ARTIFICIAL INTELLIGENCE IN BUILDING RETROFITTING

DEFICIENCIES, CAPABILITIES AND STRATEGIES

MSc Thesis P5
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Management in the Built Environment

TU Delft
Turner & Townsend

Introduction

Problem statement

THE BUILT ENVIRONMENT

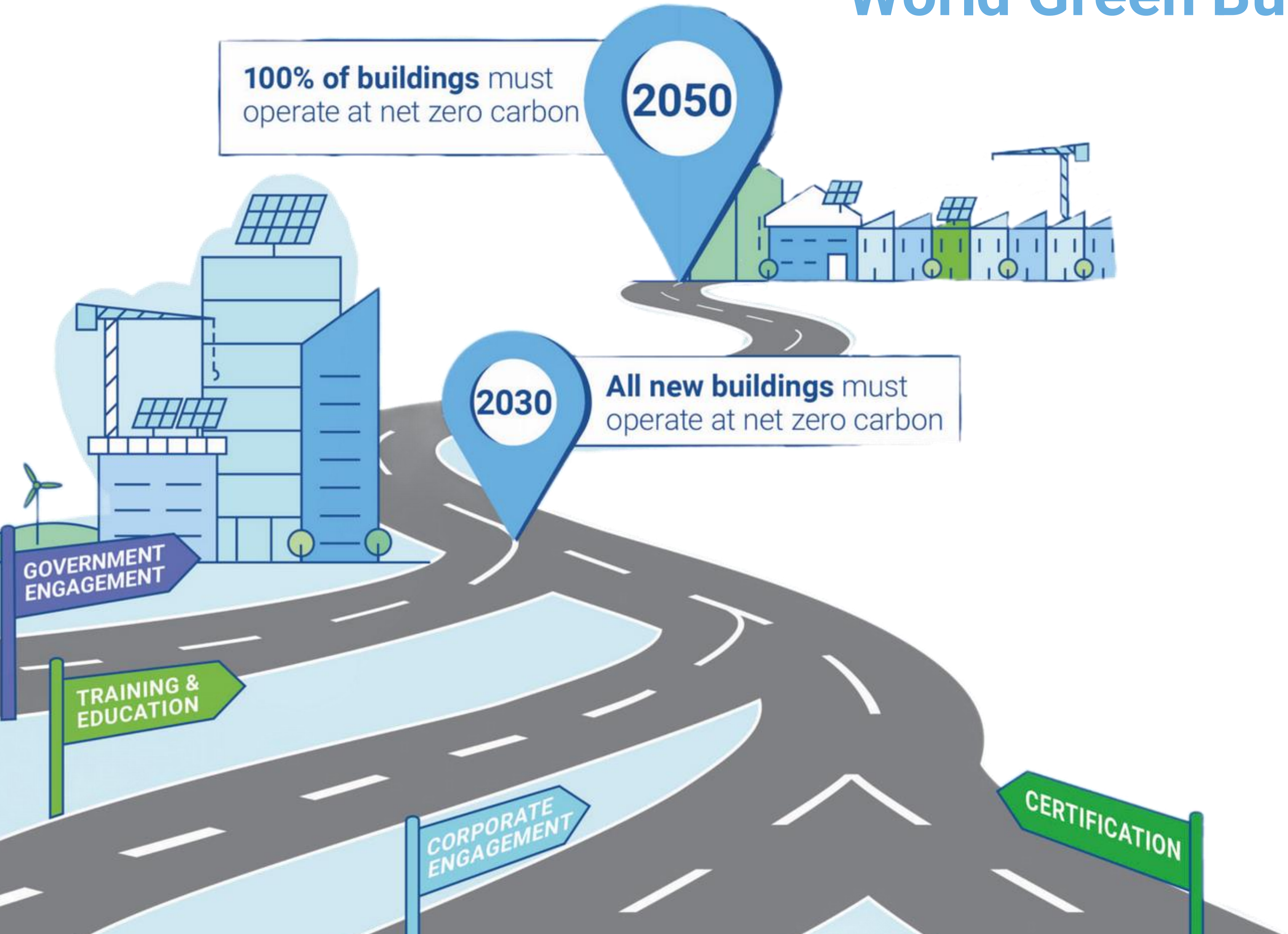
