projects, thus contributing to both theoretical knowledge and practical applications in building science, AI, and sustainable development. The study also bridges the gap between AI and construction management, creating a multidisciplinary framework for future research and development in these areas.

1.4 Research questions

The main research question that is answered in this research is:

How can AI integrate decarbonization strategies in building retrofitting to achieve net-zero building objectives in design and construction management?

Sub-research questions:

1. What is the concept of building retrofitting and its role in decarbonization strategies to achieve net-zero building objectives?

2. What is the current state of AI-driven techniques in sustainable building design?

3. What is the role of AI in decarbonization strategies to achieve net-zero building objectives?

4. How can design and construction management utilize AI in decarbonization strategies?

1.5 Research scope

The scope of this research focuses on exploring how AI-driven techniques can be integrated into the building retrofit process within the built environment, specifically targeting decarbonization strategies to achieve net-zero building objectives. The research is situated within the broader context of sustainable construction management and retrofit projects, with Turner & Townsend as the case study and interview organization.
The research aims to assess how AI can support the optimization of retrofitting projects, including energy efficiency improvements, carbon footprint reduction, and enhanced building performance. This involves evaluating Turner & Townsend's management practices and determining how AI can be used to improve decision-making, cost estimation, risk management, and project planning.

Although real-world AI applications in retrofitting at Turner & Townsend are not yet available, this research will provide a theoretical exploration of AI's potential across retrofitting phases. It will draw from best practices in AI applications in the wider construction industry to provide insight into how AI can streamline retrofitting processes, identify opportunities for energy savings, and optimize construction management workflows. Case studies and AI-driven techniques from outside of Turner & Townsend's immediate projects will be referenced to bridge the knowledge gap.

1.6 Research purpose

1.6.1 Goal and objectives

The goal of this research is to develop a comprehensive AI methodology for retrofitting buildings to achieve zero-emission objectives, particularly focusing on existing structures. The methodology aims to optimize decarbonization strategies while balancing environmental quality and cost-effectiveness. The objectives include exploring the opportunities and limitations of AI applications in retrofitting processes, understanding how AI can optimize decision-making in sustainability, and examining how AI-driven frameworks can contribute to the broader goal of zero-emission buildings. This research aims to set the groundwork for leveraging AI in transforming the built environment toward decarbonization.

1.6.2 Deliverables

This thesis aims to deliver a comprehensive roadmap for integrating AI into retrofitting projects. The frameworks ensure that AI capabilities align with practical challenges, enabling a structured, scalable, and efficient pathway to achieving net-zero building objectives.

Secondly, as a recommendation synthesized by the author an AI methodology that consist of two key components. Firstly, a key deliverable of this methodology will be AIR0, a framework designed to integrate AI-driven retrofitting processes effectively. AIR0 provides guidelines for implementing AI in the building sector, identifying critical success factors, risks, and potential barriers to adoption.

Additionally, the research will incorporate the DCM FRAIM, a decision-making framework aimed at improving construction management processes. This framework will provide a structured approach for design and construction managers to utilize AI in enhancing retrofitting outcomes. By addressing both environmental and cost-related objectives, DCM FRAIM contributes to the overall aim of creating a holistic AI-based approach for sustainable building management

1.6.3 Dissemination and Audiences

This research is aimed at professionals and academics within the field of sustainable building retrofitting and AI-driven decarbonization strategies. The primary audience includes construction management (consultants), project managers, real estate developers, and portfolio managers who are involved in building retrofitting and aiming to achieve net-zero carbon objectives. These professionals are seeking to integrate AI into their projects to optimize sustainability outcomes.

This audience is particularly interested in exploring how AI can be integrated into their projects to optimize sustainability, reduce carbon emissions, and enhance decision-making processes in both design and construction management. The research also caters to those in consultancy roles who are seeking insights on how to adopt AI methodologies in the broader context of building lifecycle management.

Additionally, this research may be valuable to design team stakeholders, such as architects, engineers, and construction management experts who are involved in retrofitting projects or aiming to apply AI methodologies in new buildings. AI experts (potential new role in construction industry) and data scientists focused on integrating advanced AI systems into building development and retrofitting processes can also find this work beneficial for identifying the types of data, tools, and frameworks required to achieve net-zero objectives effectively.

Finally, academic researchers and policymakers focused on sustainable urban development, decarbonization, and smart city initiatives could benefit from the findings and frameworks proposed in this research for future implementations of AI in the construction and built environment sectors.

CHAPTER 2

THEORETICAL BACKGROUND

2 | LITERATURE REVIEW

This literature review provides the theoretical foundation for understanding three critical components of this research, see Figure 2.0: building retrofitting techniques, the integration of artificial intelligence (AI) in sustainable building management, and the context of design and construction management. The first section focuses on the concept of building retrofitting, examining its role in decarbonization strategies aimed at achieving net-zero carbon emissions. This part of the literature review will answer SQ1: "What is the concept of building retrofitting and its role in decarbonization strategies to achieve net-zero building objectives?".

The second section delves into the current state of AI-driven techniques in sustainable building design and construction management. This part will answer SQ2: "What is the current state of AI-driven techniques in sustainable building design?".
Together, these two sections create a comprehensive framework for exploring how AI can be integrated into retrofitting strategies to enhance decarbonization efforts and improve overall building performance.

In the last part, the focus will be on design and construction management practices (DCM), which provide research context for the integration of AI and building retrofitting strategies. Although this section will not directly answer a specific sub-research question until the final sub-question 5, it will lay the groundwork by discussing current DCM practices.

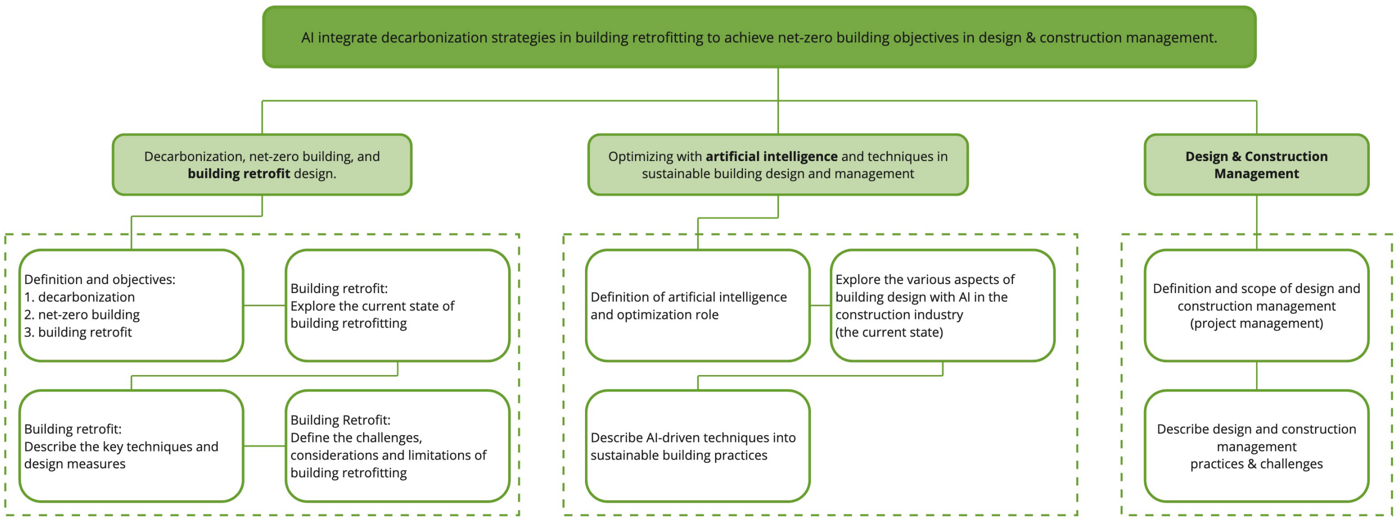

Figure 2.0: Literature review topics (own ill.)

2.1 Decarbonization and Net-Zero Building Objectives
2.1.1 Decarbonization
Definition
Decarbonization is the process of reducing carbon dioxide (CO_2) emissions through measures aimed at enhancing energy efficiency, transitioning to renewable energy, and minimizing the use of carbon-intensive resources. This concept plays a critical role in mitigating climate change by addressing the root causes of global warming. In the context of the building sector, decarbonization involves optimizing energy use, retrofitting existing structures, and incorporating technologies and practices that lower the carbon footprint across the life cycle of buildings (Marin et al., 2024; Pastore et al., 2023; Santamouris & Vasilakopoulou, 2021; Rizzoli et al., 2021).

According to Santamouris & Vasilakopoulou (2021), decarbonization within the building sector is closely linked to building retrofitting as a primary strategy for reducing greenhouse gas (GHG) emissions. Retrofitting involves updating the existing infrastructure of buildings to improve their energy efficiency and reduce their operational emissions. This process not only mitigates climate change but also has social implications, such as addressing energy poverty by lowering energy consumption and costs for vulnerable populations.

By integrating renewable energy sources and energy-saving technologies, retrofitting offers a sustainable pathway to decarbonization while ensuring that energy services remain accessible and affordable (Santamouris & Vasilakopoulou, 2021; Awuzie et al., 2024)

Objective
The primary objective of decarbonization is to achieve a net-zero emissions state, where the amount of carbon dioxide emitted is balanced by an equivalent amount of carbon removal or offset (Maka et al., 2024; Pastore et al., 2023). This objective is aligned with global climate agreements such as the Paris Agreement, which aims to limit global temperature increases to well below 2°C and pursue efforts to keep it under 1.5°C by mid-century (Rogelj et al., 2015). Achieving this goal requires systemic changes across various sectors, particularly the building industry, which is responsible for a significant portion of global emissions.

Furthermore, the successful implementation of decarbonization strategies depends heavily on supportive policy and regulatory frameworks. Rogelj et al. (2015) emphasize that strong government intervention is essential to create the conditions necessary for large-scale decarbonization efforts. Policies such as carbon pricing, energy efficiency regulations, and financial incentives for renewable energy adoption create a favorable environment for the building sector to decarbonize. In particular, regulatory frameworks that mandate energy efficiency standards in buildings, as seen in the European Union, are crucial for driving the adoption of retrofitting measures and reducing emissions across the built environment.

2.1.2 Net-Zero Carbon Emission Building

Definition
Net-zero carbon emissions are the balance between the total amount of carbon dioxide and other greenhouse gas emissions (GHGs) released into the atmosphere from human activities. They are balanced or offset by measures that remove an equivalent amount of carbon dioxide from the atmosphere or prevent its release. As illustrated in Figure 2.1, to achieve this equilibrium, through energy efficiency measures, transitioning to renewable energy sources, and minimizing the carbon footprint of materials and processes, while also employing strategies such as carbon offsetting or carbon removal projects to compensate for any remaining emissions that cannot be eliminated. The net-zero concept is crucial in the global fight against climate change, as outlined in international agreements like the Paris Agreement, which aims to limit global temperature rise to below 2°C, ideally 1.5°C, by the end of the century. To achieve this equilibrium, net-zero carbon emissions encompass both operational and embodied emissions as a whole carbon lifecycle approach (UK Green Building Council, 2019; World Green Building Council, 2024; Hill et al., n.d). Operational carbon emissions refer to the direct emissions resulting from the energy consumption of buildings, transportation, and other activities. Embodied carbon emissions, on the other hand, are the indirect emissions associated with the production, transportation, and disposal of building materials and other goods throughout their lifecycle (Roberts et al., 2020; Attia, 2018b).

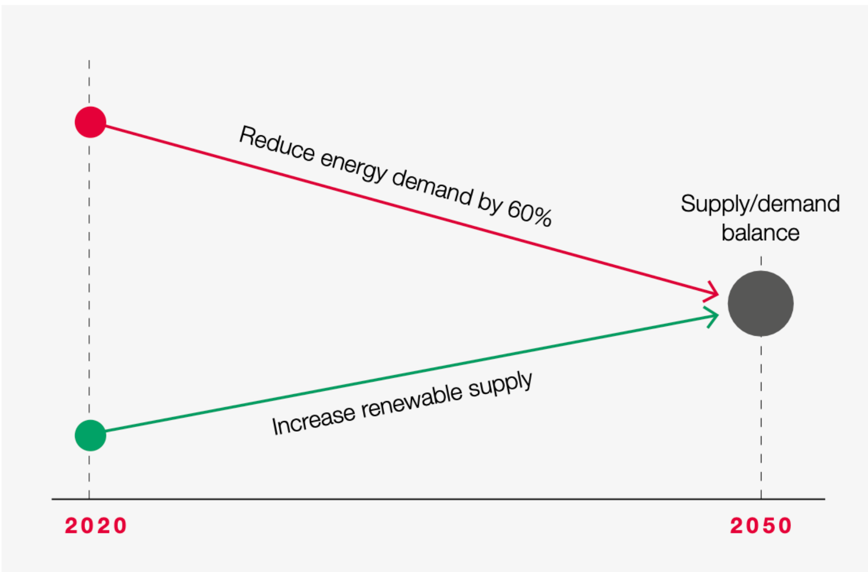

Figure 2.1: The decarbonization to net zero carbon (Hill et al., n.d)

Objective

According to the UK Green Building Council (2019), achieving net zero carbon emissions requires a multifaceted approach that includes the following steps: (1) Establish net zero carbon scope, (2) reduce construction impacts, (3) reduce operational energy use, (4) increase renewable energy supply, and lastly (5) offset any remaining carbon. These steps align with key issues and criteria for delivering buildings that contribute to a zero-carbon economy, as highlighted in research by Hill et al. (n.d). This research provides examples of solutions that fit into the five steps outlined by the UK Green Building Council (2019). These solutions include passive design, which addresses steps 1, 2, 3, and 4; building cleverly, relevant to steps 2 and 3; minimizing waste, which corresponds to step 2; transforming and reusing materials, connected to steps 2 and 3; implementing efficient systems and transitioning to electric, which aligns with steps 3 and 4; Managing demand, related to step 3; and lastly utilizing onsite renewables, associated with step 4 (Hill et al., n.d). Where all feasible measures for reducing carbon impacts have been reasonably exhausted, offsets can be utilized to cover any residual carbon, step 5, which involves offsetting any remaining carbon emissions through appropriate measures (UK Green Building Council, 2019; Hill et al., n.d).

Whole Carbon Lifecycle Assessment (Net Zero Building)

Life Cycle Assessment (LCA) is widely used to assess embodied carbon in the building sector and plays a key role in understanding the overall carbon impact of buildings (Amiri et al., 2021; Pomponi et al., 2018). While LCA is effective for evaluating carbon emissions across a building's lifecycle, it remains a data-intensive and time-consuming process with limitations in material data availability (De Wolf et al., 2017). Despite these challenges, LCA provides valuable insights into embodied carbon, which is crucial for achieving net-zero objectives. This methodology allows for the quantification of embodied carbon, operational energy, and other environmental impacts, providing a holistic view of a building's carbon footprint. While Life Cycle Assessment (LCA) is often used to assess embodied and operational carbon impacts across the building lifecycle (Amiri et al., 2021), this study focuses primarily on operational carbon risk management through tools like CRREM in the case study.

2.1.3 Formulation of Hypothesis 1:

AI can optimize data-driven coordination in net-zero building objectives. AI could support the overarching strategic approach needed to achieve net-zero carbon emissions through optimization, monitoring, and facilitation across diverse steps. This goes beyond simple decision-making by coordinating and balancing a multifaceted series of goals and actions to align with net-zero objectives.

2.2 Building Retrofitting Techniques and Design

This chapter aims to explore the key techniques and design measures associated with building retrofitting, specifically in the context of achieving net-zero building objectives. In total, eight retrofit measures in decarbonization have been found to answer sub-question 1: "What is the concept of building retrofitting and its role in decarbonization strategies to achieve net-zero building objectives?".

2.2.1 Building Retrofitting (existing buildings)

Definition

Building retrofitting refers to the process of modifying and improving the components of existing buildings to enhance their energy efficiency, functional performance, and structural integrity. Retrofit strategies typically involve the integration of new technologies and improvements aimed at optimizing the use of natural resources, such as energy and water, as well as reducing greenhouse gas emissions (De Oliveira et al., 2024; Panakaduwa et al., 2024). Over time, building retrofits have gained significant global traction as an effective means to improve energy efficiency and lower emissions, thereby aligning with the goals of sustainable development (Sarihi et al., 2020).

Objective

The primary objective of retrofitting buildings is to enhance energy efficiency, reduce operating costs, and minimize environmental impacts by decreasing the reliance on non-renewable energy sources and cutting carbon emissions. In addition to reducing energy consumption, retrofitting strategies can also lead to increased property values, improved occupant comfort, and long-term sustainable living qualities (He et al., 2021). Policies, laws, and incentives at both regional and global levels, such as energy efficiency standards and carbon reduction targets, have been established to encourage building retrofits (Sarihi et al., 2020; De Oliveira et al., 2024). The economic and social benefits of retrofitting further contribute to its growing adoption as a cost-effective strategy to meet sustainability and decarbonization objectives and align with the need to modernize the existing building stock, which comprises the majority of buildings globally.

2.2.2 Retrofit Techniques and Design Measures

The successful retrofitting of buildings to decarbonize and achieve net-zero carbon objectives relies on a combination of techniques and design measures aimed at addressing both embodied carbon and operational carbon. Embodied carbon refers to the total greenhouse gas emissions associated with the construction, materials, and processes used throughout the building's lifecycle, while operational carbon involves the emissions generated from energy use during the building's daily operations.

The following eight key techniques and design measures have been briefly elaborated to provide an understanding of the most effective retrofitting approaches. These measures are essential for enhancing building performance and achieving net-zero energy targets (Building Council, 2022; UK Green Building Council, 2022; Hassan et al., 2023; Hill et al., n.d.). They encompass both energy-efficient technologies and sustainable design practices aimed at reducing operational and embodied carbon.

Embodied carbon (Building Envelope):

1. Insulation Upgrades:
Improving insulation in walls, roofs, and floors is one of the most effective ways to reduce heat loss during winter and heat gain in summer, significantly lowering energy demand for heating and cooling. Advanced insulation materials, such as spray foam, mineral wool, and rigid foam boards, provide higher thermal resistance (R-values), contributing to the building's overall energy efficiency.

2.Window and Door Upgrades:
Replacing old windows and doors with energy-efficient alternatives, such as double or triple-glazed windows with low U-values, helps to reduce heat transfer and prevent air leakage. Low-emissivity (Low-E) coatings on windows also improve thermal performance by reflecting heat while allowing light to pass through.

3.Material Upgrades:
Using sustainable and low-carbon materials during renovations helps reduce the embodied carbon of the building. For example, recycled materials, timber, and eco-friendly concrete alternatives can lower the overall environmental impact of the retrofit. These materials contribute to a circular economy and enhance the sustainability of the building.

Operational carbon (Installations and systems):

4.HVAC System Improvements
Upgrading to high-efficiency heating, ventilation, and air conditioning (HVAC) systems can drastically reduce energy consumption. This includes installing heat pumps, which transfer heat instead of generating it, and smart thermostats that allow for optimized temperature control based on occupancy and weather conditions. According to studies, improved HVAC systems can reduce energy use by 20-40%.

5.Lighting Upgrades
Switching to LED lighting significantly reduces energy consumption compared to traditional incandescent or fluorescent bulbs. LEDs are more energy-efficient and have a longer lifespan, contributing to both energy savings and reduced maintenance costs.

6.Renewable Energy Integration
Installing solar panels or other renewable energy systems, such as wind turbines or geothermal energy, allows buildings to generate electricity on-site. This reduces reliance on the grid and lowers operational carbon emissions. Solar PV systems have become increasingly cost-effective, with some installations achieving a return on investment within five to ten years.

7.Building Management Systems (BMS)
Integrating smart building technologies and automation systems enables more efficient energy management by monitoring and adjusting building systems in real time. These systems can optimize lighting, HVAC, and other energy-consuming operations based on occupancy, weather patterns, and energy prices, leading to significant energy savings.

8.Water Efficiency Measures
Implementing low-flow fixtures, rainwater harvesting systems, and greywater recycling reduces water consumption and decreases the burden on municipal water systems. Efficient plumbing fixtures, such as low-flow toilets and faucets, help conserve water without compromising functionality.

2.2.3 Shortcomings in Building Retrofit

Challenges
Building retrofitting projects, especially those targeting improved energy efficiency, face several significant challenges. One of the most notable obstacles is the high initial cost associated with deep retrofits. These projects often require substantial upfront investment, particularly when advanced technologies and comprehensive renovations are involved. Such financial barriers can deter property owners and developers from pursuing retrofitting, even when the long-term energy savings and sustainability benefits are clear (Shaikh et al., 2017).
Additionally, the technical complexity of retrofitting, especially in older or heritage buildings, presents another major challenge. Retrofitting these structures requires meticulous planning to preserve their architectural and structural integrity, making the process more intricate and time-consuming. The necessity of maintaining historical characteristics while integrating modern energy-efficient technologies adds layers of complexity to the retrofitting process (Petkov et al., 2023; UK Green Building Council, 2022).

Moreover, the demand for retrofitting expertise has outpaced the availability of skilled labor, leading to a shortage of trained professionals. The specialized knowledge required to implement energy-efficient retrofitting techniques is in high demand, but the supply of adequately skilled professionals is insufficient. This gap in labor availability can delay projects and drive-up costs, further complicating an already challenging retrofitting landscape (UK Green Building Council, 2022).

Considerations
The age and condition of a building play an important role in determining the scope and complexity of the retrofitting process required to meet modern energy standards. Older buildings often need extensive updates, such as improved insulation, upgraded HVAC systems, and the integration of renewable energy technologies. These structures were originally built without energy efficiency as a primary consideration, making retrofitting more resource-intensive and challenging compared to newer buildings (UK Green Building Council, 2024).

Further, when selecting materials for retrofitting, it's essential to prioritize sustainable, low-carbon options that can help reduce the embodied carbon of a building. However, these materials also need to meet performance standards like durability and thermal efficiency, and they must be economically viable to ensure the retrofit remains feasible (Hill et al., n.d; UK Green Building Council, 2022).

Also, retrofitting historic or culturally significant buildings presents a unique challenge, as it involves balancing energy performance improvements with the preservation of the building's architectural and structural integrity. Sensitive interventions are required to enhance energy efficiency while maintaining the building's aesthetic and heritage value, which often adds to the complexity and cost of the project. This delicate balance can make the retrofitting of such buildings more time-consuming and expensive (Hill et al., n.d; UK Green Building Council, 2022).

Limitations
Data gaps present a significant obstacle in retrofitting projects, especially when comprehensive data for materials and retrofit strategies are unavailable. These gaps hinder decision-making processes, making it difficult for building owners and designers to assess the long-term benefits and feasibility of various retrofit options. Without sufficient performance data, it's challenging to accurately forecast the energy savings, and

sustainability impacts of certain materials or technologies, leading to uncertainty and potentially suboptimal choices (UK Green Building Council, 2022).

Besides, regulatory hurdles further complicate retrofitting efforts, particularly when dealing with the strict requirements of building codes, energy efficiency standards, and preservation laws. These regulations can significantly delay projects, especially for older buildings with unique architectural or historical significance. Navigating these often conflicting requirements—balancing energy improvements with heritage preservation—adds both complexity and cost to retrofit projects, requiring additional planning and expertise (Hill et al., n.d; UK Green Building Council, 2022).

Finally, the return on investment (ROI) for retrofitting, while offering potential long-term savings, remains a key concern for many building owners. The payback period for these investments can extend over several years, making deep retrofits less attractive despite their clear benefits, such as reduced energy consumption and improved building performance. This financial barrier discourages many property owners from committing to comprehensive retrofit projects, particularly when short-term costs seem high. (Shaikh et al., 2017; UK Green Building Council, 2022).

2.2.4 Formulation of Hypothesis 2:

Machine learning (a subset of AI) can analyze and enhance the retrofit techniques and design measures more effectively than traditional approaches. Machine learning, as introduced in the following chapter 2.3, could be strategically integrated in retrofit techniques to address both embodied carbon and operational carbon, to learn from existing or previously applied strategies to refine and develop improved applications for new projects.

2.3 Optimizing with Artificial Intelligence (Construction Industry)

This part of the literature review centers on the exploration of Artificial Intelligence as a tool and its optimization role in the construction industry. Moreover, understanding the real-world implementations within sustainable building design and management is anchored in the six dominant subsets of AI. These insights form the foundation for the next section, which will delve into five key real-world implementations, demonstrating the practical application of AI in sustainable building design and management.

2.3.1 Definition

Artificial Intelligence (AI) has rapidly become an integral component in revolutionizing various industries, and the built environment is no exception. As Atske (2022) stated, AI is positioned to integrate into most aspects of life, producing new efficiencies and enhancing human capacities. This anticipated integration marks a significant paradigm shift, positioning AI as a cornerstone in the evolution of our surroundings and daily experiences. In the context of architecture, construction, and real estate, AI applications have emerged as transformative tools, enhancing efficiency, sustainability, and overall performance (Hassan et al., 2023; Rocha et al., 2024).

The term artificial intelligence has been used for decades, carrying evolving meanings and connotations. A simplistic definition is systems capable of performing tasks that normally require human intelligence (Murphy, 2019). These tasks include learning from experience, adapting to changing inputs, reasoning, and problem-solving. AI aims to create machines capable of simulating human cognition, enabling them to understand, analyze, and respond to complex situations, ultimately improving performance and decision-making (Conway, 2018; Naeem et al., 2023; Tekouabou et al., 2023).

The diverse forms of AI deployed in the built environment range from advanced data analytics to machine learning algorithms, robotics, and smart technologies. These innovations not only streamline processes but also contribute to creating intelligent and responsive structures. In this exploration, delving into the different subfields of AI in the construction industry. Subsequently, examining how these technologies are contributing to the current state of the construction industry and how these AI technologies can be applied to zero-emission building objectives.

2.3.2 Optimization Role and Overview of AI Subsets

In the realm of Artificial Intelligence, a broad spectrum of cutting-edge technologies collaboratively defines its complex skills, revolutionizing how computers perceive, learn, and interact with the world. AI is based on different forms and methods of foundational technologies. These complementary technologies contribute to the diverse capabilities of AI systems, enabling them to perform tasks ranging from data analysis and pattern recognition to language understanding and decision-making. AI can be divided in different forms that shape its multifaceted landscape of performing task with capability to mimic certain aspects of human intelligence. Therefore, to understand the current state of AI in the construction industry, it is important to understand and identify the major subfields of artificial intelligence.

In this literature review, the six distinctive subsets of artificial intelligence are examined, ranging from the most distinctive and widely applied types to less prevalent ones. As Keserer (2024) and Smolic (2023) categorized, AI into six forms: (1) Machine learning, (2) Deep learning, (3) Robotics, (4) Neural networks, (5) Natural language processing, and (6) Genetic algorithms, each representing a distinct approach to solving complex problems and advancing the capabilities of intelligent systems. While these forms of AI technology are not mutually exclusive, these technologies are often used in combination. For instance, when discussing the implementation of Neural Networks, it inherently implies the utilization of broader Machine Learning methodologies. Together, they form a valuable framework for comprehending the current state of AI and anticipating its future advancements

(Keserer, 2024; Smolic, 2023). As mentioned by the IBM Data and AI Team (2023), "artificial intelligence, machine learning, deep learning, and neural networks can be conceptualized as a hierarchical sequence of AI systems, with each subsequent system incorporating the preceding one." Artificial intelligence is the overarching system. Machine learning is a subset of AI. Deep learning is a subfield of machine learning, and neural networks make up the backbone of deep learning algorithms. The distinguishing factor between a single neural network and a deep learning method lies in the number of node layers, or depth, with the latter requiring more than three layers (IBM Data and AI Team, 2023). See figure 2.2 with AI being the umbrella term, illustrates the intricate layers and showcasing the relationships and distinctions between these interconnected domains.

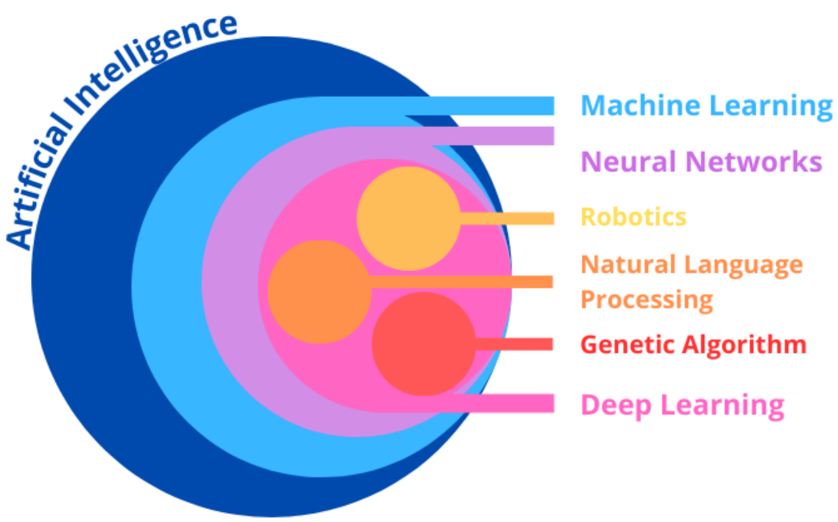

Figure 2.2: AI as an umbrella term for different subsets of technologies within artificial intelligence (own work, 2024).

Machine learning

Machine Learning (ML) is a powerful and transformative subset of artificial intelligence that empowers computers to learn from data and improve their performance over time without explicit programming. ML empowers machines to recognize patterns, make informed judgments, and adjust to new data, imitating a type of artificial intelligence that acquires knowledge and develops (Smolic, 2023). The core of machine learning rests in its capacity to evaluate extensive quantities of data, identify complex patterns within that data, and utilize those patterns to generate predictions or make judgments. Illustrating this concept, consider the predictive text feature on your smartphone. By learning from your typing patterns, this system showcases the essence of pattern recognition within machine learning. It enables the computer to identify patterns, learn, perform specific tasks, and deliver accurate results. ML algorithms differ from traditional programming in that they utilize data-driven insights to improve their comprehension and effectiveness, rather than relying on explicit instructions for specific tasks (Conway, 2018; Viriato, 2019). Furthermore, generative AI, which is a type of machine learning algorithm, focuses on creating new content such as images, text, or data by learning from patterns within existing datasets. This capability enhances the AI's ability to simulate realistic scenarios and produce innovative solutions, such as AI-generated designs or optimized construction plans Viriato, 2019.

As we delve deeper into the capabilities of machine learning, it's important to draw a distinction between the broader realm of artificial intelligence and the specific approach of machine learning within it. While artificial intelligence encompasses the broader concept of creating intelligent machines, machine learning is a specific approach within AI, focusing on the development of algorithms that enable machines to learn and adapt. While AI aims to replicate human intelligence across various domains, machine learning leverages algorithms to train machines on large datasets, enabling them to make informed decisions based on patterns and correlations (Conway, 2018; Keserer, 2024; Smolic, 2023).

(Artificial) Neural Networks

Neural networks (NN), a subset of artificial intelligence (AI) and machine learning, serve as the backbone of deep learning algorithms, mimicking the structure and function of the human brain through interconnected nodes or neurons. Inspired by their biological counterparts, these networks excel at recognizing patterns, making decisions, and executing tasks across diverse domains (Giudici et al., 2024; IBM Data and AI Team, 2023; Rossini, 2011). The potential of neural networks is expansive, and their impact is particularly notable in industries such as finance, healthcare, and manufacturing, where they enhance decision-making processes (Keserer, 2024).

As Keserer (2024) points out, neural networks exhibit remarkable adaptability in handling complex decision-making tasks, overcoming the deterministic limitations of traditional computer algorithms. The probabilistic nature of neural networks, coupled with ample computing power and labeled data, makes them versatile problem solvers across a broad spectrum of challenges. Despite their power, however, challenges such as limited interpretability and sensitivity to training data representation persist, as highlighted by both Keserer (2024) and Smolic (2023).

Nevertheless, neural networks remain a potent tool for improving decision-making processes. These networks meticulously analyze vast datasets, extracting meaningful insights to deliver tailored recommendations and search results. The foundational role of neural networks in machine learning becomes evident through their ability to rapidly classify and cluster data, thereby significantly expediting tasks such as speech and image recognition (Smolic, 2023; IBM Data and AI Team, 2023).

Deep learning

Deep learning (DL), a subset of artificial intelligence, machine learning and neural networks, has garnered significant attention due to its remarkable achievements in various domains such as computer vision, speech recognition, and autonomous vehicles (Keserer, 2024). As Keserer (2024) explained, the core of deep learning are neural networks, intricate structures comprising layers of interconnected processing nodes or neurons. The depth of these networks, characterized by numerous hidden layers, is crucial for capturing and comprehending intricate patterns in data.

The process begins with an input layer that receives external data, like images or sentences. Following layers analyze this input and transmit it across the network until the ultimate output layer produces predictions or classifications. The term "deep" in deep learning refers to the network's ability to have numerous layers, which allows it to effectively handle intricate data patterns (Smolic, 2023; Keserer, 2024). Concisely, DL is a computational approach that imitates the structure and function of the human brain. It analyzes large amounts of data and identifies complex patterns, enabling machines to make precise decisions and predictions. As an example, given by Smolic (2023) explained, Deep Learning models can help find tumors in medical images, which can lead to earlier diagnoses and better results for patients. In finance, these models help predict what will happen in the stock market, which helps investors make smart choices and get the best results.

As we explore the possibilities of deep learning, it becomes clear that although it is highly effective at automating the extraction of features and managing complex data patterns, there are certain areas that require additional improvement. As per comparison made by the IBM Data and AI Team (2023), deep learning, in contrast to machine learning, automates a greater portion of the feature extraction process, thereby reducing manual intervention. By observing patterns in data, deep learning models can appropriately cluster inputs. For instance, images of pizzas, burgers, and tacos can be grouped based on identified similarities or differences. A DL model necessitates a larger number of data points to enhance accuracy, while a machine-learning model depends on a smaller amount of data due to its underlying data structure (IBM Data and AI Team, 2023).

Robotics

The integration of robotics plays an important role in the broader landscape of artificial intelligence (AI), involving the development and programming of physical machines capable of interacting with the environment and autonomously executing tasks. This seamless interaction serves as a bridge between AI and the physical world (Brady, 1984). Robotics, as a specialized subset of AI, entails deploying AI systems in physical forms to control objects in the real world. From industrial robots performing complex manufacturing tasks to smart drones aiding in search and rescue missions, robotics exemplifies how AI can be applied in practical scenarios.

Industrial (construction) robotic systems are widespread, particularly in automating manufacturing processes. These systems excel at handling dangerous, dirty, or monotonous tasks, contributing to saving lives and extending the longevity of human jobs. The incorporation of AI enhances the speed and accuracy of manufacturing processes (Keserer, 2024).
Lastly, as Smolic (2023) notes, ongoing progress in robotics is anticipated to usher in the era of collaborative robots, or "cobots. Cobots have the potential to work alongside humans in various fields, enhancing safety, productivity, and efficiency. Particularly in sectors like manufacturing, healthcare, and logistics, robots can assume repetitive tasks with precision, allowing human workers to focus on more intricate and creative endeavors. This evolution signifies a promising future where humans and robots collaborate synergistically to create a more efficient and innovative working environment.

Natural Language Processing

Natural Language Processing (NLP) is a subset of artificial intelligence, and Deep Learning focused on enabling machines to comprehend, interpret, and respond to human language. NLP allows machines to analyze text data, extract meaning, and generate human-like responses, leading to innovations such as voice assistants (e.g., Siri and Alexa) and machine translation tools (Keserer, 2024; Smolic, 2023). Explained by Keserer (2024), NPL applications extend to chatbots proficient in handling customer queries, sentiment analysis tools assessing public opinion, and virtual assistants undertaking tasks like scheduling appointments and sending emails on behalf of users. Search engines also use NLP. Google, for instance, uses NLP to figure out what pages are about. This is how Google can return results for queries that are not just keywords (Smolic, 2023).
The significance of Natural Language Processing plays a role because it can handle subtleties in language, which makes jobs like text classification, sentiment analysis, and machine translation possible. It is a vital part of making smart systems like chatbots and personal helpers. As artificial intelligence continues to advance, NLP is poised to become even more sophisticated and accurate (Keserer, 2024).

Genetic Algorithm

Genetic Algorithms (GAs) represent an optimization subset within AI, and Deep Learning. Drawing inspiration from the principles of natural selection and evolution, GAs mimic the process by which organisms with advantageous traits are more likely to survive and reproduce. Similarly, in GAs, solutions demonstrating greater fitness for a given problem are favored and reproduced, gradually converging toward optimal solutions (Smolic, 2023). An example given by Keserer (2024), genetic algorithms are also used in machine learning and AI to improve neural networks and make them better at things like recognizing faces or playing strategy games like Go and chess.

According to Keserer (2024), the implementation of GAs typically involves four main steps: Initialization, wherea population of potential solutions is randomly generated; Evaluation, assessing the fitness of everyone against predefined criteria; Selection, favoring the fittest individuals for reproduction; and Reproduction, generating offspring from selected parents through crossover and/or mutation operators. These steps are iteratively repeated until a satisfactory solution is found or specific stopping conditions are met (Keserer, 2024). Despite their growing popularity, GAs are not without challenges. They may exhibit slower convergence on solutions, particularly in complex or expansive search spaces. Additionally, their implementation can pose difficulties for those with limited experience in computer programming or mathematics (Keserer, 2024).

Table 2.3 visuals the integration of retrofit techniques aimed at reducing either embodied carbon or operational carbon with the appropriate AI subsets. This visualization highlights how different AI technologies can be applied to specific retrofit strategies to enhance their effectiveness in achieving carbon reduction targets. For instance, machine learning algorithms can optimize all retrofit measures, while the genetic algorithm is for complex design optimization.
The figure categorizes these connections to show how AI-driven tools enhance retrofit measures in areas such as energy efficiency, material selection, and smart building technologies. For a detailed breakdown of the specific AI subsets and their corresponding retrofit techniques, which provides a comprehensive overview of how these technologies align with decarbonization efforts (UK Green Building Council, 2022; Smolic, 2023; Petkov et al., 2023; Keserer, 2024; UK Green Building Council, 2024; Hill et al., n.d.).

2.4 AI Techniques in Sustainable Building Design and Management

Subsequently, by categorizing the current state of real-world implementation into five key themes, including (1) Design, (2) Energy performance, (3) Automation and robots in construction, (4) Smart buildings, and (5) Material Database, answering sub-question 2: "What is the current state of AI-driven techniques in sustainable building design?".

2.4.1 Design
In architectural and planning, according to Nagy et al., (2017) generative design tools facilitate the exploration of diverse possibilities, speeding up the design process and fostering innovation. These tools analyze data inputs to generate multiple design alternatives, helping architects find optimal solutions that balance aesthetics and functionality (Nagy et al., 2017).

AI's subset, Genetic Algorithms offers a groundbreaking approach to optimization. These algorithms mimic the principles of natural selection and evolution, generating diverse solutions and iteratively refining them to find the most optimal design solutions. The integration of Genetic Algorithms in architectural and planning is driven by the goals of optimizing design solutions to fulfill changing environmental, functional, and aesthetic needs.

First, structural designs benefit significantly from Genetic Algorithms as well. The algorithms assist in the exploration of diverse structural configurations, optimizing for factors like load distribution, material efficiency, and overall stability. This iterative process allows architects and engineers to discover innovative structural solutions that might be challenging to identify through traditional methods (Hamidavi et al., 2018).

In addition, parametric design finds a natural alignment with Genetic Algorithms. Parametric design involves defining parameters and rules that drive the form and function of architectural elements. Genetic Algorithms enhance this process by automating the exploration of parameter combinations, facilitating the rapid evolution of design alternatives, and supporting the realization of intricate and customized architectural solutions (Nagy et al., 2017; Turrin et al., 2011).

Lastly, urban planning, as a broader field encompassing the design and organization of urban spaces, experiences a significant impact from Genetic Algorithms. These algorithms aid in optimizing land use, transportation systems, and infrastructure planning. By considering various parameters and constraints, Genetic Algorithms contribute to the development of sustainable and efficient urban environments (Son et al., 2023).

AI subfields:	Machine learning (ML)	(Artificial) Neural Networks (NN)	Deep learnings (DL)	Robotics	Natural Language Processing (NLP)	Genetic Algorithm (GA)
Net Zero Carbon Retrofit phases						
B1. Embodied carbon impacts						
1. Building envelope improvements	ML analyzing various factors such as building materials, insulation properties, and climate data to recommend the most effective retrofit solutions.	<u>*COMPLEX PROJECTS:*</u> NNs can utilized where the relationships between building envelope features and energy performance are highly complex or where there are large amounts of data to analyze for finding intricate patterns.		Robotics can automate construction tasks related to building envelope improvements, reducing labor costs and improving efficiency.		GAs can optimize building envelope designs to minimize embodied carbon emissions while meeting performance requirements.
2. Energy effiency measures	Based on the "Energy Audit" in the pre-phase, ML estimate the energy consumption and carbon emissions associated with different building configurations, helping designers make informed decisions to minimize embodied carbon in the application of the applied project.		DL models can simulate complex interactions between different factors in energy effiency and optimize building configurations for minimal embodied carbon.			
3. Materials and circular alternatives	ML algorithms can analyze materials lifecycle data and recommend circular economy strategies to minimize waste and carbon emissions.				NLP can analyze textual data materials specifications and regulations to identify sustainable and circular alternatives and considering factors such as material composition, sourcing practices, and end-of-life considerations.	GA can optimize the selection and use of materials to achieve net-zero and minimize carbon emissions. By exploring the trade-offs between different material choices, lifecycle processes and considerating the potential for reuse, recycling and remanufacturing.
4. Life Cycle Analysis (LCA) and Carbon offsetting	ML involves analyzing extensive environmental datasets to assess the impact of various carbon offset strategies and enhance their effectiveness	NNs excel in discerning intricate patterns and relationships within LCA datasets. This capability is particularly beneficial when analyzing complex interdependencies between different lifecycle stages and environmental impacts, allowing for a more comprehensive understanding of the system.				GA optimize parameters and decisions in conducting Life Cycle Analysis (LCA) studies. They identify solutions and trade-offs between environmental impacts and performance criteria.
5. Building Information Management (BIM)	ML facilitates data integration and analysis to improve collaboration and decision-making throughout the retrofit process. A foundation for more advanced analyses.	NNs can analyze BIM data to identify potential clashes or conflicts in building designs. Additionally NNs, are suitable for simpler tasks like prediction or classification, offering efficient solutions for common challenges in BIM.	DL models specialize in analyzing 3D BIM models to identify energy-efficient design features and suggest optimizations. Their ability to handle complex data structures and extract nuanced insights makes them particularly beneficial for more sophisticated analyses and optimization tasks within BIM.			
6. Business case & cost estimation (stakeholders)	ML algorithms can analyze historical project data to estimate costs and risks associated with different retrofitting options.	<u>*COMPLEX PROJECTS*</u> : NNs specialize in predicting project costs or revenue streams based on a wide range of input variables, including qualitative and quantitative factors. Additionally, NNs can be applied for time-series forecasting for estimating future costs or revenues based on historical trends and external factors.			NLP can analyze stakeholder input and project requirements to generate comprehensive business cases and cost estimates. The stakeholder needs, project objectives, and constraints, synthesizing this information into detailed documentation for decision-making.	
B2. Operational carbon targets						
1. Energy effiency measures	ML-driven analyze and simulation models can simulate building energy performance under different scenarios, allowing designers to evaluate the impact of energy efficiency measures on operational carbon emissions and energy effience measures in the embodied carbon emission as a whole life carbon. .		DL models can by enabling accurate prediction, proactive fault detection, adaptive control, personalized energy management, and optimized building design.			
2. Renewable energy integration	ML analyze weather patterns, energy demand, and system performance data to optimize the operation of renewable energy systems, maximize energy generation, and minimize reliance on fossil fuels to zero.					GAs can optimize the placement and sizing of renewable energy systems to maximize energy generation and minimize carbon emissions.
3. Smart building technologies	ML analyze building automation and control systems. To optimize occupant comfort, energy effiency, and overall building performance.		DL-based models can recommend adaptive control strategies to optimize energy efficiency and reduce carbon impacts by learning from historical data and adapting to changing environmental conditions in real-time.		NLP techniques can analyze building automation data, maintenance logs, and occupant feedback to understand building performance issues and recommend smart building technologies.	
4. Monitoring and performance tracking	ML algorithms can perform real-time monitoring of building systems and performance metrics by analyzing streaming data from sensors and IoT devices. Predict equipment failures, and optimize maintenance schedules.		DL-based predictive models inform proactive maintenance and optimization strategies by anticipating equipment degradation, energy consumption trends, and building system efficiency over time.	Robotics can automate data collection tasks for monitoring building performance, improving accuracy and efficiency.	NLP analyzing textual data, automating reporting and documentation, integrating unstructured data with analytics, and facilitating human-machine interaction during the operational building energy usage and system performance phase.	

Table 2.3: Retrofit Techniques/Measures with AI subsets (own work, based on literature review, 2024).

2.4.2 Building Energy Performance

Energy performance sector involves the application of advanced AI techniques to enhance the efficiency, reliability, and sustainability of energy systems. *By leveraging machine learning algorithms, deep learning, nature-inspired optimization methods, and (artificial) neural networks, employed to enhance energy performance, optimize consumption, and streamline energy systems.*

Machine Learning plays a foundational role in optimizing energy consumption in buildings, offering solutions that adapt to dynamic usage patterns. ML algorithms analyze historical energy data, weather conditions, and occupant behavior *to predict future consumption patterns, allowing for the proactive adjustment of building systems for optimal efficiency* (Mousavi et al., 2023; Hassan et al., 2023).

Deep Learning distinguished by its adeptness in processing intricate and non-linear relationships within extensive datasets, finds application in tasks integral to energy infrastructure. Specifically, as mentioned by Hassan et al. (2023), in domains like smart grids, deep learning algorithms excel in *accurate demand forecasting, anomaly detection, and predictive maintenance*. This accuracy enhances grid management by allowing utilities to allocate resources more effectively, preventing potential overloads and ensuring a reliable and efficient power supply (Hassan et al., 2023).

Genetic algorithms, nature-inspired algorithms, operate by simulating the process of natural selection. In the context of energy-related tasks, GA can be employed *to optimize the configuration of renewable energy systems*. For example, these algorithms can iteratively generate and refine solutions for the placement of solar panels or wind turbines in a way that maximizes energy yield while considering factors like available sunlight or wind patterns (Hassan et al., 2023; Mousavi et al., 2023).

As for Neural Networks, their application in energy consumption extends to predictive maintenance in power plants. By analyzing historical data on equipment performance and identifying patterns indicative of potential failures, NN *enable the prediction of maintenance needs*. This proactive approach minimizes downtime, reduces costs, and ensures the continuous and reliable operation of energy infrastructure. Additionally, Neural Networks can be employed in *real-time monitoring of energy consumption patterns* in smart buildings, facilitating immediate adjustments for optimal efficiency (Mousavi et al., 2023).

Therefore, monitoring energy performance is essential for diagnosing and analyzing energy consumption to collect and analyze real-time data in buildings. Energy performance involves evaluating the carbon emissions produced while it is being used. This approach, as outlined by Häkkinen et al. (2015), focuses on continuously monitoring and evaluating the energy efficiency of a building throughout its operational lifecycle. During this operational phase, it’s crucial to consider operational carbon emissions, which represent the emissions associated with the energy used to run the building, as emphasized by Roberts et al. (2020). According to Farzaneh et al. (2021), the integration of modern technologies in monitoring energy performance will predicts the future trends of energy demand using historical data.

2.4.3 Automation and Robots in Construction

The field of construction robotics is expanding, utilizing the capabilities of machines and artificial intelligence to increase productivity, enhance safety, and transform the methods of building design and construction (Monika, 2023; Delgado et al., 2019). The construction industry is characterized by a high degree of reliance on manual labor. The implementation of robotic systems and automation in various sectors has demonstrated significant efficacy in reducing labor expenses, while simultaneously enhancing productivity and quality (Delgado et al., 2019). It involves the integration of machines, artificial intelligence, and advanced technologies to perform various tasks traditionally done by human workers.

As emphasized by Monika (2023) and Delgado et al., (2019), the introduction of Robotics has brought about a paradigm shift in construction practices. Robotic applications in construction, such as bricklaying and welding, exemplify the capability of automation to execute tasks with precision and speed. These robotic systems not only contribute to increased efficiency but also address challenges associated with labor shortages, safety concerns, and the need for faster project completion (Delgado et al., 2019; Abioye et al., 2021).

Moreover, the infusion of Machine Learning (ML) has ushered in a new era of streamlined building maintenance.

From routine inspections to repairs and predictive maintenance, ML algorithms leverage historical data and real-time insights to optimize these tasks. This predictive capability not only enhances the longevity of structures but also minimizes downtime and operational disruptions, ensuring that buildings and infrastructure are maintained at peak performance (Delgado et al., 2019; Abioye et al., 2021).

2.4.4 Smart Buildings

Smart or intelligent buildings represent a shift from the environmentally focused approach of green buildings, leaning more heavily on information technology (IT). In these buildings, facilities, and systems such as air conditioning, lighting, electricity, and security undergo integrated and automated management and control. The primary objectives are to enhance energy efficiency, comfort, and security. Such buildings seamlessly integrate building management with IT systems, enabling dynamic optimization of system performance and streamlining facility operations (Rodríguez-Gracia et al., 2023; Begg & Hassan, 2006).

The advancement of building control systems into new levels of adaptability and responsiveness is increasingly dependent on subsets of Artificial Intelligence (AI), particularly neural networks and machine learning. Smart buildings encompass a paradigm shift from traditional structures, incorporating advanced technologies that enable proactive and adaptive responses to the dynamic needs of occupants and environmental conditions (Farzaneh et al., 2021; Seagraves, 2023).

At the forefront of this revolution are Neural Networks, a subset of AI and ML models inspired by the human brain's intricate neural architecture. An example given by Farzaneh et al. (2021), neural networks in building controls play a pivotal role in orchestrating various elements, including adaptive lighting, HVAC (Heating, Ventilation, and Air Conditioning) systems, and occupancy-based controls to achieve a trade-off between accuracy and computational efficiency (Begg & Hassan, 2006).

In addition, machine learnings ability to learn from data allows it to discern non-linear relationships, crucial in understanding complex systems like energy demand. ML facilitates superior performance by analyzing input data, making predictions, and evolving over time (Farzaneh et al., 2021). Smart buildings learn by information to enhance automation, personalization, and security overtime. The aim is to create intelligent, adaptive, and secure living environments for enhanced comfort and efficiency (Seagraves, 2023).

Moreover, human-computer interaction in smart buildings, especially with the integration of natural language processing, is a bridging subset in the built environment between human and computer. This category delves into the complex relationship between humans and technology in smart buildings. It reveals a story where ease of use and interaction redefine our perception and engagement with our living and working spaces. The inclusion of NLP enhances user interactions within smart building interfaces, making them more intuitive and user-friendly. An example is voice-controlled systems, as part of human-computer interaction, contribute to hands-free and seamless user experiences. Ensuring ease of use is paramount for widespread adoption and effective utilization of smart building technologies (Seagraves, 2023; Begg & Hassan, 2006). Therefore, the integration of human-computer interaction in smart buildings not only improves the technological environment, but also enables individuals to navigate and manage their surroundings effortlessly and effectively.

Lastly, digitalization refers to the complete conversion of analog processes to digital platforms, utilizing AI to improve efficiency and make property-related information more easily accessible. The overarching theme of decision-making reflects AI's role in providing data-driven insights, empowering stakeholders to make informed choices in real-time (Naeem et al., 2023; Tekouabou et al., 2023; Viriato, 2019).

2.4.5 Material Database

The choices of production techniques and material types have a substantial influence on the embodied carbon. Embodied carbon refers to the lifecycle of building materials, including extraction, manufacturing, transport, construction, and disposal (Roberts et al., 2020).

To effectively manage and reduce embodied carbon, the integration of a comprehensive material database proves indispensable. As researched by Röck et al. (2018), such a database becomes a central repository for detailed information on various construction materials, encompassing their environmental impact, energy consumption during production, transportation emissions, and end-of-life considerations. The abundance of information provided enables architects, builders, and decision-makers to make well-informed decisions that are in line with sustainability objectives and contribute to a decrease in embodied carbon. Also, the development of comprehensive databases for building components, based on universally applicable functional performance criteria such as thermal and structural properties, service life, and circularity, has the potential to greatly improve the use of Life Cycle Assessment (LCA) in optimizing buildings during the design phase (Röck et al., 2018; Shadram & Mukkavaara, 2018; Häkkinen et al., 2015).

Since machine learning algorithms can analyze extensive datasets stored in these databases, uncovering patterns and connections between environmental indicators and material attributes. This process allows for a deeper understanding of the environmental impact of materials.
In terms of material selection and recommendation, machine learning algorithms can analyze historical data on material properties, environmental impact, and performance to predict and recommend suitable materials for specific applications. Natural language processing helps in understanding and interpreting textual information about materials, facilitating the extraction of relevant data and insights (Adel et al., 2022; Von Platten et al., 2020).

Moreover, machine learning models can test and improve building designs based on the properties of materials, considering things like how much energy they use and how they affect the environment. Deep learning techniques can handle complicated relationships in big datasets, which helps find the best combinations of materials for certain design needs (Adel et al., 2022; Von Platten et al., 2020).

Table 2.4 visuals an overview of how different retrofit phases align with various AI subsets to enhance carbon reduction efforts in sustainable building projects. Each retrofit phase, such as assessment, benchmarking, design, construction, and performance monitoring, leverages specific AI technologies to optimize decision-making, resource efficiency, and operational performance. For example, the assessment and benchmarking phase relies on machine learning and neural networks to analyze large datasets and generate insights on a building's energy performance and carbon footprint. These AI techniques enable predictive analytics, allowing for more accurate benchmarking and the identification of key retrofit opportunities. See the detailed version with an explanation in Appendix 6: AI Retrofit Process Integration. As example, during the pre-retrofit phase, Building Information Modeling (BIM) is enhanced through the integration of machine learning, neural networks, and deep learning. These AI subsets improve the accuracy of design simulations, predict energy performance outcomes, and optimize material usage, all while ensuring compliance with sustainability standards.

AI subfields:	Machine learning (ML)	(Artificial) Neural Networks (NN)	Deep learnings (DL)	Robotics	Natural Language Processing (NLP)	Genetic Algorithm (GA)
Net Zero Carbon Retrofit phases						
A. Pre-retrofit: planning and assessment of decarbonisation process						
1. Assessment and benchmarking	x	x				
2. Design and planning	x		x			x
3. Energy audit	x					
4. Life Cycle Analysis (LCA) and Carbon offsetting	x	x				x
5. Building Information Management (BIM)	x	x	x			
6. Business case & cost estimation (stakeholders)	x	x			x	
B. Retrofit: optimizing building performance and integration of sustainable solutions						
B.0 Whole lifecycle carbon emission approach						
1. Barriers, opportunities, trade-offs as a whole life carbon impact.	x	x				x
2. Carbon offsets	x		x			x
B1. Embodied carbon impacts						
1. Building envelope improvements	x	x		x		x
2. Energy effiency measures	x		x			
3. Materials and circular alternatives	x				x	x
4. Waste reduction and recycling	x			x		
B2. Operational carbon targets						
1. Energy effiency measures	x		x			
2. Renewable energy integration	x					x
3. Smart building technologies	x		x		x	
4. Monitoring and performance tracking	x		x	x	x	
C. Post-retrofit: maintenance and End-of-Life						
1. Monitoring and performance management	x		x	x	x	
2. Demolition, disposal , or recycle	x			x		x

Table 2.4: AI subsets integration with the retrofit process, in the appendix is the detailed version with an explanation of each cross (x) (own work, based on literature review and hypothetical characteristics, 2024).

2.4.6 Formulation of Hypothesis 3:
AI (subsets) can reduce operational carbon emissions by optimizing energy efficiency. The ability of AI subsets to evaluate building performance in real-time enables precise predictions and adjustments. AI can ensure energy is used efficiently, minimizing waste and reducing operational carbon emissions.

2.4.7 Formulation of Hypothesis 4:
AI (subsets) can minimize embodied carbon emissions by reducing them throughout the retrofit design and construction phases. AI subsets can enhance material selection and construction processes, helping to identify low-carbon materials and optimize resource use to minimize waste. By simulating various design scenarios, AI can aid in choosing sustainable alternatives and efficient methods that align with carbon reduction goals, thus lowering the overall embodied carbon footprint in retrofitting projects.

2.5 Design and Construction Management

"Steering a project through this complex web of relationships and requirements has become a profession in its own right: Design and Construction Management (Heintz & Van Warmerdam, 2022)."

2.5.1 Definition and Scope

Design and Construction Management (DCM) refers to the planning, coordination, and control of a construction project from inception to completion, ensuring that it meets the client's requirements and is delivered within the constraints of budget, time, quality, and resources. DCM incorporates phases of the construction process, including project planning, design, procurement, construction, and post-construction management (Shah et al., 2023).

The design phase involves architectural and engineering planning, where the project team develops plans and specifications that will guide construction. During this phase, various aspects of building performance, sustainability, and safety are integrated into the design to ensure efficiency and compliance with building codes and standards.
On the other hand, construction management involves overseeing the execution of these plans, managing labor, supply chain, materials, and equipment, and ensuring compliance with schedules, budgets, and quality requirements. It also includes coordinating different teams such as contractors, engineers, and architects to ensure the project runs smoothly (Shah et al., 2023; Advances in Construction and Project Management, n.d.).

Project management is at the core of design and construction management, as it encompasses structured processes to oversee the planning, coordination, and execution of construction projects. Project management focuses on balancing the key constraints of the iron triangle of time, budget, and resources while ensuring that all project objectives align with client expectations and regulatory standards, see Figure 2.5 (Vahidi & Greenwood, 2009). Nevertheless, as industries evolve and sustainability becomes more integral to long-term success, project management is increasingly adopting a fourth critical factor: sustainability. Recent studies, such as those by Silvius et al. (2012), highlight the importance of integrating sustainability into project management frameworks, especially in industries with significant environmental and social responsibilities.

Within the context of design and construction management, project management involves setting clear milestones, allocating resources effectively, and mitigating risks to ensure successful project delivery (Shah et al., 2023). By applying project management principles, construction managers can maintain control over the entire lifecycle of the project, from early design decision-making to construction execution and post-construction evaluation (Vahidi & Greenwood, 2009; Advances in Construction and Project Management, n.d).

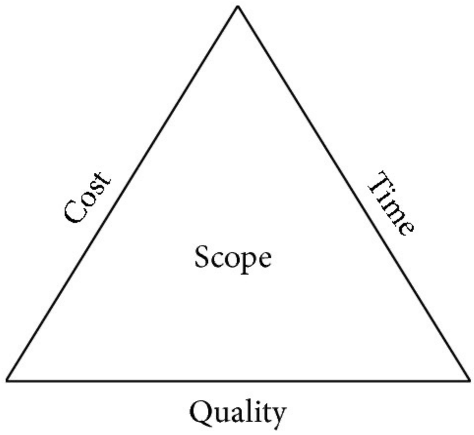

Figure 2.5: Project Management Iron Triangle (Leong et al, 2014.)

2.5.2 Design and Construction Management Practices

Early Design Decision-making

Early design decision-making is a critical phase in construction management, as decisions made during this stage heavily influence the overall outcome of a project. Key aspects such as sustainability, building materials, energy efficiency, and architectural aesthetics are determined early on. Decisions made at this point can drastically affect both the budget and the timeline of the project, as early design choices lock in significant components of the construction process. Incorporating tools like Building Information Modeling (BIM) and AI-driven simulations allows stakeholders to explore various design alternatives and assess their long-term impact on costs and performance, facilitating more informed decision-making from the project's outset (Parsamehr et al., 2022; Advances in Construction and Project Management, n.d.).

Project Planning and Scheduling

Project planning and scheduling are essential for the smooth execution of any construction project. This practice involves developing a detailed timeline that aligns all activities, such as procurement, construction, and inspections, with specific milestones to ensure project completion within the allocated time frame. Scheduling tools and AI-driven scheduling software, allow project managers to predict potential delays and adjust timelines accordingly. Effective scheduling ensures that resources, labor, materials, and equipment—are efficiently utilized, reducing waste and avoiding cost overruns (Advances in Construction and Project Management, n.d.).

Cost Estimation and Budgeting

Accurate cost estimation and budgeting are crucial for keeping the project within financial constraints. This practice involves forecasting the total cost of the project based on factors such as material costs, labor, equipment, and potential risks. Advanced software tools like BIM is increasingly used to improve accuracy in estimating costs, by providing real-time data analytics and predictive models. Proper budgeting ensures that all aspects of the project are financially viable from inception to completion, minimizing the risk of cost overruns that could compromise the project's success (Parsamehr et al., 2022; Advances in Construction and Project Management, n.d.).

Risk Management and Safety

Risk management and safety practices are integral to construction management to ensure that projects are delivered with minimal disruption and maximum safety for workers. Risk management involves identifying potential risks—such as delays, material shortages, or financial issues—and developing mitigation strategies to address them before they occur. Safety management, meanwhile, focuses on implementing protocols that protect workers on-site, such as compliance with Occupational Safety and Health Administration (OSHA) regulations (Russell et al., 2024; Advances in Construction and Project Management, n.d.).

Procurement and Supply Chain

Procurement and supply chain management are fundamental aspects of construction management that ensure the timely acquisition and delivery of materials, labor, and services needed for a project. Effective procurement involves selecting the right suppliers, negotiating contracts, and managing vendor relationships to secure quality materials at competitive prices. Supply chain management focuses on the logistics of getting these materials to the construction site efficiently, minimizing delays, and optimizing inventory levels (Advances in Construction and Project Management, n.d.).

2.5.3 Formulation of Hypothesis 5:

AI can optimize data-driven insights, enhance accuracy, and reduce human error in design and construction management practices. AI can transform traditional design and construction management practices by providing data-driven insights, improving decision-making, and minimizing human error. In conventional processes, managing vast amounts of data and ensuring accuracy is challenging and prone to mistakes. With AI, these tasks are streamlined, allowing for faster and more accurate evaluations of project needs, potential risks, and resource allocations

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2.6 Conclusion & Hypotheses

First, this literature review has aimed to provide a deeper understanding of decarbonization, net-zero objectives, and the pivotal role of building retrofitting in enhancing the performance and sustainability of existing buildings. Thus, this review aimed to answer SQ1: "What is the concept of building retrofitting and its role in decarbonization strategies to achieve net-zero building objectives?"

To conclude, building retrofitting is the process of modifying and improving existing buildings to enhance their energy efficiency, and functional performance and reduce carbon emissions. In total, eight retrofit measures in decarbonization have been found: insulation upgrades, window and door upgrades, material upgrades, operational carbon (installations), lightning upgrades, renewable energy integration, building management systems, and water efficiency measures. Together, these measures contribute to reducing embodied and operational carbon, in achieving net-zero carbon objectives.

After examining the role of building retrofitting in decarbonization and its contribution to achieving net-zero objectives, this literature review also sought to explore another critical aspect: the integration of AI-driven techniques in sustainable building design. Thus, to further expand on the understanding of sustainability in the built environment, this review aims to answer SQ2: "What is the current state of AI-driven techniques in sustainable building design?". To conclude, this transition marks the shift from discussing traditional retrofit measures to exploring how cutting-edge AI technologies are being employed to optimize energy efficiency, improve building performance, and support decarbonization efforts in modern building projects. In total, six key AI forms showcase the diverse applications of AI across various domains, highlighting how different forms of AI address specific tasks and challenges. Machine Learning and Deep Learning focus on data-driven decision-making, Robotics involves physical automation, Neural Networks mimic human brain function, NLP facilitates language understanding, and Genetic Algorithms excel in optimization problems through evolutionary principles. Therefore, AI subsets integration in sustainable building design and management can significantly enhance energy performance, streamline design processes, optimize material selection for reducing embodied carbon, integrate machines to replace manual labor and automate building systems.

Based on the literature, five hypotheses for the research are formulated to explore AI application in decarbonization strategies.

1. AI can optimize data-driven coordination in net-zero building objectives.
2. Machine learning can analyze and enhance the retrofit techniques and design measures more effectively than traditional approaches.
3. AI (subsets) can reduce operational carbon emissions by optimizing energy efficiency.
4. AI (subsets) can minimize embodied carbon emissions by reducing them throughout the retrofit design and construction phases.
5. AI can optimize data-driven insights, enhance accuracy, and reduce human error in design and construction management practices.

The literature reveals the current 'traditional' decarbonization strategies into building retrofitting and the integration of artificial intelligence subsets optimizing energy efficiency and minimizing embodied carbon in construction projects. However, several challenges inherent in traditional strategies remain, which could potentially be addressed through the application of AI technologies. Given the literature, it should be feasible to develop a methodology for mapping the theoretical and practical approaches to integrating AI technologies into decarbonization strategies. A hypothesis for integrating AI in decarbonization strategies for building retrofitting is that AI-driven technologies, such as machine learning, predictive analytics, and smart building systems, can optimize energy efficiency and minimize embodied carbon. These AI tools can help assess building performance, predict energy consumption, and recommend real-time adjustments to improve overall efficiency. Additionally, integrating AI into the material selection process and supply chain optimization could reduce embodied carbon, streamlining the design and construction phases to align with sustainability goals. AI can also automate operational tasks, improving the management of retrofitting processes and reducing human error. The hypotheses emphasize that AI, with its ability to process complex data and provide actionable insights, serves as a critical enabler in achieving net-zero building objectives. Through this research, it is expected that AI can support the achievement of net-zero objectives by enhancing decarbonization strategies in retrofitting projects, thus addressing both operational and embodied carbon emissions. To verify this hypothesis, practical testing and evaluation of AI-driven techniques in real-world retrofit projects are essential. The following chapter 3.2 Research Design will outline the framework for this exploration.

2.7 Conceptual framework

To provide a clear overview of this research, it is essential to connect the main concepts introduced earlier. The conceptual framework (figure 2.6) illustrates the presumed relationships between these primary elements, creating a cause from decarbonization strategies to a result of net-zero building objectives. Artificial Intelligence (AI) acts as the moderator variable, enhancing and enabling the feasibility, efficiency, scalability, and insights within the retrofitting process.

This conceptual framework begins with Building Retrofit Decarbonization Strategies (independent variable), focusing on embodied and operational carbon reduction through measures such as insulation upgrades, renewable energy integration, and waste reduction. These strategies address specific shortcomings in the retrofitting process, including financial barriers, data challenges, technological complexities, and regulatory hurdles. Net-Zero Building Objectives serve as the goal (dependent variable) of this framework. These objectives include minimizing embodied carbon, maximizing operational energy savings, increasing renewable energy supply, and offsetting remaining carbon emissions. AI bridges the gap between strategies and objectives (moderator variable) by addressing shortcomings and creating actionable insights, ensuring continuous improvement throughout the retrofitting process. The eight AI capabilities—ranging from real-time monitoring and predictive analytics to fault detection and compliance with regulations—support the effective application of these decarbonization strategies. By doing so, AI enhances feasibility, efficiency, and scalability while enabling the qualitative and quantitative requirements necessary for achieving net-zero objectives. Finally, Design and Construction Management (DCM) serves as the contextual variable, guiding the integration of AI into retrofitting projects.

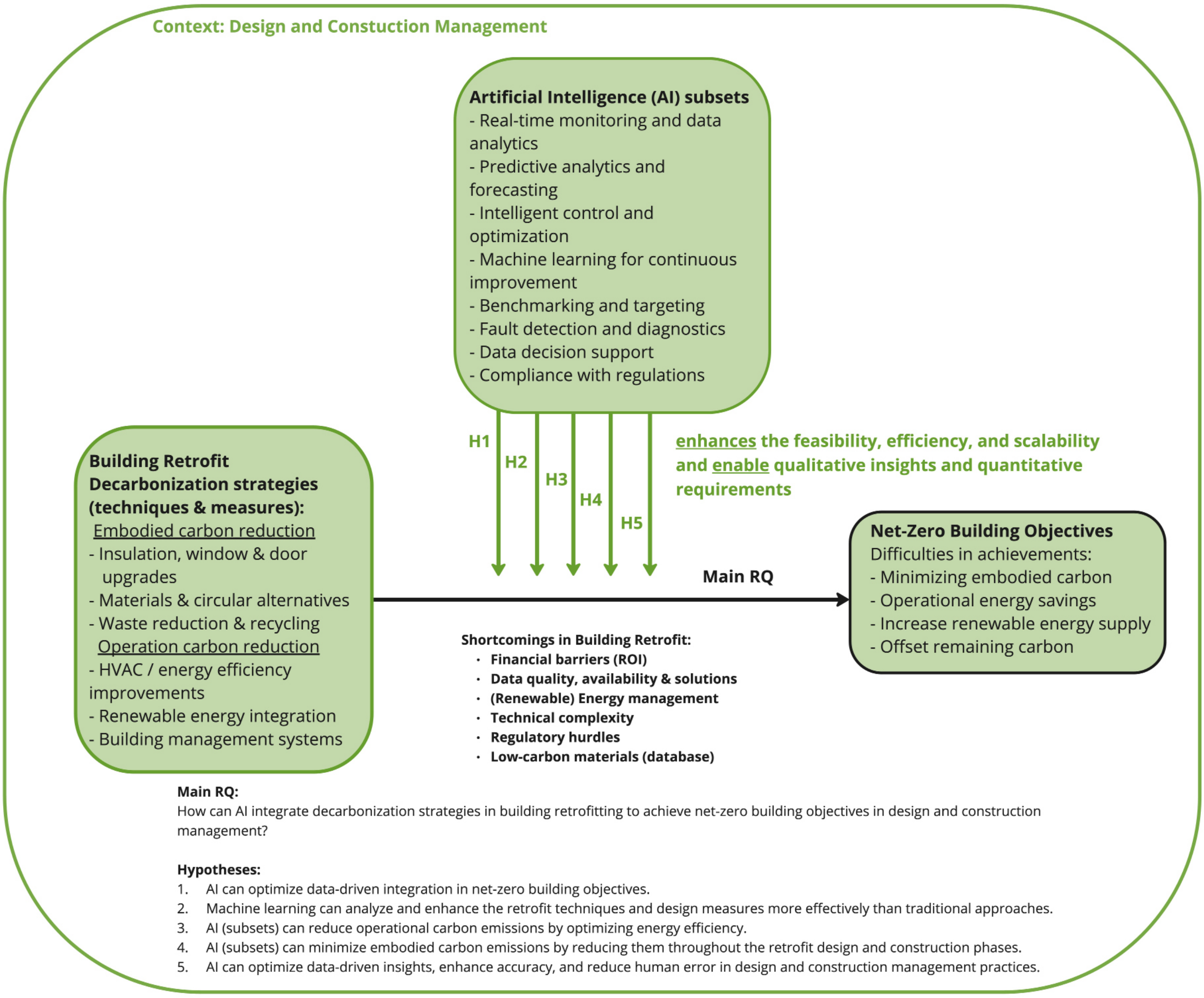

Figure 2.6: Conceptual framework (own ill.)

CHAPTER 3

METHODOLOGY

3 | METHODOLOGY

In this chapter, the research methodology will be explained in further detail, for each research question and with a detailed research design visualization. First, an explanation of the type of study is given. Thereafter, the research design and the ways of collecting and analyzing data are discussed. The chapter data plan and ethical considerations will be discussed.

3.1 Type of study

The initiation of this research involves the examination of two domains: decarbonization in building retrofitting and optimization with artificial intelligence. These theories serve as the foundation for formulating this study hypothesis. When it comes to retrofitting toward net-zero building, the study utilizes principles related to the initial phase to the operational and maintenance phase, and from energy efficiency, carbon footprint reduction, building envelope improvements, performance monitoring to materials, and waste reduction. In the field of AI, we draw upon established ideas and approaches in the subfield of AI, such as data analytics, streamlined processes, decision-making based on data and identifying multiple scenarios, and optimization based on continuous learning and predictive analytics.

This research adopts a logical, top-down approach, beginning with general theories or principles and then applying them to specific situations or observations to draw logical conclusions (Blaikie & Priest, 2019). This approach aligns with **deductive reasoning**, wherein existing theories are employed to formulate hypotheses, which are then tested through empirical research and data analysis. By starting with existing theories and principles, this research aims to derive specific predictions or expectations about the relationship between AI integration and the attainment of building retrofit toward net-zero building objectives. Through the application of deductive logic, this research seeks to explore the role of AI in sustainable building design and management, thereby contributing to a deeper understanding of the potential impacts and implications of AI integration in building retrofitting to achieve net-zero carbon objectives.

Based on the theoretical framework, the **hypothesis** was formulated to explore the potential relationship between AI and building retrofit toward net-zero objectives. This hypothesis functioned as a guiding principle for the data gathering and analysis. The findings from the data validation process either confirmed, contradicted, or refined existing ideas and hypotheses, thereby enriching our understanding of the correlation between AI and integrating decarbonization strategies in building retrofit in design and construction management.

In this research, **a qualitative approach** is employed within a deductive framework to explore the integration of AI in decarbonization strategies for building retrofitting. As emphasized by Blaikie & Priest (2019), qualitative methods are well-suited for establishing descriptions of characteristics and regularities. Although deductive reasoning typically aligns with hypothesis testing, qualitative methods are essential in this study to capture the complex and context-specific insights necessary for understanding the real-world application of theoretical models (Blaikie & Priest, 2019). By using interviews and case studies, the research aims to identify AI capabilities and challenges, offering a deeper, more nuanced exploration of AI's role in achieving net-zero building objectives, which a quantitative approach may overlook. This allows for refining existing theories based on rich, in-depth data.

3.2 Research Design

In this section, the research design is described. As explained in the previous section, qualitative methods are used in this research to answer the research questions. Each method is related to a sub-question and at least one of the objectives. An overview of the research design, illustrated in the flow of the research process and the interrelation between different steps is provided in Figure 3.0.

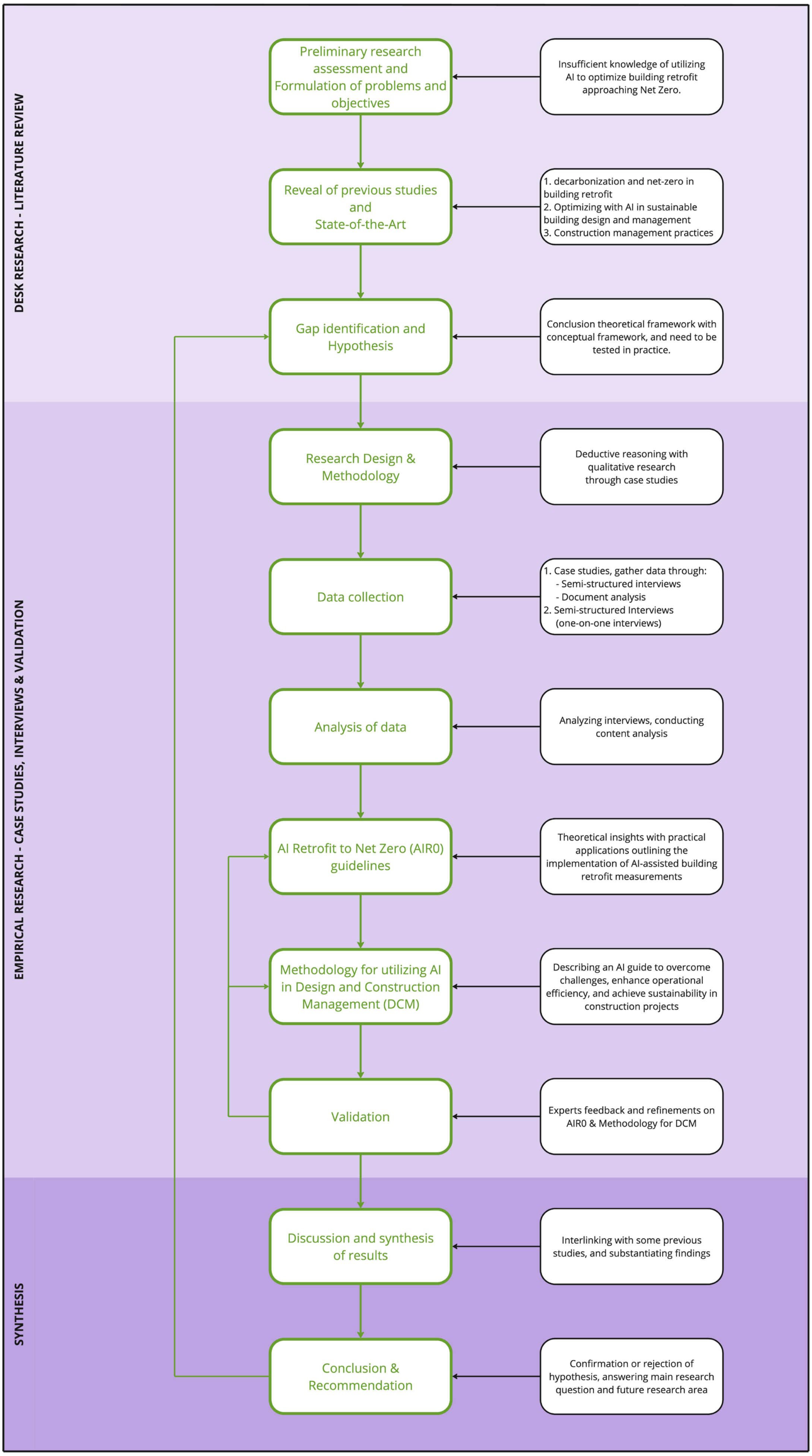

Figure 3.0: Flow of process (own ill.)

3.3 Methods and Instruments

Firstly, each sub-research question (SQ) is paired with a distinct objective and an appropriate method for collecting and analyzing data as shown in Figure 3.1. For instance, SQ1, which focuses on the concept of building retrofitting and decarbonization, is addressed through a literature review to identify key techniques and design measures. The output for this is a clear identification of these measures for building retrofitting.

Similarly, SQ2, aimed at understanding the current scope of AI in sustainable building design, also utilizes a literature review to assess the state of AI technologies, and opportunities for decarbonization. The output here is an evaluation of the AI landscape in sustainable building practices.

SQ3 and SQ4 delve deeper into the practical integration of AI in decarbonization strategies through case studies and semi-structured interviews. These methods provide empirical insights the building decarbonization strategies and their deficiencies in real-life projects. Further, through semi-structured (one-on-one) interviews the expertise of AI and retrofit/net zero is further developed. There are no AI real-life retrofitting projects at this stage, so the closest to delving into the knowledge is interviewing experts about the applicability of decarbonization strategies to achieve net zero building objectives.
Moreover, SQ4 explores AI's role in construction management to optimize building retrofitting. This is explored via semi-structured (one-on-one) interviews with construction management professionals, aiming to generate an AI methodology for overcoming challenges in construction practices. The outputs are guidelines for effective AI utilization in construction management, designed to enhance sustainability.

Lastly, a cross-case analysis is conducted to compare and synthesize findings across different case studies (chapter 4) and interview insights (chapter 5), identifying common patterns, gaps, and best practices. This analysis facilitates a comprehensive understanding of the role of AI in decarbonization strategies and its application in achieving net-zero building objectives. In addition, the validation step involves an expert panel, which is used to refine and validate the research findings. This panel provides critical feedback on the developed guidelines (AIR0) and framework (DCM FRAIM), and insights gained from the case studies and interviews. This step strengthens the credibility and applicability of the research conclusions, ensuring the recommendations are robust and actionable.

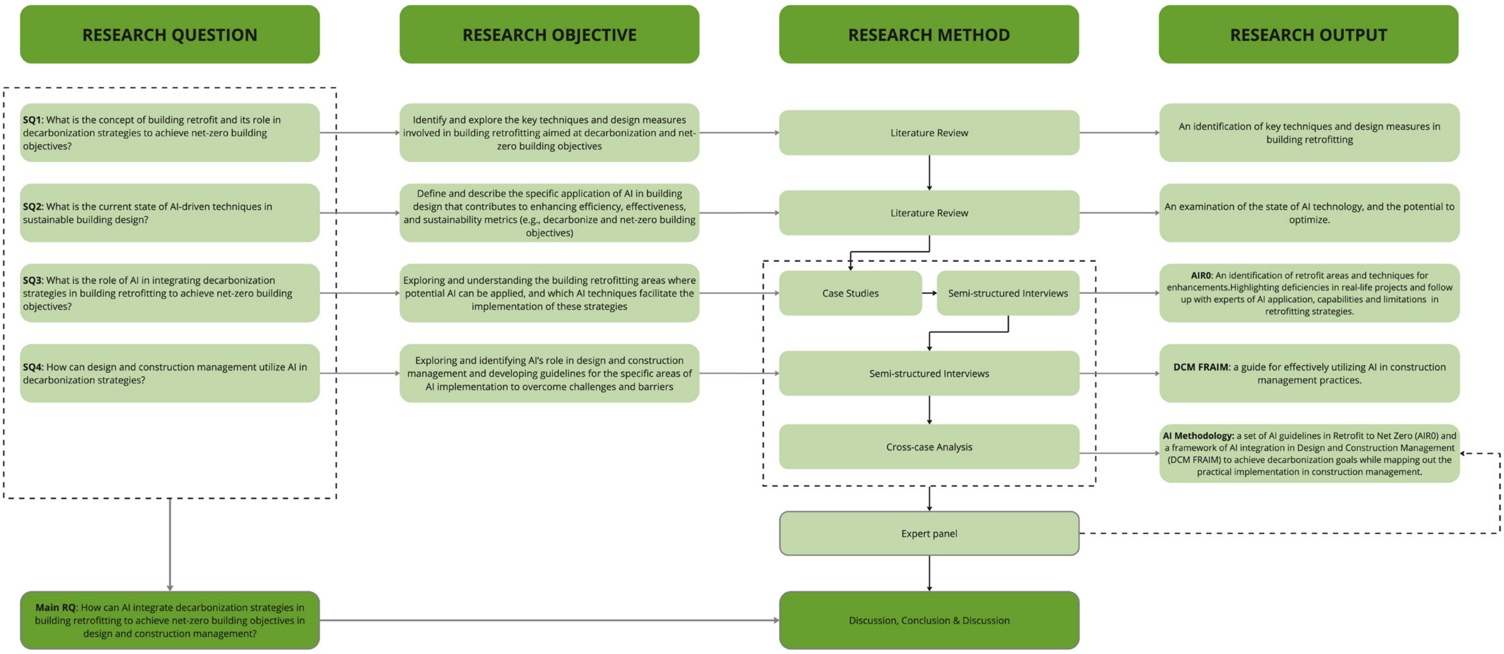

Figure 3.1: Research methods and instruments (own ill.)

3.4 Data Collection and Analysis

The research will be carried out through a graduate internship at Turner & Townsend (T&T). Turner & Townsend is a global consultancy firm specializing in real estate, infrastructure, and natural resources sectors, delivering integrated project management and cost consulting services. The selection of T&T aligns with the research focus on net-zero expertise for existing buildings, leveraging their global perspective and consultancy experience in the transition toward sustainable practices. The construction management firm can help in finding suitable research cases and get in touch with retrofit, net zero, and AI experts in the field.

The data collection process in this research involved gathering qualitative data through a combination of comprehensive case study and semi-structured interviews. These methods were chosen to capture in-depth insights and real-world experiences from industry professionals regarding the integration of AI in building retrofitting to achieve net-zero objectives.

3.4.1 Case Study Selection

According to Hollweck (2015), the reason for selecting case studies as one of the suitable research methods is that case studies can provide a detailed description of an event or process (Hollweck, 2015; Yin, 2018) Information on real-life events is useful for this research, since it is meant to guide practitioners. For sub-question 3, case studies were chosen as the primary research method because they allow for an in-depth examination of documented instances where decarbonization strategies are identified and possible AI techniques are connected to these challenges in retrofit measures. Through document analysis and interviews with stakeholders involved in these cases, the study captures valuable insights into the opportunities and challenges observed in real-world applications (Hollweck, 2015; Yin, 2018). The case selection was based on strict decarbonization criteria and alignment with net-zero objectives, ensuring that only completed retrofitting projects meeting these standards were included. This selection approach ensures that the cases reflect best practices and practical lessons from projects that have successfully incorporated decarbonization measures, providing relevant insights for achieving net-zero targets.

The cases were selected based on the following criteria:

1. Existing entire building:
Project cases must be an existing entire building (excluding office fit-outs, apartments, or partial of the building).

2. Retrofit assessment towards net zero objectives:
The cases involve projects where retrofit assessment towards net-zero building objectives has been conducted.

3. Impact based on data:
The cases have documented analyses related to energy efficiency and carbon reduction. The retrofit measures and the impact of decarbonization are evident based on building assessment reports (environmental, technical, and/or financial investment).
As a result, the selected project cases primarily focus on building retrofit and net-zero building objectives, with the understanding that these selected project cases offer valuable insights into retrofitting practices that can inform future AI-assisted initiatives. Subsequently, based on the findings from the document analysis of the projects, semi-structured interviews will be conducted to collect participants' experiences and challenges faced and to gain further valuable insights.

To ensure the validity and reliability of the case study selection, several measures were implemented. First, triangulation was employed by cross-referencing data from interviews and relevant project documentation to corroborate the findings. This approach ensured that insights drawn from different sources aligned, strengthening the overall credibility of the research. Second, detailed documentation was maintained throughout the data collection and analysis processes. This systematic recording of procedures ensures transparency and replicability, allowing future researchers to trace the research steps, thereby enhancing both the reliability and validity of the case study findings.

3.4.2 Semi-structured Interviews

However, for sub-questions 4 and 5, semi-structured interviews with experts in the field were selected as the most appropriate method. The decision to rely on interviews was driven by the absence of existing case studies where AI has already been implemented in building retrofits, as well as the lack of relevant documents on the topic. As Kvale & Brinkmann (1996) emphasize, given this gap in available empirical data, gathering direct insights from professionals with expertise in AI, construction management, and sustainable building practices became essential for identifying capabilities, risk mitigation strategies, and recommendations for AI-driven retrofit projects to achieve net-zero objectives. This method was chosen because it allows the researcher to follow a predefined set of questions related to the critical success factors for implementing AI-driven retrofit measures, risk mitigation strategies, and the role of AI in construction management for decarbonization. At the same time, it provides the flexibility to delve deeper into emerging themes and unexpected insights that may arise during the conversation.

For the third sub-question, thirteen interviews are carried out in total with various stakeholders. The preconditions criteria for selecting participants are as follows:

1. Expertise in AI or digitalization OR
2. Expertise in retrofit/net zero building AND
3. In Design and Construction Management firm.

3.5 Data Plan

The data acquired for this research will be minimized to the greatest extent possible. Only the data essential for addressing the research questions will be collected. The data and quotations will undergo anonymization. Nevertheless, it is crucial to acknowledge that certain attributes of an individual may be identified by another colleague within the organization. Code names will be employed to guarantee the anonymity of the respondents. Furthermore, the audio and video recordings of the comprehensive interviews and observations will be eliminated once the transcriptions are completed. In order to conduct thorough interviews, it is essential to have a clear understanding of the respondent's position within both the design team and their affiliated firm. The relevant projects will be gathered and stored in separate locations. If confidential matters are discussed during the meetings, they will be omitted from the transcriptions. The data will be saved in the project's storage drive in accordance with the principles of FAIR: Findable, Accessible, Interoperable, and Responsible. The ATLAS.ti software will be utilized as a tool for analyzing qualitative data. This software tool is freely available to researchers, so ensuring equal opportunities. Shenton (2004) states that qualitative data can be considered reliable if it satisfies four criteria: credibility, transferability, dependability, and confirmability. This research has implemented some potential provisions outlined by Shenton (2004). Table 3.2 provides a overview of these provisions.

The data management plan (DMP), will be created using the TU Delft DPM online platform. DMP plan explains how the data for this research project was collected, documented, and stored throughout the research. Furthermore, it explains how it will be shared afterward. During the creation of the DMP, it was evident that there was a significant probability of utilizing sensitive data for the purpose of study, particularly stored in the company's secured laptop.

Criteria	Possible provision by Shenton (2004)	Implementation in this research
Credibility	Use of appropriate, well- recognized research methods	Semi-structured interviews and case studies are used to gather in-depth data, with an deduct logic of inquiry
	Development of early familiarity with participating organizations	The research is combined with a 8-month internship, offering the opportunity for prolonged engagement with the organization and industry context.
	Triangulation through multiple methods	Multiple research methods(case study, one-on-one interviews and document analysis) to corroborate findings and reduce bias.
	Honesty in informants	Participants can withdraw from the research at any time without giving a reason, ensuring their responses are voluntary and honest.
	Frequent debriefing sessions	Sessions with both the internship organization and the mentors will widen the vision of the researcher
	Member checks to verify data accuracy	The participants are always allowed to check the results of the interviews and the case study findings
Transferability	Provision of background data to establish context	The organizational and environmental context of the research, including characteristics of the selected cases, will be thoroughly described for broader applicability.
Dependability	In-depth methodological description to enable replication	The research methods, operation of the research methods and evaluation will be described in detail
Confirmability	Triangulation to reduce researcher bias	See 'Triangulation' in 'Credibility'

Figure 3.2: The implementation in this research to ensure trustworthiness (own illustration, adopted from Shenton, 2004)

3.6 Ethical Considerations

As part of the Data Management Plan (DMP), all legal and ethical considerations were carefully reviewed. For all ethical-related questions, the response was 'no,' indicating that there were no significant ethical challenges identified in this research project. However, since the research involved handling confidential data, special care was taken to ensure privacy. Therefore, this data was only described on an aggregated level and no personal information was added (names of the interviews and other personal data).

CHAPTER 4

CASE STUDY

4 | CASE STUDY – BUILDING RETROFIT DEFICIENCIES

This chapter delves into the exploration of two case studies, with two projects that focused on retrofitting buildings to achieve energy efficiency and meet net-zero carbon goals. These projects involve comprehensive building retrofit strategies aimed at improving energy performance, reducing carbon emissions, and enhancing operational efficiency. Through a detailed analysis of these case studies, the chapter seeks to understand the existing challenges, limitations, and areas of improvement within the retrofit process. By mapping the retrofit landscape, it aims to highlight the shortcomings in decarbonization strategies including financial barriers, data deficiencies, (renewable) energy management, technological complexity, regulatory hurdles, and low-carbon materials. This analysis lays the foundation for answering sub-question 3: "What is the role of AI in integrating decarbonization strategies in building retrofitting to achieve net-zero building objectives?".

4.1.1 Introduction Case Study Projects

This chapter examines two project types, each including several buildings with various attributes, to investigate the deficiencies and potential AI in incorporating decarbonization measures into building retrofitting. These case studies were selected to provide a thorough perspective on the difficulties encountered during retrofitting in various building kinds and functions.

4.1.1.1 Case Study Project 1: Hotel Buildings Decarbonization

General

The first project, 'Case Study Project 1: Hotel Buildings Decarbonization', examines the carbon emissions reduction scenarios for four existing hotels in the client's portfolio: Hotel A in Spain, Hotel B in Italy and Hotel C and D in The Netherlands.

The client is committed to developing greener, more efficient structures with a smaller environmental imprint. The client seeks to achieve the highest level of sustainability within an optimized business case by integrating sustainability into all design aspects of its assets. The clients has set the bar that all their hotels need to be designed and delivered with a minimum A+ energy label and BREEAM 'Very Good' certificate.

Carbon and energy performance

The four Project A buildings' current carbon and energy performance have been evaluated, and all are currently not in compliance with the client's sustainable targets of achieving net zero carbon by 2042. The hotel with the largest carbon footprint is Hotel B, followed by Hotel D, Hotel C, and Hotel A.

The table below summarizes the current performance and targets for carbon intensity and electricity consumption per Project 1 asset. The "Target – carbon intensity" stated in the table below is the target for each Project 1 asset to become net zero. The "Target – electricity consumption" stated in the table below is the CRREM ("Paris Proof") energy intensity target for hotels in 2050. In addition, the estimated investment costs per asset to become net zero are summarized in the table below, along with the further measures that can be taken to make the assets more sustainable.

Aside from the target of reaching net zero, the four hotels have numerous opportunities to become more sustainable. In the realm of energy conservation, significant progress can be made. By applying the recommendations in this report, the client can progress towards increasing its hotels' energy efficiency. Also, there are other opportunities to become more sustainable, for instance, for the Hotel D Asset to recreate the 'Location rainwater system' by upgrading the rainwater system to assist in greywater usage for the building.