40%

global energy and GHG emissions

IEA, 2021
Janda et al., 2021
Boland et al.,2022
Ohene et al., 2022

Problem statement

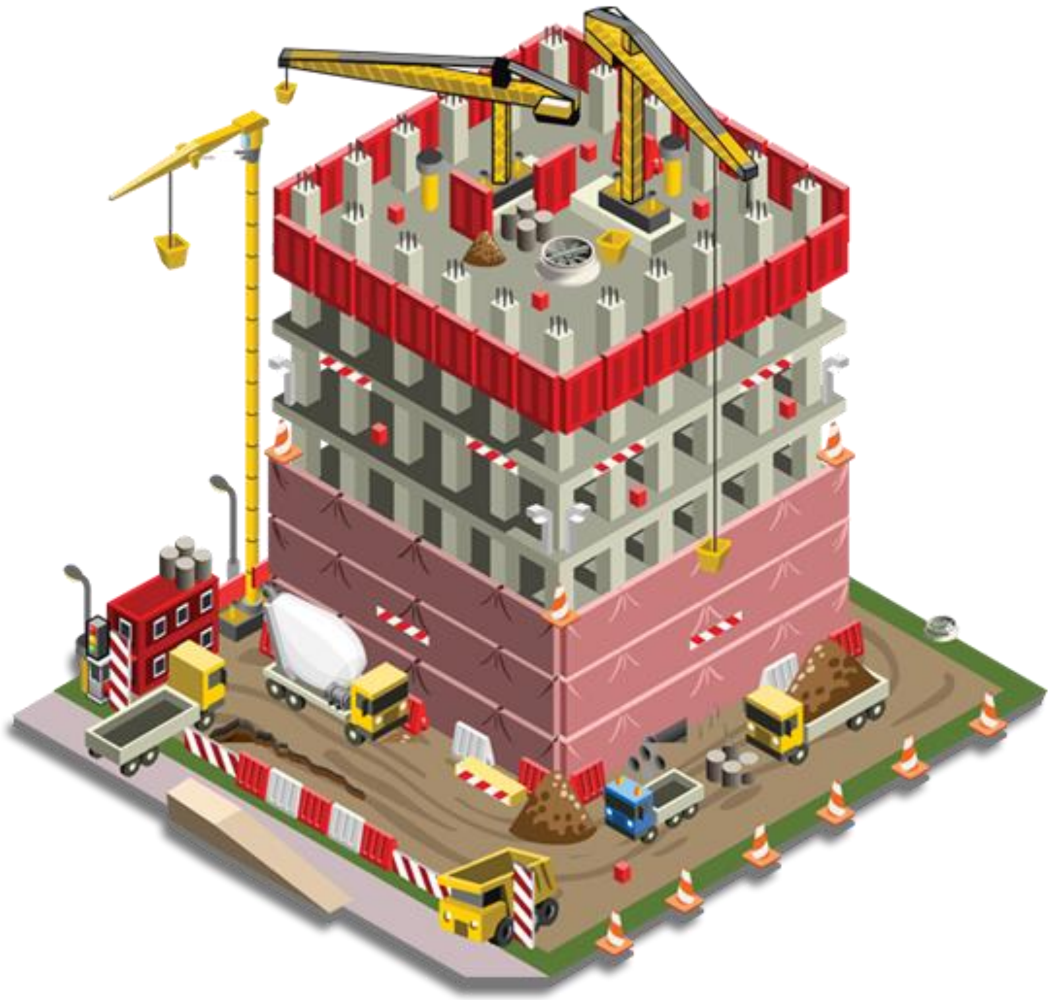
World Green Building Council



United Nations, n.d
Attia, 2018
World Green Building Council, 2022
Petkov et al., 2023