4.1.1.2 Project 2: Campus Buildings Decarbonization

General

The second project, 'Project 2: Campus Buildings Decarbonization', examines the carbon emissions reduction scenarios for the existing seven interconnected buildings with 2-3 levels and a total of approximately 15.000 sqm GFA. The asset was developed in the early 1990s and is powered by natural gas and electricity. The buildings contain office space, lab space, and data centers. The electricity and gas usage are not separately metered between building parts. The buildings vary in age, size, and use, offering insights into how campus

ASSET	Hotel A (Spain)	Hotel B (Italy)	Hotel C (the Netherlands)	Hotel D (the Netherlands)
GFA (m^2)	19,875	23,121	13,700	13,863
Construction Year	2022	2020	2020	2015
Level of floors	14 (+ basement)	4 (+ 2 basement)	10 (+basement)	11 (+ basement)
Nr. rooms	292	337	340	363
PV panels	100.000 kWh	298	298	N/A
NET ZERO				
Current - carbon intensity (kgCO2/m2/y)	23.7	55.5	38.9	45.9
Target - carbon intensity (kgCO2/m2/y)	3.5	3.5	3.1	3.1
Current- electricity consumption (kWh/m2/y)	179	180	82	153
Target - electricity consumption (kWh/m2/y)	78	78	78	78

Figure 4.0: Project 1 summary of hotels A, B, C, and D (Based on Turner & Townsend Europe Limited, 2023B, 2022C, 2023D, 2023E)

buildings face the decision-making challenge of restoring (retrofitting) or demolishing and/or rebuilding or combining both to achieve the clients' sustainability targets. Lastly, commit to becoming carbon neutral until 2030 and take operational and financial challenges into the project's feasibility.

Carbon and energy performance

The Project 2 buildings' current carbon and energy performance have been evaluated, and the campus is currently not in compliance with the client's sustainable targets of achieving net zero carbon by 2030. The table below summarizes the current performance and targets for carbon intensity and electricity consumption of Project 2.

Item	Target	Current
Electricity generated on-site	N/A	0 kWh
Natural gas consumption	N/A	1,232,129 kWh
Embodied carbon	300 $kgCO_2$ eq/m²	N/A
Operational Carbon Intensity	0 $kgCO_2$ eq/m²/year (scope 1)	15.14 kg CO2 eq/m²/year
Renewable Energy (total onsite)	>10% of end energy use	0%
Heat supply	Electric	Gas
Cooling GWP	<1000	>1000 in all building except building 5
E-mobility Infrastructure	10% fully equipped vehicle charging 30% provisions for vehicle charging. Consider provisions for e-bikes	No electric parking provisions

Table 4.1: Project 2 summary of campus buildings (Based on Turner & Townsend Europe Limited, 2021, 2022B)

4.1.2 Interview Participants

The selection of participants for the case study interviews is based on their direct participation in the chosen projects for examination. Furthermore, in these interviews, the participants are selected by purposive sampling, meaning they must have actively participated in, or overseen elements of the particular retrofitting projects selected for the case study. Hence, this ensures that their perspectives and experiences are recognized for the challenges, limitations, and opportunities of the retrofit process, thereby identifying possible enhancements, such as the integration of artificial intelligence, to provide an understanding of AI's potential in building retrofitting projects.

The interviewees were given the choice of location, but due to convenience, all interviews were conducted online via Microsoft Teams. All interviews are conducted in English and recorded with the permission of the interviewees for the purpose of making the interview transcripts. The transcripts were analyzed using thematic analysis to identify key patterns and insights related to sub-question 3 objectives.

Case Study Project 1	Participant	Interview date
Interviewee 1	Cost Manager (incl. carbon/targets)	13-MAY-2024
Interviewee 2	Project Manager	16-MAY-2024
Interviewee 5	Net Zero Director	22-MAY-2024

Table 4.2: Interview Participants (case study project 1)

Case Study Project 2	Participant	Interview date
Interviewee 2	Project Manager	16-MAY-2024
Interviewee 3	Cost Manager (incl. carbon/targets)	16-MAY-2024
Interviewee 4	Cost Manager (incl. carbon/targets)	21-MAY-2024
Interviewee 5	Net Zero Director	22-MAY-2024

Table 4.3: Interview Participants (case study project 2)

4.1.2.1 Interview topics

The questions are mainly formulated based on the document analysis from each project report. These are formulated to delve deeper into the insights and retrofit measures of each project by the stakeholder. The topics are shown in Table 4.4:

Topic	Questions
General acknowledgement	Can you introduce the project? What were the project objectives?
Building retrofitting	What were the building retrofitting measures in this project? What were the challenges or limitations in each of the scenarios? How do you think [certain factor] influences building retrofit? Can you provide examples of successful initiatives or projects that have resulted in significant improvements in energy efficacy, waste management, or other decarbonization of this project?
Net Zero building objectives	Can you describe the projects and the decarbonization efforts to net-zero building? What are the lessons learned from this specific net-zero project/situation? How are energy performance utilized to optimize energy efficiency and reduce carbon emission in building operations? How is embodied carbon versus the operation carbon aligned in this specific project?

Table 4.4: Case study interview topics

4.1.2.3 Coding (ATLAS.ti)

Given the deductive approach of this chapter, closed coding was employed to align with predefined themes. In addition, a few open codes were created to ensure that the analysis captured unexpected themes or gaps not initially covered by the conceptual framework.

Closed coding	**Sub-code**
Financial barriers	High upfront costs of advanced systems (e.g., TES)
	Limited access to financial resources
	ROI concerns for retrofitting investments
	Budgetary constraints in large-scale projects
Data quality, availability and solutions	Incomplete or outdated datasets
	Absence of real-time monitoring
	Reliance on assumptions for calculations
	Missing sub-metered energy data
(Renewable) Energy management	Inadequate long-term renewable energy procurement policies
	Misalignment in PV panel installations
	Low renewable energy adoption rates
	Roof constraints for PV systems
Technical complexity	Difficulty in upgrading existing (legacy) systems
	Integration challenges for modern retrofitting technology
	Complex interactions between building envelope and installations
Regulatory hurdles	Asbestos removal delays
	Inconsistent or evolving regulations
	Compliance with local and international standards
Low-carbon materialsX (database)	Poor insulation and airtightness
	Limited data on insulation values
	Aging infrastructure and facades
	Sustainable material selection
	Carbon database
Open coding: Health and Safety Risks	 Asbestos presence in older buildings Challenges in adhering to safety protocols in existing buildings

Table 4.5: Closed coding in ATLAS.ti

4.1.3 Analysis: Building Retrofit Deficiencies (NO AI IN CASE STUDIES)

In the analysis of the retrofitting project for Project 1 "Hotel Buildings Decarbonization" and 2 "Campus Buildings Decarbonization," both interview data and document analysis provided valuable insights into the challenges, limitations, and patterns of the retrofit process. The key patterns are comprehensively summed up (Table 4.25) and categorized into retrofit themes below.

4.1.3.1 Energy Efficiency & Installations

Energy efficiency emerged as a primary focus in both projects, with key measures such as renewable energy integration, heat recovery systems, and building energy management systems.
For Project 1, the lack of a structured renewable energy procurement policy in Hotel A/B/C/D hindered efforts to reduce emissions from electricity use (Scope 2). While switching to certified renewable electricity with a guarantee of origin would eliminate carbon emissions without upfront costs, these hotels continue to rely on the national energy mix, which includes fossil fuels. Similarly, renewable energy integration, such as PV panels in Hotel B, encountered data errors during feasibility analysis due to human oversight.

"You need a connection on the grid. If you buy gray electricity, you're not sustainable because it comes from gas." – Interviewee 5

Active energy management systems in Hotel A-D, though implemented, lacked consistent controls and monitoring, limiting potential savings. Heat recovery in air handling units (AHUs) was found effective, with annual energy reduction estimates ranging between 15.6 and 27.0 kWh/m^2, but outdated systems in Hotels C and D posed challenges in achieving higher efficiency gains. Similarly, high initial investment costs constrained the adoption of Thermal Energy Storage (TES), despite its potential to reduce cooling energy demand by up to 50%. However, these heat recovery AHUs and TES face cost barriers despite their high energy-saving potential. The high upfront costs for advanced systems create significant financial barriers to broader adoption, limiting the scalability of these technologies in retrofitting projects.
In Project 2, energy efficiency measures such as replacing gas-fired boilers with heat pumps and sub-metering faced barriers due to shared energy systems and lack of granular energy data. These limitations restricted opportunities for targeted interventions and real-time monitoring.

"If you compare the investment cost to raise your RC value against your cooling capacity or installation options, you will see that your first and base step to getting there is to do the installation part and then secondary to look at the building fabric and also not just from a practical perspective. Also, from a government perspective, you will get more incentive to install solar panels and a heat recovery system than to upgrade the building fabric." – Interviewee 3

One of the most critical retrofit measures was removing gas-based heating systems and installing electric heat pumps. Interviewees 4 and 5 emphasized that this shift was vital in transitioning away from fossil fuel dependency and aligning with the net-zero objectives. The retrofitted buildings could considerably reduce their carbon emissions by utilizing electric heat pumps, emphasizing cleaner energy sources, such as renewable electricity generated on-site.

4.1.3.2 Building envelope

Although secondary to energy systems, the building envelope plays an important role in minimizing energy loss and ensuring retrofitted systems operate optimally.

"The challenge was the information that was available for the current condition of the building." – Interviewee 3

For Project 1, improvements were primarily limited to roof insulation, with modest energy savings of ±0.5 kWh/m^2 annually in Hotel D. Similarly, lift upgrades in Hotel D contributed to operational energy efficiency but had minimal impact on carbon reduction.

In Project 2, aging facades and minimal insulation in older buildings highlighted the need for extensive structural upgrades. Replacing windows and frames could reduce energy intensity by up to 50-60 kWh/m^2 annually, but limited data on insulation quality posed challenges in developing accurate retrofit plans.

4.1.3.3 Operational Deficiencies

Operational deficiencies, particularly incomplete and outdated data, emerged as a recurring issue in both projects. Reports relied on historical data that did not reflect current building conditions or account for post-pandemic operational changes.

In Project 1, the interviews revealed major issues with *both the quality and completeness of the data, such as missing updates and outdated information*. Several interviewees mentioned that reports were often based on old data, with recent changes not always being included. On top of that, energy data affected by the COVID-19 pandemic was missing, which added uncertainty and made energy performance assessments less reliable. *Without the complete datasets, it's hard to get an accurate picture of actual energy use* since buildings weren't operating at full capacity during the pandemic, which could lead to misleading conclusions when planning retrofits or energy-saving measures. These data were excluded from the documents without explaining or informing about the transparency of the datasets.

"We had limited information to use, so if we had more detailed information, our figures would be more accurate." – Interviewee 3

Technical due diligence reports for Project 2 identified gaps in energy performance data and insulation values, complicating the planning and execution of retrofit measures. Similarly, shared systems and lack of sub-metering limited insights into individual building energy consumption, further hindering efficiency improvements.

A key point raised by Interviewee 1 highlights a shift in approach regarding operational deficiencies. Instead of relying heavily on previous data, which may not fully capture the current state of the building or account for recent changes, the focus is shifting toward analyzing building characteristics at present. Interviewee 1 explained, *"So what we try to do with the different programs is put the building into the program, and then instead of analyzing what happened to the building, to predict the future of the building."*

" It doesn't mean building on the existing previous data, but like building on parameters of new data points to create future predictions." – Interviewee 1

This means looking at things on the building-facing side (North, South, West, East of windows/room function), insulation quality, human occupancy, and installation packages rather than being stuck with outdated information on energy usage over the last months and years. By focusing on these present-day characteristics, the advances program can create more accurate forecasts for future retrofitting needs and improvements, making it easier to optimize energy efficiency and meet decarbonization goals. This approach helps overcome the issues caused by missing or incomplete data from the past.

These gaps in data further highlight the operational inefficiencies already present across Project 1 and 2. This finding is supported by interviewees 4 and 5, who confirmed that the air handling units in buildings 2 to 6 are not only aging but also limited by low ceiling heights, which restricts their performance. Additionally, interviewees 3, 4, and 5 have discussions about the broader theme of operational deficiencies in the outdated building performance. The concept is embedded in the need to improve and optimize building operations for better energy efficiency and functionality.

4.1.3.4 Assumptions in Projects

Both projects relied heavily on assumptions due to gaps in data. For instance, energy consumption estimates for Hotels A-D in Project 1 were extrapolated based on similar assets rather than real-time data. Similarly, assumptions about PV panel outputs and insulation quality in Project 2 introduced uncertainties in retrofit outcomes.

"It was a limitation of the data, and I think it was a challenge of the project, but we are consultants in that sense. So, no matter what you need to deliver. So, we made assumptions ourselves, okay, it was not operational." - Interviewee 2

4.1.4 Overview of Retrofit Deficiencies

To summarize, the analysis of the retrofit process across both Project 1 and Project 2 highlights significant challenges, limitations, and recurring themes. Table 4.6 provides an overview of the key deficiencies identified in building retrofitting based on both case studies.

Building retrofitting measure	Challenge and/or limitation	Outcome in this situation
Procurement of renewable energy	Guarantee of origin and committing to this in a long-term policy. Availability of renewable energy sources.	Higher operational costs and reduced carbon reduction opportunities.
Renewable energy generation - PV panels	Data error / placement on roofs The precise decrease in energy consumption 'assumptions'.	Missed carbon reduction and energy-saving potential.
Building Energy Management	Detailed controls and proactive energy management. Ongoing monitoring and modifications of setpoints.	Higher operational costs
The heat recovery system in the air handling units	Energy-inefficient and constrained by the ceiling heights, limiting their ability to perform optimally.	Higher operational costs and energy waste.
Thermal Energy Storage (TES) for heating and ventilation	High Investment Cost Space requirement Uncertainty in energy savings	Delayed adoption and missed carbon reduction opportunities.
LED lights	The precise decrease in energy consumption 'assumptions'.	Missed operational efficiency and higher energy costs.
Not sub-metered between multiple buildings	Identifying high energy-consuming areas and limits opportunities for targeted efficiency improvements.	Missed operational efficiency and higher energy costs on long-term.
Building Envelope - Replacing the facades, including windows and frame	No specific data on the insulation values of the facades and windows of the different buildings	Higher heating/cooling costs and carbon emissions.
Previous energy data sets to calculate improvements	The quality and completeness of the data, such as missing updates and outdated information. Accurate picture of actual energy.	Energy saving Operational efficiency
Technical due diligence process	The lack of complete and accurate data	Higher risk of inefficiencies and project delays.
Hazardous material (Asbestos)	Health risk and common in old buildings Adds complexity and delays to the project. Strict safety protocols and increased costs	Delayed retrofit timelines and increased costs.
Assumptions - Energy consumption data; - PV panels energy productions; and creating assumptions in general instead of concrete data.	Pose potential challenges, and the project data outcome. Risks and uncertainties, as they may not accurately reflect the actual conditions or requirements of the buildings, leading to adjustments and complexity later in the project.	Missed opportunities for accurate planning and optimization.

Table 4.6: Case Study Deficiencies, Mapping the Retrofit Landscape (NO AI IN CASE STUDIES) – challenges and llimitations

CHAPTER 5

SEMI-STRUCTURED INTERVIEWS

5 | INTERVIEWS – AI CAPABILITIES & DCM

This chapter explores the expert insights gathered from semi-structured interviews on the role of artificial intelligence (AI) in building retrofitting projects aimed at achieving net-zero objectives. Specifically, the chapter delves into how AI capabilities are perceived in terms of their potential and limitations within decarbonization strategies. This analysis forms the foundation for evaluating AI's applicability in addressing the deficiencies identified in Chapter 4. The discussion is structured around the eight AI capabilities identified in the conceptual framework, offering a comprehensive view of their contributions and challenges in practice.

5.1 Introduction to Semi-structured interviews

The data derived from semi-structured interviews highlights key themes and success factors in AI integration. By analyzing expert opinions, these interviews explore a variety of capabilities, risks and mitigations, and recommendations related to AI-driven retrofitting projects aimed at net-zero outcomes. Along with this, Interviewees contributed unique insights based on their practical experiences, including the role of design and construction management practices in retrofit projects.

5.1.1 Interview Participants

The selection of participants for the one-on-one interviews is based on their expertise in AI or retrofit/net-zero knowledge in practice.

Experts in AI	Participant	Interview date
Interviewee 6	Cost Manager and AI research & development team	07-MAY-2024
Interviewee 9	IT/digitalization Consultant	08-MAY-2024
Interviewee 10	IT Director	10-MAY-2024
Interviewee 14	Digitalization Consultant	16-MAY-2024
Interviewee 15	IT Assiociate Director	20-MAY-2024
Interviewee 16	Retrofit Project manager and AI research & development team	20-MAY-2024
Interviewee 17	Digitalization Consultant and AI research & development team	21-MAY-2024
Interviewee 18	Project Manager and AI research & development team	05-JUNE-2024

Table 5.0: Interview Participants with AI knowledge (one-on-one interviews)

Experts in Retrofit/Net Zero	Participant	Interview date
Interviewee 6	Cost Manager and AI research & development team	07-MAY-2024
Interviewee 7	Associate Director (sustainability and project management)	07-MAY-2024
Interviewee 8	Sustainability Consultant (projectmanager)	08-MAY-2024
Interviewee 11	Commercial Sustainability Director	13-MAY-2024
Interviewee 12	Net Zero Director	15-MAY-2024
Interviewee 13	Sustainability Consultant (project manager)	16-MAY 2024
Interviewee 14	Digitalization Consultant	16-MAY-2024
Interviewee 16	Project Manager and AI research & development team	20-MAY-2024
Interviewee 18	Project Manager and AI research & development team	05-JUNE-2024

Table 5.1: Interview Participants with Retrofit/Net Zero knowledge (one-on-one interviews)

The interviewees were given the choice of location, but due to convenience, all interviews were conducted online via Microsoft Teams. All interviews are conducted in English and recorded with the permission of the interviewees for the purpose of making the interview transcripts. The transcripts were analyzed using thematic analysis to identify key patterns and insights related to sub-questions 3 and 4 objectives.

5.1.2 Interview topics

The questions are mainly formulated based on the document analysis from each project report. The topics are shown in Table 5.2:

Topic	Questions
General acknowledgement	Can you introduce yourself?
Building retrofitting	Can you describe a typical process of retrofitting a building from initial to end? The process of initializing the project to decarbonizing the existing building and maintaining the retrofitted building. • Can you elaborate on specific criteria or parameters crucial for successful retrofitting towards net-zero emissions, considering both technical feasibility and practical implementation? From your expertise, what are the key challenges in integrating various retrofit elements seamlessly to achieve net-zero emission in buildings? • Can you explain the limitations of these retrofit elements? (building envelope, energy efficiency, materials, waste, renewable energy, etc.) • - What can the opportunities be when these limitations and challenges of individual retrofit elements are integrated and optimized? From your perspective, what role do policy and regulation play in incentivizing or mandating the adoption of net-zero retrofitting practices?

Net Zero building objectives	In your opinion, what are the most effective strategies for reducing embodied carbon impacts during the retrofitting process of existing buildings? • What are the challenges and limitations? How can we ensure that operational carbon targets are realistically set and achieved in retrofitted net-zero emission buildings? Are there any best practices or benchmarks to follow? • Can you elaborate on specific criteria or parameters that will enhance the operational carbon emission phase? How do you envision the role of advanced technology, beyond AI, in achieving the optimization in the retrofit process to net-zero emission building?
Artificial Intelligence role	In your expertise, what are the key areas where AI can contribute most significantly to the process? - How do you see this situation in the process of individual key components in making a building more sustainable to net zero? • What specific challenges and limitations do you encounter with AI? • What can the opportunities be when these limitations and challenges are addressed? Can you elaborate on specific AI algorithms or techniques that hold promise for optimizing energy efficiency and reducing carbon footprint in retrofit projects? • What are the criteria and parameters for AI to optimize these tasks? What role do you see AI playing in seamlessly integrating various retrofit elements to achieve a holistic net-zero emission outcome? What challenges do you foresee in implementing AI-driven solutions for retrofitting existing buildings, and how can these challenges be addressed effectively? **Opportunities** From your expertise, can you provide insights into how AI technologies potentially contributed to improving the accuracy and efficiency of managing consultancies? • Are there other specific characteristics or parameters that enhance management consultancies' outcomes? • Are there any specific AI algorithms or techniques that have been particularly effective?
Design and Construction Management	In what ways do management consultancies influence the decision-making process and mitigate risk associated with influencing data for AI adoption? • How does this impact other actors & stakeholders in projects? • What are the key elements/factors for input data that result in output data? Garbage In, Garbag Out (GIGO) What are the potential benefits of integrating AI technologies into the tasks and execution of actors and stakeholders involved in projects? • How can AI enhance the effectiveness and efficiency of actors and stakeholders? • What are the main challenges or barriers faced by actors and stakeholders in adopting AI technologies, and how can these challenges be effectively addressed? How do you envision the interdisciplinary collaboration between AI experts and professionals in the field projects(e.g., managing consultancies, architecture, engineering, project managers, investors) for achieving project goals/individual goals? In what ways do actors and stakeholders benefit from the involvement of management consultancy practices in AI-assisted methods? In what ways do management consultancies influence the decision-making process and mitigate risk in projects (in retrofitting)? • How does this impact other actors & stakeholders in the building retrofit? • What are the key elements/factors for input data that result in output data? Garbage In, Garbage Out (GIGO) Are there strategies that actors/stakeholders can influence the overall success of the project? • And how are these strategies achieved and integrated into the retrofit process to net zero? • What are the potential opportunities for these actors & stakeholders through the management consultancy practices perspective? How important are stakeholder engagement and collaboration in the successful implementation of net-zero retrofitting projects? What strategies have you found effective in engaging diverse stakeholders throughout the process? What are the key technical challenges associated with integrating AI into management consultancy practices? • What about in relevance to project optimization? **Limitations** What are the limitations of AI in management consultancy practices for a project?

Table 5.2: One-on-one semi-structured interview topics

5.1.3 Coding (ATLAS.ti)

For Chapter 5, a deductive approach using closed coding was adopted (See Table 5.3). Predefined categories based on the conceptual framework were used to analyze expert insights regarding the capabilities and limitations of AI in decarbonization strategies.

Closed coding	Sub-code
Deficiencies in Retrofit Strategies	Energy inefficiency
	Financial constraints
	Data
	Building envelope limitations
	Operational inefficiencies
	Regulatory hurdles
AI Capabilities	Real-time data integration
	Predictive analytics for proactive measures
	Energy optimization using intelligent control systems
	Embodied carbon minimization through material optimization
	Enhanced decision-making and accuracy
AI Limitations	Financial barriers
	Data quality and availability issues
	Technical complexity and system integration challenges
	Stakeholder resistance
	Human intelligence, creativity and out of the box thinking
Impact of AI on Net-Zero Objectives	Energy reduction
	Integration challenges for modern retrofitting technology
	Carbon emissions reduction
	Renewable energy integration
	Inconsistent or evolving regulations
	Operational efficiency improvement
Hypothesis Validation	Hypothesis 1: Data-driven integration is feasible with AI
	Hypothesis 2: AI can refine retrofit techniques more effectively
	Hypothesis 3: AI supports operational carbon reduction
	Hypothesis 4: AI minimizes embodied carbon
	Hypothesis 5: AI reduces human error and enhances decision-making

Table 5.3: Closed coding in ATLAS.ti

5.2 Artificial Intelligence's Real-World Applicability

This chapter describes how experts perceive AI's practicality in the current landscape of building retrofitting:

1. What Experts Believe AI Can Realistically Do
   Discuss tangible benefits AI has already demonstrated or could achieve in retrofitting projects.
2. What Experts Believe AI Cannot Yet Do
   Focus on limitations, including feasibility issues, resistance to adoption, and the gaps that still need to be bridged.
3. What Needs to Change for AI to Succeed
   Summarize expert suggestions for improving AI's applicability, creating a forward-looking discussion that sets up Chapter 6.

5.2.1 What Experts Believe AI Can Realistically Do

This section delves into the practical contributions of artificial intelligence (AI) to building retrofitting projects, as perceived by industry experts. AI's capabilities are already transforming how decarbonization and net-zero objectives are approached by enabling data-driven insights, optimizing energy use, and improving decision-making. However, the successful application of AI hinges on understanding its realistic potential across various domains, from defining measurable objectives to balancing technological solutions with project-specific requirements.

5.2.1.1 Defined and Measurable Objectives

According to all interviewees, implementing successful AI-driven strategies for decarbonization and achieving net-zero building objectives requires providing a clear roadmap and criteria for assessing progress. Successful AI integration in retrofitting projects includes having well-defined, feasible, and measurable objectives in building retrofit projects aimed at achieving net-zero outcomes, which ensure clarity and adaptability during the implementation phase. These objectives form the foundation for AI to deliver targeted improvements to achieve decarbonization and net-zero outcomes.

The AI capabilities that align with this is Benchmarking and Targeting and Predictive Analytics and Forecasting. Establishing clear objectives helps stakeholders set priorities, allocate resources effectively, and maintain alignment throughout the project's lifecycle. The interviewees emphasized that measurable objectives in AI-driven retrofit projects should focus on the following key metrics for AI implementation:

1.Energy savings

First, the energy consumption in the building projects needs to be defined to allow improvements based on data-driven benchmarking with AI. Interviewees highlighted the importance of setting quantifiable energy-saving targets, measured in kWh or percentage reduction. These targets are vital because they provide a clear benchmark for assessing the effectiveness of the retrofit measures. Without specific, measurable energy-saving objectives, it becomes difficult to gauge whether energy-saving initiatives are successful or falling short. Currently, many existing buildings and retrofit stakeholders must rely on traditional methods and assumptions for monitoring, optimizing, and adjusting systems like HVAC, lighting, and energy usage patterns, which may not capture real-time data and insights into existing buildings. Interviewees pointed out that these traditional approaches are often more manual, time-consuming, and less efficient, and they lack previous data to drive the cause of enhancing energy reduction.

"Having a clear energy efficiency target allows us to measure progress and adapt strategies during the implementation phase to ensure we meet those net-zero goals." – Interviewee 8

Hence, by establishing well-defined and measurable energy savings early in the process, the retrofit project ensures that energy efficiency is feasible and realistic to meet long-term expectations. Clear energy-saving objectives allow for data-driven decision-making and effectively continually adapt to changing circumstances, ensuring that energy reduction efforts are sustained over time. AI's role in this context is powerful, providing real-time data insights and monitoring that traditional methods often cannot achieve. For instance, AI can track and analyze energy consumption patterns, identify inefficacies, and recommend improvements based on predictive models. Therefore, the stakeholders can have clear energy savings targets to monitor progress and adjust strategies accordingly to ensure energy reduction in buildings. Ultimately, defining measurable energy-saving objectives ensures that AI can work optimally, using data to continually monitor, refine, and adjust systems for maximum energy efficiency, thus making the retrofit effective and scalable.

" They actually used artificial intelligence to optimize the energy consumption in the building based on how often a particular part of the building is being used. Uh, and this relates to net zero in the sense that, uh, you can, as I said, optimize energy consumption based on usage." – Interviewee 9

2.Carbon Footprint Reduction

The second measurable objective is to reduce carbon emissions, measured in CO2 equivalent per year. Interviewees emphasized that establishing clear carbon footprint reduction targets in projects is to provide clarity and accountability in evaluating the impact of retrofitting strategies. The components of carbon footprint reduction include improving building efficiency, optimizing material usage, and lowering energy consumption. These still require careful planning and defined objectives, but they depend heavily on manual analysis, expert judgment, and traditional monitoring systems.

"aligning building projects with carbon reduction targets, especially to meet the demands of global standards like the Paris Agreement." – Interviewee 15

In traditional approaches to carbon footprint reduction, the process often begins with an energy audit or a carbon assessment, where baseline carbon emissions are calculated based on the building's energy usage, material choices, and operational inefficiencies. Interviewee 18 mentioned, "We typically start with a detailed carbon audit, but it takes time and requires a lot of manual data collection." These audits give stakeholders an understanding of where carbon emissions are concentrated but rely on static data, typically gathered annually or semi-annually, which limits the ability to track real-time changes or make dynamic adjustments.

Another challenge with this manual approach is the lack of real-time monitoring. Decisions about carbon reductions often rely on estimated data or long-term averages, which makes it harder to identify specific inefficiencies or opportunities for improvement on an ongoing basis.

"You can make an impact by switching to renewable energy sources or improving insulation, but you don't have immediate feedback to know how effective those changes are until the next audit." – Interviewee 11

Material selection is another critical aspect of reducing the carbon footprint, particularly in terms of embodied carbon. Interviewee 13 mentioned that "choosing sustainable materials, like low-carbon concrete or recycled steel, is one way we can reduce the carbon impact of a building, but sourcing those materials and assessing their impact takes time and involves navigating complex supply chains." The manual process of evaluating and sourcing materials with lower embodied carbon can be inefficient, and without AI's ability to process large datasets, identifying the most effective materials for a project is more challenging.

Thus, carbon footprint reduction that leveraging data allows for a defined objective for AI to consider a data-driven approach to these factors to improve areas such as energy consumption, material selection, and operation efficiencies. For example, AI can analyze energy sources, suggesting sustainable alternatives like renewable energy systems. It can also assess material usage, recommending low-carbon options for key elements of the building envelope, such as windows, walls, and floors, where traditional materials may have higher embodied carbon.

"AI systems help reduce operational carbon by suggesting alternatives for energy sources and materials, such as solar panels or sustainable construction materials, to lower the overall carbon footprint." – Interviewee 8

Additionally, sustainable materials and energy-efficient designs, when optimized through AI, ensure that both embodied carbon (from construction materials) and operational carbon (from energy use during a building's life) are minimized. This reduces the building's overall carbon footprint and provides an objective way for stakeholders to assess whether retrofitting measures are effective in contributing to decarbonization and achieving net-zero outcomes.

"Embodied carbon in construction materials and operational carbon from building use, especially when replacing high-carbon materials with low-carbon alternatives." – Interviewee 12

To conclude, without well-defined carbon reduction objectives, it is challenging to assess the effectiveness of retrofit measures and to pinpoint whether the applied measures are genuinely reducing emissions or simply making marginal improvements.

3.Operation Efficiency
Third, operational efficiency needs to track energy use intensity (EUI) over time. This metric, which measures energy consumption per square meter of a building annually, provides effectiveness in the post-retrofit phase. Through monitoring and data collection, traditional methods of data collection, such as manual meter readings, building audits, and periodic inspections. This means that data on HVAC systems, lighting, and energy use is gathered at intervals rather than continuously.

"Traditional systems require manual oversight, which means inefficiencies can go unnoticed for weeks or months." – Interviewee 9

Moreover, defining objectives for building operations often depends on predefined schedules and human intervention. For example, HVAC systems might be set on a fixed schedule regardless of actual occupancy or real-time needs. Interviewees pointed out that managing energy use during peak demand periods can be challenging. For instance, building operators must rely on general estimates and manual controls to balance energy use, which can lead to higher costs and energy waste during peak times. Measurable operational efficiency is crucial to ensuring that retrofitted systems deliver the expected improvements in energy performance. Without clear and measurable objectives, it becomes difficult to track whether operational enhancements are reducing energy consumption and improving building performance effectively. Interviewee 12 noted that "manual systems often fall short in providing real-time insights, making it harder to optimize building operations dynamically." Setting clear objectives, such as energy use intensity (EUI) targets, helps create a structured framework to assess the performance of building systems, allowing for timely adjustments and ensuring alignment with net-zero goals.

"Having real-time operational data to make adjustments quickly," – Interviewee 10

Through an AI-driven role that monitors and analyzes real-time operational data, it ensures continuous and sustainable efficiency improvements. This enables energy use based on real-world building performance, which reduces wastage and makes more accurate adjustments to energy consumption in the operational phase.

4.Cost Savings
Moreover, cost savings in AI-driven retrofit projects are focused on the Return on Investment (ROI) and the payback period of retrofitting investments. Interviewees repeatedly emphasized that financial viability is key to ensuring long-term success and net zero objectives. One important distinction is between OPEX (operational expenditures) and CAPEX (capital expenditures). Interviewee 13 discussed how focusing on reducing OPEX through energy-saving measures like smart lighting and HVAC systems can shorten payback periods, making retrofit projects more financially attractive. Similarly, by identifying the most efficient retrofitting solutions, AI systems can help ensure that CAPEX provides a strong ROI, thus balancing the initial investment with ongoing operational savings.

"so you can measure that from a carbon perspective, as in carbon saved, you could measure it from a financial *perspective, CAPEX spent versus OPEX saved. So, you're saving from implementing."- Interviewee 8*

The factor of AI-driven is to identify the most effective strategies for reducing both energy consumption and operational costs. It can prioritize retrofitting actions based on real-time performance data, ensuring that investment target areas with the highest potential for savings are aligned with the project's cost-saving objectives.

5.Building Performance Standards

Subsequently, building performance standards, such as LEED, Edge certification, and BREEAM, provide critical benchmarks for assessing and improving the sustainability of retrofitted buildings. Several interviewees noted the importance of adhering to these standards, as they offer both an assurance of quality and a measurable way to track progress towards net-zero building objectives. For instance, Interviewee 7 highlighted that achieving certifications like LEED or BREEAM helps quantify the sustainability impact of retrofitting projects, offering a structured framework for assessing improvements in areas such as energy efficiency, water use, and material selection. Furthermore, these certifications act as motivators for building owners, as they add long-term value and appeal, particularly in markets where sustainable buildings are increasingly in demand. As referenced by Interviewee 9, the value of certifications indirectly discusses the importance of building standards and ensuring that retrofits align with current market demands for sustainability. The emphasis on "market demand for sustainable solutions" implies the importance of certification to demonstrate value to clients.

Thus, AI systems can detect inefficiencies or deviations from the required performance levels and suggest corrective actions. By defining clear building performance objectives aligned with measurable certifications, to ensure sustainability standards.

Interviewees stressed that this adaptability is crucial for achieving net-zero outcomes, as it allows stakeholders to track and verify sustainability metrics throughout the lifecycle of the building. Ultimately, this ensures that the building's environmental impact is minimized while also providing financial and reputational value through recognized certification.

Thus, defining clear building performance objectives aligned with recognized standards is essential for ensuring that AI-driven retrofits maintain a high level of sustainability and effectiveness. This helps stakeholders continuously monitor progress, guaranteeing that both the retrofit process and the building's operations meet internationally recognized sustainability criteria.

5.2.1.2 Retrofit: Optimizing Installations AND Building Envelope Improvements

The second AI can do, AI can involve a distinction between retrofit projects in The Netherlands and those outside the country (United Kingdom, Canada, United Arab Emirates, Africa), particularly concerning the integration of building envelope improvements and optimizing (energy) installations. Both are fundamental to achieving net-zero building objectives because improving the envelope reduces demand, and optimizing installations increases energy efficiency and integrates renewable energy.

Interviewees emphasized different approaches. Some mentioned the importance of starting with installations and energy improvements, while others started by upgrading the building envelope. The critical factor here is understanding when to prioritize building envelope improvements versus installation optimization and find an effective balance or project-specific division that is cost-effective but also contributes significantly to the building's net-zero objectives. ***The AI capabilities that aligns with this is Data Decision Support.***

"First step is optimization. Second step is building fabrics. Third step is your current heating system and 4th step is on site renewables and then fifth step in quotation is offsetting essentially." – Interviewee 8

Based on all the Interviewees in the Netherlands and a few international ones, the common pattern is to focus on energy improvements, such as HVAC systems, lighting upgrades, and renewable energy installations, as a starting point. Interviewee 8 noted, *"In many cases, it's easier to make quick energy gains by upgrading to high-efficiency systems like heat pumps or LED lighting. The return on investment is clearer and faster than some structural changes."*

Also, energy system improvements also have the advantage of being more flexible. Interviewee 11 explained that while building envelope improvements require physical changes to the structure, installations can be adapted more easily and scaled depending on energy needs.

"Usually, the starting point is around what could be done to refine the existing equipment. So, can you change things in the control settings and try to look at how energies are being used? So is the air conditioning operating or the ventilation operating 24 hours a day? Can you reduce it when places are occupied? The same for lighting."- Interviewee 11

In terms of installation improvements, several interviewees noted that government incentives play a significant role in promoting these upgrades. For instance, Interviewee 7 pointed out that government subsidies and tax incentives for renewable energy installations, such as heat pumps and solar panels, have made these improvements more financially attractive to building owners. Similarly, Interviewee 10 mentioned the growing support for smart energy solutions like automated HVAC systems, which are often eligible for energy efficiency grants and rebates. These policies and financial incentives, especially in regions like The Netherlands, encourage building owners to prioritize installations that maximize energy efficiency and renewable energy use.

Hence, installation improvements often offer more immediate returns and are easier to implement. They allow building owners to start benefiting from energy savings sooner, particularly in cases where building envelope improvements might not be possible due to budget constraints or building restrictions. However, focusing solely on energy installations without addressing building envelope inefficiencies can result in a less-than-optimal overall retrofit. If the building envelope remains poorly insulated, for instance, significant heat loss can still occur through the walls, windows, floors, and roof. This can lead to higher energy consumption as HVAC systems or other energy installations must work harder to maintain internal temperatures.
Even so, starting with the building envelope, many interviewees pointed out that improvements, such as adding insulation, improving windows, and upgrading roofing, are essential to reducing overall heating and cooling loads. By improving the building's thermal efficiency, energy demand for HVAC systems is significantly reduced, making energy improvements more impactful.

"Year 1 is metering behavior change. Building fabric starts in year one. Year 2 building fabric continues. Draft proofing starts in year three. The building fabric continues, building management systems are installed, lighting upgrades are also completed. Year 4, and HVAC upgrades and HVAC controls are done. Year 5, solar PV. And year 6 and 7 are heat pumps." – Interviewee 13

This focus on the building envelope is driven by the need to first optimize the passive energy efficiency of a structure. By reducing heat loss and improving insulation, buildings need less energy to maintain comfortable temperatures, making any energy system improvements more efficient. However, these upgrades can be costly and, in some cases, technically challenging.

"So you always adopt what is called a fabric-first approach, where you ensure that the building in question is *thermally insulated in the best possible way." – Interviewee 8*

Therefore, AI enables the prioritization of optimizing installations versus building envelope improvements by providing data-driven insights. This makes AI a potential tool for determining which interventions will have the most impact on energy efficiency and achieving net-zero outcomes. This approach ensures retrofit projects integrate passive energy efficiency (through the building envelope) and active installation improvements for project-specific needs and objectives. ***The AI capabilities that aligns with this is Real-Time Monitoring and Data Analytics and Intelligent Control and Optimization.***

"You can't say one element is more important than the other cause to interlinked. There are certain types of installations that are more sustainable than others, but they don't work with an uninsulated building." – Interviewee 4 (case study)

5.2.1.3 Regulatory and Policy Compliance

Subsequently AI can do, the compliance with existing and evolving building codes, energy efficiency regulations, and sustainability standards. AI's ability to track, monitor, and adjust to new regulations makes it a powerful tool for aligning retrofit projects with regulatory requirements. Adhering to national and international policies, such as the Paris Agreement or local building regulations, is essential for achieving long-term success in decarbonization efforts. The AI capabilities that align with this is Compliance with Regulations.

”one of the things that are always good, to explain, it’s kind of the rules and regulations that are currently in place and when they need to meet certain regulations because sometimes it does add up to invest in an early stage compared to doing that in a later stage.” Interviewee 7

Several interviewees emphasized the importance of integrating AI systems that can automatically track compliance with environmental regulations, ensuring that buildings meet and exceed (country) governmental mandates. For instance, Interviewee 12 highlighted that “with AI, we can track compliance with changing environmental standards, which is crucial for projects aiming for long-term sustainability.” This points to AI’s adaptability in maintaining compliance with both current and future regulations, allowing retrofitting efforts to stay relevant as policies evolve.

“…like let’s say the news rules and regulations because I think one of the issues isn’t even if you look at sustainability from a European level and if you look at it from let’s say Brussels perspective there. So many different directives and rules and regulations, and these will be updated. And what is it 2027 again and you know like there there’s a lot of information and I think the more there is yeah, the more difficult it will be for clients to actually understand what they need to do... You know, like “door bomen het bos niet meer zien (English: be overwhelmed, not see the wood for the trees)” because there’s just so much.” – Interviewee 7

Moreover, governmental incentives aimed at promoting sustainable building practices can be effectively leveraged through AI. Interviewee 11 mentioned, *”And then what you get is sort of best practice that’s maybe incentivized, or that’s coming from the top down, where people look at their peers and try to be better than them.”* This emphasizes the potential role of AI in not only ensuring compliance with evolving regulations but also optimizing financial outcomes by identifying government support programs or tax incentives linked to sustainability objectives.

In addition, by integrating AI systems that can track and adapt to regulatory changes, stakeholders can ensure that their retrofitting projects are compliant with the latest regulations while optimizing performance. This allows buildings to meet sustainability targets, receive relevant certifications, and remain feasible remain financially attractive by taking advantage of incentives and cost-saving opportunities in the long term perspective.

“So, being able to look at multiple different parameters and the kind of trade-offs in different scenarios, looking at what regulation or policy or inflation might do. So you can kind of quite quickly get a lot of analysis to give you a lot, a lot of outcomes.” – Interviewee 11

5.2.2 What Experts Believe AI Cannot Yet Do

Despite AI’s transformative potential in building retrofitting, several limitations hinder its full applicability. This section explores the critical gaps in data quality, availability, and structuring, as well as potential solutions like baseline metering and the use of present-day building characteristics to overcome these challenges.

5.2.2.1 Data Quality, Availability and Structuring

“AI is really about data. So, AI can’t create any data. It works off the data it’s fed.” – Interviewee 6

The first finding of AI cannot yet do lies in the quality and availability of the data that feeds the AI systems. The input data’s granularity, structure, and reliability are highly reliant on the effectiveness of AI in any retrofit project. All the interviewees highlight the importance of accurate data quality and availability as the cornerstone for AI-driven decarbonization and achieving net-zero building objectives. Along with quality and availability, the data structuring of reliable data sets for AI models to deliver actionable insights effectively. The capabilities that hinder AI’s capacity to leverage its core capabilities are Real-Time Monitoring and Data Analytics, Predictive Analytics and Forecasting, and Intelligent Control and Optimization.

“It really depends on how accurate the data or what your model is, whether it’s if it’s, let’s say it’s a forecast system, it would depend on how accurate your system is to real-world data.” – Interviewee 9

1.Data Quality
Data quality refers to the accuracy, reliability, completeness, and relevance of the information provided to AI systems, which can include everything from energy consumption data to building performance metrics and material use. Poor data quality leads to unreliable insights, ineffective optimization, and, ultimately, suboptimal decision-making. As a result, AI will make decisions based on flawed assumptions, which can result in ineffective retrofitting strategies, increased costs, or failure to meet energy and carbon reduction goals. Interviewee 15 emphasized the importance of reliable data for AI systems to deliver actionable insights. "You need good quality data to be able to do this… The data you put into it is the quality of the output you get from it". For example, if energy consumption data is inaccurately measured, the AI will be unable to accurately model the building's energy use patterns. Thus, AI may recommend energy-saving measures that are either unnecessary or ineffective.

"COVID changed how buildings were used, and a lot of the data we collected during that time is not reflective of normal operations. This makes it hard to use AI effectively if we rely too heavily on that data." - Interviewee 12

During the pandemic, where irregular building usage created anomalies in the data, potentially distorting the data quality in specific years of COVID. Hence, these energy data points cannot be used, and this shows how external factors like the pandemic can affect data accuracy.

"The challenge with using post-COVID data is that it doesn't accurately reflect standard building usage, so the data may give recommendations that aren't applicable once things return to normal." – Interviewee 9

Moreover, the interviewees referred to the granular and detailed data to break down energy consumption data to the individual components of a building's systems, such as HVAC, lighting, and heating. Interviewee 8 mentioned the need for this level of detail, particularly in energy consumption and usage patterns. For example, AI can identify which areas of the building use the most energy, track fluctuations in energy use during peak hours, and recommend specific actions to reduce wastage. Interviewee 13 pointed out, *"Getting meters and monitoring systems that are efficient allows better management of the building's energy"*. Real-time sub-metering data is crucial for providing this level of detail.

"You need a constant stream of data to see what's working and what isn't. AI helps, but if we don't have the data coming in, it's like working blind." – Interviewee 11

"If the data isn't accurate, it won't be as useful if the data is messy, it won't be as useful either, so you would have to go in and remove any. You may have to go in and remove any unnecessary or unused characteristics in the data, but that shouldn't be too hard, honestly." – Interviewee 9

2.Data Availability
Multiple interviewees, including Interviewees 9 and 12, emphasized the challenge of incomplete or inconsistent datasets, especially in older buildings, where legacy data systems are less structured and standardized. For AI systems to function optimally, they must have access to sufficient data. In the context of building retrofitting, this includes both historical and real-time data about the building's energy performance, material usage, and overall operational efficiency. Many older buildings were constructed, and the 2D drawings are lost or inaccurate. As a result, the quality and availability of data in these buildings are often limited to outdated or incomplete records, making it difficult to establish accurate baselines for energy consumption, material usage, building state and renovation data, and operational efficiency. This data gap can hinder the successful integration of AI systems, which rely on comprehensive datasets to function optimally. For example, historical data on energy usage in older buildings may not exist in digital form, or the data might be fragmented across different systems, formats, or periods. This lack of structured and consistent information can make it difficult for AI algorithms to identify trends or create accurate models of a building's energy performance before retrofitting. Interviewees raised concerns about this limitation, noting that older buildings often lack detailed performance histories, making it harder to apply AI's full capabilities without first addressing data collection.

"Data, the availability of data, and the level of data required to teach a model." – Interviewee 16

Interviewee 12, mentioned, "When you're dealing with older infrastructure, often there are gaps in the available data, making it hard to assess current performance accurately." This illustrates a common problem in older buildings where data records may be sparse, and integrating new technologies to gather accurate performance data can be resource-intensive.

"Missing or irrelevant data can cause inefficiencies in the retrofit process, as AI may spend time processing information that doesn't directly contribute to energy or carbon reduction goals" – Interviewee 12

"So artificial intelligence is not limited; it just has to be available datasets for each to feed into and give you the output you need. So, the opportunities for it to help us decarbonize our built environment are just endless." – Interviewee 18

For newer (after 2000) buildings, despite the availability of modern technologies and systems to collect detailed data, many clients are not taking full advantage of these capabilities. Interviewees pointed out that cost, effort, and the client's lack of awareness are the primary barriers to comprehensive data collection. This highlights the gap even in newer buildings, where advanced metering systems like sub-metering or smart sensors might not be installed due to client decisions, despite the fact that such data could provide invaluable insights for AI-driven retrofitting efforts. In many cases, the potential energy and cost savings from having real-time, granular data are not fully realized due to a lack of initial investment in data collection infrastructure.

"the primary challenge is that clients aren't collecting it, but sort of the reason for that is often because either they don't know they need to or they don't have a mechanism to do so." – Interviewee 7

3.Data Structuring

Some interviewees highlighted the structuring of legacy data. Even when data exists, it may not be readily usable by AI systems because it could be in formats incompatible with modern digital platforms. In these cases, stakeholders must undertake data conversion or cleaning processes to make the information accessible and meaningful for the AI system.

"…clean up those data to make it read better, or we can, so some of the data is quite dirty that we cannot really learn anything from there."- Interviewee 8

" We have an awful lot of data. I think the problem is structuring it in the right way. So, without having any clear policies and guidance, it's it will probably take longer for the AI engines to be able to interrogate and find out what we are looking for." – Interviewee 10

Thus, inconsistent data sources such as energy meters, manual logs, or building management systems need to be structured. For instance, the implementation of standardization ensures all data follows a standardized format (e.g., units of measurement, time intervals). Also, data cleaning and removing or correcting inaccurate, incomplete, or duplicated data entries to ensure that only high-quality data is fed into the AI system.

"But you also need to understand the engine and how it interprets and reads that data." – Interviewee 10

"I don't know if you've realized it, but in in my opinion, construction data is very unstructured. The construction industry is really struggling to structure its data, and I don't think that. I think like every industry, things that are very unique and every project is very unique and it is unique to a set and degree." – Interviewee 15

4.Data Solutions

In several cases, interviewees highlighted that the availability of legacy data, such as historical energy consumption records or material use data, may not always be essential for retrofit. For example, Interviewee 9 mentioned that older buildings often lack detailed historical data, and the absence of legacy data shouldn't make the retrofitting process more difficult. Instead, alternative strategies can be used to gather the necessary baseline information.

In situations where legacy data is not available or incomplete, a solution mentioned by Interviewees is the use of baseline metering or zero metering. This process involves establishing a detailed, real-time assessment of the building's current performance. Through baseline metering, retrofitting projects can measure and analyze the existing conditions of the building's systems, including lighting, cooling, heating, materials conditions, and other building characteristics of that moment of measuring. The idea is to "set a baseline" from which improvements and future performance can be measured.

"…you do null meting (English word: zero/baseline metering)… take a look. Describe everything. Make pictures that say this is not good in maintenance. This is it, and this is what it's in there. Everything is measured. So the Lightning, the cooling machines, the heat pumps the air handling, you install the stuff, and then you know, OK, this is what we have in the building." – Interviewee 12

"Therefore, historical data is less important because you're taking the situation at face value at the time of retrofit, whereas when you're for other clients (public sector), Historical data is far more important because we want to map out what it's cost them over time historically and into the future post-refit. And therefore, that data becomes far more important." – Interviewee 8

[the following data is interesting research data found in Chapter 4: Case Study. This could be a solution for AI cannot yet do…]

In addition to baseline metering, highlighted in the case study is the building characteristics retrofit measurement modeling. Interviewee 1 noted that rather than depending on previous data, the emphasis shifts toward analyzing current building characteristics. These characteristics include structural elements, existing infrastructure, and operational inefficiencies that can be directly observed and assessed without relying heavily on legacy data. Similarly, Interviewee 8 emphasized the value of understanding a building's present physical attributes, which allows retrofitting efforts to advance more efficiently even in the absence of historical data. This approach allows retrofitting projects to move forward efficiently even when historical data is limited, focusing on present-day building characteristics to improve the existing situation.

5.2.3 What Needs to Change for AI to Succeed

This section explores the key changes and strategies required to enhance the applicability and success of AI in achieving net-zero objectives through retrofitting projects. Building on expert interviews, it identifies practical recommendations that address project-specific factors, the optimization of AI algorithms, the need for stakeholder engagement, and robust measurement and verification processes.

5.2.3.1 Project-Specific Factors

While AI offers advanced solutions for optimizing and accelerating building retrofitting projects, the necessity of AI-driven implementations depends on several project-specific factors. These factors include the building's location, age, size, existing infrastructure, and the availability of sustainable materials and technologies. In cases where the building size, complexity, or energy systems are simpler, the cost of integrating AI might outweigh the benefits, or the standardization of retrofit without AI can be applied to the general retrofit building cases. Therefore, AI may not be a one-size-fits-all solution but should be considered based on the scope and ambition of the retrofit.

"AI is not always necessary for smaller-scale projects where manual adjustments and traditional techniques might suffice." – Interviewee 13

On the other hand, Interviewee 15 emphasized the unique value AI brings to large, complex retrofitting projects: *"When we deal with larger portfolios or energy-intensive buildings, AI becomes essential for handling the sheer volume of data and optimizing performance at multiple levels."* In these cases, AI can help maximize energy efficiency, manage resource consumption, and ensure continuous monitoring through real-time data analytics, which would be challenging to handle manually.

Thus, the decision to integrate AI should be based on a detailed analysis of the building's specific needs, technical feasibility, and financial constraints. Smaller-scale or less energy-intensive projects may achieve satisfactory results without the need for AI. Whereas more complex, data-driven projects aimed at achieving stringent decarbonization goals will benefit from AI-driven strategies. The key is to match the technological solution with the complexity and scope of the retrofit, ensuring that AI is deployed where it can deliver measurable value. Therefore, integration AI should be evaluated on a project-by-project basis, ensuring that it adds real value where necessary. At the same time, traditional approaches may still suffice for less complex retrofitting efforts. ***The AI capabilities that aligns with this are Predictive Analytics and Forecasting, Data Decision Support, and Benchmarking and Targeting.***

"So a challenge is that what works in one house might not work in another, umm. And therefore you have to pay really for the individual designs of each of the properties." – Interviewee 8

5.2.3.2 AI Algorithms Selection and Optimization

Secondly, the algorithm's role in the AI system determines how effectively it can predict energy usage patterns, optimize HVAC systems, integrate renewable energy sources, adapt to real-time changes in building performance, and much more integration into the retrofit measures. Interviewees consistently emphasized that selecting the appropriate AI algorithm is essential for accurately modeling a building's energy profile and ensuring that retrofit interventions deliver the desired energy and carbon reductions.
As Interviewee 6 mentioned along the lines of AI, it is as good as the algorithm driving it. If you don't choose the right algorithm for the specific building or the data you have, the AI will struggle to make accurate predictions. This underscores the importance of algorithm selection in ensuring that the AI system aligns with the building's unique characteristics and energy consumption patterns.

"You don't know what is the AI tool. That's the challenge. Which AI tool are you going to use?"
– Interviewee 6

"So let's say I'm head of head of finance. I need to know how this AI system that we're proposing to implement is going to give me a return on investment in this time frame. That's what I need to know. That's where the AI expert comes in and can say, well, actually, it would do it this if I'm the program manager; I need to know that actually if this AI tool that we're implementing supports people in doing their job and also support the program in achieving what it needs to." – Interviewee 17

The importance of using building-specific algorithms was a recurring theme among interviewees. Some highlighted that algorithms should not follow a "one-size-fits-all" approach, as buildings have unique energy consumption behaviors and operational dynamics. Instead, algorithms need to be adaptable to each building's characteristics. This customized strategy allows AI to more efficiently model, forecast, and enhance energy consumption according to the specific requirements of each project.

"It will either standardization, so everybody's capturing information in the same way, or it will and be able to bridge those gaps, so aggregated data which is all in different varieties, different sources and things like that, then the machine learning model will be able to kind of pick out the bits that are relevant for what it's looking for." – Interviewee 16

Additionally, some interviewees emphasized algorithms for cost-effectiveness are as important as energy efficiency. They highlighted the need for AI systems to provide insights into energy savings and financial metrics such as Return on Investment (ROI) and payback periods. This dual focus ensures that retrofitting decisions align with financial sustainability and decarbonization objectives. In addition, several interviewees noted that algorithm optimization should be an ongoing process. As more data is collected, algorithms can be refined to become more accurate over time, improving their predictions and recommendations. This continuous refinement allows AI systems to adapt to new data and evolving building conditions.

"And one thing I'd also look at is costs. Cost to set up an AI tool. It's not cheap. Also, look into how much AI is used in data centers. In terms of how much energy is used to use AI.⍰" – Interviewee 6

While several interviewees advocated for the customization of AI algorithms tailored to each building's energy profile, a recurring discussion centered around the potential benefits of using standardized models to save on implementation costs. According to Interviewees, applying standardized algorithms in specific areas such as baseline energy predictions, and the same type of building characteristics could reduce upfront costs by avoiding the need for custom solutions on each project. This perspective highlights a balance between cost-efficiency and the need for accuracy in decarbonization objectives. On the other hand, Interviewees emphasized that while standardization might save costs initially, it could lead to inefficiencies over time, particularly in buildings with unique operational behaviors. Hence, standardization might be feasible for simpler or less energy-intensive projects but requires careful assessment to ensure it fits into the retrofit project. ***The AI capabilities that aligns with this are Machine Learning for Continuous Improvement, Fault Detection and Diagnostics, and Data Decision Support.***

"…that look at sort of standardization and trying to understand how you can use modern methods of construction and other things to sort of standardize the component process. But fundamentally, they don't work and this you have the right kind of data and that is the single biggest challenge." – Interviewee 16

5.2.3.3 Stakeholder Engagement and Adoption

"So I think it is very important that these different players interact with each other and then look at the long-term picture because otherwise, it's really hard to achieve a shared benefit if everyone is just looking for their own benefit on their own." – Interviewee 15

The third recommendation for the success of AI-driven retrofit projects aimed at achieving net zero is engaging the right stakeholders from the start. You can't just bring in AI solutions for decarbonization and expect them to work without involving everyone with a say in the project. This means bringing together a wide range of experts and professionals, such as building managers, AI specialists, sustainability experts, policymakers, and financial backers to collaborate and align on shared goals.

"And so I think that the way I see it is that AI experts will have to be we need them because they only know the different impacts that it will have on different stakeholders and who needs to know what and why they need to know what." – Interviewee 17

For AI-driven strategies to be effective, everyone involved must be on the same page. AI specialists and sustainability experts, for example, need to work closely with construction teams and building managers to ensure that the technology being introduced fits with the building's needs and goals. Having early buy-in from key stakeholders helps smooth out the process and prevents any surprises later on. It's particularly important to ensure building owners and operators understand how AI can help improve energy efficiency and cut carbon emissions. As Interviewee 10 explained, if building owners don't clearly see the benefits, they might hesitate to invest in AI systems. Likewise, Interviewee 14 emphasized that policymakers have a big role in providing regulations and incentives to support decarbonization.

"Building the software isn't the hardest part. Well, actually, it is hard, but it's not the hardest part. The hardest bit is to get people on board a lot. People, people don't like change. People like to do things the way they do it because that's the majority of people." – Interviewee 15

In some cases, however, too many stakeholders can complicate decision-making. As Interviewee 3 remarked, *"Too many chefs in the kitchen"* can lead to miscommunication and delays, highlighting the importance of managing stakeholder involvement efficiently. For example, Interviewee 6 emphasized that the building owners, being the ones with financial authority, are often the most critical stakeholders, as they are the ones who ultimately need to believe in and invest in AI solutions for decarbonization to move forward.

"So it's really hard to explain how the machine learning model actually works, like the backlog of AI. Oh, so I guess it's like a black box. People don't really trust. You can see, that maybe probably in lots of the projects we work with is like people asked for some of the I won't call it an I will say it's more advanced analytic things, but it turns out they do not trust those results. I guess it's a challenge that I face at work. " – Interviewee 14

Trust in AI is another key issue. Many stakeholders may be hesitant to fully trust AI-generated insights. Interviewee 14 noted the "black box" nature of AI, making it difficult to explain how the models work, which in turn causes skepticism among business stakeholders. To overcome this challenge, Interviewee 3 suggested that validation of AI outputs by trusted parties could help to build trust in the data and analysis, reassuring stakeholders that the technology can reliably support decarbonization efforts. ***The AI capabilities that align with this are Data Decision Support and Real-Time Monitoring and Data Analytics***

"And that is a major barrier to actually the true deployment of AI and delivering decarbonization for effectively the lowest possible outcome. Price is the willingness of the value chain within construction to actually get on board with that. So, to do that, you need to provide them with a structure or a framework that will give them value outside of pure monetary value. So can they understand better what they're doing? What can they learn from that thing? So the whole piece around machine learning and AI is how do you influence the value chain to give them insights and analysis that they've never had before? That's the really important piece. And yeah, you're right. It's a major barrier. " – Interviewee 16

5.2.3.4 Measurement and Verification

The last recommendation is the measurement and verification of AI-driven techniques in retrofitting projects. Establishing clear and robust metrics allows stakeholders to accurately gauge the impact of AI systems in reducing energy consumption and carbon emissions. A key challenge discussed in 5.2.2 What Experts Believe AI Cannot Yet Do, as several interviewees highlighted, is that while AI can significantly expedite processes, its outputs are only as good as the data it is fed.

"I think the limitation of the dangers that I see with AI as a tool is learning from stuff that isn't correct. So you, but like what I said earlier, just being generally relatively skeptical, you want to make sure that I never want to be in a position where I rely totally gospel on what AI spits out and because I just don't think that's necessarily the most sensible way of going about it. And I think that the danger to becoming with AI, in general, is to become lethargic. And that is because you rely on AI. To generate stuff so quickly, people become. Lethargic with they trust AI." – Interviewee 8

Based on Interviewee 8, this highlights the importance of having a ***human validation process*** to ensure that AI outputs are accurate and that decarbonization outcomes are being achieved as intended. AI systems should not operate in isolation but should be part of a continuous feedback loop where their outputs are regularly verified and adjusted by human operators.

"I'm not really in a position to say whether five years' time they are accurately measured, but I would like to hope that after a project is completed, there is some sort of verification process whereby you ensure that deliver the savings." – Interviewee 8

Moreover, as noted by Interviewee 11, is a need for ***agreed-upon processes to measure and verify the outcomes*** AI systems generate. "If you don't have agreement on the process to follow, using AI to optimize and refine it becomes more challenging because you don't have the mechanism necessarily to review and verify that." This underlines the importance of having a well-structured, transparent process for AI-driven retrofitting efforts to ensure compliance with sustainability goals. As this loops back to a transparent backlog and a process to verify the data that puts out of the AI system.

"You have people that are putting in stuff, and it needs to be validated and, I think, checked by someone to see if it's what is in. I actually comply against the specification, and if it's correct, but within the AI technology environment, I don't know if there's a body or a company or a person who could validate that data and say yes, it's correct, or if it complies with a certain norm. I think that is the only way how you can validate or check the data that is right or wrong or needs to be worked on." – Interviewee 3 (case study)

Therefore, while AI can process and put out a lot of data, human verification remains crucial to ensuring that these strategies are grounded in reality and not compromised by faulty data or inaccurate assumptions. Interviewees emphasized the question of measurement and verification processes in projects, and how stakeholders can ensure that AI tools contribute effectively to decarbonization while delivering measurable, long-term outcomes aligned with regulatory standards and financial goals. ***The AI capabilities that align with this are Machine Learning for Continuous Improvement, Real-Time Monitoring and Data Analytics, and Benchmarking and Targeting.***

"I think it will be, yeah, maybe generate something and then a person needs to go and validate it and make sure that it's correct, which is and in which is interesting, right? Because in that way, you almost like to train the system, right? So you say, well, this wasn't correct and the system will say, OK, well I need to, I need to do it differently." – Interviewee 15

However, there is a risk that AI tools, if not properly monitored, may perpetuate errors based on ***flawed data or human bias***. Interviewee 15 also cautioned, "Make sure that you also cover the kind of downfalls like if the data isn't correct, what happens then?" This statement underscores the importance of both ***the accuracy of input data and the necessity of human oversight in validating AI outputs***, especially to counteract potential biases introduced by human input during the data collection and validation.

"There are very few people and I think it's also very easy. To not realize until it's too late, like until like quite a big mistake has happened. It's not always obvious that there is a, let's say, a bias or some kind of error." – Interviewee 15

"You can have sort of unconscious biases within your AI learning model, and it would probably reflect the organizational culture that you have and whether that's a good or a bad thing. I'm not sure. It would probably be more biased towards you, so that sort of a downfall." – Interviewee 17

5.2.4 Summary AI's role

Aspect	What AI Can Do	What AI Cannot Yet Do	Changes Needed for Success
Energy Efficiency	Optimize HVAC, lighting systems, and energy use through real-time monitoring and predictive models.	Struggle to integrate with poorly insulated or outdated systems in older buildings.	Implement baseline metering to establish starting points; improve sub-metering and data granularity for ongoing optimization.
Carbon Reduction	Suggest low-carbon materials, optimize building envelope designs, and recommend renewable solutions.	Rely on static, fragmented data; cannot provide real-time embodied carbon analysis.	Improve data sharing across the supply chain; promote sustainable material databases with standardized data formats.
Cost Optimization	Forecast ROI and payback periods; recommend cost-efficient retrofitting strategies and schedules.	Limited by incomplete financial datasets and fluctuating material costs.	Strengthen AI algorithms to address financial volatility; improve stakeholder engagement for better cost estimation inputs.
Regulatory Compliance	Track evolving building codes and standards; ensure adherence to policies such as the Paris Agreement.	Struggle with fragmented regulatory frameworks and lack of standardized data.	Develop AI systems that adapt to regional and international standards while simplifying compliance processes for stakeholders.
Operational Efficiency	Streamline project timelines, phase retrofitting measures, and optimize resources.	Struggle with limited real-time adjustments in smaller, less complex projects.	Apply phased AI implementation for simpler buildings first; scale up to complex projects as AI systems improve.
Data Quality and Access	Analyze patterns in large datasets; provide actionable insights for decision-making.	Cannot function without clean, reliable, and well-structured data inputs.	Standardize data collection processes; clean and structure legacy data for compatibility with AI systems.
Stakeholder Trust	Provide transparent, actionable insights to guide decision-making.	Faces skepticism due to the "black box" nature of AI and lack of trust in predictions.	Engage stakeholders early in projects; validate AI outputs with human oversight to build confidence in AI-driven decisions.
Material Procurement	Recommend sustainable materials based on carbon footprint and lifecycle analysis.	Struggle to optimize supply chains without comprehensive material data.	Encourage supply chain collaboration and transparency; ensure materials have traceable and comparable sustainability certifications.
Risk Management	Predict project delays, cost overruns, and system failures through historical data.	Struggle to predict risks in projects with incomplete datasets or unforeseen variables.	Refine algorithms for real-time adaptability; strengthen financial and operational risk analysis capabilities.
Ethical Oversight	Enhance decision-making with advanced analytics and automation.	Cannot account for emotional intelligence or nuanced ethical considerations.	Maintain human involvement for decisions requiring empathy; ensure AI is programmed with ethical guidelines to avoid biases and errors.
Accountability	Provide precise metrics to measure energy savings and carbon reductions.	Cannot ensure data input accuracy or rectify biases on its own.	Establish strict data validation and quality control processes; clarify accountability for data accuracy across stakeholders.
Client Communication	Automate reporting, generate clear summaries, and visualize energy and carbon data.	Cannot replace human interaction or interpret emotions and nuanced client needs.	Combine AI-driven insights with human-led discussions to maintain personal engagement with clients.

Table 5.4: Summary of AI's role in Building Retrofitting based on experts insights (interviews)

5.2.5 Further Recommendations for AI Implementation

This section provides targeted recommendations to enhance the successful implementation of AI in building retrofitting projects. By addressing systemic challenges and proposing actionable strategies, it aims to create a foundation for industry-wide adoption of AI technologies. Recommendations focus on advancing digitalization, adopting phased approaches, fostering collaboration across the supply chain, and emphasizing the importance of human-AI partnerships. These strategies are designed to overcome existing barriers, such as fragmented data systems, stakeholder skepticism, and technological complexities, ensuring AI-driven solutions align with decarbonization objectives and industry needs.

5.2.5.1 Advocate for Industry-Wide Digitalization

At present, many retrofit projects suffer from incomplete or unstructured data, which limits the potential of AI to make informed decisions and deliver optimized solutions. To ensure that AI can function effectively, it must have access to standardized, well-structured data across the industry. This requires increased collaboration between various stakeholders, including building owners, construction professionals, AI developers, and policymakers.

"We need a shift in how data is presented both internally and externally for AI to link and perform what needs to be done." – Interviewee 9

"It'll either standardization, so everybody's capturing information in the same way, or it will and be able to bridge those gaps, so aggregated data which is all in different varieties, different sources and things like that, then the machine learning model will be able to kind of pick out the bits that are relevant for what it's looking for."- Interviewee 17

Digitalizing the building sector would involve not only upgrading data collection systems (such as IoT devices and sensors) but also creating platforms for real-time data sharing across multiple projects. By having access to aggregated data from multiple sources, AI could draw more accurate conclusions. This transformation toward digitalization would also facilitate cross-project learning, where insights from one project could be applied to others, improving overall efficiency in the building sector.

"If there isn't willingness around sharing that data and information because they don't see the value in it, whereas putting a machine learning model in the middle may actually give both of those data owners insights and analysis that they didn't have before because they only owned the data sets, they didn't have the aggregation of that information so that it will be a challenge in terms of overcoming data sharing agreements and where that information can come from and who the data owners are as well." – Interviewee 16

However, while advocating for industry-wide digitalization is critical for AI-driven retrofits, the rapid pace of technological innovation presents a significant challenge. As Interviewee 15 pointed out, the fast evolution of technology creates a "constant race to stay relevant," making it difficult for companies to keep up. This rapid change can overwhelm especially larger organizations, which tend to be slower in adapting to technological advancements. Additionally, decisions made today may quickly become obsolete, requiring continuous adjustments. While the speed of innovation can drive improvements, it also forces frequent reevaluation of strategies and investments, which can be both resource-intensive and disruptive.

"I think the other thing is that technology innovates quickly. So there are different kinds of things happening day by day. So sometimes you make a decision that fits you now, but it won't be the best solution. Probably. Maybe in a week. So I guess that's also it's a good thing and a bad thing you have to change everything you have done, that's also something." – Interviewee 14

The AI capabilities that align with this recommendation Real-Time Monitoring and Data Analytics, and Data Decision Support.

5.2.5.2 Phased Approach to AI Implementation

AI implementation in building retrofitting projects should adopt a phased approach, beginning with new builds where data is more structured and accessible before scaling up to legacy buildings or more complex projects. AI is most effective when it has a well-structured data environment, making new builds the ideal starting point for gaining experience and refining AI systems.

"I think doing net zero on a new build is significantly easier than an existing building." - Interviewee 11

This step-by-step integration enables stakeholders to gradually see the impact of AI, increasing acceptance of the technology and providing time to address any technical or operational challenges that may arise. By demonstrating clear value in smaller-scale applications, this phased approach also minimizes resistance from building owners and operators, who may be hesitant about investing in AI for larger systems without seeing its proven success.

"The point long here is it will always be easier to do this for new buildings, right? Always and it's because you can easily, uh. You can easily influence most of these things at the design stage." – Interviewee 18

Moreover, starting with basic tools such as data analytics or sub-metering, allows teams to familiarize themselves with AI technologies and their potential benefits without committing significant resources upfront. Interviewee 15 emphasized the importance of gradual implementation, stating, *"The first step is to use data technology to understand the data; the second one is more advanced machine learning tools."* This step-by-step process ensures that AI is introduced in a controlled and manageable manner, reducing risks and allowing for lessons learned along the way.

Thus, starting small might involve applying AI to monitor energy usage, identifying inefficiencies, or collecting real-time data from building systems. By doing this, stakeholders can gain a deeper understanding of their building's operational characteristics and performance. Once teams are comfortable with these simpler applications, they can begin to implement more advanced AI-driven technologies, such as predictive maintenance or energy optimization systems, which rely on more sophisticated algorithms and larger datasets. ***The AI capabilities that align with this recommendation are Predictive Analytics and Forecasting, and Intelligent Control and Optimization.***

5.2.5.3 Collaboration Across the Supply Chain

"Yeah, and that's the big challenge, which is actually where you've got maybe conflicting priorities. We are still trying to, and the only way we can address that really is by being in a space where we say to people you have to be open and transparent. There is no kind of, though no criticism, no judgment. There's no pushback. You create a safe space for people to share." – Interviewee 11

The data required by AI systems to optimize material sourcing and cost, assess embodied carbon, and enhance project efficiency often spans multiple stakeholders, from suppliers and manufacturers to contractors and clients. Therefore, data sharing across the supply chain becomes a vital element in enabling AI to perform effectively. This highlights the growing need for suppliers and manufacturers to recognize the importance of data transparency and to begin sharing information that AI can use to deliver optimized, sustainable solutions. ***The AI capabilities that align with this recommendation Fault Detection and Diagnostics, and Compliance with Regulations.***

"It's the other side of the fence, so you've got to you've got to be transparent and you've got to be really clear, I think. But that's the point around the ethics are the collective sort of norms and values of the majority of people in the industry. So if you're, if the industry isn't on board, then you look like the odd one out using AI. If the industry is on board, then it's just common practice. So I think that's where you have to try and get to and have that influence to say." – Interviewee 17

However, as highlighted by multiple interviewees, data anonymity is critical to gaining stakeholder trust and ensuring compliance with privacy regulations. Interviewee 16 emphasized, *"It's people understanding that the data that's being collected is aggregated and anonymous, it's not tracking them in any way,"* while Interviewee 10 added, *"As an example of anonymity, you know people can benchmark themselves against* *others without knowing the names of those companies."* These insights underscore the critical need for anonymizing and safeguarding data while enabling AI platforms to facilitate seamless collaboration across the supply chain.

"I think that is the potential for AI to be able to identify anomalous data. For example, if you're a client working with a lot of different contractors and you ask them for data, some of them will give you full, accurate data. Some of them might not. AI probably has the potential to identify that and say, hang on, this data set is an outlier." – Interviewee 11

Hence, AI specialist integration into the construction industry is becoming increasingly crucial. As noted by Interviewee 17, AI specialists are often underestimated in the industry, yet their expertise is vital for ensuring that AI-driven strategies are effectively utilized. These specialists understand the AI methodologies required to harness construction data, enabling the implementation of AI systems that can streamline processes, optimize supply chains, and ensure sustainability goals are met. AI experts play a critical role in aligning technological solutions with the needs of all stakeholders, knowing the specific impacts on various aspects of construction management, from material sourcing to energy optimization. Their involvement ensures that AI methodologies are not only applied but tailored to the specific demands of construction projects and stakeholders, optimizing decision-making processes, improving efficiency, and reducing carbon footprints across the supply chain.

5.2.5.4 Human-AI Partnership

"You have to remember the big fear about AI: You could lose a job. Yeah, so it needs to be done in the right way, where it's still human-led but backed by AI and not led by AI." – Interviewee 6

AI should complement, not replace, human judgment. Interviewee 14 emphasized the importance of maintaining human involvement in the decision-making process, particularly in complex retrofitting projects: *"How you choose your tools is quite important… It's all based on human decisions, although there could be artificial ways"* (Interviewee 14). This approach ensures that AI is guided by expert insights, with human professionals applying their contextual knowledge to AI-generated recommendations. ***The AI capabilities that align with this recommendation Machine Learning for Continuous Improvement, and Benchmarking and Targeting.***

"Sargent nature, which means its ability to actually behave like a human being, the right thing you know, you can try to make it behave like a human being at the end of the day, you know you still talking to a robot or and it still feels a certain type of way, you know, like, imagine you saying that your best friend is a robot." – Interviewee 18

This underscores the need for AI to work alongside human decision-makers rather than acting as a standalone system. AI cannot fully grasp the nuances of human thought, emotional intelligence, or context, which makes human oversight crucial to avoid overly mechanized or inappropriate responses in real-world scenarios.

"People's responsibility, so if you are working with sort of a machine that isn't going to correct you in what you import, you have to be really sure of the quality that you're inputting." – Interviewee 17

In a "Human-AI Partnership," the collaboration between humans and machines is essential for optimizing performance in construction management. Machines are not meant to replace human capabilities entirely; instead, they complement and enhance human expertise. Interviewee 10 emphasized that while machines can handle repetitive, mundane tasks, the complex decision-making still requires human judgment. In this partnership, humans are responsible for guiding the AI, teaching it the right processes to ensure it delivers accurate results. AI cannot function without precise human input, and interviewees recognized the importance of feeding quality data into these systems to avoid the *"garbage in, garbage out"* problem. It was noted that AI customizations must be constantly refined, much like how humans learn and adapt over time.

"Even with that alert that you would get that a project is going to be delayed at the end of the day, it comes down to the project managers and the actual humans you know, to make corrective actions on it." – Interviewee 9

One main challenge discussed by Interviewees was the risk of human complacency. With AI handling more tasks, there's a risk that people might become less engaged in their work, leading to lethargic performance and poor decision-making. This underlines the need for an active, mindful partnership between humans and AI, ensuring that the technology is used effectively while human oversight remains integral.

The following data is analyzed to address Sub-Question 4 (SQ4): "How can design and construction management utilize AI in decarbonization strategies?" This section explores the integration of AI across various stages of Design and Construction Management (DCM), highlighting its potential to enhance project efficiency, sustainability, and decision-making.

5.3 Role of AI in Design & Construction Management

Across the interviews, several key roles for AI in Design and Construction Management (DCM) practices were identified, which align with optimizing project efficiency, improving decision-making, and ensuring projects meet objectives. AI's ability to analyze vast amounts of data, predict outcomes, and streamline processes means it can be used effectively at every design and construction management stage. From project planning and resource management to real-time monitoring and risk mitigation, AI offers opportunities to revolutionize traditional DCM practices. This section will delve into the specific areas of AI integration within DCM, as identified in the interviews, exploring how AI can contribute to advances in DCM practices while addressing challenges related to technical, financial, and environmental feasibility.

"But I think for construction, the biggest opportunity for AI is to bridge the gap between site and computer. And if you can do that, that will unlock all manner are changes within construction more generally as well." – Interviewee 16

5.3.1 Early-Stage Design and Scenario Planning

In construction management, early-stage decision-making is crucial for embedding decarbonization strategies effectively into retrofit projects. Interviewee 7 highlighted how AI can offer stakeholders multiple design options, allowing them to compare strategies like refurbishment versus demolition and rebuilding. AI tools can simulate how various design choices, such as selecting energy-efficient materials or systems, will influence future energy consumption and overall building sustainability. These advanced tools allow project teams to evaluate design alternatives early on, ensuring that decisions are made in alignment with long-term decarbonization objectives. AI helps optimize material usage, identifying opportunities for reuse, thus minimizing the carbon footprint of the construction process.

"So it's more of advisory. So from the project management bit and also from let's say there's the advisory consultant bit, it's now to come up with a strategy. We will not necessarily do the design and all that, but we will be able to advise at design stage. This is what can be done. This is what you know, these are the options you have and as the project managers to make it so clear and what we do is we'll enable the client to actually, you know, actualize that plan." – Interviewee 18

In practice, AI's integration into construction management during early design phases allows for efficient iterations of design plans, making the process more sustainable and cost-effective. Project managers can also use AI to track materials across different projects, facilitating reuse and significantly lowering the embodied carbon of a building. Therefore, implementing AI in the early design phase can support better decision-

making that aligns with decarbonization goals from the beginning of the project.
Furthermore, Interviewees highlight the scenario analysis, AI allows construction managers to evaluate multiple design and construction options, providing insights into their carbon impacts. As Interviewee 9 mentioned, *"AI can challenge the design by simulating different options, such as turning a building slightly to optimize solar panel efficiency or suggesting alternative materials."* This capacity enables project managers to make better decisions that align with both financial and decarbonization goals. AI's ability to simulate various construction approaches, materials, and design strategies allows for real-time adjustments, reducing carbon emissions during construction. This flexibility ensures that decision-makers can optimize both the environmental and financial outcomes of their projects.

To conclude, AI's scenario modeling is not limited to design; it can also be applied to investment strategies. AI can generate multiple financial scenarios, offering construction managers and stakeholders different pathways for retrofitting and decarbonization. Interviewee 13 highlighted how AI could help by providing options for clients, *"AI could provide multiple scenarios for clients... for example, one scenario for investing as soon as possible, and another for delaying investments"*. This allows decision-makers to adjust strategies dynamically, considering changing financial and environmental conditions.

5.3.2 Project Planning and Scheduling

Construction management can utilize AI to evaluate project timelines and assess risks, such as material shortages or adverse weather conditions. Interviewees discussed how AI allows for more precise planning, giving project managers the tools to mitigate risks early in the design phase. This predictive approach ensures smoother project execution, reducing the likelihood of unexpected setbacks.
One of the significant advantages of AI in construction management is its ability to optimize project schedules. By analyzing previous project data, AI identifies inefficiencies and improves task sequencing. Interviewee 10 explained that AI optimizes project sequencing by predicting the most efficient steps in the design and construction process, reducing project durations and emissions.

"AI can help us speed up the process around design and how we build it, so we get the right sequencing" - Interviewee 10

Following in construction management by optimizing retrofit timelines and phased investment strategies. AI models can help project managers create strategic, phased approaches for building retrofits, helping to efficiently plan resources and investments. Interviewee 13 pointed out that AI-driven models can project costs for each year of the retrofit and divide them into specific measures, such as heat pumps, lighting upgrades, and building fabric approach.

"With this model, the client can see the projected cost for each year of the retrofit... split into various retrofit measures like heat pumps and lighting upgrades" – Interviewee 13

This enables construction managers to better align retrofit activities with deadlines, tenant agreements, and resource availability, which is essential for middle to large-scale retrofitting projects involving multiple buildings. But also, for smaller building projects, AI can assist in ensuring that resource allocation is efficient, minimizing downtime and unnecessary costs, while still optimizing energy savings and sustainability outcomes.

5.3.3 Risk Management

By leveraging historical data and project insights, AI can forecast potential issues and offer mitigation strategies, improving decision-making and reducing the likelihood of project delays, cost overruns, or failure to meet sustainability goals.

"I think what it means for them is that, you know, if you think of the construction industry it's like 20 years behind. It's certainly not technology-like other than a kind of safety. Tech isn't really a huge part of what we do. Okay. And what it does is it develops the industry to say you can be more automated, you can be more digitally enabled for accuracy, for safety, for reducing costs." – Interviewee 17

Interviewees discussed the area where AI is particularly valuable is in predictive maintenance. AI can predict when construction equipment or systems are likely to fail, allowing proactive maintenance before costly or environmentally harmful breakdowns occur. This reduces both unexpected delays and the emissions associated with inefficient operations, ensuring that construction activities remain aligned with decarbonization targets. Next mentioned by the Interviewees, AI can predict risks such as material shortages, fluctuating prices, or unforeseen structural challenges, and provide recommendations for alternative materials or design adjustments. For instance, Interviewee 12 highlighted the volatility of material prices, explaining how AI could help predict price surges and suggest necessary adjustments to keep the project within budget. AI models can also forecast the best time to implement specific retrofitting measures, considering financial, lease, and carbon-saving factors.

In addition to mitigating construction management risk is also highly effective in predicting design-related risks. According to Interviewees AI can suggest alternative materials or construction techniques that may be less vulnerable to delays or disruptions while still contributing to decarbonization goals. Interviewees discussed AI's capacity to optimize project timelines by forecasting the ideal time to implement retrofitting measures based on factors like financial viability, lease agreements, and potential carbon savings.
By modeling multiple risk factors, such as unexpected material costs or structural challenges, AI supports real-time adjustments that can keep projects on track and within budget, while still achieving their decarbonization targets. In essence, AI offers construction managers a dynamic risk management tool that allows them to foresee issues, propose timely solutions, and ensure the overall sustainability of their construction projects.

5.3.4 Cost Estimation and Accuracy

The ability of AI tools to automate cost estimation and budgeting processes significantly enhances the accuracy and efficiency of financial planning. This ensures that projects remain financially viable while aligning with sustainability goals. AI assists in modeling long-term financial outcomes, providing accurate predictions of return on investment (ROI) for decarbonization measures. This capability is critical in retrofitting projects, where private investors and stakeholders need a clear financial justification to proceed. Interviewee 8 mentioned that AI-generated financial models are often essential in assessing the feasibility of such projects. Construction managers can use AI-driven financial analysis tools to simulate various investment scenarios, predict savings from energy-efficient measures, and calculate long-term operational costs. This process ensures that clients can make well-informed financial decisions about retrofit investments.

"If we can work with an organization or understand that gap, like every project, every program overruns; it overgoes on cost, it overgoes on budget, and it overruns on time. If you can save even 5% of that across all the global programs. We instantly become the organization for everything." – Interviewee 16

AI's capacity to analyze market trends, material prices, and project logistics enables it to optimize costs while meeting decarbonization targets. Interviewee 10 highlighted that AI could even search for price lists and compare suppliers to provide cost-effective and sustainable solutions. For example, AI could "surf the web, find price lists, and build a cost plan for sourcing components at the lowest carbon impact." In construction management, this feature helps develop cost-efficient carbon reduction strategies by identifying low-cost, low-carbon materials and recommending suppliers that follow sustainable practices. This capability reduces the financial burden of decarbonization on construction managers and clients. Also, providing precise financial forecasting that accounts for fluctuating material costs and long-term benefits of decarbonization. Construction managers often face challenges with financial planning due to unpredictable material costs and uncertain long-term savings. AI systems integrate financial data from past projects and forecast future costs for materials like steel or insulation. For example, Interviewee 12 mentioned that due to global events, such as the Ukraine conflict, material prices have fluctuated drastically, making budgeting more complex. AI can forecast such cost changes and simulate financial scenarios based on energy savings and sustainability investments, helping construction managers maintain budget accuracy.

"And a lot of I can guarantee you if you talk to some of the business people, they would say that I want 100% confidence interval or something like that which makes no sense. It is technically speaking, it doesn't really make any sense. Uh, so you can get something like a 99.99% confidence interval, but you know, realistically, population-wise speaking, you're not ever going to get 100% confidence interval because it's just it's just not possible. Umm, like from my understanding of it, but yeah, I understanding the system or understanding the tools that you're using and the analysis itself is very important." – Interviewee 9

5.3.5 Automate Routine Task

Report writing, document analysis, and data summarization handling these repetitive tasks with AI allows project managers and other key stakeholders to focus on more complex, value-adding activities that require human judgment, such as creative problem-solving or building client relationships. One of the most time-consuming tasks in construction management is the creation of reports and documentation that track project progress. AI can significantly reduce the workload in these areas by automating report generation. Interviewee 13 highlighted this benefit: *"If I could put this model into AI and have it written the report for me, that would be nice... it would save us a lot of time"*. By automating these tasks, AI not only saves time but also ensures consistency and accuracy in reporting. This can help reduce human error and create more reliable records of project progress.

Accurate reporting is essential for tracking energy consumption, material use, and overall decarbonization efforts in retrofit projects. Interviewee 14 pointed out the efficiency AI could bring to this process: *"Reporting processes… can definitely be replaced by AI technology"* (Interviewee 14). With AI's ability to process large datasets, project managers can quickly assess sustainability metrics and energy usage, making data-driven decisions to meet carbon reduction targets. This automation ensures that reporting is completed faster and more accurately than manual methods.

Moreover, AI's data-processing capabilities make it easier to analyze large amounts of information related to construction projects. Interviewee 14 emphasized that AI can extract valuable insights from complex datasets, helping to evaluate carbon footprints and efficiency improvements in real-time. This allows construction managers to make informed decisions that align with sustainability and decarbonization goals.
For instance, administrative tasks such as compliance documentation, cost estimation, and scheduling can also be automated using AI, significantly reducing the workload for construction managers. As Interviewee 15 mentioned, *"AI can write reports... and then our people just need to review it and correct it"*. AI's ability to take over administrative tasks like report generation not only increases efficiency but also enhances project outcomes. AI helps to ensure that documentation is kept up to date and accurate while reducing the burden on project managers.

"that allows you to focus more time on your mentally engaging activities, like how exactly do you help the client? How exactly do you give the client more return value for their money and such like nuances?"
– Interviewee 18

5.3.6 Procurement and Supply Chain Management

Interviewee 6 highlighted the importance of AI in procurement, especially when it comes to sourcing sustainable materials. *"AI tools can ensure that we're choosing the right suppliers based on carbon footprint, sustainability certifications, and proximity to the site"*. This is crucial for meeting decarbonization targets, as sourcing materials with a lower embodied carbon can significantly reduce the overall environmental impact of construction projects.

"Procuring certified renewable energy with a guarantee of its origins. OK, for the renewable energy, yeah, if ou want, if you are on the grid and you really need renewable energy because the PV panels are not doing it in the winter, you need the connection." – Interviewee 5 (case study)

Thus, AI tools can be used to assess suppliers based on sustainability metrics, ensuring that construction materials meet the project's decarbonization objectives. By analyzing factors such as the carbon footprint of materials, their transportation distance, and the sustainability certifications of suppliers, AI can help project managers make informed procurement decisions. In addition, tracking the embodied carbon of materials throughout the supply chain provides construction managers with real-time visibility into the carbon impact of their procurement choices. Interviewees emphasized on better decision-making and ensured that the project's carbon footprint remains within acceptable limits. Also, automatically recommends alternative materials that meet performance specifications while offering a lower carbon footprint. This feature allows construction managers to make more sustainable choices without sacrificing quality or functionality. Furthermore, sourcing materials locally, as suggested by AI, can significantly reduce transportation emissions. Thereby further lowering the carbon emission.

"the client's preferences some of them would want very high specifications, which then will force you to import some of these things, right, as opposed to just using locally made materials. And you could argue as well: once we start importing materials that footprint of, you know, transporting it from one point to another, it kind of beats the purpose of where you want to be green as well." – Interviewee 18

5.3.7 Quality Control and Assurance

AI systems can detect deviations from established quality standards, enabling immediate corrective actions to avoid defects or subpar work. By doing so, AI enhances construction quality, reduces rework, and helps prevent costly mistakes that could delay project timelines or increase expenses. Interviewees mention one of the key benefits of AI in quality control is its ability to analyze vast amounts of data from various construction processes. AI tools can assess material quality, ensure adherence to design specifications, and track project progress to verify that all tasks are executed according to the required standards. Additionally, AI can generate insights into where quality issues are most likely to arise, allowing project managers to proactively address potential problems before they escalate. Thus, the reduction in errors and defects directly contributes to lower project costs, as fewer resources are required to fix problems after they occur.

"So, it's a matter of guiding people on how to use AI, right? But even when you get output back, this is what you can do. So have a look at it run date through the quality checks that you will normally run through your normal report. Right? Have it peer reviewed so that at the end of the day." – Interviewee 18

Additionally, AI-driven quality control tools often include predictive analytics, which can identify trends or patterns in construction data. For instance, AI can forecast the likelihood of a material or process failing based on historical performance data. According to Interviewees as an example, allowing project teams to optimize the use of resources, reduce waste, and enhance overall efficiency. These systems also help ensure that compliance with building codes and regulations is maintained, reducing the risk of legal penalties or project delays.

"How do you create a cycle where you've used something for a month and then you go back and you say actually, what's the what's the accuracy of this data that's inputted? What are the anomalies? Are the anomalies supposed to be anomalies, or do they actually need correcting? And I think that's the only way to reduce the risks, to be honest, is really safeguarding the quality of data that goes into it, umm, and ensuring that people have the right capability and skills to be able to use the tool properly to import quality data. But then also have a level of assurance that they have done this properly." – Interviewee 17

5.3.8 Data Security & Privacy

Data security and privacy are critical issues when utilizing AI, particularly when it comes to protecting sensitive information and adhering to legal requirements. Interviewees expressed concerns about the handling, sharing, and storing of data, especially considering evolving regulations like GDPR (General Data Protection Regulation). For instance, Interviewee 17 highlighted the varying legal requirements across countries, emphasizing how these inconsistencies create challenges in ensuring that AI systems comply with data protection laws. This reflects the broader concern about the potential misuse of personal and proprietary data, making it essential for organizations to prioritize robust data security measures.

The moral concern here extends beyond mere compliance; it's about the ethical responsibility to protect client data and intellectual property. Interviewees further emphasized this, questioning how construction management teams ensure confidentiality when AI systems are involved in decision-making processes. This concern speaks to the core ethical issue of trust. Clients need assurance that their data won't be compromised or misused, which is a critical hurdle for companies looking to adopt AI on a broader scale.

Furthermore, there is a broader ethical issue regarding data ownership and the willingness to share data for AI-driven insights. Interviewee 16 noted that while AI might be the catalyst that encourages data sharing by revealing its value, this can only happen if ownership and control of data are clear. Many organizations remain wary of sharing their information, fearing a loss of control or misuse. This reluctance reflects a broader need for education and transparency about how AI systems handle data and what safeguards are in place to protect it.

"And where does the information go? Where is it stored? And it also needs a lot of information from us to be able to make this analysis. I think that's where the risk is. Yeah, that's where an issue lies." – Interviewee 4 (case study)

"Not particularly willing to allow their data to be used in different ways, and I think that is probably one of the big risks for most organizations is, well, what's actually going to happen with our information and our data. And so there's a whole education piece around that and protection and sort of and barrier, not barriers, stages that we'd need to put in place to be able to truly deploy AI in a in a usable way." – Interviewee 16

Another significant risk highlighted by Interviewee 15 is cyber security. The growing threat of cyberattacks and data theft poses a serious challenge for AI-driven systems, which rely on vast amounts of data. This introduces a new dimension of risk where data protection is not just about regulatory compliance but also about defending against malicious actors who may seek to exploit vulnerabilities in AI systems to acquire company, project, and client data.

"Like so, I think the loss of the data is really important, like cyber attacks and like in general like stealing of data is going be become like quite a big business." – Interviewee 15

5.3.9 People and Ethics (Human Intelligence)

AI brings many efficiencies to construction management, in the areas discussed earlier. These tools can enhance transparency, streamline processes, and improve overall project management. However, Interviewees emphasize despite these advantages, the ethical and human dimensions of human interaction remain critical. One of the key findings is that while AI can assist with technical tasks, clients still prefer human interaction. The emotional intelligence and empathy that come naturally to people are areas where AI, even in its most advanced forms, falls short. In construction management, where client relationships are built on trust, emotional understanding, and quick decision-making, relying solely on AI could create a disconnect. This highlights the importance of maintaining human involvement, particularly in client-facing roles, where understanding emotions, tone, and body language are essential to communication.

" People still recognize people, I don't think society is at a point where, you know, we are in an industry that offers a service customer service. I don't think our clients would respond well to being spoken to by a machine. They want to speak to people, they want to, you know, feel kind of emotion from people. They want to have sort of a tone in someone's voice and things that make us quote-unquote human." – Interviewee 18

Another important point is that AI can sometimes overwhelm clients with too much information. While AI excels at generating vast amounts of data and offering multiple options, humans often find it challenging to interpret these data-heavy insights. Stakeholders may struggle to process a range of AI-generated scenarios, especially when they are presented with complex trade-offs between cost, environmental impact, and timelines. As Interviewee 18 stated, *"So how you see it happens like AI systems gave us more accurate and predictable data and we have to translate that to the client."* Therefore, AI should be designed not only to provide information but to distill it into actionable insights that are easy for clients to understand and apply. This emphasizes the need for human professionals to guide the client through the decision-making process, ensuring that AI's insights are interpreted in ways that align with the client's needs and objectives.

"One of the limitations of AI is that it's definitely not human. People respond well to people in our industry; you know, I went to see a client the other day, and we sat in a room, and I could instantaneously say something; I instantly knew whether they liked or disliked what I said. AI can't pick up on that. It can't pick up on facial expressions. It can't pick up on, you know when you walk into a room, and you're just like this, the energy feels like different." – Interviewee 17

Stakeholders still want the assurance of human oversight and guidance. As Interviewee 4 (case study) noted, "I would still want that human contact to tell me it will actually... I'll hold your hand and walk you through it." This personal touch is essential, especially in complex decision-making scenarios where clients might feel overwhelmed by too much data or too many options. Interviewee 15 highlights, *"It's hard when you are presented with six options... your brain is more likely to just shut down and focus on the fast metric on the page. But it's quite hard to also consider different weights and like which methods to me most and which one* *has where impact in relation to the other. So like, I think we need to acknowledge that this is quite hard for the human brain to actually understand."*

Moreover, Interviewees highlight the ethical concerns in how AI systems are programmed and used in construction management. If AI is not carefully designed or trained on diverse data sets, it could perpetuate existing biases within the industry. The potential for bias in AI decision-making is a risk that needs to be addressed, especially in an industry where inclusivity and equity are ongoing challenges. Implementing AI without careful consideration of these biases could lead to unfair or biased outcomes, reinforcing existing inequalities in construction practices. Similarly, Interviewee 6 pointed out the broader challenge AI poses to job security, remarking, *"So, we need to make it work in a way that it doesn't replace us. It enhances us."*

"A lot of, let's be honest, I wouldn't say that construction is the most inclusive industry. So there is a lot of bias, right? It's not a general like from all different aspects." – Interviewee 15

Additionally, there are concerns about job displacement and the role AI will play in the future of work. While AI can enhance efficiency by automating routine tasks, there is apprehension about whether it will replace human workers, particularly in decision-making roles. Many professionals see AI as a tool that should complement, rather than replace, human intelligence. It is essential to frame AI as an enhancement to human expertise, enabling professionals to make more informed decisions by providing them with better data, rather than a technology that will render human involvement obsolete.

"I think humanity has a tendency to always put itself first in any circumstances like people are self-interested."
– Interviewee 17

Lastly, the success of AI integration in construction management hinges on ensuring that clients and professionals remain involved in the process. While AI can automate many aspects of project management, from cost estimates to scheduling, it cannot replace the human touch required in building client relationships or navigating the complexities of ethical decision-making. Interviewees stated that AI should be viewed as a tool to support, not supplant, human decision-making, ensuring that projects benefit from both the efficiency of technology and the empathy and relational intelligence that only humans can provide.

"Sargent nature, which means its ability to actually behave like a human being, the right thing you know, you can try to make it behave like a human being at the end of the day, you know you still talking to a robot or and it still feels a certain type of way, you know, like, imagine you saying that your best friend is a robot."
– Interviewee 18

5.3.10 Accountability

The issue of responsibility in AI-driven construction management raises important questions about the accountability of both humans and machines. Interviewees emphasized that while AI can enhance efficiency and decision-making, it is ultimately the responsibility of humans to ensure the quality of the input data and the accuracy of AI-driven outcomes. AI cannot be left to operate without oversight, as it lacks the ability to correct mistakes or assess the nuances of human input.

"Yeah, and that's a bit we looked at in the people like people's responsibility. So if you are working with sort of a machine that isn't going to correct you in what you import, you have to be really sure of the quality that you're inputting." – Interviewee 17

Interviewees highlight there is a need to ensure that the data fed into AI systems is free from errors and biases, as AI cannot discern inaccuracies on its own. This requires a high level of human diligence in data management, especially since AI models learn from the data they receive and may perpetuate errors if the input is not carefully monitored.

One of the most significant findings is the role of humans in ensuring the quality of data fed into AI systems. Since AI relies heavily on input data to generate outputs, inaccuracies or biases in the data can lead to flawed results. AI systems do not have the capacity to correct errors on their own, making it the responsibility of those handling the data to ensure that it is accurate, relevant, and free from bias. This is particularly important because AI systems learn from the data they receive, and incorrect or skewed inputs can lead to systemic errors over time. In this sense, human intervention is crucial for maintaining the integrity of the AI system and ensuring its outputs are reliable. Interviewee 17 highlighted how biases can be introduced into AI by the way data is inputted, often reflecting the specific culture or language of an organization. This can lead to AI models that are skewed toward the norms of a particular company, making it difficult to standardize across industries or geographies.

"I think there will need to be quite strict guidelines of how what kind of quality. How do you assure the quality? Because you can't just say, Oh well, AI did it. No, it's our responsibility to make sure the data is correct." – Interviewee 15

Moreover, there is also the issue of gender bias in AI programming, as noted by the interviewee. If the majority of AI programmers are men, the language and decision-making processes within AI systems may unintentionally reflect sexist tendencies, using gendered language or making decisions that do not account for gender diversity. This can lead to outputs that are not universally applicable or even discriminatory in certain contexts. Therefore, it is essential for the people developing and using AI systems to remain vigilant in identifying and mitigating any biases that may affect the system's outputs.

"Like biases like a lot of the programmers of AI or like majority men and so there was like there's a lot of studies that have come out recently that there's a lot of like sexism within AI bots and the terminology that they use, they often are biased towards like he or like using he or him rather than like gender-neutral language. The words that they use are not gender-decoded. They're just like more biased to men, so it's really interesting, like how the programming and the imports and the sort of parameters that you set can really influence the bias of AI." – Interviewee 17

For instance, if the input data is not reflective of real-world conditions or is outdated, the resulting reports and insights generated by the AI could be misleading. This underscores the need for stringent quality control over the data that AI systems rely on. Construction managers and teams must ensure that the data is not only accurate but also relevant to the project at hand. Without this, there is a risk that the AI might recommend actions based on faulty assumptions, leading to inefficiencies and even project delays. While AI can process vast amounts of data and automate reporting, human professionals must be responsible for verifying that the data being used is accurate and contextually appropriate for the project.

"I would say make sure that you also cover the kind of like downfalls like the if the data isn't correct, what happens then?" – Interviewee 15

Lastly, there is a risk that if AI is left unchecked, and reports are generated and shared without sufficient human review, important nuances or errors might be overlooked. This could result in a situation where machines communicate and process data amongst themselves, with little human intervention, leading to potential gaps in decision-making and accountability.

"Also, if AI is creating the reports and summarizing them, who is actually reading them? It creates this weird thing where all of the machines are communicating with each other, and we are just like, whatever…"
– Interviewee 15

CHAPTER 6

CROSS-CASE ANALYSIS

6 | CROSS-CASE – ANALYSIS & SYNTHESIS

This chapter presents a cross-case analysis that integrates the findings from Chapter 4 and Chapter 5 with the conceptual model. It evaluates how Artificial Intelligence (AI) can enhance the feasibility, efficiency and scalability and enable qualitative insights and quantitative requirements to achieve net-zero building objectives and how these strategies can reciprocally strengthen AI's application in building retrofitting. The chapter seeks to elucidate the synergy between AI and decarbonization measures, aligning with the main research question: How can AI integrate decarbonization strategies in building retrofitting to achieve net-zero building objectives in design and construction management?

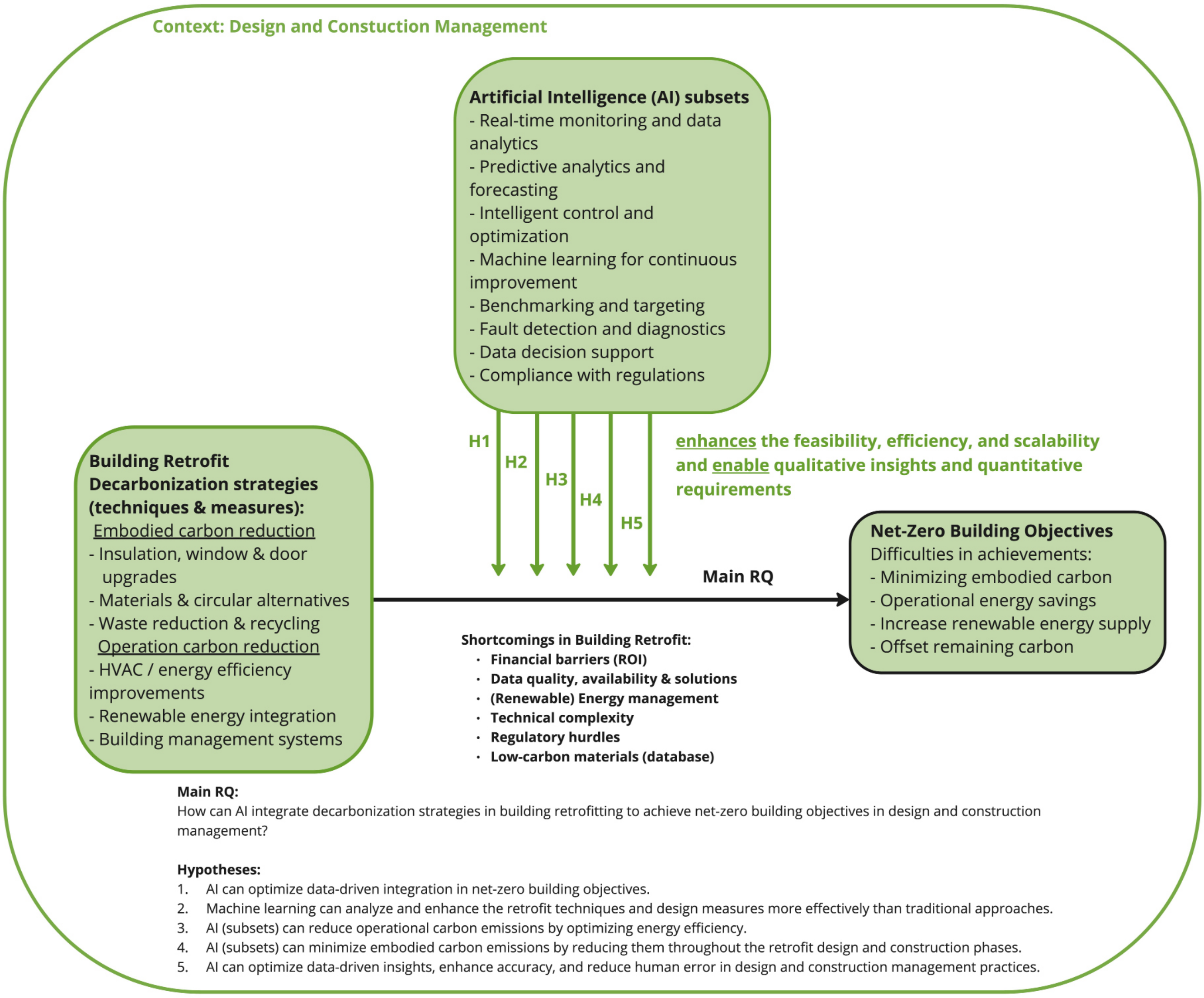

Figure 6.0: Conceptual framework dual-axis perspective (own ill.)

6.1 Introduction

The analysis adopts a dual-axis perspective, as represented in the conceptual model (See Figure 6.0). The horizontal arrow reflects the shortcomings and opportunities in decarbonization strategies identified in Chapter 4, while the vertical arrows represent AI's capabilities and limitations as highlighted in Chapter 5. This chapter synthesizes these dimensions to provide an overarching narrative on the role of AI in bridging existing gaps and enabling more effective decarbonization strategies.

6.2 AI as a Bridge to Address Shortcomings in Decarbonization Strategies

In this section, the results of the case studies, interviews, and combined desk research will be presented and discussed. The aim is to define how AI can address the shortcomings of retrofit decarbonization strategies and help achieve the challenging net-zero building objectives as the end goal.

6.2.1 Data Collection and Analysis

One of the key areas where AI can make a significant impact is in data accuracy and management. As seen in the table, issues like incomplete or outdated data sets, as well as incorrect assumptions about energy consumption and renewable energy production, hinder the progress of retrofitting efforts. AI could help mitigate these problems by enabling *real-time data collection, analysis, and validation*. Machine learning algorithms could improve the quality of input data by identifying gaps or errors and offering more reliable estimations for energy consumption, PV panel outputs, or other key performance indicators. Interviewees discuss the potential for AI to streamline data collection and simplify the process of determining which steps are necessary for retrofitting projects. Interviewees mentioned using *benchmarking data from past projects, but there's always the risk of errors*, especially with human input and reliance on Excel. AI can help *by reducing human mistakes and automating tasks like data collection and analysis*. This ensures retrofit measures are based on accurate, up-to-date information, leading to better decision-making and project outcomes.

"If AI can read it off a plan, that would be great... it would remove a lot of human errors." – Interviewee 4

In addition to its data analysis, AI has the potential to improve decision-making by providing *smart, data-driven recommendations and pointing out any missing information*. By seamlessly analyzing large datasets and identifying gaps, AI can help make sense of complex situations, leading to better, quicker decisions. As interviewee 4 mentioned, *"AI could help flag missing data or suggest improvements, making the whole process faster and more accurate."* Furthermore, with predictive analytics, AI will base decision-making on benchmarking, patterns, and predictive analysis.

6.2.2 Proactive Energy Management & Monitoring/Adjustments

For measures like building energy management and thermal energy storage (TES), AI has the potential to optimize system performance by constantly monitoring and adjusting controls in real-time. Advanced AI systems could analyze patterns of energy use and recommend adjustments to improve efficiency, particularly in cases where ongoing modifications to setpoints are necessary. Moreover, advanced AI could be employed to optimize complex variables like energy storage performance, minimizing uncertainties and optimizing space requirements for technologies like TES.

"It will be good if AI can mention... you need to look at heat systems, then look at building fabric, and at the same time have a square meter allowance for what it will cost." – Interviewee 3

Regarding renewable energy generation, such as PV panels, AI could enhance deployment and performance tracking by ensuring accurate placement and energy production calculations. AI tools, combined with Robotics, could assist in maintaining and adjusting solar panels in real-time, ensuring optimal performance. AI could also provide insights into how these renewable systems can integrate more seamlessly with the building's existing energy infrastructure, improving both energy efficiency and carbon reduction. Moreover, AI can predict the best locations for installing solar panels by analyzing factors like sunlight exposure, shading, and seasonal weather patterns. Once installed, AI-driven systems can monitor the performance of these renewable assets in real time, using predictive algorithms to ensure they generate optimal power. By integrating renewable energy systems more effectively with the building's existing infrastructure, AI helps optimize energy efficiency and reduce carbon emissions, directly contributing to decarbonization strategies.

Additionally, AI could help tackle operational inefficiencies by providing more precise monitoring of energy usage, particularly in buildings that are not sub-metered. This would enable the identification of high energy-consuming areas, allowing for targeted interventions and improving overall building performance. Machine learning models could continuously refine these insights over time, learning from patterns in the building's energy consumption and recommending future optimizations.
Furthermore, predictive maintenance and equipment management enabled by AI help predict when systems

and equipment will need maintenance, reducing downtime and ensuring that all systems operate efficiently. This predictive capability is crucial for maintaining the energy performance of retrofitted buildings in the long term. As Interviewee 3 noted, *"AI can predict when maintenance is needed and prevent unexpected breakdowns, ensuring that systems keep running efficiently after the retrofit."*

"Active energy management includes continuously monitoring energy use and improving efficiency through better insulation and energy management." – Interviewee 12

Moreover, LED systems and AI could play an important role in *optimizing lighting efficiency and energy consumption*. Machine learning can adjust LED brightness and usage based on occupancy patterns, time of day, and natural light availability. By *continuously learning from these patterns, machine learning algorithms could further refine how LEDs are used, ensuring minimal energy waste while maintaining optimal lighting conditions*. Additionally, neural networks can monitor the performance of the LED systems to detect inefficiencies, recommend replacements or upgrades, and schedule predictive maintenance to ensure maximum lifespan and energy savings.

Last, for thermal energy storage (TES), AI can enhance system performance by predicting energy demand and *optimizing* the charging and discharging cycles of TES units. Complex AI could be applied to find *the most efficient combinations* of variables such as temperature, time of day, and energy usage patterns. This not only improves the efficiency of TES systems but also reduces operational costs and space requirements. AI can also identify peak demand times, ensuring that stored energy is used when it is most needed, balancing supply and demand in real-time, and minimizing energy waste.

6.2.3 Optimizing Design and Materials (for low carbon footprint)

By automating aspects of technical due diligence, AI could assist in filling gaps in the assessment of building envelope conditions, such as insulation values or asbestos risks. This could include using Machine Learning and Natural Language Processing to process and interpret large datasets of past building assessments or technical documents. Additionally, Robotics could be used for on-site assessments, offering a more detailed evaluation of hard-to-reach areas or hazardous materials. This would streamline the retrofitting process and allow for more accurate cost and performance predictions, simplifying the planning and execution of retrofit measures.

With AI and machine learning, selecting materials like insulation and window types could be fine-tuned to strike a better balance between cost and energy efficiency, ultimately lowering the building's carbon footprint. As Interviewee 4 pointed out, *"AI could help recommend the most efficient materials while keeping costs in check,"* which is essential for meeting low-carbon goals. On top of that, advanced AI subsets predictive maintenance for systems like HVAC could help tackle inefficiencies in real-time, as Interviewee 3 noted. This would not only boost energy efficiency after retrofitting but also help maintain long-term performance, contributing even more to decarbonization efforts.

Interviewees mentioned using AI to optimize the overall retrofitting process, including material selection, to achieve energy reduction and carbon-neutral objectives. AI could provide insights into the energy efficiency of various materials in real-time, ensuring that the selection process aligns with the project's sustainability goals. The use of advanced AI systems could further enhance this by identifying patterns in material performance data across different retrofit projects, thereby refining the decision-making process.

6.2.4 Compliance with Regulations (incentives)

Based on the interviewees in the context of compliance with *regulations, by feeding the compliance data, AI can automate the verification of compliance with local, national, and international standards*. One of the key challenges in building retrofitting, particularly for projects aiming at decarbonization and net-zero objectives, is ensuring adherence to complex and often evolving regulations regarding energy performance, safety standards, and environmental impact. AI can streamline this process by offering Automated Compliance Checks. Through advanced algorithms, can continuously scan project data against regulatory frameworks, identifying any areas where the building design or materials fall short of required standards. As Interviewees discussed, ensuring accurate data input is a significant hurdle in retrofitting projects, and AI can mitigate these issues *by flagging inconsistencies and automatically aligning project specifications with compliance needs.*

For example, when retrofitting a building to improve energy performance, AI tools can cross-reference the chosen materials and technologies with regulatory standards such as the Energy Performance of Buildings Directive (EPBD) in the EU or local building codes that mandate energy efficiency improvements. Interviewees highlighted the difficulty of staying updated with regulations, especially when they vary between regions or sectors. Machine Learning could address this by maintaining up-to-date databases of regulations and standards and providing instant feedback on whether the retrofit design meets the necessary criteria.

Additionally, AI systems equipped with Natural Language Processing (NLP) could automatically process large volumes of textual data, including legal documents, technical standards, and certification requirements, providing actionable insights in real-time. This would allow project teams to focus on executing the retrofit instead of manually tracking compliance, as Interviewee 1 suggested during discussions on the complexity of managing documentation in large projects.

Beyond regulatory checks, AI can also ensure that the retrofit measures comply with voluntary standards like LEED, BREEAM, or WELL certifications, which promote energy efficiency, health, and well-being in buildings. AI's ability to process large datasets and make real-time adjustments ensures that projects not only meet legal minimums but also aim for higher sustainability goals.

[In the following section, AI's role is discussed in areas beyond the direct scope of the retrofit process or net-zero objectives, touching on broader applications that may still influence the overall construction project outcomes.]

6.2.5 Improving Construction Management

AI's role extends beyond energy efficiency and decarbonization and significantly impacts improving construction management practices in retrofitting projects. All the interviewees highlighted that AI's potential in this field is substantial, offering opportunities to improve scenario thinking, project planning, cost-saving, mitigating risks, and enhancing overall efficiency.

One of the key opportunities AI brings to construction management is scenario planning. AI could enable more sophisticated scenario planning by automatically suggesting different pathways based on cost, building conditions, and government incentives. This would allow clients and consultants to choose the best retrofitting options based on data-driven insights. As interviewee 3 pointed out, *"Providing that within a quick research... this will help increase our productivity when doing estimates."* In addition to improving productivity, AI subset ML could track market conditions and fluctuations in material prices, offering more accurate cost estimates and helping with procurement decisions. This results in more informed decisions based on data-driven insights, enabling the removal of assumptions and reducing uncertainties in the retrofitting process.

"AI can also track market conditions and fluctuations in prices, improving cost estimates and helping with decisions about material procurement," interviewee 3.

Additionally, it is based on Machine Learning-based construction scheduling, where AI can optimize construction timelines. This optimization is achieved through efficient use of machinery, waste reduction, and better coordination of resources, ensuring the retrofitting process is as sustainable as possible. Interviewee 4 mentioned that AI could help streamline construction scheduling and reduce errors through automation, stating, *"With AI, we could ensure smoother coordination between resources, machinery, and timelines, ultimately cutting down on waste and inefficiencies."*

Another notable use of AI in construction management is its role in *risk mitigation and cost saving.* AI technology already reduces human errors and improves cost reporting by providing alerts when discrepancies or issues arise. In addition to improving cost accuracy, AI offers significant potential in decision-making. By processing large datasets, Machine Learning and Deep Learning can flag missing information, identify potential bottlenecks, and recommend improvements. This capability allows for faster, more accurate decision-making.

Interviewee 4 commented, *"AI could help highlight missing data or recommend improvements, making the whole process faster and more accurate, ensuring we're not missing critical elements during planning."*

Along with AI cost efficiency through prioritization, retrofitting efforts should be focused on the most critical areas. By prioritizing high-energy-use zones such as spaces with frequent occupancy, AI ensures that the most impactful changes are made first. In contrast, lower-priority zones, such as corridors, can remain unchanged.

"Focus on specific zones where energy is needed the most and leave other areas like corridors. AI can help target these high-consumption areas for more efficient retrofitting." – Interviewee 3

6.2.6 Criteria and Parameters for Achieving Net-Zero objectives with AI

In achieving net-zero objectives, AI employs a variety of criteria and parameters to optimize building retrofitting efforts. These data points allow AI to continuously monitor, analyze, and adjust building systems in real time to maximize energy efficiency and carbon reduction.

Energy consumption patterns *are one of the primary inputs AI uses to drive optimization. Through the analysis of historical and real-time energy consumption data, AI systems can forecast future demand and optimize operations to fulfill those requirements effectively. This not only mitigates energy waste but also guarantees that systems operate at optimal capacity.*

"AI systems can monitor energy patterns to anticipate potential inefficiencies and modify operations to avert them" – Interviewee 2

Interviewees validates that AI incorporates meteorological data to dynamically modify heating, cooling, and renewable energy production. By incorporating local weather forecasts, AI can predict variations in temperature, sunlight, and wind speed, enabling real-time modifications to energy systems to ensure building comfort while reducing energy use. This feature is especially beneficial for overseeing renewable energy sources such as solar panels, guaranteeing their efficient operation across varying weather conditions. However, this specific use of weather data was not explicitly highlighted by the interviewees, indicating a potential area of opportunity for future exploration in integrating weather data.

Moreover, ***building occupancy data*** gathered through sensors is crucial in AI optimization endeavors. Sensors can ascertain the occupancy of a space at any moment, enabling the AI to modify heating, lighting, and ventilation systems accordingly. This not only boosts energy efficiency but also improves passenger comfort by directing resources to areas of greatest demand. It can also forecast trends for peak energy consumption.

"AI can optimize resource utilization based on occupancy levels." – Interviewee 3

Along with the previous one, AI evaluates ***energy source data, optimizing the equilibrium between renewable and non-renewable energy sources to attain a minimal carbon footprint***. By prioritizing the utilization of renewable energy when accessible and resorting to more efficient non-renewable sources just when indispensable, AI systems contribute to reducing overall emissions.

To conclude, ***performance benchmarks*** inform the retrofitting procedure mentioned by all the interviewees. AI evaluates present energy consumption and emissions according to industry standards and benchmarks for net-zero and energy-efficient structures, confirming that the retrofitting strategies align with the established objectives. These benchmarks help identify areas for improvement and the most effective strategies to meet energy and carbon reduction targets. Additionally, AI can track benchmarks for costs, planning schedules, and other factors using data from previous projects, helping to streamline decision-making and project management.

"AI can consistently assess our advancement relative to energy efficiency benchmarks, offering immediate feedback on our successes and shortcomings" – Interviewee 4

6.2.7 Synergy of AI and Decarbonization Strategy

In addressing the challenges of Chapter outlined in the table 6.1, AI has the potential to improve data accuracy, optimize real-time energy management, integrate renewable energy systems, and minimize embodied carbon more effectively into retrofitted buildings. By leveraging AI technologies such as Machine Learning, and advanced AI systems, such as Neural Networks, and Genetic Algorithms, the retrofit processes become more scalable and efficient, allowing for precise decision-making and continuous improvements.

Beyond the direct goals of retrofitting and achieving net-zero objectives, AI also plays a vital role in other aspects of construction projects. AI enhances scenario planning by offering data-driven strategies based on costs, building conditions, and incentives, helping project teams make more informed decisions. Additionally, AI improves construction scheduling by optimizing timelines, boosting equipment efficiency, and minimizing waste. When it comes to risk mitigation and cost-saving, AI helps by detecting potential discrepancies early, reducing human error, and providing real-time adjustments. Lastly, AI ensures retrofitting efforts are prioritized effectively, focusing on areas with the highest energy consumption for maximum impact.

Building retrofitting measure	Challenge and/or limitation	AI's capabilities (role)	Subset of AI	Retrofit to Net-Zero Goal(s)
Procurement of renewable energy	Guarantee of origin and committing to this in a long-term policy. Availability of renewable energy sources.	AI could optimize procurement strategies and energy sourcing decisions based on real-time data on renewable availability.	Machine learning	Carbon reduction Renewable energy integration Energy reduction
Renewable energy generation PV panels	Data error / placement on roofs The precise decrease in energy consumption 'assumptions'.	AI could ensure accurate placement of PV panels, real-time energy production monitoring, and integration with existing infrastructure.	Advanced AI system: (e.g., Neural Networks, Robotics.)	Carbon reduction Energy efficiency Renewable energy integration (Building resilience)
Building Energy Management	Detailed controls and proactive energy management. Ongoing monitoring and modifications of setpoints.	AI-driven energy management systems could monitor, adjust, and optimize energy consumption patterns in real-time to improve efficiency.	Advanced AI system: (e.g., Neural Networks, Deep Learning.)	Energy efficiency
The heat recovery system in the air handling units	Energy-inefficient and constrained by the ceiling heights, limiting their ability to perform optimally.	AI could monitor and adjust heat recovery systems for optimal performance, predicting inefficiencies and improving overall operation.	Machine learning, Advanced AI system: (e.g., Neural Networks)	Energy efficiency Operational efficiency
Thermal Energy Storage (TES) for heating and ventilation	High Investment Cost Space requirement Uncertainty in energy savings	AI could optimize TES performance by predicting energy demand and managing storage cycles, reducing uncertainties in energy savings.	Machine learning, Advanced AI system: (e.g., Neural Networks)	Energy efficiency Operational efficiency
LED lights	The precise decrease in energy consumption 'assumptions'.	AI can optimize lighting efficiency by adjusting LED brightness and usage based on occupancy patterns and natural light availability.	Machine learning, Advanced AI system: (e.g., Neural Networks)	Energy efficiency
Not sub-metered between multiple buildings	Identifying high energy-consuming areas and limits opportunities for targeted efficiency improvements.	AI can provide more precise monitoring of energy usage, identifying high-energy areas and recommending targeted interventions.	Machine learning, Advanced AI system: (e.g., Deep learning)	Operational efficiency Energy efficiency
Building Envelope - Replacing the facades, including windows and frame	No specific data on the insulation values of the facades and windows of the different buildings	AI could automate and enhance building envelope assessments, predicting energy savings and selecting the optimal materials for insulation.	Advanced AI system: (e.g., Neural Networks Genetic Algorithm)	Minimize embodied carbon (Building resilience)
Previous energy data sets to calculate improvements	The quality and completeness of the data, such as missing updates and outdated information. Accurate picture of actual energy.	AI can analyze and fill gaps in previous data sets, providing real-time data collection and improving accuracy for energy predictions.	Machine learning, Advanced AI system: (e.g., Neural Networks.)	Energy reduction Operational efficiency
Technical due diligence process	The lack of complete and accurate data	AI could automate technical due diligence by analyzing building conditions, detecting issues like insulation quality or potential hazards.	Machine learning, Advanced AI system: (e.g., Natural Language Processing)	Operational efficiency
Hazardous material (Asbestos)	Health risk and common in old buildings Adds complexity and delays to the project. Strict safety protocols and increased costs	AI can help identify hazardous materials and optimize risk management, ensuring compliance with safety protocols.	Advanced AI system: (e.g., Robotics, Natural Language Processing)	(Occupant comfort and health)
Assumptions - Energy consumption data; - PV panels energy productions; and creating assumptions in general instead of concrete data.	Pose potential challenges, and the project data outcome. Risks and uncertainties, as they may not accurately reflect the actual conditions or requirements of the buildings, leading to adjustments and complexity later in the project.	AI can reduce reliance on assumptions by providing data-driven insights and accurate predictions for retrofit projects or projects in general.	Machine learning, Advanced AI system: (e.g., Neural Deep Learning)	Carbon reduction Energy reduction (Occupant comfort and health) Minimize embodied carbon

Table 6.1: AI's Potential Role in the Retrofit Deficiencies– Synthesis of Chapter 4 and 5 (own ill.)

6.3. Validation (Expert Panel)

In this chapter the main take aways from the case-study research and one-on-one will be tested in the validation session. After the validation session the frameworks in the Chapter 9 Recommendation will be refined through the experts feedback.

Validation of results with an expert panel

After comparing the results from case-study research with findings in theoretical research some preliminary conclusions were established. Since this research is based on four specific cases and the conclusions to be drawn are meant to support developers and other supply chain actors in the entire Netherlands, the results need to be validated before a generalization can be made. For this validation, an expert panel of three was selected based on the following criteria:

- At least one AI expert in the panel
- At least one retrofit/net zero expert in the panel
- Personally worked in design or construction management projects.

Panel 1

Name	Expertise
Participant 1	AI
Participant 2	AI
Participant 3	Net zero building

Panel 2

Name	Expertise
Participant 4	Retrofit/ Net Zero and AI background knowledge
Participant 5	Retrofit
Participant 6	AI

Table 6.2: Expert panel participants and expertise

The panel was briefly informed about the research topic beforehand and a short presentation with a summary of the research process. The participants were shown the AIR0 framework and the DCM frame. The participant were given the choice of location, but due to convenience, all interviews were conducted online via Microsoft Teams. All interviews are conducted in English and recorded with the permission of the interviewees for the purpose of making the interview transcripts. The summary of the plenary discussions are described below.

Questions to be ask in Expert panels:

1. In your experience, what key risks or barriers have you encountered in integrating AI into building retrofits? How well does the AIR0 model address these challenges?"
2. How practical do you think the AIR0 model and its limitation are for achieving net-zero in real-world retrofitting projects?
3. How well does the DCM FRAIM balance AI integration with the traditional goals of construction management (cost, quality, time) while also addressing decarbonization objectives?"

Summary / take-aways for frameworks

Expert Panel 1 comprised an AI consultant and a digitalization consultant. Key discussions focused on distinguishing the roles of the AIR0 and DCM FRAIM frameworks and addressing risks and accountability in applying AI. The feedback emphasized the need to clearly define AI subsets and their specific capabilities, drawing on the literature review. Panelists also highlighted the importance of balancing AI's capabilities with human intelligence and accountability in decision-making processes.

Expert Panel 2 included a retrofit/net-zero consultant and a project manager. Discussions revolved around the practical application of the AIR0 matrix, particularly in developing a business case for AI integration and prioritizing sustainable procurement and stakeholder engagement. The panel recommended clarifying how to use the AIR0 matrix for synergistic integration of retrofit measures. For the DCM FRAIM, feedback centered on enhancing stakeholder engagement, particularly concerning people and ethics, and aligning AI core components with specific project outcomes rather than broad objectives.

The expert panels reinforced the need to refine the frameworks for practical implementation, ensuring clarity, alignment with real-world challenges, and a focus on ethical considerations and measurable outcomes. Their insights strengthened the overall applicability and robustness of the proposed methodology.

6.4 Testing Hypotheses: AI's Role in Decarbonization Strategies

The hypotheses proposed in the conceptual model are tested through this analysis, using insights from Chapters 4 and 5:

Hypothesis 1: AI optimizes data-driven integration in net-zero objectives.
Supported: AI's real-time monitoring and data analytics address data quality and availability issues, ensuring accurate benchmarking and continuous performance improvement.

Hypothesis 2: Machine learning enhances retrofit techniques and measures.
Supported: Machine learning optimizes energy systems and building envelopes, reducing operational inefficiencies and improving carbon reduction outcomes.

Hypothesis 3: AI reduces operational carbon by optimizing energy efficiency.
Supported: Intelligent control systems and fault detection tools enhance the performance of HVAC and lighting systems, directly reducing operational carbon.

Hypothesis 4: AI minimizes embodied carbon through material optimization.
Partially Supported: While AI provides insights into material selection, its effectiveness is dependent on the availability of low-carbon material databases and the digitalization of industry.

Hypothesis 5: AI enhances decision-making accuracy in design and construction management.
Supported: Scenario modeling and data decision support tools enable stakeholders to make informed decisions, improving project outcomes.

The cross-case analysis demonstrates that AI acts as a powerful tool for decarbonization strategies, addressing key deficiencies and amplifying opportunities. By leveraging AI's capabilities, professionals can overcome the complexities of retrofitting projects and align their efforts with net-zero building objectives. The reciprocal relationship between AI and decarbonization strategies underscores the need for an integrated approach, where each dimension supports and enhances the other, ultimately advancing sustainable building practices in design and construction management.

CHAPTER 7

DISCUSSION

7 | DISCUSSION

The discussion chapter presents the findings of this research, which are critically analyzed and placed within the broader context of existing literature and real-world practices. The aim is to synthesize the insights gained from the case study and semi-structured interviews, connecting them to the theoretical framework presented earlier. The discussion will also highlight the challenges and limitations encountered during the research, ensuring the findings remain relevant in the context of the rapidly evolving AI landscape.

7.1 Theory versus Practice

Building Retrofitting to Achieve Net Zero

The objective of achieving net-zero carbon emissions, as defined by the UK Green Building Council (2019), emphasizes the following steps: (1) Establish net zero carbon scope, (2) reduce construction impacts, (3) reduce operational energy use, (4) increase renewable energy supply, and lastly (5) offset any remaining carbon. In the context of this research, specifically in sections 4.1.3, Analysis: Building Retrofit Deficiencies & Project (Part 1), and 5.2.2, Critical Success Factors (AI in Retrofit to Net Zero), the first four steps are closely aligned with both the theoretical framework and the findings from the case study projects.
However, the fifth step, which involves offsetting any remaining carbon, was notably absent from the case study discussions and not explicitly addressed by the interviewees. The case studies and interviews primarily focused on optimizing building performance by addressing operational energy impacts, with a secondary emphasis on reducing construction-related carbon emissions and increasing the use of renewable energy. Despite the importance of carbon offsetting in achieving true net-zero emissions, long-term strategies like carbon offsetting remain more difficult to address. Despite its additional role in achieving true net-zero emissions, long-term strategies such as carbon offsetting present significant challenges and are often more difficult to implement or take into practice.

In addition to optimizing building performance, the theoretical strategies as emphasized by Building Council (2022) and Hassan et al. (2023), for reducing embodied and operational carbon are recognized, but practical challenges, including financial constraints, technical limitations, and regulatory barriers, often prevent their full implementation. The case study findings show that operational carbon reduction measures, particularly HVAC improvements and lighting upgrades, were more widely adopted, while embodied carbon strategies, such as material upgrades and advanced insulation, were more difficult to implement in practice. This gap between theory and practice underscores the need for better financial incentives, clearer guidelines, and more accessible technologies to facilitate the widespread adoption of carbon reduction strategies in retrofitting projects. Moreover, the case study and interviewees revealed a distinct trade-off between operational and embodied carbon reduction. In many instances, retrofitting efforts prioritized reducing operational carbon through energy efficiency improvements and renewable energy integration, while embodied carbon measures were deprioritized due to their higher upfront costs and longer payback periods. As a result, these trade-offs highlight the complex decision-making process in retrofitting, where stakeholders must balance short-term operational benefits with long-term embodied carbon reductions, depending on the specific financial and technical context of each project.

The challenges and considerations outlined in the literature 2.2.3 reflect many of the practical difficulties identified in the case studies and interview findings. The high initial cost associated with retrofitting projects, particularly those incorporating advanced technologies like AI-driven optimization or renewable energy integration, was a recurring concern among interviewees. While the literature emphasizes the long-term savings potential of such deep retrofits (Shaikh et al., 2017), the empirical data showed that many stakeholders prioritize short-term financial viability over long-term sustainability. This reflects a significant barrier to the full implementation of retrofitting projects, especially when immediate returns on investment are unclear or stretched over a long period.

Additionally, the lack of skilled labor and expertise, as highlighted in the literature, was similarly identified by respondents as a major limitation. Several interviewees pointed out that specialized knowledge in enhancing energy efficiency requires specialized knowledge in areas like advanced materials, energy systems, and sustainable practices. The addition of AI-driven technologies intensifies this demand for expertise. Many interviewees highlighted the growing complexity of retrofitting projects, noting that the skillset required to integrate AI effectively is not widely available. This shortage of AI and data expertise compounds the existing labor challenges, further driving up project costs and causing delays. In regions where retrofitting practices are still emerging, the gap in both traditional retrofitting skills and AI integration knowledge poses a significant barrier to the widespread adoption of advanced, energy-efficient retrofitting solutions.

Artificial Intelligence

The literature 2.4.2 section emphasizes the potential of AI tools, such as Genetic Algorithms, in optimizing architectural and structural designs. These tools are recognized for their ability to explore diverse design alternatives and enhance both aesthetic and functional outcomes (Nagy et al., 2017; Hamidavi et al., 2018). In 4.2's Role in Decarbonization case study (Part 2) partially validates the theoretical claims, with AI-based design tools proving useful in optimizing structural configurations and material use. However, challenges emerged, particularly with fragmented data and the absence of a robust data infrastructure in retrofitting projects, limiting AI's ability to fully optimize designs.

The application of AI, particularly machine learning and deep learning, is central to improving energy performance in buildings. The literature 2.4.2 suggests that AI can optimize energy consumption, predict demand, and automate the management of energy systems based on real-time data (Mousavi et al., 2023; Hassan et al., 2023). Neural networks and Genetic Algorithms play an integral role in enhancing predictive maintenance, energy system configuration, and renewable energy optimization. The findings of AI-driven techniques such as machine learning and neural networks successfully predicted energy consumption patterns, allowing for proactive adjustments in energy management systems. However, these systems were primarily effective in newer buildings with integrated smart technologies. Retrofitting older buildings presented a challenge due to outdated energy infrastructure, which limited the availability of real-time data. Additionally, financial constraints often hampered the installation of necessary sensors and IoT devices. These practical barriers highlight the discrepancy between the theoretical potential of AI in energy optimization and the limitations posed by existing infrastructure in retrofitting projects.

Further, robotics and automation have been touted in the literature 2.4. 3 as transformative for construction, offering improved productivity, safety, and precision (Delgado et al., 2019; Abioye et al., 2021). AI-enabled robotic systems are capable of handling labor-intensive tasks like bricklaying, welding, and predictive maintenance, which significantly reduces labor costs and improves the quality of work. Although, the findings from the case study support the literature's theoretical benefits of robotics, but real-world applications remain limited in retrofitting projects. Many construction firms involved in retrofitting projects relied heavily on traditional labor, limiting the scalability of robotic applications.

The literature describes how machine learning and deep learning can analyze extensive material databases to optimize material selection based on environmental performance, cost, and lifecycle assessments (Roberts et al., 2020; Röck et al., 2018). The interview findings corroborate the theoretical potential of AI in material selection during retrofitting. AI systems proved capable of optimizing material choices to reduce embodied carbon and improve sustainability outcomes. However, the case study also revealed that existing material databases were often incomplete or lacked standardized data, limiting the effectiveness of AI systems in making fully informed decisions.

Additionally, the lack of integration between AI-driven material selection tools and existing Building Information Modeling (BIM) systems further hindered the efficiency of material optimization processes. The need for comprehensive and standardized databases is crucial for AI to fully realize its potential in selecting low-carbon materials and reducing the embodied carbon in retrofitting projects.

AI Retrofit to Net Zero

The literature strongly advocates for AI's potential to improve data collection and management, particularly through machine learning algorithms, by identifying gaps, correcting errors, and providing accurate energy consumption estimates (Mousavi et al., 2023). However, in practice, the findings from the interviews reveal limitations in current retrofitting projects. Interviewees pointed out the continued reliance on outdated tools, like Excel, and incomplete datasets, which hinder the full realization of AI's potential. Although AI can indeed reduce human errors and automate data collection, the absence of a robust, real-time data infrastructure in the case study projects restricted its effectiveness. This disconnect illustrates the critical need for the establishment of reliable, integrated data systems to support the optimization capabilities of AI in retrofitting projects.

AI, particularly through neural networks and machine learning, can continuously optimize energy management by analyzing real-time data and adjusting system settings for improved energy efficiency (Hassan et al., 2023). While this was confirmed in newer buildings within the case study, where AI played an effective role in energy optimization, older buildings faced substantial barriers. Interviewees noted that outdated infrastructure, particularly the lack of sub-meters, sensors, and IoT devices necessary for real-time monitoring, limited the application of AI-driven solutions. Without these foundational upgrades, AI's ability to drive proactive energy management remains underutilized.

Furthermore, AI can automate compliance with local and international standards, streamlining the often-complex regulatory processes involved in retrofitting (UK Green Building Council, 2022). The empirical findings support this claim, with interviewees noting that AI helped automate regulatory checks, reducing the risk of non-compliance. However, they also pointed out that keeping up with evolving and region-specific regulations remained a challenge, indicating that AI systems alone were not enough to fully overcome this hurdle. The findings suggest that while AI can significantly aid compliance efforts, there remains a need for more adaptive and dynamic systems that can keep pace with regulatory changes across different regions.

Along with this, this limitation suggests that while AI is a powerful tool for enhancing compliance, it is not a complete solution. The literature does not fully address the need for AI systems that can automatically update themselves in response to changes in laws and regulations. The empirical evidence points to a gap in current AI applications where manual intervention is still required to keep regulatory databases updated and to ensure compliance across different jurisdictions. This creates an opportunity for further development of adaptive, machine learning-driven compliance systems that can continuously evolve in response to regulatory changes without needing constant manual updates.

Lastly, retrofitting older buildings presents a unique set of challenges due to incomplete and outdated data, which hinders AI's ability to perform accurate benchmarking, energy management, and material selection. These limitations lead to underestimations in real-world applications, often resulting in inefficiencies in energy savings and carbon reduction efforts.
For instance, Mousavi et al. (2023) emphasize the importance of accurate data collection and management in AI's ability to optimize energy consumption and building performance. Incomplete data, as is common in older structures, directly limits AI's potential to accurately benchmark current performance levels or predict future energy savings. This disconnects between AI's theoretical capabilities and the practical reality in older buildings leads to significant underestimations in both energy management and carbon reduction.
Similarly, Roberts et al. (2020) discuss the role of AI in material optimization and carbon footprint assessment. While AI can theoretically reduce embodied carbon by selecting low-carbon materials based on comprehensive datasets, older buildings often lack such data. This gap forces AI to rely on assumptions or incomplete information, which can result in inaccurate material recommendations and suboptimal carbon reduction strategies. This aligns with the empirical findings, where incomplete material databases in older retrofitting projects hindered AI's ability to fully optimize material selection.

Moreover, the literature discusses the necessity of real-time monitoring for AI to make ongoing adjustments in energy management systems (Hassan et al., 2023). Older buildings typically do not have the infrastructure to support such monitoring, thus limiting AI's capacity to optimize energy use. As noted in the empirical research, without real-time data, AI's potential to manage energy systems in older buildings is significantly constrained, which leads to inefficiencies in energy savings and missed opportunities for carbon reduction.

7.2 Quality of Research Design

To assess the overall quality of the research design in this thesis, three key criteria are evaluated:

Construct Validity

Construct validity examines whether the observations and relationships identified by the researcher accurately represent the phenomenon being studied, or if they are influenced by the researcher's own biases (Yin, 2018). To improve construct validity in this thesis, multiple sources of evidence were used. These included a combination of semi-structured interviews with experts, case study data, and expert panels discussions to validate the initial findings. Specifically, the thesis gathered data from total of 18 in-depth interviews with stakeholders across several building retrofit projects, supplemented by a structured case study to evaluate AI's role in achieving net-zero objectives. The use of triangulation—employing different methods and sources—strengthened the validity of the research outcomes. Moreover, the expert panel discussion provided critical feedback on the initial results, enhancing the construct validity by allowing for external evaluation and confirming the accuracy of the conclusions (Yin, 2018).

External Validity

External validity refers to the extent to which the results of the study can be generalized to other settings, populations, or situations (Yin, 2018). Unlike quantitative research, which can be generalized statistically, case study research is generalized analytically based on the researcher's ability to apply findings to similar contexts. The scope of this research was focused on the retrofitting of buildings to achieve net-zero carbon emissions using AI-driven strategies. While the findings are not specific for the Netherlands, particularly in the context of national regulations and retrofitting projects, they offer valuable insights for other regions or countries facing similar retrofitting challenges, especially where AI is applied in construction management. However, it is important to note that while the findings may be applicable to projects in developed economies with similar regulatory frameworks, the economic and political environments in different countries may affect the generalizability. Further research could be required to confirm if similar barriers, opportunities, and success factors would be relevant in a different geopolitical or economic climate.

Reliability

Reliability assesses whether other researchers can replicate the study and achieve the same results (Yin, 2018). In this thesis, every stage of the research was carefully documented to enhance reliability. The research design, including the protocols for both the semi-structured interviews and case study analysis, has been systematically recorded to allow for replication. The methodology described By triangulating the findings, following Shenton's (2004) principles of credibility, transferability, dependability, and confirmability, the study reinforced the robustness of its results.
in Chapter 3 provides a detailed explanation of the approach used for data collection and analysis.

Additionally, the interview protocols are available for reference, and the use of ATLAS.ti software for qualitative analysis ensures a structured and reproducible coding process. By documenting these steps extensively, the research enhances its reliability, enabling future researchers to replicate the study under similar conditions and verify the results.

7.3 Limitations

Selection of Case Study Projects

The research focused on a single comprehensive case study, primarily in the initial phases of retrofitting projects aiming for net-zero carbon emissions. However, a significant limitation arises from the fact that net-zero objectives were not fully measurable within the scope of the project, as the targets were outlined but not yet executed.

Moreover, the case study did not include projects where AI implementations had been carried out in practice. This limited the ability to directly assess the effectiveness of AI-driven strategies for achieving net-zero objectives. As a result, the generalizability of the findings is somewhat constrained. While the case study offers valuable insights into the early stages of AI integration in retrofitting, it does not capture the full range of experiences or challenges that might be encountered during the implementation phase, particularly in diverse building types. This reflects the fact that AI in building retrofitting is still a rising and relatively new area, with few real-world cases of fully integrated AI systems at this time. As a result, the generalizability of the findings is constrained. While the study provides valuable insights into the potential for AI integration in retrofitting, the lack of current practical examples and measurable outcomes limits the scope.

Interview Selection and Participants Bias
Second, the interview participants were primarily selected through the context of the graduation internship, which may have introduced a certain level of bias. Although the interviewees were industry professionals with relevant expertise, their perspectives may have been shaped by their specific roles, company policies, or project experiences during the internship. This might limit the openness of the responses or reflect a narrower view of the industry, particularly within the specific framework of the organization hosting the internship. As a result, these perspectives may not fully represent the broader industry or offer a complete view of AI integration in construction management. Therefore, while these insights are valuable, the findings should be interpreted with caution, keeping in mind the potential bias and limitations in participant diversity. Future studies should aim to include a wider range of industry professionals across different organizations and project types to gather a more comprehensive understanding of AI's role in retrofitting and construction management.

Rapid Evolution of AI technologies
Moreover, the research is limited by the rapidly evolving nature of AI technologies. The field of AI is advancing quickly, and new developments in machine learning, data analytics, and digital twin technologies could significantly alter the landscape of AI applications in retrofitting. Thus, the findings of this study should be understood within the context of current technology and industry practices, which are likely to evolve in the near future. The findings and recommendations may become outdated or less relevant as new AI technologies and applications emerge, limiting the long-term applicability of the research.

Lack of Quantitative Data
In addition, the research primarily relies on qualitative data from interviews and case studies, with limited quantitative analysis of the AI systems' impact on energy savings or carbon reduction. While qualitative insights are valuable, the absence of quantitative data limits the ability to measure AI's precise effectiveness in building retrofits. Without concrete metrics, it is challenging to determine the scale of AI's impact on retrofitting projects, such as the exact energy or carbon savings attributable to AI.

Technological Readiness
Lastly, many older buildings may not have the technological infrastructure to support AI implementation. Issues such as a lack of sub-metering, outdated HVAC systems, or insufficient data collection infrastructure can hinder AI's effectiveness. As a result, the research may overestimate the readiness of the building stock for AI integration, particularly for older buildings that lack smart technologies. The findings may not be easily applied to buildings that require significant upgrades before AI can be effectively implemented.

CHAPTER 8

CONCLUSION

8 | CONCLUSION

This research explored the potential of integrating AI into decarbonization strategies for building retrofitting, aiming to achieve net-zero objectives. Through an in-depth analysis of the literature, case studies, and semi-structured interviews, the findings provide key insights into how AI can be leveraged to optimize energy efficiency, reduce embodied carbon, and improve construction management practices. The main research question of the research is broken down into four sub questions which will help answer the main question step-by-step. The conclusion per sub-question is summarized below.

8.1. Sub-question one

"What is the concept of building retrofit and its role in decarbonization strategies to achieve net-zero building objectives?"

Based on the literature review, building retrofit refers to the process of modifying existing buildings to improve their energy efficiency, reduce carbon emissions, and extend the building's lifespan. This approach focuses on improving operational and embodied carbon reduction by addressing outdated systems and materials contributing to energy inefficiencies. The key decarbonization strategies identified include:

Energy efficiency improvements: upgrading insulation, windows, doors, and HVAC systems to reduce energy demand for heating, cooling, and lighting.

Operation carbon reduction: implementing smart building management systems to optimize energy use and integrating renewable energy systems like solar panels to decrease reliance on grid power. implementing smart building management systems to optimize energy use and integrating renewable energy systems like solar panels to decrease reliance on grid power.

Embodied carbon reduction: utilizing sustainable, low-carbon materials and prioritizing waste reduction and recycling to lower the carbon footprint of the construction process.

Renewable energy integration: incorporating on-site renewable energy generation such as solar panels and wind turbines to offset carbon emissions associated with energy consumption.

Smart building technologies: leveraging IoT, smart sensors and potential AI to manage and optimize building performance in real-time, adjusting to conditions such as occupancy and external weather factors.

Water efficiency measures: incorporating systems like low-flow fixtures, rainwater harvesting, and greywater recycling to reduce water consumption and the associated energy used in water treatment.
(Water efficiency measures were considered outside the scope of this research as participants provided limited data, indicating these strategies play a smaller role in the broader decarbonization efforts of building retrofitting).

8.2. Sub-question two

"What is the current state of AI-driven techniques in sustainable building design?"

Based on the literature review, the current state of AI-driven techniques in sustainable building design shows significant potential in optimizing various aspects of energy efficiency, resource management, and sustainability. The integration of AI technologies in sustainable building design is primarily focused on the following key areas:

First, generative Design and Optimization: AI tools such as generative design algorithms enable architects and designers to explore a wide range of design possibilities rapidly. These tools analyze data inputs related to energy performance, material sustainability, and spatial requirements to generate design alternatives that optimize for both functionality and environmental impact.

Second, predictive energy management: AI-driven machine learning models can predict building energy consumption based on real-time data inputs such as weather conditions, occupant behavior, and historical energy use. These predictive models allow for real-time adjustments in building operations to optimize energy efficiency and reduce carbon footprints.

Third, smart building systems: AI-powered smart building technologies, including the Internet of Things (IoT) sensors and automated control systems, are increasingly used to enhance operational efficiency. These systems can autonomously adjust lighting, heating, ventilation, and air conditioning (HVAC) systems based on occupancy levels and environmental conditions, leading to substantial energy savings.

Fourth, material selection and embodied carbon reduction: AI helps streamline the material selection process by analyzing large datasets of material properties, environmental impact, and lifecycle assessments. Machine learning algorithms recommend sustainable, low-carbon materials that reduce the embodied carbon of the building while ensuring durability and cost-efficiency.

Fifth, robotics, and automation in construction: AI-driven robotics and automation technologies have started transforming construction practices. Robots are used for tasks such as bricklaying, welding, and site inspections, improving precision, reducing labor costs, and minimizing construction waste.

Lastly, integration with renewable energy systems: AI systems are used to optimize the integration and operation of renewable energy technologies, such as photovoltaic (PV) panels and wind turbines. These AI-driven systems ensure efficient energy generation, monitor system performance in real-time, and predict maintenance needs, contributing to the overall sustainability of the building design.

8.3. Sub-question three

“What is the role of AI in integrating decarbonization strategies in building retrofitting to achieve net-zero building objectives?”

As revealed in the Case Studies and One-on-One interviews, several challenges hindered the effective implementation of decarbonization strategies, such as outdated energy infrastructure, incomplete or inaccurate data, limited adoption of renewable energy systems, and a lack of smart technologies for real-time energy management. AI’s primary role is to address these deficiencies through key AI capabilities, such as real-time monitoring, predictive analytics, and intelligent control, which are instrumental in addressing the complexities of retrofitting projects.

What AI Can Do

Real-time monitoring and data analytics allow for continuous data collection from building systems, such as HVAC performance and material degradation. By providing instant feedback on the condition of insulation, windows, and doors, this capability ensures optimal thermal efficiency. However, in practice, older buildings with outdated infrastructure often lack the real-time data infrastructure required for AI to perform at its full potential, resulting in underestimations in energy savings and carbon reduction efforts.

Similarly, ***predictive analytics and forecasting*** provide valuable insights by analyzing historical data to forecast energy demands and material performance. This capability allows AI to proactively adjust energy management systems to optimize performance. For embodied carbon, AI predicts how materials will degrade over time, while for operational carbon, it anticipates peak energy demands. In practice, however, the lack of reliable historical data in many retrofitting projects limits the precision of these forecasts, underscoring the need for better data integration in retrofitting efforts.

In addition, ***intelligent control and optimization*** autonomously adjusts building operations based on real-time data, thereby reducing energy waste and ensuring that building systems operate efficiently. In the context of retrofitting, this capability optimizes the use of materials and renewable energy systems, such as solar panels, by continuously monitoring and adjusting performance. The integration of these systems, particularly in older buildings, is often hindered by the cost of retrofitting outdated systems, limiting the impact of AI’s optimization potential.

Moreover, ***machine Learning for continuous Improvement*** enables AI to learn from past data and refine its operations over time. This capability is particularly valuable in retrofitting, as it helps continuously improve the performance of building systems and materials. For operational carbon, machine learning identifies patterns in energy consumption and occupancy, allowing for more targeted energy-saving measures. Nevertheless, the success of this capability is contingent on the availability of high-quality data, which is often lacking in older buildings.

Furthermore, ***benchmarking and targeting*** help set realistic energy and carbon reduction targets by comparing current building performance with industry standards. This capability allows AI to identify the most impactful areas for improvement. However, incomplete data sets and inconsistent benchmarking practices in retrofitting projects limit AI's ability to provide accurate targets for carbon reduction, especially in cases where historical energy performance data is unavailable.

Additionally, ***fault detection and diagnostics*** play a crucial role in identifying inefficiencies in building systems. AI's ability to detect faults in HVAC systems, insulation, or lighting ensures that energy inefficiencies are addressed quickly. In practice, the effectiveness of this capability is reduced by the lack of adequate sensor networks in older retrofitted buildings, which limits AI's ability to continuously monitor and diagnose issues.

Similarly, ***data decision support*** enhances decision-making by processing complex data sets and offering actionable insights. For retrofitting projects, AI can analyze data on material use, energy consumption, and carbon emissions to suggest optimal retrofit strategies. However, the absence of fully integrated data systems in retrofitting projects hampers AI's ability to offer precise recommendations, particularly in relation to the choice of materials and energy-saving systems.

Finally, ***compliance with regulations*** is another area where AI demonstrates significant potential. By automating compliance checks against national and international energy standards, AI ensures that retrofitting projects meet regulatory requirements.

What AI Cannot Yet Do

Despite its potential, AI faces critical limitations due to data quality, availability, and structuring issues. Older buildings often lack the infrastructure for real-time data collection, and historical records are frequently incomplete or inaccurate. This limits AI's capacity to deliver precise forecasts or actionable recommendations. Similarly, fragmented or unstructured datasets require significant pre-processing, delaying project timelines. AI also struggles with broader implementation in small-scale or less complex retrofit projects where manual techniques may suffice, making it less cost-effective in certain scenarios. Additionally, the "black box" nature of AI models often causes skepticism among stakeholders, underlining the need for greater transparency and trust-building in AI systems.

To maximize AI's potential, recommendations include advancing industry-wide digitalization, fostering collaboration across supply chains, and implementing a phased approach that begins with structured environments like new builds. Finally, a human-AI partnership is essential to ensure AI complements human expertise rather than replaces it, maintaining oversight and enhancing trust in the technology.

8.5. Sub-question four

"How can design and construction management utilize AI in decarbonization strategies?"

The integration of AI into design and construction management plays an important role in utilizing decarbonization strategies in retrofitting projects. AI enhances early-stage design through scenario modeling, enabling optimized energy efficiency and reduced carbon emissions from the outset. Project planning benefits from AI's ability to streamline task sequencing and resource allocation, minimizing delays and ensuring timely installation of energy-efficient systems. AI-driven risk management mitigates construction disruptions, reducing the likelihood of costly overruns and improving overall project outcomes. Additionally, AI automates routine tasks such as energy performance monitoring, allowing teams to focus on strategic decision-making

aligned with sustainability goals. Procurement processes are optimized through AI's assessment of low-carbon materials, ensuring sustainable sourcing and reducing embodied carbon. AI improves cost estimation by integrating real-time market data, ensuring financial sustainability throughout the project lifecycle. Quality control is enhanced as AI identifies defects early, minimizing rework and improving energy efficiency. Furthermore, AI ensures compliance with regulatory standards, keeping projects aligned with decarbonization objectives. Human oversight remains necessary to ensure ethical decision-making, particularly in the adoption of AI technologies.
Ultimately, AI integration in design and construction management not only optimizes the traditional iron triangle of time, cost, and quality but also extends its impact by significantly reducing carbon emissions and enhancing energy efficiency.

The answers to the four sub-questions set a foundation based on which the main research question can be answered.

8.6. Answering the research question

"How can AI integrate decarbonization strategies in building retrofitting to achieve net-zero building objectives in design and construction management?"

AI has the potential to play a transformative role in integrating decarbonization strategies into building retrofitting to achieve net-zero objectives, but its current application is still developing. Throughout this research, it has become evident that AI's ability to optimize energy efficiency, reduce operational and embodied carbon, and streamline construction management processes is highly valuable in retrofitting efforts. AI enables real-time monitoring, predictive analytics, optimization, benchmarking and targeting, fault detection, and data decision support, which can greatly improve energy management by identifying inefficiencies, optimizing system performance, reducing overall energy demand and improving embodied carbon outcomes through informed design choices during retrofitting.

In terms of embodied carbon, AI's capability in material selection and lifecycle assessment facilitates more sustainable construction choices. By analyzing material data and identifying low-carbon alternatives, AI helps minimize the carbon footprint of retrofitting projects. However, the current infrastructure, especially in older buildings, presents challenges, such as outdated or incomplete data, which limits AI's full potential. Overcoming these data limitations will be critical for achieving accurate benchmarks and meaningful carbon reductions.

From a construction management perspective, AI offers advantages in project planning, cost optimization, and risk management, aligning both traditional goals of time, cost, and quality, and sustainability objectives like carbon reduction. AI also facilitates regulatory compliance by automating processes to meet evolving energy efficiency and carbon reduction standards. Also, risk management is another area where AI excels. By identifying potential project risks early, such as supply chain disruptions, material shortages, or unforeseen energy inefficiencies, AI enables construction managers to proactively address issues before they escalate.

In conclusion, while AI presents immense opportunities for achieving net-zero building objectives, its successful implementation in retrofitting requires overcoming existing barriers, advancing AI capabilities, and improving data availability. Through continuous development, AI can significantly contribute to decarbonizing the built environment, integrating operational efficiency, material sustainability, and regulatory alignment to drive retrofitting toward net-zero outcomes.
Therefore, this research indicates that achieving net-zero carbon-building objectives is particularly challenging due to the emerging role of AI and the lack of standardized definitions and benchmarks for AI-driven decarbonization strategies.

To navigate the implementation of AI in decarbonization strategies and construction management processes, this study has developed guidelines (author synthesis) in the Recommendation Chapters 9.3 and 9.4. These AIR0 guidelines and DCM FRAIM can be utilized by construction managers to better incorporate AI in addressing embodied carbon, optimizing energy use, and accelerating decision-making processes within retrofitting projects. As AI continues to advance, these recommendations will help in bridging the gap between theory and practice, ensuring that AI-driven technologies are aligned with achieving net-zero-building goals.
In this research, the guidelines developed aim to address the integration of AI-driven decarbonization strategies within building retrofitting projects to achieve net-zero objectives. The guidelines emphasize the importance of a structured approach that can be adapted to various building retrofit measures of a project. For instance, AI can assist in setting specific operational and embodied carbon targets, allowing for more informed decisions based on accurate, data-driven insights. By appointing roles such as an AI specialist to ensure that data is continuously monitored and analyzed throughout the retrofit, these targets can be continuously refined.

The findings of this research underscore that while the path to net-zero is complex and filled with challenges, AI offers a lens of possibility—where smart algorithms meet sustainable practices, and where human ingenuity complements technological innovation. The successful integration of AI-driven strategies into retrofitting could redefine the boundaries of what is achievable in construction management and environmental stewardship. In the end, the promise of AI is not merely in its current applications and but in its ability to evolve, adapt, and transform existing buildings into sustainable and future-proof assets—simplifying processes and enhancing the feasibility, efficiency, and scalability of retrofitting the existing building stock.

CHAPTER 9

RECOMMENDATIONS

9 | RECOMMENDATIONS

The main recommendation for in design and construction management, but also for other market parties and government bodies to use, is the AI Methodology. Additional recommendations to the market and possible leads for further academic research are described below.

9.1 Recommendations for future research

First, it is recommended to enhance the AI Methodology, as AI technology is rapidly evolving. Future research should focus on continuously updating the framework to reflect the latest advancements in AI capabilities, ensuring that the methodology remains relevant and effective. Additionally, further exploration is required into how AI can be more effectively integrated into the initial design phases of retrofitting projects to maximize both operational and embodied carbon reductions. This involves investigating emerging AI tools that could offer more predictive insights and deeper analysis in real-time, thus improving decision-making for construction management teams. Expanding the scope of AI's applications in different building types and geographical regions will also help validate the scalability and versatility of the technology for achieving net-zero objectives across diverse retrofitting scenarios.

Secondly, future research should focus on expanding the application of AI-driven strategies specifically in the design of new buildings to meet net-zero carbon objectives. Unlike retrofitting projects, where existing constraints shape AI integration, new building design offers a blank canvas for AI technologies to fully optimize energy efficiency, material selection, and carbon reduction from the ground up.

Thirdly, the role that stakeholders such as project developers, building owners, and policymakers play in decision-making regarding AI integration for decarbonization strategies should be further investigated. The impact of commitments to net-zero carbon from these key stakeholders is increasingly influencing their approach to retrofitting, as they seek solutions that align with both their sustainability goals and regulatory requirements. As AI becomes a more critical component of achieving net-zero carbon objectives, understanding how these stakeholders value AI-driven retrofitting processes and the ways in which they incorporate AI capabilities into their decision-making will be vital for driving the adoption of AI technologies across the industry. This increased emphasis on decarbonization could significantly enhance the adoption of AI-driven retrofitting, fostering broader integration of AI in both policy and practice.

Finally, the role of AI-driven carbon tracking and offsetting in decision-making processes should be explored further. According to the findings of this research, the use of AI to monitor and manage carbon emissions is currently not seen as a significant driver for real estate developers due to insufficient data on long-term cost savings and carbon benefits. A study investigating the tipping point—where AI-powered carbon management systems begin to significantly influence decision-making and project prioritization—could provide valuable insights into how AI could enhance the financial and environmental outcomes in retrofitting projects. Understanding at what point AI-driven carbon offsetting becomes a compelling factor in project planning would be crucial for future adoption.

9.2 Recommendations for practice

AI specialists can bridge the gap between advanced technologies and practical applications. Their role includes simplifying AI outputs so that general practitioners, unfamiliar with the intricacies of AI, can make informed decisions and fully leverage AI's potential in decarbonization strategies. AI experts should focus on creating user-friendly platforms that integrate data collection, predictive analytics, and machine learning for optimizing retrofitting projects. Developing customized algorithms for specific building conditions and providing clear outputs for construction managers can ensure the smooth application of AI technologies.

Moreover, construction managers need to be proactive in incorporating AI from the earliest stages of retrofitting projects. Ensuring early engagement with AI specialists will allow for the development of optimized schedules, cost projections, and material selection based on real-time data. Training in AI tools will be critical for understanding their full capabilities.

In addition, building owners and developers should consider AI technologies not just for compliance with sustainability standards but also as tools that can deliver long-term financial savings and operational efficiency. They should work closely with AI specialists and construction managers to ensure that retrofit projects align with both environmental goals and financial incentives.

Furthermore, government bodies and regulators play a crucial role in driving AI adoption in retrofitting. Incentivizing AI integration through tax credits, grants, or policy support for carbon reduction will encourage more developers and practitioners to adopt AI in retrofitting projects. Policymakers should also ensure clear guidelines and standards for using AI in meeting regulatory goals.

Lastly, architects and designers should integrate AI tools into their workflows, particularly in the design phase. AI can support material selection, energy consumption modeling, and future-proofing buildings against evolving sustainability standards. By using AI to evaluate various design scenarios, architects can ensure optimal energy and material efficiency.

9.3 Authors recommendation

These frameworks represent the author's synthesis of empirical research and literature, offering a thoughtful recommendation for applying AI in decarbonization strategies. Rooted in the intersection of data-driven insights and practical challenges, it reflects the author's perspective on leveraging AI to address complexities in retrofitting existing buildings while aligning with sustainability goals.

9.3.1 AIR0 Guidelines

This model represents the seven critical success factors for implementing AI in Retrofit to Net Zero objectives. The visualization corresponds to the context provided in Chapter 4 Case Study and Chapter 5. See Appendix 3: AI Methodology - AIR0, for detailed information. The PDF version is full pixels.

The AIR(0) Guidelines presented in Table 7.0 illustrate the integration of AI capabilities with building retrofit measures to achieve net-zero objectives. This framework is designed to categorize and align various AI-driven functionalities with specific retrofit strategies, enhancing decision-making, execution, and verification processes. The cells within the table illustrate how specific AI capabilities (such as Predictive Analytics or Machine Learning) interact with the retrofit measures. Water efficiency measures and the AI subset Robotics was not included, since the case study and the interviewees did not provide input for this.
For example, integrating Fault Detection in HVAC Systems enhances operational efficiency by identifying issues early, thereby optimizing energy use and prolonging the system's lifecycle. Similarly, using Predictive Analytics in Renewable Energy Integration helps in forecasting energy production, ensuring better alignment with decarbonization goals. In this framework, the goals of the AI-driven retrofit measures are represented using color coding:

Green: Represents Energy Savings—aiming to optimize energy consumption and reduce waste.

Blue: Signifies Carbon Reduction—focusing on minimizing the carbon footprint of the building's operations and construction processes.

Red: Highlights Operational Efficiency—ensuring streamlined performance and cost-effectiveness through AI-driven automation and predictive insights.

Artificial **I**ntelligence **R**etrofit To **Net-Zero** (AIR0) framework

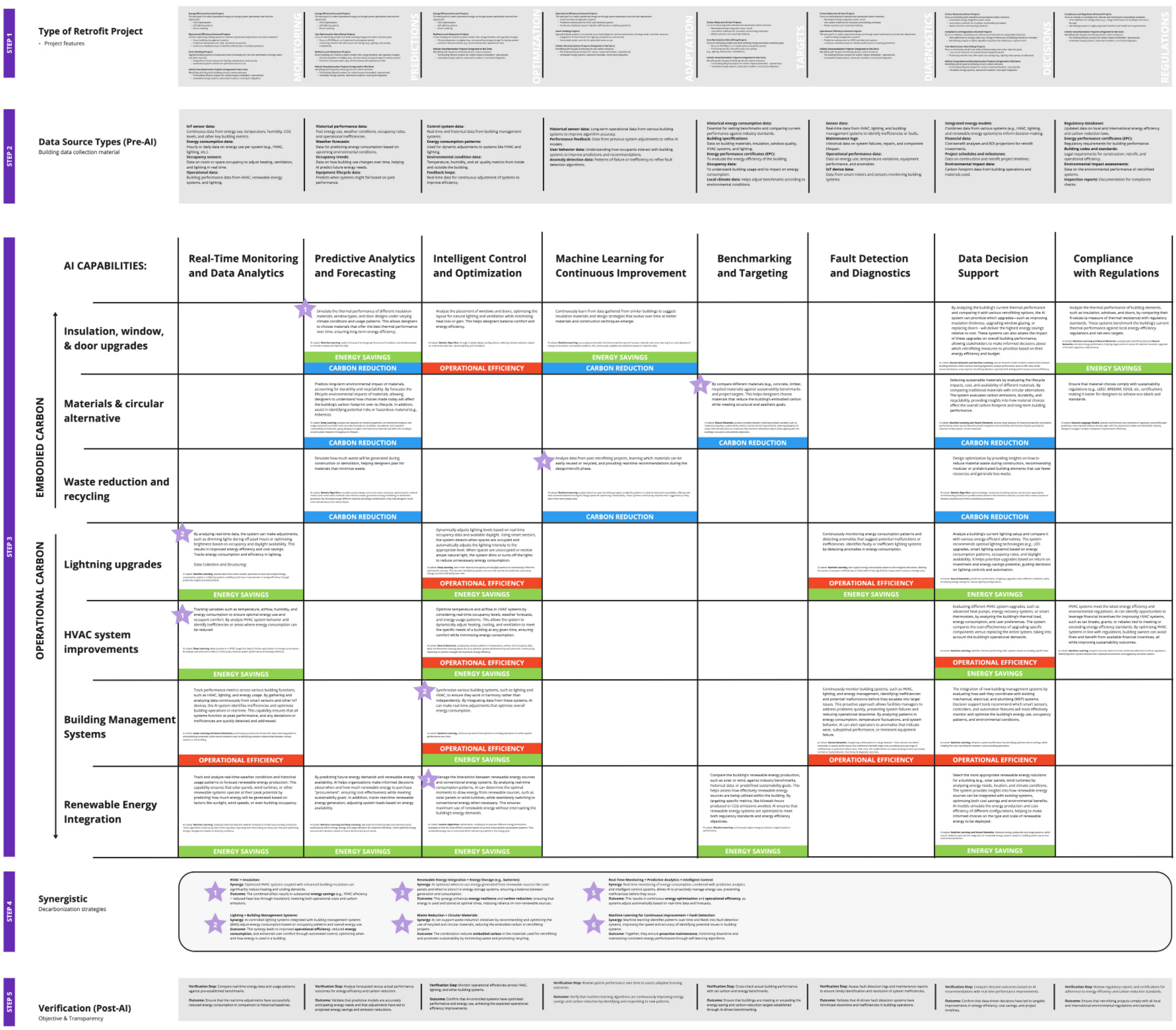

Figure 7.0: **A**rtificial **I**ntelligence **R**etrofit To **Net-Zero** (AIR0) framework (own ill.)

9.3.2 DCM FRAIM)

This model represents the design and construction management areas for implementing AI in their practices. The visualization corresponds to the context provided in section 7.1. See Appendix 3: AI Methodology – DCM FRAIM, for the detailed framework. The PDF version is full pixels.

The proposed framework is structured across three distinct hierarchical levels to systematically illustrate AI integration within Design and Construction Management (DCM) for retrofitting projects with the data collected from the interviewees and the literature review.

The first Level represents the Ten Pillars, which define the primary areas of AI integration in building retrofits and DCM practices. These pillars encompass critical stages of the construction lifecycle, such as early-stage design and scenario planning, predictive analysis, risk mitigation, and construction optimization, among others.

The second Level focuses on the Core Components within each pillar. These components highlight the specific AI-driven capabilities and technologies required to enhance decision-making and performance. They capture AI tools, techniques, and methodologies that facilitate the implementation of advanced analytics, intelligent control systems, and real-time data monitoring.

The third Level presents the Outcomes of AI integration, which are categorized by their respective goals: enery savings (represented in green), carbon reduction (represented in blue), and operational efficiency (represented in red). These outcomes indicate the direct, measurable impacts of AI on project performance and sustainability, aligning with overarching net-zero objectives.

This hierarchical structure is applied uniformly across all ten AI integration areas, with early-stage design and scenario planning serving as a model for the application of this framework. By linking AI capabilities with specific retrofit measures and expected outcomes, this framework ensures that each stage of the construction process is optimized for both environmental and operational performance.

Design and **C**onstruction **M**anagement **AI Fram**ework (DCM FRAIM)

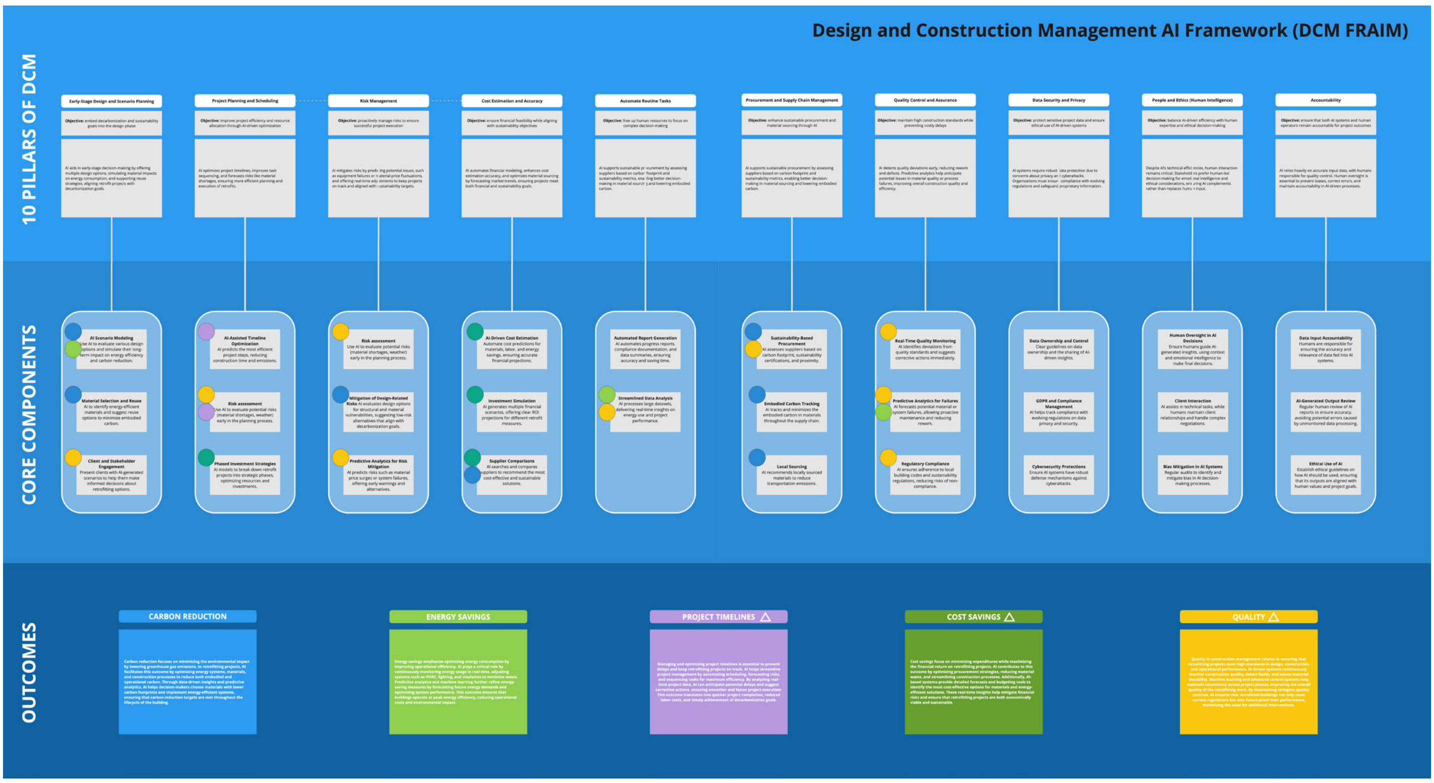

Figure 7.1: **D**esign and **C**onstruction **M**anagement **AI fram**ework (DCM FRAIM) (own ill.)

CHAPTER 10

REFLECTION

10 | REFLECTION

In this final chapter, a reflection is provided on the research and research process. First, the relation to the wider academic field is reflected upon. Thereafter, a reflection on the methodology and findings is presented. Finally, a more personal reflection on the graduation laboratory is shared.

10.1 Relation to the wider academic field

Reflecting on the wider academic field, my research sits at the intersection of artificial intelligence (AI), decarbonization strategies, and building retrofitting. The integration of AI in sustainable building design is an emerging topic in both academic and practical discussions, particularly as the construction sector is one of the largest contributors to global carbon emissions. This research adds a fresh perspective to the academic conversation, focusing specifically on how AI can optimize retrofitting processes to achieve net-zero carbon-building objectives.

As my research aligns with contemporary sustainability and technology-driven innovations, it builds on existing discussions about the role of AI in the built environment. Moreover, my work addresses gaps in research related to the use of AI not only as a predictive tool but also as a practical method for driving decarbonization in retrofit projects. As AI-driven solutions evolve, they offer new pathways for enhancing energy efficiency and reducing carbon emissions, but more research is needed to explore their full potential in different building types and regulatory contexts.

Through my research, I have seen firsthand the complexity of merging two advanced concepts—AI and decarbonization. As much as AI is heralded as a potential solution to carbon-intensive building processes, the implementation of AI-driven strategies in real-world retrofitting projects presents several critical challenges, such as data quality and stakeholder engagement. Theoretical advancements made during this project contribute to a deeper understanding of how AI can be harnessed effectively within the broader academic discourse on sustainable design and construction management.

10.2 Methodology and Findings

In the methodology section, it's important to reflect on the decision to incorporate semi-structured interviews as a primary research tool alongside or even instead of case studies. Initially, the research design focused heavily on case studies, as suggested by the academic context and mentor guidance.
However, it became apparent during the research process that semi-structured interviews offered a more flexible and insightful method to gather expert knowledge on critical success factors, challenges, and real-world applications of AI in decarbonization and building retrofitting.

The decision to adopt semi-structured interviews was driven by several factors. Firstly, although case studies are valuable for providing a comprehensive, documented analysis of real-life instances, they often lack the depth of subjective insight necessary to fully understand emerging and complex fields such as AI integration in retrofitting. By using interviews, the research could tap into the tacit knowledge and experiences of professionals directly engaged in the field, revealing insights that are not always documented in case studies.

Another factor was the limited availability of documented AI-driven retrofit projects, which posed a challenge for the case study approach. Given the relatively nascent stage of AI applications in retrofitting, the scarcity of empirical data meant that case studies alone could not provide a sufficient basis for answering the research questions. In contrast, semi-structured interviews allowed access to the latest developments, challenges, and critical factors directly from the professionals who are pioneering these approaches, thus filling the data gap left by the case study method.
Moreover, semi-structured interviews offer a flexible approach that allows researchers to probe deeper into specific topics as they arise, making it ideal for exploratory research. While case studies offer a more rigid structure, interviews allow for the exploration of emerging themes and unexpected insights that contribute to the richness of the data. This flexibility was particularly useful for investigating the complex dynamics of AI in building retrofitting, where theoretical models alone are insufficient for capturing the full range of real-world considerations.

However, case studies were not entirely excluded. Instead, they were used as supplementary tools to provide context and validate the findings from the interviews. The combination of both methods ensured a more comprehensive and nuanced understanding of the research topic, balancing theoretical exploration with practical insights.This methodological shift highlights the importance of adaptability in research design, especially in a rapidly evolving field such as AI-driven retrofitting. Although case studies provide valuable background and validation, the use of semi-structured interviews enabled a more immediate and focused exploration of current challenges and opportunities, making the research more relevant and timelier.

The AI methodology in *9.3 Author Recommendation* developed through AIR0 and DCM FRAIM frameworks provides a structured approach to integrating AI into retrofitting projects by outlining specific capabilities, inputs, outputs, and critical success factors. One of its strengths is its ability to streamline complex decision-making processes, including energy management, material optimization, and regulatory compliance, by leveraging real-time data, predictive analytics, and machine learning. The methodology also offers practical tools for optimizing both operational and embodied carbon reductions, improving energy efficiency, and ensuring continuous system improvements in retrofitting projects.
The DCM FRAIM framework also integrates traditional construction management goals, such as cost, quality, and time, alongside sustainability objectives, making it highly compatible with existing industry practices. By offering a clear and well-defined roadmap for incorporating AI, the methodology addresses the technological and operational gaps that often hinder AI adoption. Additionally, the methodology simplifies AI complexity by creating user-friendly guidelines, which are critical in helping construction managers, project stakeholders, and AI specialists collaborate effectively. This comprehensive framework can increase the trust and adoption of AI in retrofitting projects by providing tangible results, risk mitigation strategies, and a structured approach to achieving net-zero goals.

While AI has the capacity to outperform humans in certain data-driven tasks, such as real-time monitoring, optimization, and predictive analytics, it is still best positioned as a complementary tool rather than a full replacement for human expertise. AI excels in handling large volumes of data, identifying patterns, and optimizing resource allocation in ways that humans struggle to match. For instance, AI can continuously monitor building systems, adjusting them in real-time to optimize energy use, while also providing predictive insights into future performance, all tasks that require high levels of precision and constant vigilance, which are challenging for humans to achieve consistently.
However, human judgment remains critical in areas where AI lacks context, creativity, or ethical consideration. For example, human experts bring a nuanced understanding of project constraints, stakeholder priorities, and long-term strategic goals that AI cannot fully replicate. Human decision-makers are also essential for interpreting AI-generated outputs and making adjustments based on real-world complexities that AI might not account for, such as unforeseen market changes, regulatory shifts, or specific project conditions.

To end the reflection, two reflection questions that relate to the content of my work are presented:
1. What are the strengths of the AI methodology (AIR0 and DCM FRAIM) developed, and how can they contribute to increasing the adoption of AI in retrofitting projects?
2.Can AI surpass human expertise in decision-making for retrofitting projects, or does it function best as a support tool for human judgment?

10.3 Graduation laboratory

Choosing a theme for my graduation research was not difficult for me. I was determined to investigate something groundbreaking—something valuable and new or that had the potential to bring a fresh perspective to the academic field. The group I joined in the graduation laboratory perfectly aligned with my aspirations, as it encouraged research on game-changing and innovative topics. This was ideal for me, as I wanted to challenge the boundaries of current knowledge.
In the end, my focus on the intersection of artificial intelligence (AI), decarbonization strategies, and building retrofitting turned into a highly adventurous academic challenge. However, this journey was not without its many difficulties. The complexity of the subject, supervisor feedback, and recommendations caused delays in my research, and at times my motivation dropped. Yet, despite these setbacks, my desire to succeed pushed me forward. My goal was to deliver results that would not only contribute to the academic discussion but also provide a meaningful framework that could potentially drive change in the industry. Focusing on the innovative and emerging technology of 'Artificial Intelligence' to achieve sustainable (net-zero) objectives transforms traditional construction into a future-ready industry, with a lasting sustainable impact.

In an era where our climate evolves more rapidly than anticipated.
Where challenges arise and solutions are innovated.
We stand at a crossroads, a moment debated.
Seeking harmony with nature, a future unabated.

- Po Au Xu

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APPENDICES

Appendix 1: Informed Consent Form Interview

Appendix 2: Interview Protocol Case Study & Semi-structured Interviews

Appendix 3: AI Methodology – AIR0 & DCM FRAIM

Appendix 4: HREC Checklist

Appendix 5: Data Management Plan

Appendix 6: AI Retrofit Process Integration (Hypothesis and initial phase, study work)

Informed Consent Form Interview May 6th, 2024

You are being invited to participate in a research study titled "*AI Methodology for Decarbonization to Net-Zero Emission Building (Retrofit Process)*". This study is conducted by Kai Xu from the TU Delft, who is currently graduating in Management in the Built Environment. This research is combined with an internship at Turner & Townsend in Amsterdam.

The purpose of this research study is to learn more about designing an AI methodology in the decarbonization process aimed at achieving net-zero emission buildings. The AI methodology guides the integration of individual decarbonization elements and key components of net-zero building design through AI-based predictive modeling, continuous learning and improvement, optimization techniques, and data-driven decision-making. This integration can facilitate the potential achievement of environmental objectives by maximizing energy efficiency, minimizing greenhouse gas emissions, and promoting sustainable building practices while simultaneously addressing cost-effectiveness concerns through strategic resource allocation, investment prioritization, and actor and stakeholder engagement through the decarbonization process.

Your participation consists of a semi-structured interview, which will take you approximately 60 minutes to complete. During the interview, we will ask for your insights and perspectives on the integration of key components of decarbonization and how AI methodology can be effectively utilized to optimize these components in achieving net-zero emission buildings. Your valuable insights will contribute to a deeper understanding of the potential synergies between AI technology and decarbonization efforts within the built environment sector.

As with any research activity, there may be risks associated with participating. However, we will take all necessary precautions to ensure the confidentiality and anonymity of your responses. Your answers will be anonymized, and personal data will be handled with utmost care. The interview audio recording will be securely destroyed at the end of the research.

Participating in this study is entirely voluntary, and you can withdraw at any time. You are free to decline to answer any questions or omit any information you prefer not to share.
If you would like to participate in this study, would you please complete and sign the attached statements?

Thank you for participating in this study.

Sincerely,

P.A. Xu (Kai)

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PLEASE TICK THE APPROPRIATE BOXES	Yes	No
A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICPANT TASKS AND VOLUNTARY PARTICIPATION		
1. I have read and understood the study information dated 06/05/2024, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
3. I understand that taking part in the study involves:	☐	☐
• *An audio-recorded interview. Written notes might be taken.* • *The audio-recorded interview will be transcribed as text, and will be destroyed at the end of the research.*		
4. I understand that the study will conclude upon completion of the interview.	☐	☐
B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)		
5. I understand that taking part in the study also involves collecting specific personally identifiable information (PII) and associated personally identifiable research data (PIRD) with the potential risk of my identity being revealed.	☐	☐
• PII: In the Informed Consent Form, the names and email addresses will be collected for administrative purposes. The Informed Consent forms will be stored separately from the other data and securely. They will only be accessible to the study team. The collected data will be anonymized, and the names will be codified.		
6. I understand that the following steps will be taken to minimize the threat of a data breach, and protect my identity in the event of such a breach	☐	☐
• *Data will be anonymized.* • *Data will be stored securely, accessible only to the study team.* • *Anonymous data in transcription of the audio-recording*		
7. I understand that personal information collected about me that can identify me, such as my name or country of work, will not be shared beyond the study team.	☐	☐
8. I understand that the (identifiable) personal data I provide will be destroyed within 6 months after the research has ended.	☐	☐
C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION		
9. I agree that my responses, views or other input can be quoted anonymously in research outputs	☐	☐

Signatures

__________________________ __________________________ _______________

Name of participant [printed] Signature Date

I, as legal representative, have witnessed the accurate reading of the consent form with the potential participant and the individual has had the opportunity to ask questions. I confirm that the individual has given consent freely.

__________________________ __________________________ _______________

Name of witness Signature Date

I, as a researcher, have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participants understood what they were freely consenting to.

__________________________ __________________________ _______________

Name of researcher [printed] Signature Date

Study contact details for further information:
P.A. Xu (Kai), (+316 43742888, p.a.xu@student.tudelft.nl)

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Interview Protocol Hybrid: AI | RETROFIT-NET ZERO [EN)

First of all, thank you so much in advance for sharing your insights. Before we start the interview, we would like to ask your permission for various aspects of your participation in our research. First, you should be aware that your participation is completely voluntary. You have the right not to answer questions, and you can decide to terminate your participation in the study at any time without giving any reason. It is important to understand that your responses will be retained for research purposes.

My name is Kai Xu, and I study Management in the Built Environment at TU Delft. In my thesis, I explore and develop an AI methodology in the decarbonization process aimed at achieving net-zero emission buildings. Before we start the interview, I would like to ask your permission to make an audio recording during the interview. This recording will be deleted after completing my thesis. The data will be kept encrypted and processed anonymously.

I would like to start the recording and repeat the question if you give permission.

[Start recording]

Do you give permission for an audio recording to be made?

[Authorization by interviewer]

Furthermore, the full explanation for consent can be found in the following document [informed consent form interview], which you (already) signed, provided you agree.

The interview will last approximately 60 minutes. We'll talk about insights and perspectives on the integration of key components of decarbonization and how AI methodology can be effectively utilized to optimize these components in achieving net-zero emission buildings. Secondly, the role of the management consultancy practices influencing AI and impacting actors & stakeholders. Lastly, the insights of integrating managing consultancy with AI to potentially optimize the retrofit process. The interview questions will be X.A or X.B will be applied to your field of expertise. Before we start, do you have any questions?

Introduction Interview

As briefly explained, I research Artificial Intelligence methods in the decarbonization process to achieve net-zero emission buildings. The existing building stock is the big elephant in the room to decarbonize and achieve the built environment decarbonization targets by 2030 and 2050. Artificial Intelligence is an advanced technology based on data-driven algorithms and computational models that enable machines to learn from and adapt to patterns in data, allowing them to perform a task that mimics human intelligence. In this research, I focus specifically on developing a guide for artificial intelligence use in the decarbonization process in the built environment. This research is not about designing or creating a new type of AI technology but more about the application of AI to solve problems or achieve specific objectives in net-zero emission building design.

1.0 Background

First of all, can you introduce yourself? Who are you, and what is your position/current role?

What is your expertise in AI, Net-Zero, Retrofit Building, or multiple expertise in these fields?
- And how often do you apply this expertise to projects or other scenarios?

Have you only worked at this company or also at other companies with this expertise(s)?

- And was there a difference between these companies?

2.A AI: multifaced landscape of AI-assisted/or driven solutions
[Questions for experts in AI technology]

AI subfields:	Machine learning (ML)	(Artificial) Neural Networks (NN)	Deep learnings (DL)	Robotics	Natural Language Processing (NLP)	Genetic Algorithm (GA)
Net Zero Carbon Retrofit phases						
A. Pre-retrofit: planning and assessment of decarbonisation process						
1. Assessment and benchmarking	x	x				
2. Design and planning	x		x			x
3. Energy audit	x					
4. Life Cycle Analysis (LCA) and Carbon offsetting	x	x				x
5. Building Information Management (BIM)	x	x	x			
6. Business case & cost estimation (stakeholders)	x	x			x	
B. Retrofit: optimizing building performance and integration of sustainable solutions						
B.0 Whole lifecycle carbon emission approach						
1. Barriers, opportunities, trade-offs as a whole life carbon impact.	x	x				x
2. Carbon offsets	x		x			x
B1. Embodied carbon impacts						
1. Building envelope improvements	x	x		x		x
2. Energy effiency measures	x		x			
3. Materials and circular alternatives	x				x	x
4. Waste reduction and recycling	x			x		
B2. Operational carbon targets						
1. Energy effiency measures	x		x			
2. Renewable energy integration	x					x
3. Smart building technologies	x		x		x	
4. Monitoring and performance tracking	x		x	x	x	
C. Post-retrofit: maintenance and End-of-Life						
1. Monitoring and performance management	x		x	x	x	
2. Demolition, disposal , or recycle	x			x		x

As we delve into the pivotal role of artificial intelligence (AI) in the decarbonization of existing buildings, we focus on its potential contributions, challenges, and opportunities in the retrofitting process towards achieving net-zero emissions. In this first part, we explore the multifaceted landscape of AI-driven solutions, aiming to uncover key areas of impact, specific techniques, and potential challenges.

In your expertise, what are the key areas where AI can contribute most significantly to the process?

- How do you see this situation in the process of individual key components in making a building more sustainable to net zero?
- What specific challenges and limitations do you encounter with AI?
- What can the opportunities be when these limitations and challenges are addressed?

Can you elaborate on specific AI algorithms or techniques that hold promise for optimizing energy efficiency and reducing carbon footprint in retrofit projects?

- What are the criteria and parameters for AI to optimize these tasks?

How can AI technologies be leveraged to optimize the retrofitting process for achieving net-zero emission in buildings?

- Can you name factors/key components that will contribute to AI?

What role do you see AI playing in seamlessly integrating various retrofit elements to achieve a holistic net-zero emission outcome?

How can AI-driven data analytics and predictive modeling enhance decision-making processes in prioritizing retrofit measures for maximum carbon reduction in buildings?

- What are the criteria and parameters for AI to optimize these tasks?

What challenges do you foresee in implementing AI-driven solutions for retrofitting existing buildings, and how can these challenges be addressed effectively?

2.B Retrofit & Net Zero: multifaced landscape of building retrofit towards net-zero

[Questions for experts in Retrofit or/and Net Zero]

AI subfields:	Machine learning (ML)	(Artificial) Neural Networks (NN)	Deep learnings (DL)	Robotics	Natural Language Processing (NLP)	Genetic Algorithm (GA)
Net Zero Carbon Retrofit phases						
A. Pre-retrofit: planning and assessment of decarbonisation process						
1. Assessment and benchmarking	x	x				
2. Design and planning	x		x			x
3. Energy audit	x					
4. Life Cycle Analysis (LCA) and Carbon offsetting	x	x				x
5. Building Information Management (BIM)	x	x	x			
6. Business case & cost estimation (stakeholders)	x	x			x	
B. Retrofit: optimizing building performance and integration of sustainable solutions						
B.0 Whole lifecycle carbon emission approach						
1. Barriers, opportunities, trade-offs as a whole life carbon impact.	x	x				x
2. Carbon offsets	x		x			x
B1. Embodied carbon impacts						
1. Building envelope improvements	x	x		x		x
2. Energy effiency measures	x		x			
3. Materials and circular alternatives	x				x	x
4. Waste reduction and recycling	x			x		
B2. Operational carbon targets						
1. Energy effiency measures	x		x			
2. Renewable energy integration	x					x
3. Smart building technologies	x		x		x	
4. Monitoring and performance tracking	x		x	x	x	
C. Post-retrofit: maintenance and End-of-Life						
1. Monitoring and performance management	x		x	x	x	
2. Demolition, disposal , or recycle	x			x		x

As we delve into the pivotal realm of net-zero emission and focus on retrofitting buildings in this interview, we start with the multifaced landscape of the retrofit process in the context of net-zero emission building. In this first part, the various components of the retrofit process to decarbonize an existing building are unraveled and identified.

Can you describe a typical process of retrofitting a building from initial to end? The process of initializing the project to decarbonizing the existing building and maintaining the retrofitted building.

- Can you elaborate on specific criteria or parameters crucial for successful retrofitting towards net-zero emissions, considering both technical feasibility and practical implementation?

From your expertise, what are the key challenges in integrating various retrofit elements seamlessly to achieve net-zero emission in buildings?

- Can you explain the limitations of these retrofit elements?
(building envelope, energy efficiency, materials, waste, renewable energy, etc.)
- What can the opportunities be when these limitations and challenges of individual retrofit elements are integrated and optimized?

In your opinion, what are the most effective strategies for reducing embodied carbon impacts during the retrofitting process of existing buildings?

- What are the challenges and limitations?

How can we ensure that operational carbon targets are realistically set and achieved in retrofitted net-zero emission buildings? Are there any best practices or benchmarks to follow?

- Can you elaborate on specific criteria or parameters that will enhance the operational carbon emission phase?

From your perspective, what role do policy and regulation play in incentivizing or mandating the adoption of net-zero retrofitting practices?

How do you envision the role of advanced technology, beyond AI, in achieving the optimization in the retrofit process to net-zero emission building?

3.A AI: actors and stakeholders role and impact
[Questions for experts in AI technology]

Actors & Stakeholders:	NGOS / Trade Associations / Proffesional Institutions	Investors (banks, funders, etc.)	Developers	Landlords / Owners	Occupiers	Facilities Managers / Maintenance	Contractors	Material & Product Manufacturers	Architects	Building Services Engineers	Structural Engineers
Net Zero Carbon Retrofit phases											
A. Pre-retrofit: Planning and assessment of decarbonisation process											
1. Assessment and benchmarking	X	X	X								
2. Design and planning			X			X	X		X	X	X
3. Energy audit		X	X			X	X		X		
4. Life Cycle Analysis (LCA) and Carbon offsetting	X		X	X			X	X	X		X
5. Building Information Management (BIM)		X				X	X	X	X		X
6. Business case & cost estimation (stakeholders)		X	X	X							
B. Retrofit: Optimizing building performance and integration of sustainable solutions											
B.0 Whole lifecycle carbon emission approach											
1. Barriers, opportunities, trade-offs as a whole life carbon impact	X		X				X		X	X	X
2. Carbon offsets			X								
B1. Embodied carbon impacts											
1. Building envelope improvements							X		X		X
2. Energy effiency measures							X		X	X	
3. Materials and circular alternatives							X	X	X	X	X
4. Waste reduction and recycling							X	X	X		X
B2. Operational carbon targets											
1. Energy effiency measures						X	X	X	X	X	
2. Renewable energy integration							X		X	X	
3. Smart building technologies					X	X	X			X	
4. Monitoring and performance tracking					X	X	X			X	
C. Post-retrofit: Maintenance and end-of-life											
1. Monitoring and performance management					X	X				X	
2. Demolition, disposal, or recycle							X	X	X	X	X

Next part is understanding how management consultancy practices engage with actors and stakeholders, uncovering their roles, strategies, challenges, and opportunities in shaping the success of AI integration in building retrofitting projects. Furthermore, we aim to explore actors & stakeholder engagement and collaboration and uncover strategies, challenges, and opportunities that shape the success of the management consultancy.

In your expertise, how do you perceive the role of management consultancies to the client and other actors & stakeholders?

- In what ways do management consultancies influence projects?
(provide expertise, recommend solutions, facilitate implementation)
- In what ways can this influence AI utilization in projects?

In what ways do management consultancies influence the decision-making process and mitigate risk associated with influencing data for AI adoption?

- How does this impact other actors & stakeholders in projects?
- What are the key elements/factors for input data that result in output data?
Garbage In, Garbag Out (GIGO)

What are the potential benefits of integrating AI technologies into the tasks and execution of actors and stakeholders involved in projects?

- How can AI enhance the effectiveness and efficiency of actors and stakeholders?
- What are the main challenges or barriers faced by actors and stakeholders in adopting AI technologies, and how can these challenges be effectively addressed?

How do you envision the interdisciplinary collaboration between AI experts and professionals in the field projects(e.g., managing consultancies, architecture, engineering, project managers, investors) for achieving project goals/individual goals?

In what ways do actors and stakeholders benefit from the involvement of management consultancy practices in AI-assisted methods?

3.B Retrofit & Net Zero: actors and stakeholders role and impact
[Questions for experts in Retrofit or/and Net Zero]

Actors & Stakeholders:	NGOS / Trade Associations / Proffesional Institutions	Investors (banks, funders, etc.)	Developers	Landlords / Owners	Occupiers	Facilities Managers / Maintenance	Contractors	Material & Product Manufacturers	Architects	Building Services Engineers	Structural Engineers
Net Zero Carbon Retrofit phases											
A. Pre-retrofit: Planning and assessment of decarbonisation process											
1. Assessment and benchmarking	X	X	X								
2. Design and planning			X			X	X		X	X	X
3. Energy audit		X	X			X	X		X		
4. Life Cycle Analysis (LCA) and Carbon offsetting	X		X	X			X	X	X		X
5. Building Information Management (BIM)		X				X	X	X	X		X
6. Business case & cost estimation (stakeholders)		X	X	X							
B. Retrofit: Optimizing building performance and integration of sustainable solutions											
B.0 Whole lifecycle carbon emission approach											
1. Barriers, opportunities, trade-offs as a whole life carbon impact	X		X				X		X	X	X
2. Carbon offsets			X								
B1. Embodied carbon impacts											
1. Building envelope improvements							X		X		X
2. Energy effiency measures							X		X	X	
3. Materials and circular alternatives							X	X	X	X	X
4. Waste reduction and recycling							X	X	X		X
B2. Operational carbon targets											
1. Energy effiency measures						X	X	X	X	X	
2. Renewable energy integration							X		X	X	
3. Smart building technologies					X	X	X			X	
4. Monitoring and performance tracking					X	X	X			X	
C. Post-retrofit: Maintenance and end-of-life											
1. Monitoring and performance management					X	X				X	
2. Demolition, disposal, or recycle							X	X	X	X	X

Next part is understanding the roles and challenges faced by management consultancies in the retrofit to net zero. In this part, we aim to explore stakeholder engagement and collaboration and uncover strategies, challenges, and opportunities that shape the success that shape the success of management consultancy practices.

In your expertise, how do you perceive the role of management consultancies to the client and other actors & stakeholders?

- In what ways do management consultancies influence projects?
(provide expertise, recommend solutions, facilitate implementation)

In what ways do management consultancies influence the decision-making process and mitigate risk in projects (in retrofitting)?

- How does this impact other actors & stakeholders in the building retrofit?
- What are the key elements/factors for input data that result in output data?
Garbage In, Garbage Out (GIGO)

Are there strategies that actors/stakeholders can influence the overall success of the project?

- And how are these strategies achieved and integrated into the retrofit process to net zero?
- What are the potential opportunities for these actors & stakeholders through the management consultancy practices perspective?

How important are stakeholder engagement and collaboration in the successful implementation of net-zero retrofitting projects? What strategies have you found effective in engaging diverse stakeholders throughout the process?

Can you elaborate on the communication, coordination, and decision-making among actors/ stakeholders involved in the retrofit?

- Can you elaborate on the effectiveness and efficiency of these actors/stakeholders?
- Challenges, limitations, and opportunities?

4.A AI: integrating AI and Management Consultancy
[Questions for experts in AI technology]
As we explore the intersection of integrating AI technology and management consultancies, I aim to understand and identify innovative applications and potential contributions of AI in evaluating and/or AI-driven optimization in retrofitting. This part is to uncover the opportunities, challenges, and limitations of AI with management consultancy practices.

Opportunities

From your expertise, can you provide insights into how AI technologies potentially contributed to improving the accuracy and efficiency of managing consultancies?

- Are there other specific characteristics or parameters that enhance management consultancies' outcomes?
- Are there any specific AI algorithms or techniques that have been particularly effective?

In what ways can AI-driven analytics improve the identification and prioritization in projects?

What opportunities exist for AI to streamline project management processes and enhance efficiency in projects?

- How can AI enhance the capabilities of management consultancy practices in strategic planning and decision-making for project initiatives?

What opportunities do you see for AI-driven solutions to address specific pain points or inefficiencies encountered by actors and stakeholders throughout the process?

- What role is expected from actors and stakeholders (human oversight) in the integration of AI in their role and execution of tasks?
(E.g., informed decision-making, AI is outsourcing, organizational goals, and ethical considerations in their use of AI)

Challenges

What are the key technical challenges associated with integrating AI into management consultancy practices?

- What about in relevance to project optimization?

How do data-related challenges, such as data availability and quality, impact the effectiveness of AI integration in consultancy practices?

What are the challenges for mitigating risks or giving a realistic future predictive modeling?

What challenges arise in terms of skill gaps and capacity building when implementing AI within management consultancy firms?

- How do regulatory and ethical considerations pose challenges to the integration of AI in consultancy practices?

What challenges exist in terms of stakeholder acceptance and trust in AI-driven solutions proposed by management consultancies?

Limitations

What are the limitations of AI in management consultancy practices for a project?

How do limitations in AI algorithms and models impact their applicability and accuracy in optimizing strategies?

What are the limitations of management consultancy practices in effectively leveraging AI due to organizational constraints or resistance to change?

4.B Retrofit & Net Zero: environmental assessments
[Questions for experts in Retrofit or/and Net Zero]

As we explore the intersection of integrating AI technology and management consultancies. I aim to understand and identify innovative applications and potential contributions of AI in evaluating and/or AI-driven optimization in retrofitting. This part is to uncover the opportunities, challenges, and limitations of AI with management consultancy practices.

Opportunities
From your expertise, can you provide insights into how managing consultancies can potentially improve accuracy and efficiency?

- Are there other specific characteristics or parameters that enhance management consultancies' outcomes?

In what ways can managing consultancy practices improve the identification and prioritization of retrofitting opportunities for buildings?

What opportunities do you see for optimization in building retrofitting to enhance environmental sustainability and cost-effectiveness?

- Based on the retrofitting, how do you envision AI recommending and predicting decisions for the retrofitting process?

What opportunities exist for strategic planning and decision-making optimization to streamline project management processes and enhance efficiency in retrofit projects toward net zero?

What opportunities do you see for consultancies solutions to address specific pain points or inefficiencies encountered by actors and stakeholders throughout the (retrofit) process?

- What role is expected from actors and stakeholders (human oversight) in the integration of AI in their role and execution of tasks?
  (E.g., informed decision-making, AI is outsourcing, organizational goals, and ethical considerations)

Challenges
What are the key technical challenges associated with current management consultancy practices?

- What about in relevance to retrofitting optimization?

How do data-related challenges, such as data availability and quality, impact the effectiveness of decision-making in retrofitting projects?

- How about managing consultancy accuracy & quality?

What are the challenges for mitigating risks or giving a realistic future predictive modeling in projects?

What challenges arise in terms of skill gaps and capacity building when implementing AI within management consultancy firms?

- How do regulatory and ethical considerations pose challenges to the integration of AI in consultancy practices?

What challenges exist in terms of stakeholder acceptance and trust in AI-driven solutions proposed by management consultancies? And how can these be addressed?

Limitations
What are the limitations of management consultancy practices for a project?

- What are the limitations of AI in addressing the complexities of building retrofitting projects, particularly in existing data or data collection?

How do (these) limitations in management consultancies impact their applicability and accuracy in optimizing strategies?

What are the limitations of management consultancy practices in effectively leveraging AI due to organizational constraints or resistance to change?

In your expertise, what are the limitations of AI (such as environmental and cost-effectiveness objectives) considerations in retrofit projects?

5.0 Closure
Are there any aspects that have not yet been discussed during this interview that you would like to discuss?

Are there any other people you would recommend involving in this research?

Once again, thank you very much for your contribution to my research. I will send the transcript so you can have the option to propose adjustments. If you have any questions or suggestions afterward, you can always contact me.

[End of interview]

STEP 1

Type of Retrofit Project

- Project features

MONITORING

Energy Efficiency-Focused Projects
The main goal is to reduce operational energy use through system optimization and real-time adjustments.
- HVAC optimization
- LED lighting systems
- Smart metering

Operational Efficiency-Centered Projects
Prioritize optimizing building systems to maximize operational performance and reduce downtime.
- Smart building management systems
- Predictive maintenance for HVAC and electrical systems
- Continuous feedback loops to identify inefficiencies in building operations

Smart Building Projects
Upgrade building systems to incorporate smart technologies for real-time optimization of energy, water, and other resources.
- Integration of smart sensors for lighting, temperature, and security
- Automated system controls for optimized resource use

Holistic Decarbonization Projects (Integrated to Net Zero)
Retrofitting with the goal of achieving net-zero carbon emissions.
- Full building lifecycle analysis for carbon impact (embodied + operational).
- renewable energy systems, advanced insulation, smart grid integration.

PREDICTIONS

Energy Efficiency-Focused Projects
The main goal is to reduce operational energy use through system optimization and real-time adjustments.
- HVAC optimization
- LED lighting systems
- Smart metering

Cost-Optimization Retrofitting Projects
Focus on minimizing retrofit costs while achieving energy and carbon reduction goals.
- Focus on ROI (Return on Investment) and payback period
- Prioritizing retrofits that offer quick cost savings (e.g., lighting, heat pumps, installations)

Resilience and Adaptation Projects
Ensure buildings are resilient to future climate risks, energy demands, and regulatory changes.
- Climate adaptation strategies (e.g., stormproofing, energy storage for backup power)
- AI-driven risk assessments (e.g., environmental and operational risks)

Holistic Decarbonization Projects (Integrated to Net Zero)
Retrofitting with the goal of achieving net-zero carbon emissions.
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OPTIMIZATION

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- LED lighting systems
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ADAPTATION

Operational Efficiency-Centered Projects
The main goal is to reduce operational energy use through system optimization and real-time adjustments.
- Smart building management systems
- Predictive maintenance for HVAC and electrical systems
- Continuous feedback loops to identify inefficiencies in building operations

Smart Building Projects
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TARGETS

Carbon Reduction-Driven Projects
Focus on minimizing both embodied and operational carbon emissions.
- Renewable energy integration (solar, wind)
- Low-carbon materials for insulation and building envelopes
- Waste reduction and recycling initiatives

Cost-Optimization Retrofitting Projects
Focus on minimizing retrofit costs while achieving energy and carbon reduction goals.
- Focus on ROI (Return on Investment) and payback period
- Prioritizing retrofits that offer quick cost savings (e.g., lighting, heat pumps, installations)

Holistic Decarbonization Projects (Integrated to Net Zero)
Retrofitting with the goal of achieving net-zero carbon emissions.
- Full building lifecycle analysis for carbon impact (embodied + operational).
- renewable energy systems, advanced insulation, smart grid integration.

DIAGNOSTICS

Carbon Reduction-Driven Projects
Focus on minimizing both embodied and operational carbon emissions.
- Renewable energy integration (solar, wind)
- Low-carbon materials for insulation and building envelopes
- Waste reduction and recycling initiatives

Operational Efficiency-Centered Projects
The main goal is to reduce operational energy use through system optimization and real-time adjustments.
- Smart building management systems
- Predictive maintenance for HVAC and electrical systems
- Continuous feedback loops to identify inefficiencies in building operations

Holistic Decarbonization Projects (Integrated to Net Zero)
Retrofitting with the goal of achieving net-zero carbon emissions.
- Full building lifecycle analysis for carbon impact (embodied + operational).
- renewable energy systems, advanced insulation, smart grid integration.

DECISIONS

Carbon Reduction-Driven Projects
Focus on minimizing both embodied and operational carbon emissions.
- Renewable energy integration (solar, wind)
- Low-carbon materials for insulation and building envelopes
- Waste reduction and recycling initiatives

Compliance and Regulation-Oriented Projects
Focus on meeting or exceeding local, national, and international sustainability standards.
- Strict adherence to energy codes (e.g., Energy Performance of Buildings Directive in Europe)
- Retrofitting projects in highly regulated industries like healthcare or government

Cost-Optimization Retrofitting Projects
Focus on minimizing retrofit costs while achieving energy and carbon reduction goals.
- Focus on ROI (Return on Investment) and payback period
- Prioritizing retrofits that offer quick cost savings (e.g., lighting, heat pumps, installations)

Holistic Comprehensive Decarbonization Projects (Integrated to Net Zero)
Retrofitting with the goal of achieving net-zero carbon emissions.
- Full building lifecycle analysis for carbon impact (embodied + operational).
- renewable energy systems, advanced insulation, smart grid integration.

REGULATIONS

Compliance and Regulation-Oriented Projects
Focus on meeting or exceeding local, national, and international sustainability standards.
- Strict adherence to energy codes (e.g., Energy Performance of Buildings Directive in Europe)
- Retrofitting projects in highly regulated industries like healthcare or government

Holistic Decarbonization Projects (Integrated to Net Zero)
Retrofitting with the goal of achieving net-zero carbon emissions.
- Full building lifecycle analysis for carbon impact (embodied + operational).
- renewable energy systems, advanced insulation, smart grid integration.

STEP 2

Data Source Types (Pre-AI)

Building data collection material

IoT sensor data:
Continuous data from energy use, temperature, humidity, CO2 levels, and other key building metrics.
Energy consumption data:
Hourly or daily data on energy use per system (e.g., HVAC, lighting, etc.).
Occupancy sensors:
Data on room or space occupancy to adjust heating, ventilation, and lighting in real time.
Operational data:
Building performance data from HVAC, renewable energy systems, and lighting.

Historical performance data:
Past energy use, weather conditions, occupancy rates, and operational inefficiencies.
Weather forecasts:
Data for predicting energy consumption based on upcoming environmental conditions.
Occupancy trends:
Data on how building use changes over time, helping AI predict future energy needs.
Equipment lifecycle data:
Predicts when systems might fail based on past performance.

Control system data:
Real-time and historical data from building management systems.
Energy consumption patterns:
Used for dynamic adjustments to systems like HVAC and lighting.
Environmental condition data:
Temperature, humidity, and air quality metrics from inside and outside the building.
Feedback loops:
Real-time data for continuous adjustment of systems to improve efficiency.

Historical sensor data: Long-term operational data from various building systems to improve algorithm accuracy.
Performance feedback: Data from previous system adjustments to refine AI models.
User behavior data: Understanding how occupants interact with building systems to improve predictions and recommendations.
Anomaly detection data: Patterns of failure or inefficiency to refine fault detection algorithms.

Historical energy consumption data:
Essential for setting benchmarks and comparing current performance against industry standards.
Building specifications:
Data on building materials, insulation, window quality, HVAC systems, and lighting.
Energy performance certificates (EPC):
To evaluate the energy efficiency of the building.
Occupancy data:
To understand building usage and its impact on energy consumption.
Local climate data: Helps adjust benchmarks according to environmental conditions.

Sensor data:
Real-time data from HVAC, lighting, and building management systems to identify inefficiencies or faults.
Maintenance logs:
Historical data on system failures, repairs, and component lifespan.
Operational performance data:
Data on energy use, temperature variations, equipment performance, and anomalies.
IoT device data:
Data from smart meters and sensors monitoring building systems.

Integrated energy models:
Combines data from various systems (e.g., HVAC, lighting, and renewable energy systems) to inform decision-making.
Financial data:
Cost-benefit analyses and ROI projections for retrofit investments.
Project schedules and milestones:
Data on construction and retrofit project timelines.
Environmental impact data:
Carbon footprint data from building operations and materials used.

Regulatory databases:
Updated data on local and international energy efficiency and carbon reduction laws.
Energy performance certificates (EPC):
Regulatory requirements for building performance.
Building codes and standards:
Legal requirements for construction, retrofit, and operational efficiency.
Environmental impact assessments:
Data on the environmental performance of retrofitted systems.
Inspection reports: Documentation for compliance checks.

STEP 3

AI CAPABILITIES:

Real-Time Monitoring and Data Analytics | Predictive Analytics and Forecasting | Intelligent Control and Optimization | Machine Learning for Continuous Improvement | Benchmarking and Targeting | Fault Detection and Diagnostics | Data Decision Support | Compliance with Regulations

EMBODIED CARBON

Insulation, window, & door upgrades

Predictive Analytics and Forecasting (1)
Simulate the thermal performance of different insulation materials, window types, and door designs under varying climate conditions and usage patterns. This allows designers to choose materials that offer the best thermal performance over time, ensuring long-term energy efficiency.
AI subset: **Machine Learning**, used to forecast the energy performance of insulation and windows based on climate models and historical data.
ENERGY SAVINGS / CARBON REDUCTION

Intelligent Control and Optimization
Analyze the placement of windows and doors, optimizing the layout for natural lighting and ventilation while minimizing heat loss or gain. This helps designers balance comfort and energy efficiency.
AI subset: **Genetic Algorithm**, through multiple design configurations, selecting the best solutions based on criteria like heat loss, natural lighting, and ventilation.
OPERATIONAL EFFICIENCY

Machine Learning for Continuous Improvement
Continuously learn from data gathered from similar buildings to suggest insulation materials and design strategies that evolve over time as better materials and construction techniques emerge.
AI subset: **Machine Learning**, too analyze and predict the thermal performance of various materials over time, learning from vast datasets of energy consumption and weather patterns. ML continuously updates its predictions based on real-time data.
ENERGY SAVINGS / CARBON REDUCTION

Data Decision Support
By analyzing the building's current thermal performance and comparing it with various retrofitting options, the AI system can prioritize which upgrades—such as improving insulation thickness, upgrading window glazing, or replacing doors—will deliver the highest energy savings relative to cost. These systems can also assess the impact of these upgrades on overall building performance, allowing stakeholders to make informed decisions about which retrofitting measures to prioritize based on their energy efficiency and budget.
AI subset: **Neural Networks and Machine Learning**. Neural networks model complex relationships between building elements, while machine learning algorithms analyze performance data to offer data-driven recommendations, ensuring that retrofitting decisions optimize both energy performance and cost-efficiency.

Compliance with Regulations
Analyze the thermal performance of building elements, such as insulation, windows, and doors, by comparing their R-values (a measure of thermal resistance) with regulatory standards. These systems benchmark the building's current thermal performance against local energy-efficiency regulations and net-zero targets.
AI subset: **Machine Learning and Neural Networks**, evaluate past retrofitting data and **Neural Networks** simulate energy performance, helping target precise R-values for optimal insulation upgrades in line with regulatory requirements.
ENERGY SAVINGS

Materials & circular alternative

Predictive Analytics and Forecasting
Predicts long-term environmental impact of materials, accounting for durability and recyclability. By forecasts the lifecycle environmental impacts of materials, allowing designers to understand how choices made today will affect the building's carbon footprint over its lifecycle. In addition, assist in identifying potential risks or hazardous material (e.g., Asbestos).
AI subset: **Deep Learning**, analyze vast datasets on material properties, environmental impacts, and usage scenarios to provide more accurate forecasts on durability, recyclability, and long-term sustainability of materials, giving designers insights into how these materials will affect the building's overall carbon footprint throughout its lifecycle.
CARBON REDUCTION

Benchmarking and Targeting (4)
By compare different materials (e.g., concrete, timber, recycled materials) against sustainability benchmarks and project targets. This helps designers choose materials that reduce the building's embodied carbon while meeting structural and aesthetic goals.
AI subset: **Neural Networks**, process complex datasets involving multiple variables such as material properties, sustainability metrics, and structural requirements, allowing designers to make informed decisions on materials that minimize embodied carbon while aligning with the building's structural and aesthetic objectives.
CARBON REDUCTION

Data Decision Support
Selecting sustainable materials by evaluating the lifecycle impacts, cost, and availability of different materials. By comparing traditional materials with circular alternatives. The system evaluates carbon emissions, durability, and recyclability, providing insights into how material choices affect the overall carbon footprint and long-term building performance.
AI subset: **Machine Learning and Neural Networks**, process large datasets of material properties and project performance, while neural networks predict long-term environmental and financial impacts, guiding the selection of low-impact, circular materials.
CARBON REDUCTION

Compliance with Regulations
Ensure that material choices comply with sustainability regulations (e.g., LEED, BREEAM, EDGE, etc. certification), making it easier for designers to achieve eco-labels and standards.
AI subset: **Natural Language Models**, process and interpret vast amounts of regulatory and certification guidelines, ensuring that material choices align with the required eco-labels and standards, helping designers navigate complex compliance requirements efficiently.

Waste reduction and recycling

Predictive Analytics and Forecasting
Simulate how much waste will be generated during construction or demolition, helping designers plan for materials that minimize waste.
AI subset: **Genetic Algorithm**, simulate various design and construction scenarios, optimizing for material choices and construction methods that minimize waste generation during retrofitting or demolition processes. By iterating through different material and design combinations, they help designers make informed decisions that reduce waste.
CARBON REDUCTION

Machine Learning for Continuous Improvement (4)
Analyze data from past retrofitting projects, learning which materials can be easily reused or recycled, and providing real-time recommendations during the design/retrofit phase.
AI subset: **Machine Learning**, analyze data from past retrofitting projects to identify patterns in material reuse and recyclability, offering real-time recommendations during the design phase for optimizing sustainability. These systems continuously improve their suggestions as they learn from more project data.
CARBON REDUCTION

Data Decision Support
Design optimization by providing insights on how to reduce material waste during construction, recommending modular or prefabricated building elements that use fewer resources and generate less waste.
AI subset: **Genetic Algorithm**, optimize design choices by simulating various construction approaches, recommending modular or prefabricated elements that minimize material use and reduce waste, based on iterative solutions that mimic evolutionary processes.
CARBON REDUCTION

OPERATIONAL CARBON

Lightning upgrades

Real-Time Monitoring and Data Analytics (2)
By analyzing real-time data, the system can make adjustments, such as dimming lights during off-peak hours or optimizing brightness based on occupancy and daylight availability. This results in improved energy efficiency and cost savings. Tracks energy consumption and efficiency in lighting.

Data Collection and Structuring:
AI subset: **Machine Learning**, process data from smart sensors, past data to track and analyze energy consumption patterns in lighting systems, enabling continuous improvement in energy efficiency through predictive insights and adjustments.
ENERGY SAVINGS

Intelligent Control and Optimization
Dynamically adjusts lighting levels based on real-time occupancy data and available daylight. Using smart sensors, the system detects when spaces are occupied and automatically adjusts the lighting intensity to the appropriate level. When spaces are unoccupied or receive ample natural light, the system dims or turns off the lights to reduce unnecessary energy consumption.
AI subset: **Deep Learning**, learn from historical occupancy and daylight patterns to continuously refine the optimization process. This ensures that lighting systems are not only reactive but predictive, optimizing energy use more efficiently over time.
OPERATIONAL EFFICIENCY / ENERGY SAVINGS

Fault Detection and Diagnostics
Continuously monitoring energy consumption patterns and detecting anomalies that suggest potential malfunctions or inefficiencies. Identifies faulty or inefficient lighting systems by detecting anomalies in energy consumption.
AI subset: **Machine Learning**, learn typical energy consumption patterns and recognize deviations, allowing the system to pinpoint inefficiencies or faults before they significantly impact performance or energy costs.
OPERATIONAL EFFICIENCY / ENERGY SAVINGS

Data Decision Support
Analyze a building's current lighting setup and compare it with various energy-efficient alternatives. The system recommends optimal lighting technologies (e.g., LED upgrades, smart lighting systems) based on energy consumption patterns, occupancy rates, and daylight availability. It helps prioritize upgrades based on return on investment and energy savings potential, guiding decisions on lighting controls and automation.
AI subset: **Neural Networks**, predict the performance of lighting upgrades under different conditions, while simulating energy savings for various lighting configurations.
ENERGY SAVINGS

HVAC system improvements

Real-Time Monitoring and Data Analytics (1)
Tracking variables such as temperature, airflow, humidity, and energy consumption to ensure optimal energy use and occupant comfort. By analyze HVAC system behavior and identify inefficiencies or areas where energy consumption can be reduced
AI subset: **Deep Learning**, detects patterns in HVAC usage that lead to further optimization of energy consumption. By analyze vast amounts of data to continuously improve system performance and energy efficiency.
ENERGY SAVINGS

Intelligent Control and Optimization
Optimize temperature and airflow in HVAC systems by considering real-time occupancy levels, weather forecasts, and energy usage patterns. This allows the system to dynamically adjust heating, cooling, and ventilation to meet the specific needs of a building at any given time, ensuring comfort while minimizing energy consumption.
AI subset: **Neural Networks**, recognizing complex patterns in temperature, airflow, and occupancy data, while reinforcement learning allows the AI to optimize system performance by trial and error, continuously improving its control strategies for maximum energy efficiency.
OPERATIONAL EFFICIENCY / ENERGY SAVINGS

Data Decision Support
Evaluating different HVAC system upgrades, such as advanced heat pumps, energy recovery systems, or smart thermostats, by analyzing the building's thermal load, energy consumption, and user preferences. The system compares the cost-effectiveness of upgrading specific components versus replacing the entire system, taking into account the building's operational demands.
AI subset: **Machine Learning**, identifies the best-performing HVAC systems based on building-specific data.
OPERATIONAL EFFICIENCY / ENERGY SAVINGS

Compliance with Regulations
HVAC systems meet the latest energy efficiency and environmental regulations. AI can identify opportunities to leverage financial incentives for improving HVAC systems, such as tax breaks, grants, or rebates tied to meeting or exceeding energy efficiency standards. By optimizing HVAC systems in line with regulations, building owners can avoid fines and benefit from available financial incentives, all while improving sustainability outcomes.
AI subset: **Machine Learning**, analyzes real-time data to ensure continued adherence to these regulations, identifying when systems deviate from expected benchmarks and suggesting corrective actions.

Building Management Systems

Real-Time Monitoring and Data Analytics
Track performance metrics across various building functions, such as HVAC, lighting, and energy usage. By gathering and analyzing data continuously from smart sensors and other IoT devices, the AI system identifies inefficiencies and optimizes building operations in real time. This capability ensures that all systems function at peak performance, and any deviations or inefficiencies are quickly detected and addressed.
AI subset: **Deep Learning and Neural Networks**, processing vast amounts of real-time data, detecting patterns, and predicting anomalies, while neural networks excel at identifying complex relationships between various systems in the building.
OPERATIONAL EFFICIENCY

Intelligent Control and Optimization (2)
Synchronize various building systems, such as lighting and HVAC, to ensure they work in harmony rather than independently. By integrating data from these systems, AI can make real-time adjustments that optimize overall energy consumption.
AI subset: **Machine Learning**, continuously learns from patterns in building operations to refine system performance over time.
OPERATIONAL EFFICIENCY / ENERGY SAVINGS

Fault Detection and Diagnostics
Continuously monitor building systems, such as HVAC, lighting, and energy management, identifying inefficiencies and potential malfunctions before they escalate into larger issues. This proactive approach allows facilities managers to address problems quickly, preventing system failures and reducing operational downtime. By analyzing patterns in energy consumption, temperature fluctuations, and system behavior, AI can alert operators to anomalies that indicate wear, suboptimal performance, or imminent equipment failure.
AI subset: **Neural Networks**, recognizing subtle patterns in large datasets. These subsets can detect anomalies in system performance that traditional methods might miss, providing early warnings of inefficiencies or potential malfunctions. Over time, the model refines its understanding of what constitutes normal vs. faulty behavior, improving its diagnostic accuracy.
OPERATIONAL EFFICIENCY

Data Decision Support
The integration of new building management systems by evaluating how well they coordinate with existing mechanical, electrical, and plumbing (MEP) systems. Decision support tools recommend which smart sensors, controllers, and automation features will most effectively monitor and optimize the building's energy use, occupancy patterns, and environmental conditions.
AI subset: **Machine Learning**, enhances system performance by identifying optimal control settings, while helping fine-tune coordination between various building operations.
OPERATIONAL EFFICIENCY

Renewable Energy Integration

Real-Time Monitoring and Data Analytics
Track and analyze real-time weather conditions and historical usage patterns to forecast renewable energy production. This capability ensures that solar panels, wind turbines, or other renewable systems operate at their peak potential by predicting how much energy will be generated based on factors like sunlight, wind speeds, or even building occupancy.
AI subset: **Machine Learning**, analyzing historical data and weather forecasts to model future energy production. These algorithms continuously learn from new data, improving their forecasting accuracy over time and optimizing energy management based on evolving conditions.
ENERGY SAVINGS

Predictive Analytics and Forecasting
By predicting future energy demands and renewable energy availability, AI helps organizations make informed decisions about when and how much renewable energy to purchase "procurement", ensuring cost-effectiveness while meeting sustainability goals. In addittion, tracks real-time renewable energy generation, adjusting system loads based on energy availability.
AI subset: **Machine Learning and Deep Learning**, learning from historical data and real-time inputs continuously refines energy storage and usage decisions for maximum efficiency. And to optimize energy procurement decisions based on future demand and price trends.
ENERGY SAVINGS

Intelligent Control and Optimization (3)
Manage the interaction between renewable energy sources and conventional energy systems. By analyzing real-time consumption patterns, AI can determine the optimal moments to draw energy from renewable sources, such as solar panels or wind turbines, while seamlessly switching to conventional energy when necessary. This ensures maximum use of renewable energy without interrupting the building's energy demands.
AI subset: **Genetic Algorithms**, optimization, enabling AI to evaluate different energy distribution strategies to find the most efficient solution based on current and projected consumption patterns. That renewable energy use is maximized while maintaining stability in the energy grid.
ENERGY SAVINGS

Benchmarking and Targeting
Compare the building's renewable energy production, such as solar or wind, against industry benchmarks, historical data, or predefined sustainability goals. This helps assess how effectively renewable energy sources are being utilized within the building. By targeting specific metrics, like kilowatt-hours produced or CO2 emissions avoided, AI ensures that renewable energy systems are optimized to meet both regulatory standards and energy efficiency objectives.
AI subset: **Machine Learning**, continuously adjust energy production targets based on performance.
ENERGY SAVINGS

Data Decision Support
Select the most appropriate renewable energy solutions for a building (e.g., solar panels, wind turbines) by analyzing energy needs, location, and climate conditions. The system provides insights into how renewable energy sources can be integrated with existing systems, optimizing both cost savings and environmental benefits. AI models simulate the energy production and cost-efficiency of different configurations, helping to make informed choices on the type and scale of renewable energy to be deployed.
AI subset: **Machine Learning and Neural Networks**, forecasts energy production and usage patterns, while neural networks optimize the integration of renewable energy systems based on building performance and environmental factors.
ENERGY SAVINGS

STEP 4

Synergistic

Decarbonization strategies

1. **HVAC + Insulation:**
Synergy: Optimized HVAC systems coupled with enhanced building insulation can significantly reduce heating and cooling demands.
Outcome: The combined effect results in substantial **energy savings** (e.g., HVAC efficiency + reduced heat loss through insulation), lowering both operational costs and carbon emissions.

2. **Lighting + Building Management Systems:**
Synergy: AI-controlled lighting systems integrated with building management systems (BMS) adjust energy consumption based on occupancy patterns and overall energy use.
Outcome: This synergy leads to improved **operational efficiency**, reduced **energy consumption**, and enhanced user comfort through automated control, optimizing when and how energy is used in a building.

3. **Renewable Energy Integration + Energy Storage (e.g., batteries):**
Synergy: AI optimizes when to use energy generated from renewable sources like solar panels and when to store it in energy storage systems, ensuring a balance between generation and consumption.
Outcome: This synergy enhances **energy resilience** and **carbon reduction**, ensuring that energy is used and stored at optimal times, reducing reliance on non-renewable sources.

4. **Waste Reduction + Circular Materials:**
Synergy: AI can support waste reduction initiatives by recommending and optimizing the use of recycled and circular materials, reducing the embodied carbon in retrofitting projects.
Outcome: The combination reduces **embodied carbon** in the materials used for retrofitting and promotes sustainability by minimizing waste and promoting recycling.

5. **Real-Time Monitoring + Predictive Analytics + Intelligent Control:**
Synergy: Real-time monitoring of energy consumption, combined with predictive analytics and intelligent control systems, allows AI to proactively manage energy use, preventing inefficiencies before they occur.
Outcome: This results in continuous **energy optimization** and **operational efficiency**, as systems adjust automatically based on real-time data and forecasts.

6. **Machine Learning for Continuous Improvement + Fault Detection:**
Synergy: Machine learning identifies patterns over time and feeds into fault detection systems, improving the speed and accuracy of identifying potential issues in building systems.
Outcome: Together, they ensure **proactive maintenance**, minimizing downtime and maintaining consistent energy performance through self-learning algorithms.

STEP 5

Verification (Post-AI)

Objective & Transparency

Verification Step: Compare real-time energy data and usage patterns against pre-established benchmarks.
Outcome: Ensure that the real-time adjustments have successfully reduced energy consumption in comparison to historical baselines.

Verification Step: Analyze forecasted versus actual performance outcomes for energy efficiency and carbon reduction.
Outcome: Validate that predictive models are accurately anticipating energy needs and that adjustments have led to projected energy savings and emission reductions.

Verification Step: Monitor operational efficiencies across HVAC, lighting, and other building systems.
Outcome: Confirm that AI-controlled systems have optimized performance and energy use, achieving the expected operational efficiency improvements.

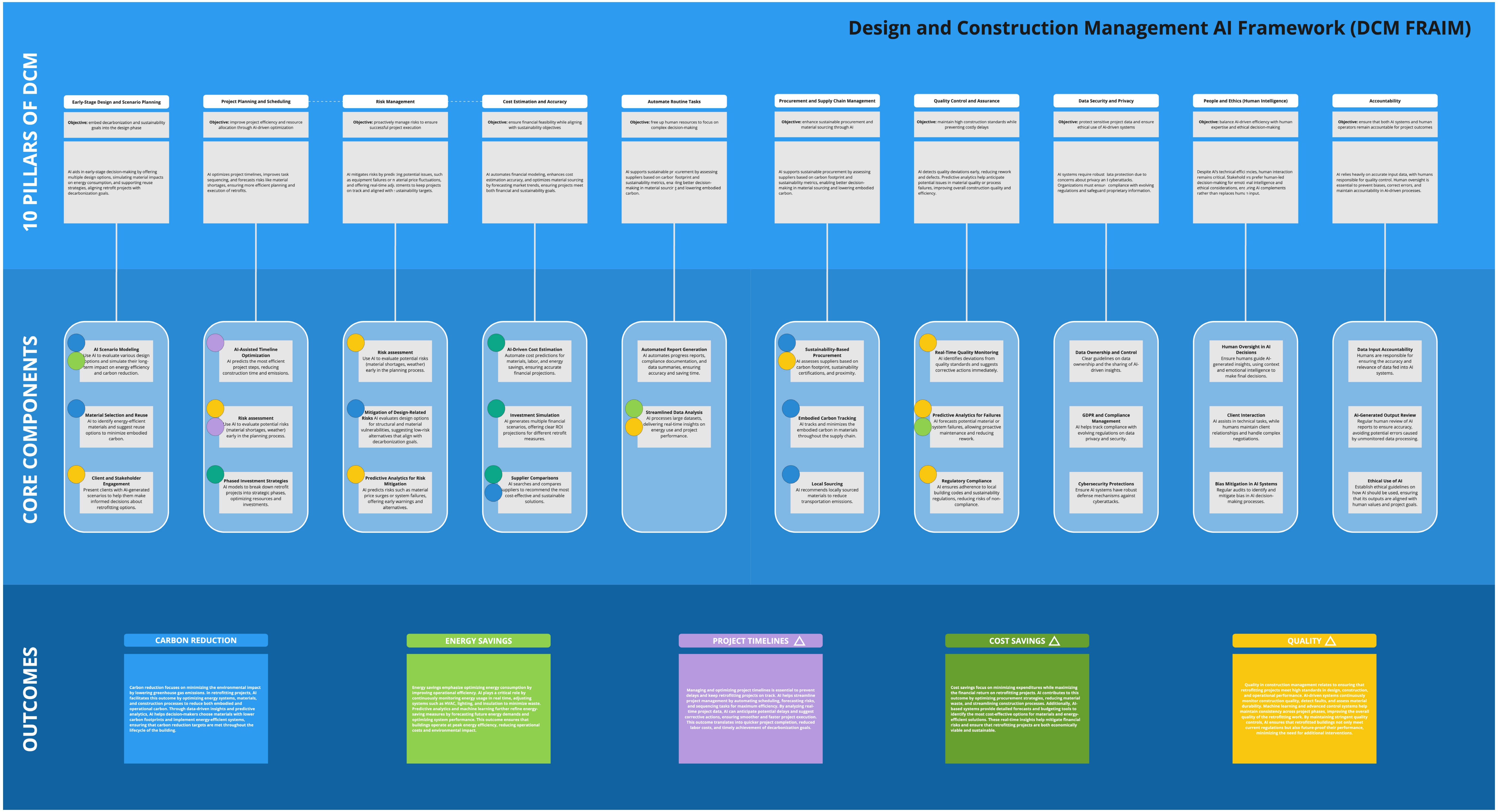
Verification Step: Review system performance over time to assess adaptive learning outcomes.
Outcome: Verify that machine learning algorithms are continuously improving energy savings and carbon reduction by identifying and responding to new patterns.

Verification Step: Cross-check actual building performance with set carbon and energy benchmarks.
Outcome: Ensure that buildings are meeting or exceeding the energy-saving and carbon-reduction targets established through AI-driven benchmarking.

Verification Step: Assess fault detection logs and maintenance reports to ensure timely identification and resolution of system inefficiencies.
Outcome: Validate that AI-driven fault detection systems have minimized downtime and inefficiencies in building operations.

Verification Step: Compare decision outcomes based on AI recommendations with real-time performance improvements.
Outcome: Confirm that data-driven decisions have led to tangible improvements in energy efficiency, cost savings, and project timelines.

Verification Step: Review regulatory reports and certifications for adherence to energy efficiency and carbon reduction standards.
Outcome: Ensure that retrofitting projects comply with all local and international environmental regulations and standards.


Design and Construction Management AI Framework (DCM FRAIM)
10 PILLARS OF DCM
Early-Stage Design and Scenario Planning
Objective: embed decarbonization and sustainability goals into the design phase
AI aids in early-stage decision-making by offering multiple design options, simulating material impacts on energy consumption, and supporting reuse strategies, aligning retrofit projects with decarbonization goals.
Project Planning and Scheduling
Objective: improve project efficiency and resource allocation through AI-driven optimization
AI optimizes project timelines, improves task sequencing, and forecasts risks like material shortages, ensuring more efficient planning and execution of retrofits.
Risk Management
Objective: proactively manage risks to ensure successful project execution
AI mitigates risks by predic ing potential issues, such as equipment failures or n aterial price fluctuations, and offering real-time adj stments to keep projects on track and aligned with ustainability targets.
Cost Estimation and Accuracy
Objective: ensure financial feasibility while aligning with sustainability objectives
AI automates financial modeling, enhances cost estimation accuracy, and optimizes material sourcing by forecasting market trends, ensuring projects meet both financial and sustainability goals.
Automate Routine Tasks
Objective: free up human resources to focus on complex decision-making
AI supports sustainable pr curement by assessing suppliers based on carbo footprint and sustainability metrics, ena ling better decision-making in material sourci and lowering embodied carbon.
Procurement and Supply Chain Management
Objective: enhance sustainable procurement and material sourcing through AI
AI supports sustainable procurement by assessing suppliers based on carbon footprint and sustainability metrics, enabling better decision-making in material sourcing and lowering embodied carbon.
Quality Control and Assurance
Objective: maintain high construction standards while preventing costly delays
AI detects quality deviations early, reducing rework and defects. Predictive analytics help anticipate potential issues in material quality or process failures, improving overall construction quality and efficiency.
Data Security and Privacy
Objective: protect sensitive project data and ensure ethical use of AI-driven systems
AI systems require robust ata protection due to concerns about privacy an cyberattacks. Organizations must ensur compliance with evolving regulations and safeguard proprietary information.
People and Ethics (Human Intelligence)
Objective: balance AI-driven efficiency with human expertise and ethical decision-making
Despite AI's technical effic ncies, human interaction remains critical. Stakehold rs prefer human-led decision-making for emoti nal intelligence and ethical considerations, ens ring AI complements rather than replaces hum n input.
Accountability
Objective: ensure that both AI systems and human operators remain accountable for project outcomes
AI relies heavily on accurate input data, with humans responsible for quality control. Human oversight is essential to prevent biases, correct errors, and maintain accountability in AI-driven processes.
CORE COMPONENTS
AI Scenario Modeling
Use AI to evaluate various design options and simulate their long-term impact on energy efficiency and carbon reduction.
Material Selection and Reuse
AI to identify energy-efficient materials and suggest reuse options to minimize embodied carbon.
Client and Stakeholder Engagement
Present clients with AI-generated scenarios to help them make informed decisions about retrofitting options.
AI-Assisted Timeline Optimization
AI predicts the most efficient project steps, reducing construction time and emissions.
Risk assessment
Use AI to evaluate potential risks (material shortages, weather) early in the planning process.
Phased Investment Strategies
AI models to break down retrofit projects into strategic phases, optimizing resources and investments.
Risk assessment
Use AI to evaluate potential risks (material shortages, weather) early in the planning process.
Mitigation of Design-Related Risks AI evaluates design options for structural and material vulnerabilities, suggesting low-risk alternatives that align with decarbonization goals.
Predictive Analytics for Risk Mitigation
AI predicts risks such as material price surges or system failures, offering early warnings and alternatives.
AI-Driven Cost Estimation
Automate cost predictions for materials, labor, and energy savings, ensuring accurate financial projections.
Investment Simulation
AI generates multiple financial scenarios, offering clear ROI projections for different retrofit measures.
Supplier Comparisons
AI searches and compares suppliers to recommend the most cost-effective and sustainable solutions.
Automated Report Generation
AI automates progress reports, compliance documentation, and data summaries, ensuring accuracy and saving time.
Streamlined Data Analysis
AI processes large datasets, delivering real-time insights on energy use and project performance.
Sustainability-Based Procurement
AI assesses suppliers based on carbon footprint, sustainability certifications, and proximity.
Embodied Carbon Tracking
AI tracks and minimizes the embodied carbon in materials throughout the supply chain.
Local Sourcing
AI recommends locally sourced materials to reduce transportation emissions.
Real-Time Quality Monitoring
AI identifies deviations from quality standards and suggests corrective actions immediately.
Predictive Analytics for Failures
AI forecasts potential material or system failures, allowing proactive maintenance and reducing rework.
Regulatory Compliance
AI ensures adherence to local building codes and sustainability regulations, reducing risks of non-compliance.
Data Ownership and Control
Clear guidelines on data ownership and the sharing of AI-driven insights.
GDPR and Compliance Management
AI helps track compliance with evolving regulations on data privacy and security.
Cybersecurity Protections
Ensure AI systems have robust defense mechanisms against cyberattacks.
Human Oversight in AI Decisions
Ensure humans guide AI-generated insights, using context and emotional intelligence to make final decisions.
Client Interaction
AI assists in technical tasks, while humans maintain client relationships and handle complex negotiations.
Bias Mitigation in AI Systems
Regular audits to identify and mitigate bias in AI decision-making processes.
Data Input Accountability
Humans are responsible for ensuring the accuracy and relevance of data fed into AI systems.
AI-Generated Output Review
Regular human review of AI reports to ensure accuracy, avoiding potential errors caused by unmonitored data processing.
Ethical Use of AI
Establish ethical guidelines on how AI should be used, ensuring that its outputs are aligned with human values and project goals.
OUTCOMES
CARBON REDUCTION
Carbon reduction focuses on minimizing the environmental impact by lowering greenhouse gas emissions. In retrofitting projects, AI facilitates this outcome by optimizing energy systems, materials, and construction processes to reduce both embodied and operational carbon. Through data-driven insights and predictive analytics, AI helps decision-makers choose materials with lower carbon footprints and implement energy-efficient systems, ensuring that carbon reduction targets are met throughout the lifecycle of the building.
ENERGY SAVINGS
Energy savings emphasize optimizing energy consumption by improving operational efficiency. AI plays a critical role by continuously monitoring energy usage in real time, adjusting systems such as HVAC, lighting, and insulation to minimize waste. Predictive analytics and machine learning further refine energy-saving measures by forecasting future energy demands and optimizing system performance. This outcome ensures that buildings operate at peak energy efficiency, reducing operational costs and environmental impact.
PROJECT TIMELINES △
Managing and optimizing project timelines is essential to prevent delays and keep retrofitting projects on track. AI helps streamline project management by automating scheduling, forecasting risks, and sequencing tasks for maximum efficiency. By analyzing real-time project data, AI can anticipate potential delays and suggest corrective actions, ensuring smoother and faster project execution. This outcome translates into quicker project completion, reduced labor costs, and timely achievement of decarbonization goals.
COST SAVINGS △
Cost savings focus on minimizing expenditures while maximizing the financial return on retrofitting projects. AI contributes to this outcome by optimizing procurement strategies, reducing material waste, and streamlining construction processes. Additionally, AI-based systems provide detailed forecasts and budgeting tools to identify the most cost-effective options for materials and energy-efficient solutions. These real-time insights help mitigate financial risks and ensure that retrofitting projects are both economically viable and sustainable.
QUALITY △
Quality in construction management relates to ensuring that retrofitting projects meet high standards in design, construction, and operational performance. AI-driven systems continuously monitor construction quality, detect faults, and assess material durability. Machine learning and advanced control systems help maintain consistency across project phases, improving the overall quality of the retrofitting work. By maintaining stringent quality controls, AI ensures that retrofitted buildings not only meet current regulations but also future-proof their performance, minimizing the need for additional interventions.

Delft University of Technology
HUMAN RESEARCH ETHICS
CHECKLIST FOR HUMAN RESEARCH
(Version January 2022)

IMPORTANT NOTES ON PREPARING THIS CHECKLIST

1. An HREC application should be submitted for every research study that involves human participants (as Research Subjects) carried out by TU Delft researchers
2. Your HREC application should be submitted and approved **before** potential participants are approached to take part in your study
3. All submissions from Master's Students for their research thesis need approval from the relevant Responsible Researcher
4. The Responsible Researcher must indicate their approval of the completeness and quality of the submission by signing and dating this form OR by providing approval to the corresponding researcher via email (included as a PDF with the full HREC submission)
5. There are various aspects of human research compliance which fall outside of the remit of the HREC, but which must be in place to obtain HREC approval. These often require input from internal or external experts such as Faculty Data Stewards, Faculty HSE advisors, the TU Delft Privacy Team or external Medical research partners.
6. You can find detailed guidance on completing your HREC application here
7. Please note that incomplete submissions (whether in terms of documentation or the information provided therein) will be returned for completion **prior to any assessment**
8. If you have any feedback on any aspect of the HREC approval tools and/or process you can leave your comments here

I. Applicant Information

PROJECT TITLE:	AI optimize decarbonization in building retrofitting
Research period: *Over what period of time will this specific part of the research take place*	December 2023 till November 2024
Faculty:	Architecture, Urbanism & Building Sciences
Department:	Management in the Built Environment
Type of the research project: *(Bachelor's, Master's, DreamTeam, PhD, PostDoc, Senior Researcher, Organisational etc.)*	Master's degree
Funder of research: *(EU, NWO, TUD, other – in which case please elaborate)*	The research is supervised by the TU Delft in collaboration with a graduation company; Turner & Townsend Amsterdam. The graduation company pays the student an internship compensation.
Name of Corresponding Researcher: *(If different from the Responsible Researcher)*	P.A. Xu
E-mail Corresponding Researcher: *(If different from the Responsible Researcher)*	p.a.xu@student. tudelft.nl
Position of Corresponding Researcher: *(Masters, DreamTeam, PhD, PostDoc, Assistant/ Associate/ Full Professor)*	-
Name of Responsible Researcher: ***Note:** all student work must have a named Responsible Researcher to approve, sign and submit this application*	Prof.dr.ir. R. (Ruben) Vrijhoef
E-mail of Responsible Researcher: *Please ensure that an institutional email address (**no Gmail, Yahoo, etc.**) is used for all project documentation/ communications including Informed Consent materials*	r.vrijhoef@tudelft.nl
Position of Responsible Researcher : *(PhD, PostDoc, Associate/ Assistant/ Full Professor)*	Researcher

II. Research Overview

NOTE: You can find more guidance on completing this checklist here

a) Please summarise your research very briefly (100-200 words)

What are you looking into, who is involved, how many participants there will be, how they will be recruited and what are they expected to do?

Add your text here – (please avoid jargon and abbrevations)
As part of case studies research, in which 2 cases will be reviewed, 18 participant in total will be selected based on the 2 case studies and relevance project experience. These 18 participants are selected to conduct an interview with and from these individual interviews is expected to share their expertise on one of the case studies based on relevance project experience and expertise background. Furthermore, after the case studies research, there will be 2 expert panels created to use the individual interviews data, processed the findings and implement these into a first prototype of synthesizes. These 2 expert panels (3 participants per expert panel group) is selected from the individual interviews to take part in to the expert panels. This is based on their expertise, participation into another round of interviewing, and mostly on their experience and expertise background to provide feedback and further refinements for the prototype and the formulated synthesizes.

b) **If your application is an additional project** related to an existing approved HREC submission, please provide a brief explanation including the existing relevant HREC submission number/s.

Add your text here – (please avoid jargon and abbrevations)
-

c) **If your application is a simple extension of, or amendment to,** an existing approved HREC submission, you can simply submit an HREC Amendment Form as a submission through LabServant.

III. Risk Assessment and Mitigation Plan

***NOTE:** You can find more guidance on completing this checklist here*

Please complete the following table in full for all points to which your answer is "yes". Bear in mind that the vast majority of projects involving human participants as Research Subjects also involve the collection of **Personally Identifiable Information (PII)** and/or **Personally Identifiable Research Data (PIRD)** which may pose potential risks to participants as detailed in Section G: Data Processing and Privacy below.

To ensure alignment between your risk assessment, data management and what you agree with your Research Subjects you can use the last two columns in the table below to refer to specific points in your Data Management Plan (DMP) and Informed Consent Form (ICF) – **but this is not compulsory**.

It's worth noting that **you're much more likely to need to resubmit your application if you neglect to identify potential risks**, than if you identify a potential risk and demonstrate how you will mitigate it. If necessary, the HREC will always work with you and colleagues in the Privacy Team and Data Management Services to see how, if at all possible, your research can be conducted.

			If YES please complete the Risk Assessment and Mitigation Plan columns below.		*Please provide the relevant reference #*	
ISSUE	**Yes**	**No**	**RISK ASSESSMENT – what risks could arise?** *Please ensure that you list ALL of the actual risks that could potentially arise – do not simply state whether you consider any such risks are important!*	**MITIGATION PLAN – what mitigating steps will you take?** *Please ensure that you summarise what actual mitigation measures you will take for each potential risk identified – do not simply state that you will e.g. comply with regulations.*	**DMP**	**ICF**
A: Partners and collaboration						
1. Will the research be carried out in collaboration with additional organisational partners such as: • One or more collaborating research and/or commercial organisations • Either a research, or a work experience internship provider[1] *[1] If yes, please include the graduation agreement in this application*	Yes		Confidentially breaches: mishandling of sensitive information or proprietary data could lead to legal actions. The research data from projects in the graduation organization (internship).	To ensure that this will not happen no unessary data will be collected, and the personal data will be anonymized after collecting the data (interviews, expert panels, transcripts, case studies). The sensitive data and anonymized data will be primary stored on a secure TU Delft OneDrive and temporary stored at the secured internship network. This will not be shared with third parties until after graduation.	x	
2. Is this research dependent on a Data Transfer or Processing Agreement with a collaborating partner or third party supplier? *If yes please provide a copy of the signed DTA/DPA*						
3. Has this research been approved by another (external) research ethics committee (e.g.: HREC and/or MREC/METC)? *If yes, please provide a copy of the approval (if possible) and summarise any key points in your Risk Management section below*		No				

			If YES please complete the Risk Assessment and Mitigation Plan columns below.		*Please provide the relevant reference #*	
ISSUE	**Yes**	**No**	**RISK ASSESSMENT – what risks could arise?** *Please ensure that you list ALL of the actual risks that could potentially arise – do not simply state whether you consider any such risks are important!*	**MITIGATION PLAN – what mitigating steps will you take?** *Please ensure that you summarise what actual mitigation measures you will take for each potential risk identified – do not simply state that you will e.g. comply with regulations.*	**DMP**	**ICF**
B: Location						
4. Will the research take place in a country or countries, other than the Netherlands, within the EU?		No				
5. Will the research take place in a country or countries outside the EU?		No				
6. Will the research take place in a place/region or of higher risk – including known dangerous locations (in any country) or locations with non-democratic regimes?		No				
C: Participants						
7. Will the study involve participants who **may** be vulnerable and possibly (legally) unable to give informed consent? (e.g., children below the legal age for giving consent, people with learning difficulties, people living in care or nursing homes,).		No				
8. Will the study involve participants who **may** be vulnerable under specific circumstances and in specific contexts, such as victims and witnesses of violence, including domestic violence; sex workers; members of minority groups, refugees, irregular migrants or dissidents?		No				
9. Are the participants, outside the context of the research, in a dependent or subordinate position to the investigator (such as own children, own students or employees of either TU Delft and/or a collaborating partner organisation)? *It is essential that you safeguard against possible adverse consequences of this situation (such as allowing a student's failure to participate to your satisfaction to affect your evaluation of their coursework).*		No				
10. Is there a high possibility of re-identification for your participants? (e.g., do they have a very specialist job of which there are only a small number in a given country, are they members of a small community, or employees from a partner company collaborating in the research? Or are they one of only a handful of (expert) participants in the study?	Yes		There is a possibility of re-identification of the participants (the graduation organization is named in the research final report). But the data collected from the interviews, transcripts or case studies is possible to re-identification if you look deep into the specific case projects in the case studies and who work on the specific project, and have insight knowledge on the list of participants that are interviewed in the internship.	- Participants will be informed on the channels through which the research will be shared. - The audio files will be deleted after the transcribation and the video files (Microsoft Teams recording) will be stored at the secured internship organization network. The transcript will be validated by the participants before publication. - Transcripts will be pseudonomysed. By doing this in the case study projects for the interviews, the participants personal information will not be stored and know outside the project team. This results, that the participants can not be identified.	x	x

			If YES please complete the Risk Assessment and Mitigation Plan columns below.		*Please provide the relevant reference #*	
ISSUE	**Yes**	**No**	**RISK ASSESSMENT – what risks could arise?** *Please ensure that you list ALL of the actual risks that could potentially arise – do not simply state whether you consider any such risks are important!*	**MITIGATION PLAN – what mitigating steps will you take?** *Please ensure that you summarise what actual mitigation measures you will take for each potential risk identified – do not simply state that you will e.g. comply with regulations.*	**DMP**	**ICF**
				- On top of this, participants are warned of such risk before the participants (informed consent form).		
D: Recruiting Participants						
11. Will your participants be recruited through your own, professional, channels such as conference attendance lists, or through specific network/s such as self-help groups	**Yes**		The participants will be recruited though the network of Turner & Townsend Amsterdam (graduation internship organization). This could result in a bias in participation selection. And the research conclusion is difficult to transfer to a different context, because the participants are all within the graduation organization. This could potentially results in generalization. The sample recruited through the network of the internship may not be representative of the broader population, affecting the generalization of research findings.	- Consideration whether the recruitment method aligns with the research objectives, and the intended scope of the study. - Diversity participant recruitment from other organizations, to broaden the sample and reduce the risk of bias.		
12. Will the participants be recruited or accessed in the longer term by a (legal or customary) gatekeeper? (e.g., an adult professional working with children; a community leader or family member who has this customary role – within or outside the EU; the data producer of a long-term cohort study)		**No**				
13. Will you be recruiting your participants through a crowd-sourcing service and/or involve a third party data-gathering service, such as a survey platform?		**No**				
14. Will you be offering any financial, or other, remuneration to participants, and might this induce or bias participation?		**No**				
E: Subject Matter *Research related to medical questions/health may require special attention. See also the website of the CCMO before contacting the HREC.*						
15. Will your research involve any of the following: • Medical research and/or clinical trials • Invasive sampling and/or medical imaging • Medical and *In Vitro Diagnostic Medical* Devices Research		**No**				
16. Will drugs, placebos, or other substances (e.g., drinks, foods, food or drink constituents, dietary supplements) be administered to the study participants? *If yes see here to determine whether medical ethical approval is required*		**No**				

			If YES please complete the Risk Assessment and Mitigation Plan columns below.		*Please provide the relevant reference #*	
ISSUE	**Yes**	**No**	**RISK ASSESSMENT – what risks could arise?** *Please ensure that you list ALL of the actual risks that could potentially arise – do not simply state whether you consider any such risks are important!*	**MITIGATION PLAN – what mitigating steps will you take?** *Please ensure that you summarise what actual mitigation measures you will take for each potential risk identified – do not simply state that you will e.g. comply with regulations.*	**DMP**	**ICF**
17. Will blood or tissue samples be obtained from participants? *If yes see here to determine whether medical ethical approval is required*		**No**				
18. Does the study risk causing psychological stress or anxiety beyond that normally encountered by the participants in their life outside research?		**No**				
19. Will the study involve discussion of personal sensitive data which could put participants at increased legal, financial, reputational, security or other risk? (e.g., financial data, location data, data relating to children or other vulnerable groups) *Definitions of sensitive personal data, and special cases are provided on the TUD Privacy Team website.*		**No**				
20. Will the study involve disclosing commercially or professionally sensitive, or confidential information? (e.g., relating to decision-making processes or business strategies which might, for example, be of interest to competitors)	**Yes**		Participants can share data that have sensitive information of harm their own company or projects, since it could leak their strategies or NDA's on specific projects.	- I will ask them not to share their sensitive information and after pseudonomyzed transcription, the recordings will be deleted. - I will not unessary collect names of companies, projects or individuals, so participants and projects are hard or impossible to identify. The informed consent forms are stored the the TU Delft one drive. - On top of this, participants are warned of suck risk before participation.		
21. Has your study been identified by the TU Delft Privacy Team as requiring a Data Processing Impact Assessment (DPIA)? *If yes please attach the advice/ approval from the Privacy Team to this application*		**No**				
22. Does your research investigate causes or areas of conflict? *If yes please confirm that your fieldwork has been discussed with the appropriate safety/security advisors and approved by your Department/Faculty.*		**No**				
23. Does your research involve observing illegal activities or data processed or provided by authorities responsible for preventing, investigating, detecting or prosecuting criminal offences *If so please confirm that your work has been discussed with the appropriate legal advisors and approved by your Department/Faculty.*		**No**				
F: Research Methods						
24. Will it be necessary for participants to take part in the study without their knowledge and consent at the time? (e.g., covert observation of people in non-public places).		**No**				

			If YES please complete the Risk Assessment and Mitigation Plan columns below.		*Please provide the relevant reference #*	
ISSUE	**Yes**	**No**	**RISK ASSESSMENT – what risks could arise?** ***Please ensure that you list ALL of the actual risks that could potentially arise – do not simply state whether you consider any such risks are important!***	**MITIGATION PLAN – what mitigating steps will you take?** ***Please ensure that you summarise what actual mitigation measures you will take for each potential risk identified – do not simply state that you will e.g. comply with regulations.***	**DMP**	**ICF**
25. Will the study involve actively deceiving the participants? (For example, will participants be deliberately falsely informed, will information be withheld from them or will they be misled in such a way that they are likely to object or show unease when debriefed about the study).		**No**				
26. Is pain or more than mild discomfort likely to result from the study? And/or could your research activity cause an accident involving (non-) participants?		**No**				
27. Will the experiment involve the use of devices that are not 'CE' certified? *Only, if 'yes': continue with the following questions:*		**No**				
• Was the device built in-house?						
• Was it inspected by a safety expert at TU Delft? *If yes, please provide a signed device report*						
• If it was not built in-house and not CE-certified, was it inspected by some other, qualified authority in safety and approved? *If yes, please provide records of the inspection*						
28. Will your research involve face-to-face encounters with your participants and if so how will you assess and address Covid considerations?	**Yes**		The strict Covid regulations have been lifted in The Netherlands. And most of the interviews are done in an digital online interview. The reason is because a lot of participants are flexible with working from home or at office. So a digital form is practical in this situation and linked to the recording on Microsoft Teams.	A digital online meeting could be the solution in this case.		
29. Will your research involve **either:** a) "big data", combined datasets, new data-gathering or new data-merging techniques which might lead to re-identification of your participants **and/or** b) artificial intelligence or algorithm training where, for example biased datasets could lead to biased outcomes?	**Yes, B**		By using ChatGPT, using a subset of AI, Natural Language Processing (NLP) for analyzing and synthesizing interview transcripts and case study results. This could results in: 1. Ethical considerations, potential harms to participants (privacy breaches, discriminatory outcomes) and broader societal impacts (unfair treatments) 2. Research integrity, addressing these concerns ensures the integrity and reliability of research findings.	1. Data anonymization, with personal data will be deleted or pseudonymized before entering the NLP text input into ChatGPT. 2. Raw data will be evaluated before entering it into ChatGPT to us NLP. 3. Ethical AI practices, with fairness of mitigating biases of AI results to implement fairness testing and validation methods. Simply, checking and re-evaluating the synthesizes, the results with human intelligence to validate the data.		

			If YES please complete the Risk Assessment and Mitigation Plan columns below.		*Please provide the relevant reference #*	
ISSUE	**Yes**	**No**	**RISK ASSESSMENT – what risks could arise?** ***Please ensure that you list ALL of the actual risks that could potentially arise – do not simply state whether you consider any such risks are important!***	**MITIGATION PLAN – what mitigating steps will you take?** ***Please ensure that you summarise what actual mitigation measures you will take for each potential risk identified – do not simply state that you will e.g. comply with regulations.***	**DMP**	**ICF**
G: Data Processing and Privacy						
30. Will the research involve collecting, processing and/or storing any directly identifiable PII (Personally Identifiable Information) including name or email address that will be used for administrative purposes only? (eg: obtaining Informed Consent or disbursing remuneration)	**Yes**		The informed consent forms and the transcripts can be linked to eachother when stored in the location.	On the informed consent forms, participants are asked to sign with their name and signature. These forms will be stored in the primary TU Delft OneDrive separately from the interview transcripts, to which only I have access. Also, the numbering of the interview transcripts and the informed consent forms are randomly organized. So linking one of the informed consent forms to one of the many participants interview is an puzzle for extern people.	**x**	**x**
31. Will the research involve collecting, processing and/or storing any directly or indirectly identifiable PIRD (Personally Identifiable Research Data) including videos, pictures, IP address, gender, age etc and **what other Personal Research Data** (including personal or professional views) will you be collecting?	**Yes**		Video and audio recording (MP4 file) could leak and and people face + voice could be recognized. The back-up audio recording (MP3 file) could leak and people voice could be recognized.	The video and audio recording will be deleted after the transcribing the interviews and will be deleted as soon as possible. After the transcripts are approved by the participants, the MP4 file will be deleted. The MP4 will be temporarily stored on the highly secured internship organization network. This is because of the large files and the risk of transferring these files from one network to another. So keeping these recordings on the highly secured network (graduation internship organization) instead of transferring it to my personal work laptop and then uploading it on the TU Delft project drive/one drive is preventing leaking these data These MP4 files will be deleted from the internship network after the transcripts are approved. The back-up audio file MP3 files will be deleted right after the interview take place, when it's validated that the first way of video and audio recording is succeeded.	x	x
32. Will this research involve collecting data from the internet, social media and/or publicly available datasets which have been originally contributed by human participants	Yes		Yes, research papers will form the basis of the thesis. This research starts from a literature study (theoretical research). This could lead to bias in interpreting research from publicly available datasets.	- Comprehensive literature review (wide range of academic sources) - Critical analyses and synthesis on these publicly available datasets. - Awareness of Confirmation bias.		

			If YES please complete the Risk Assessment and Mitigation Plan columns below.		*Please provide the relevant reference #*	
ISSUE	**Yes**	**No**	**RISK ASSESSMENT – what risks could arise?** *Please ensure that you list ALL of the actual risks that could potentially arise – do not simply state whether you consider any such risks are important!*	**MITIGATION PLAN – what mitigating steps will you take?** *Please ensure that you summarise what actual mitigation measures you will take for each potential risk identified – do not simply state that you will e.g. comply with regulations.*	**DMP**	**ICF**
33. Will your research findings be published in one or more forms in the public domain, as e.g., Masters thesis, journal publication, conference presentation or wider public dissemination?	**Yes**		The thesis will be published on the public availaible TU Delft educational repository.	All personal data will be pseudonymized, participants have signed the informed consent forms and approved their transcripts.	x	x
34. Will your research data be archived for re-use and/or teaching in an open, private or semi-open archive?	**Yes**		Same answer as question 33.	Same answer as question 33.	x	x

H: More on Informed Consent and Data Management

__NOTE:__ You can find guidance and templates for preparing your Informed Consent materials) here

Your research involves human participants as Research Subjects if you are recruiting them or actively involving or influencing, manipulating or directing them in any way in your research activities. This means you must seek informed consent and agree/ implement appropriate safeguards regardless of whether you are collecting any PIRD.

Where you are also collecting PIRD, and using Informed Consent as the legal basis for your research, you need to also make sure that your IC materials are clear on any related risks and the mitigating measures you will take – including through responsible data management.

Got a comment on this checklist or the HREC process? You can leave your comments here

IV. Signature/s

Please note that by signing this checklist list as the sole, or Responsible, researcher you are providing approval of the completeness and quality of the submission, as well as confirming alignment between GDPR, Data Management and Informed Consent requirements.

Name of Corresponding Researcher (if different from the Responsible Researcher) (print)
Po Au

Signature of Corresponding Researcher:

Date: 07-07-2024

Name of Responsible Researcher (print)

Signature (or upload consent by mail) Responsible Researcher:

Date:

V. Completing your HREC application

Please use the following list to check that you have provided all relevant documentation

Required:

- **Always:** This completed HREC checklist
- **Always:** A data management plan (reviewed, where necessary, by a data-steward)
- **Usually:** A complete Informed Consent form (including Participant Information) and/or Opening Statement (for online consent)

Please also attach any of the following, if relevant to your research:

Document or approval	Contact/s
Full Research Ethics Application	After the assessment of your initial application **HREC will let you know if and when you need to submit additional information**
Signed, valid Device Report	Your Faculty HSE advisor
Ethics approval from an external Medical Committee	TU Delft Policy Advisor, Medical (Devices) Research
Ethics approval from an external Research Ethics Committee	Please append, if possible, with your submission
Approved Data Transfer or Data Processing Agreement	Your Faculty Data Steward and/or TU Delft Privacy Team
Approved Graduation Agreement	Your Master's thesis supervisor
Data Processing Impact Assessment (DPIA)	TU Delft Privacy Team
Other specific requirement	Please reference/explain in your checklist and append with your submission

Plan Overview

A Data Management Plan created using DMPonline

Title: Master Thesis Po Au Xu: AI optimize decarbonization in building retrofitting

Creator: Po Au Xu

Affiliation: Delft University of Technology

Template: TU Delft Data Management Plan template (2021)

Project abstract:

Current studies, revealed through the literature review, focused on individual areas in bridging the gap between AI technologies and zero-emission buildings within the broader terms of decarbonization. These individual areas typically center on linking AI with various facets such as design and construction processes, energy performance, cost-effectiveness, high-efficiency technical systems, material lifecycle. The existing studies tends to approach these elements as isolated components.

However, it is unclear how to incorporate these isolated components into artificial intelligence for analyzing, identifying, and optimizing decarbonization process as transformative tools while incorporating all environmental quality and cost-effectiveness objectives. The main barriers are the availability of detailed data, insufficient knowledge available in science and practice, and the appropriateness of tools, methods, and guidelines for incorporating artificial intelligence in the zero-emission process. Therefore, there is a lack of insight into the opportunities and challenges in artificial intelligence application to enable and accelerate zero-emission buildings. The intersection of AI methodology and zero-emission building process is explored in this research.

The aim of this research is to provide insight into the development of an AI methodology for zero-emission buildings, especially retrofitting existing buildings, to identify and optimizes. The terms, methodology, and context may vary, but the fundamental principles established can serve as a valuable foundation for the broader integration of AI in diverse building typologies, facilitating advancements toward sustainable and zero-emission buildings in the built environment.

ID: 155329

Start date: 01-12-2023

End date: 01-11-2024

Last modified: 07-07-2024

Master Thesis Po Au Xu: AI optimize decarbonization in building retrofitting

0. Administrative questions

1. Name of data management support staff consulted during the preparation of this plan.

My faculty data steward, Janine Strandberg, has reviewed this DMP on [date].

2. Date of consultation with support staff.

I. Data description and collection or re-use of existing data

3. Provide a general description of the type of data you will be working with, including any re-used data:

Type of data	File format(s)	How will data be collected (for re-used data: source and terms of use)?	Purpose of processing	Storage location	Who will have access to the data
Recorded interviews in which the participant is asked to elaborate on their expertise in their department (AI, retrofit existing buildings, net-zero). Further, their insights about these developments in their position within a project and organization, without naming exact company or project name.	.mp3 (Audio recording on smartphone) .mp4 (Microsoft Teams video recording)	Recorded by an audio recorder on a smartphone and Microsoft Teams video recording on the laptop. These recordings will be deleted after the participant has approved the transcriptions.	To collect data on insights and knowlegde of the participant in the case study projects. In order to answer the subquestions of AI in building retrofit and management practices.	Temporarily stored at the secured internship organization network (secured global network). Preventing transferring the MP4 files from the secured laptop to my personal work laptop. Uploading the MP.4 files on the TU Delft one-drive from the secured internship network. The smartphone audio recording is used as a temporary storage space in case the laptop recording fails. Right after the interview, when it becomes clear that the laptop recording is successful, the MP3 will be deleted from the smartphone.	Student: Po Au Xu - MSc, thesis student. is accessible on the internship organization network (laptop).
Pseudenomysed interview transcripts	.docx	The transcript will be created using mp3 files.	To be able to read, code, and cite the interviewees. To pseudonymize the information/data from the interviews.	Primary stored at the TU Delft one-drive used for this project. Temporarily stored at the TU Delft one-drive used for the project.	Student & Supervisors: Po Au Xu - MSc, thesis student. Ruben Vrijhoef - 1st thesis mentor Aksel Ersoy - 2nd thesis mentor
Recordings of validation session (expert panel)	.mp3 (Audio recording on smartphone) .mp4 (Microsoft Teams video recording)	Recorded by an audio recorder on a smartphone and Microsoft Teams video recording on the laptop. These recordings will be deleted after the participant has approved the transcriptions.	To collect information, data, and feedback on the synthesized outcomes from the case studies (including interviews). This will result in engaging in a discussion, gathering feedback, and refining the research.	Temporarily stored at the secured internship organization network (secured global network). Preventing transferring the MP4 files from the secured laptop to my personal work laptop. Uploading the MP.4 files on the TU Delft one-drive from the secured internship network. The smartphone audio recording is used as a temporary storage space in case the laptop recording fails. Right after the interview, when it becomes clear that the laptop recording is successful, the MP3 will be deleted from the smartphone	Student: Po Au Xu - MSc, thesis student. is accessible on the internship organization network (laptop).
Pseudenomysed transcripts of validation sessions (expert panels)	.docs	The transcript will be created by using the MP4 file.	To be able to read, code, and cite the interviewees. To pseudonymize the information/data from the interviews.	Primary stored at the TU Delft one-drive used for this project.	Student & Supervisors.

4. How much data storage will you require during the project lifetime?

- < 250 GB

II. Documentation and data quality

5. What documentation will accompany data?

- Data will be deposited in a data repository at the end of the project (see section V) and data discoverability and re-usability will be ensured by adhering to the repository’s metadata standards
- Methodology of data collection

III. Storage and backup during research process

6. Where will the data (and code, if applicable) be stored and backed-up during the project lifetime?

- OneDrive
- Another storage system - please explain below, including provided security measures

Secured graduation internship network (Turner & Townsend): The temporary storage of video and audio files of the interviews and expert panels are stored at the highly secured internship organization network (secured laptop, system). This prevents it from transferring the MP4 files from transferring it from private network to my personal worklaptop and then uploading it on the TU Delft OneDrive. This network is highly secured by the internship organization. These MP4 files are deleted as soon as possible when the transcripts are approved by the participants.

For this research project, we'll use the TU Delft OneDrive to store the data for the project. As discussed with the project team (supervisors), the TU Delft OneDrive is sufficient to store the limited data for this research project. The secured internship network is temporarily stored for the video and audio files. The reason for not using project storage at TU Delft is the data collected can hardly damage the participants, is pseudonymized very quickly, and the participants are informed about the entire data collection and management process beforehand. The TU Delft OneDrive will be used for the informed consent forms, interview transcripts (pseudonymized), and expert panel transcripts (pseudonymized).

IV. Legal and ethical requirements, codes of conduct

7. Does your research involve human subjects or 3rd party datasets collected from human participants?

- Yes

People from the global internship organization are sharing data that can be linked to their position or who was interviewed, so the cases, as well as the participant's positions within these projects, will be completely pseudonymised.

8A. Will you work with personal data? (information about an identified or identifiable natural person)

If you are not sure which option to select, first ask your Faculty Data Steward for advice. You can also check with the privacy website . If you would like to contact the privacy team: privacy-tud@tudelft.nl, please bring your DMP.

- Yes

B. Retrofit: optimizing building performance and integration of sustainable solutions						
B.0 Whole lifecycle carbon emission approach						
1. Barriers, opportunities, trade-offs as a whole life carbon impact.	ML assist in identifying barriers, opportunities, and trade-offs related to carbon impact by analyzing large datasets and identifying patterns.	NN models intricate interactions between various factors affecting carbon emissions, such as building materials, energy consumption patterns, transportation logistics, and more. Task as predictive modeling, pattern recognition, and optimization in scenarios where the data is high-dimensional or contains nonlinear relationships.				GA can assist in identifying and addressing challenges and opportunities related to carbon emissions throughout the entire lifecycle of a process. Analyze complex systems and evaluate the trade-offs between different strategies for reducing carbon emissions.
2. Carbon offsets	ML analyze carbon offset project data and recommend appropriate offsetting strategies based on (historical) project requirements and objectives.		DL models can analyze environmental datasets to identify suitable locations and opportunities for carbon offset projects. These models excel in processing complex environmental data, such as land use patterns, biodiversity hotspots, and carbon sequestration potential.			GAs can optimize the selection of carbon offset projects to maximize environmental impact and cost-effectiveness. GAs can identify the most efficient portfolio of offset projects.
B1. Embodied carbon impacts						
1. Building envelope improvements	ML analyzing various factors such as building materials, insulation properties, and climate data to recommend the most effective retrofit solutions.	*COMPLEX PROJECTS:* NNs can utilized where the relationships between building envelope features and energy performance are highly complex or where there are large amounts of data to analyze for finding intricate patterns.		Robotics can automate construction tasks related to building envelope improvements, reducing labor costs and improving efficiency.		GAs can optimize building envelope designs to minimize embodied carbon emissions while meeting performance requirements.
2. Energy effiency measures	Based on the "Energy Audit" in the pre-phase, ML estimate the energy consumption and carbon emissions associated with different building configurations, helping designers make informed decisions to minimize embodied carbon in the application of the applied project.		DL models can simulate complex interactions between different factors in energy effiency and optimize building configurations for minimal embodied carbon.			
	ML algorithms can analyze materials lifecycle data and recommend circular economy strategies to minimize waste and carbon emissions.				NLP can analyze textual data materials specifications and regulations to identify sustainable and circular alternatives and considering factors such as material composition, sourcing practices, and end-of-life considerations.	GA can optimize the selection and use of materials to achieve net-zero and minimize carbon emissions. By exploring the trade-offs between different material choices, lifecycle processes and considerating the potential for reuse, recycling and

18. Does the processing of the personal data result in a high risk to the data subjects?

If the processing of the personal data results in a high risk to the data subjects, it is required to perform a Data Protection Impact Assessment (DPIA). In order to determine if there is a high risk for the data subjects, please check if any of the options below that are applicable to the processing of the personal data during your research (check all that apply).
If two or more of the options listed below apply, you will have to complete the DPIA. Please get in touch with the privacy team: privacy-tud@tudelft.nl to receive support with DPIA.
If only one of the options listed below applies, your project might need a DPIA. Please get in touch with the privacy team: privacy-tud@tudelft.nl to get advice as to whether DPIA is necessary.
If you have any additional comments, please add them in the box below.

- Systematic monitoring

19. Did the privacy team advise you to perform a DPIA?

- No

22. What will happen with personal research data after the end of the research project?

- Anonymised or aggregated data will be shared with others
- Personal research data will be destroyed after the end of the research project

23. How long will (pseudonymised) personal data be stored for?

- 10 years or more, in accordance with the TU Delft Research Data Framework Policy

24. What is the purpose of sharing personal data?

- For research purposes, which are in-line with the original research purpose for which data have been collected

25. Will your study participants be asked for their consent for data sharing?

- Yes, in consent form - please explain below what you will do with data from participants who did not consent to data sharing

If the participants do not consent to data sharing, this data will not be stored or processed.

V. Data sharing and long-term preservation

27. Apart from personal data mentioned in question 22, will any other data be publicly shared?

- All other non-personal data (and code) produced in the project

Appendix 6: AI Retrofit Process Integration (Hypothesis and initial phase, study work)

Net Zero Carbon Retrofit phases						
A. Pre-retrofit: planning and assessment of decarbonisation process						
1. Assessment and benchmarking	ML data-driven insights to enhance assessment and benchmarking by historical data and identifying patterns for comparison. ML models can enable more informed decisions during the assessment phase.	NNs can process complex and large datasets of building performance metrics to automatically identify and extract the most relevant features from historical data, potentially improving the accuracy and efficiency of the benchmarking process.				
2. Design and planning	ML generates optimized design solutions by learning from past projects and predicting alternative configurations' performance		DL identifies energy-efficient features and recommends design improvements from building design data.			GA iteratively evolve design solutions to meet predefined criteria and constraints, maximizing efficiency and project objectives
3. Energy audit	ML analyze energy consumption patterns and identify opportunities for effiency improvements.					
4. Life Cycle Analysis (LCA) and Carbon offsetting	ML involves analyzing extensive environmental datasets to assess the impact of various carbon offset strategies and enhance their effectiveness	NNs excel in discerning intricate patterns and relationships within LCA datasets. This capability is particularly beneficial when analyzing complex interdependencies between different lifecycle stages and environmental impacts, allowing for a more comprehensive understanding of the system.				GA optimize parameters and decisions in conducting Life Cycle Analysis (LCA) studies. They identify solutions and trade-offs between environmental impacts and performance criteria.
5. Building Information Management (BIM)	ML facilitates data integration and analysis to improve collaboration and decision-making throughout the retrofit process. A foundation for more advanced analyses.	NNs can analyze BIM data to identify potential clashes or conflicts in building designs. Additionally NNs, are suitable for simpler tasks like prediction or classification, offering efficient solutions for common challenges in BIM.	DL models specialize in analyzing 3D BIM models to identify energy-efficient design features and suggest optimizations. Their ability to handle complex data structures and extract nuanced insights makes them particularly beneficial for more sophisticated analyses and optimization tasks within BIM.			
6. Business case & cost estimation (stakeholders)	ML algorithms can analyze historical project data to estimate costs and risks associated with different retrofitting options.	*COMPLEX PROJECTS*: NNs specialize in predicting project costs or revenue streams based on a wide range of input variables, including qualitative and quantitative factors. Additionally, NNs can be applied for time-series forecasting for estimating future costs or revenues based on historical trends and external factors.			NLP can analyze stakeholder input and project requirements to generate comprehensive business cases and cost estimates. The stakeholder needs, project objectives, and constraints, synthesizing this information into detailed documentation for decision-making.	
B. Retrofit: optimizing building performance and integration of sustainable solutions						
B.0 Whole lifecycle carbon emission approach						
1. Barriers, opportunities, trade-offs as a whole life carbon impact.	ML assist in identifying barriers, opportunities, and trade-offs related to carbon impact by analyzing large datasets and identifying patterns.	NN models intricate interactions between various factors affecting carbon emissions, such as building materials, energy consumption patterns, transportation logistics, and more. Task as predictive modeling, pattern recognition, and optimization in scenarios where the data is high-dimensional or contains nonlinear relationships.				GA can assist in identifying and addressing challenges and opportunities related to carbon emissions throughout the entire lifecycle of a process. Analyze complex systems and evaluate the trade-offs between different strategies for reducing carbon emissions.
2. Carbon offsets	ML analyze carbon offset project data and recommend appropriate offsetting strategies based on (historical) project requirements and objectives.		DL models can analyze environmental datasets to identify suitable locations and opportunities for carbon offset projects. These models excel in processing complex environmental data, such as land use patterns, biodiversity hotspots, and carbon sequestration potential.			GAs can optimize the selection of carbon offset projects to maximize environmental impact and cost-effectiveness. GAs can identify the most efficient portfolio of offset projects.

B1. Embodied carbon impacts						
1. Building envelope improvements	ML analyzing various factors such as building materials, insulation properties, and climate data to recommend the most effective retrofit solutions.	*COMPLEX PROJECTS:* NNs can utilized where the relationships between building envelope features and energy performance are highly complex or where there are large amounts of data to analyze for finding intricate patterns.		Robotics can automate construction tasks related to building envelope improvements, reducing labor costs and improving efficiency.		GAs can optimize building envelope designs to minimize embodied carbon emissions while meeting performance requirements.
2. Energy effiency measures	Based on the "Energy Audit" in the pre-phase, ML estimate the energy consumption and carbon emissions associated with different building configurations, helping designers make informed decisions to minimize embodied carbon in the application of the applied project.		DL models can simulate complex interactions between different factors in energy effiency and optimize building configurations for minimal embodied carbon.			
3. Materials and circular alternatives	ML algorithms can analyze materials lifecycle data and recommend circular economy strategies to minimize waste and carbon emissions.				NLP can analyze textual data materials specifications and regulations to identify sustainable and circular alternatives and considering factors such as material composition, sourcing practices, and end-of-life considerations.	GA can optimize the selection and use of materials to achieve net-zero and minimize carbon emissions. By exploring the trade-offs between different material choices, lifecycle processes and considerating the potential for reuse, recycling and remanufacturing.
4. Waste reduction and recycling	ML analyse waste management processes, predict waste generation rates, and identify opportunities for recycling and repurposing materials.			Robotics can automate sorting and recycling processes on construction sites, improving efficiency and reducing waste sent to landfills.		
B2. Operational carbon targets						
1. Energy effiency measures	ML-driven analyze and simulation models can simulate building energy performance under different scenarios, allowing designers to evaluate the impact of energy efficiency measures on operational carbon emissions and energy effience measures in the embodied carbon emission as a whole life carbon. .		DL models can by enabling accurate prediction, proactive fault detection, adaptive control, personalized energy management, and optimized building design.			
2. Renewable energy integration	ML analyze weather patterns, energy demand, and system performance data to optimize the operation of renewable energy systems, maximize energy generation, and minimize reliance on fossil fuels to zero.					GAs can optimize the placement and sizing of renewable energy systems to maximize energy generation and minimize carbon emissions.
3. Smart building technologies	ML analyze building automation and control systems. To optimize occupant comfort, energy effiency, and overall building performance.		DL-based models can recommend adaptive control strategies to optimize energy efficiency and reduce carbon impacts by learning from historical data and adapting to changing environmental conditions in real-time.		NLP techniques can analyze building automation data, maintenance logs, and occupant feedback to understand building performance issues and recommend smart building technologies.	
4. Monitoring and performance tracking	ML algorithms can perform real-time monitoring of building systems and performance metrics by analyzing streaming data from sensors and IoT devices. Predict equipment failures, and optimize maintenance schedules.		DL-based predictive models inform proactive maintenance and optimization strategies by anticipating equipment degradation, energy consumption trends, and building system efficiency over time.	Robotics can automate data collection tasks for monitoring building performance, improving accuracy and efficiency.	NLP analyzing textual data, automating reporting and documentation, integrating unstructured data with analytics, and facilitating human-machine interaction during the operational building energy usage and system performance phase.	

C. Post-retrofit: maintenance and End-of-Life						
1. Monitoring and performance management	ML analyze real-time data from building systems and equipment. Detecing anomalies and predicting potential failures, proactive maintenance and efficient resource allocation to prolong the lifespan.		DL models can analyze sensor data from building systems and predict future performance	Robotics streamlines data collection processes, allowing for more frequent monitoring and timely detection of performance issues.	NLP techniques analyze textual data, such as maintenance reports and performance logs, to extract insights and facilitate decision-making. This process involves not only tracking energy usage and system performance but also actively managing maintenance schedules, identifying potential issues, and optimizing building operations to ensure continued efficiency and sustainability over the building's lifecycle	
2. Demolition, disposal, or recycle	ML analyzing data on material composition, recycling capabilities, and environmental regulations.			Robotics can streamlines the demolition and recycling workflow, accelerating the sorting and recovery of valuable materials while minimizing manual labor and environmental impact.		GAs analyze various disposal and recycling options to determine the most cost-effective and environmentally sustainable strategies for decommissioning retrofitted/new buildings. GA optimizes factors such as transportation costs, recycling facility availability, market prices for recycled materials, and environmental impact assessments.