Problem statement

New building

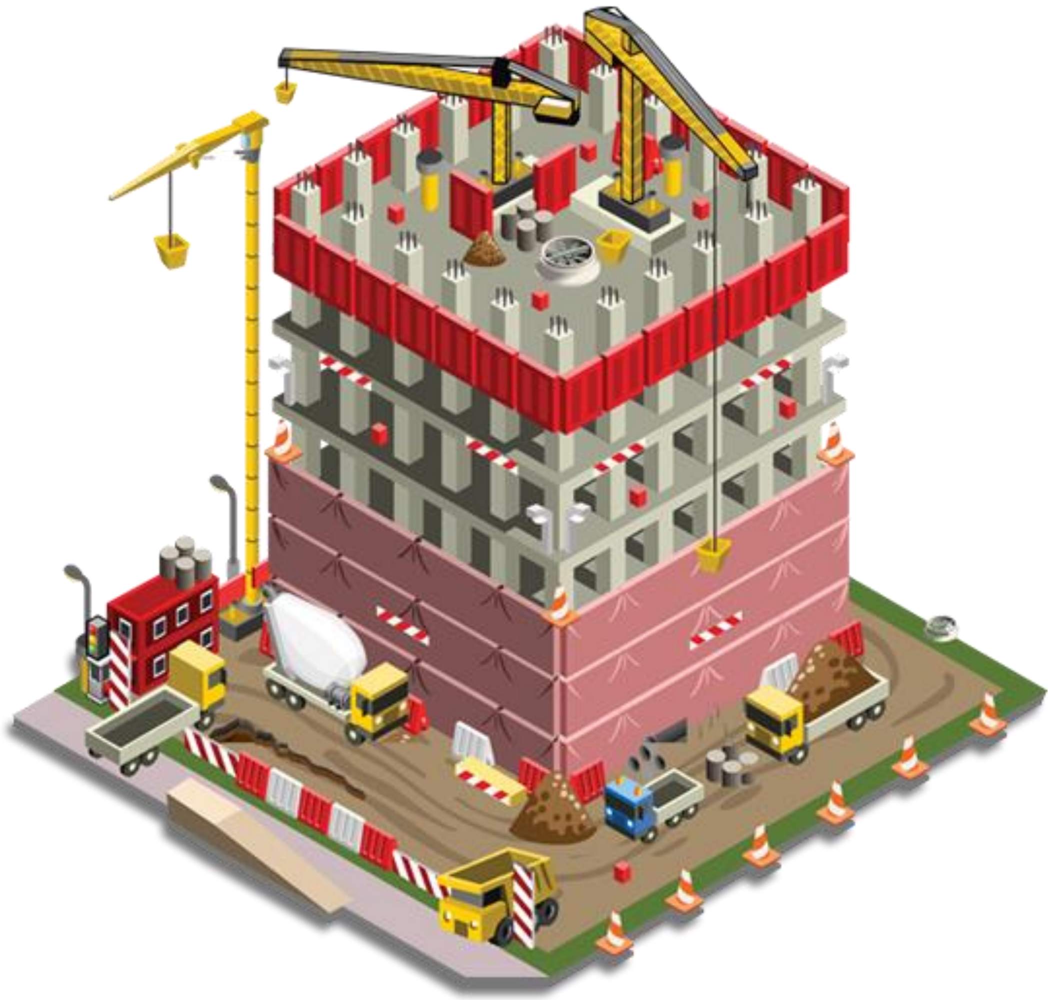


Existing building

Max Fordham LLP, n.d
Ruparathna et al. 2016
IEA, 2022.
Petkov et al., 2023

Problem statement

New building



Existing building

Max Fordham LLP, n.d
Ruparathna et al. 2016
IEA, 2022.
Petkov et al., 2023

Problem statement

what’s new…?


AI

Artificial Intelligence (AI)

emerges as a transformative force

Mora-Esperanza, 2004
Conway, 2018
Viriato, 2019
Abioye et al., 2021
Tekouabou et al. 2023

Main research question

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?

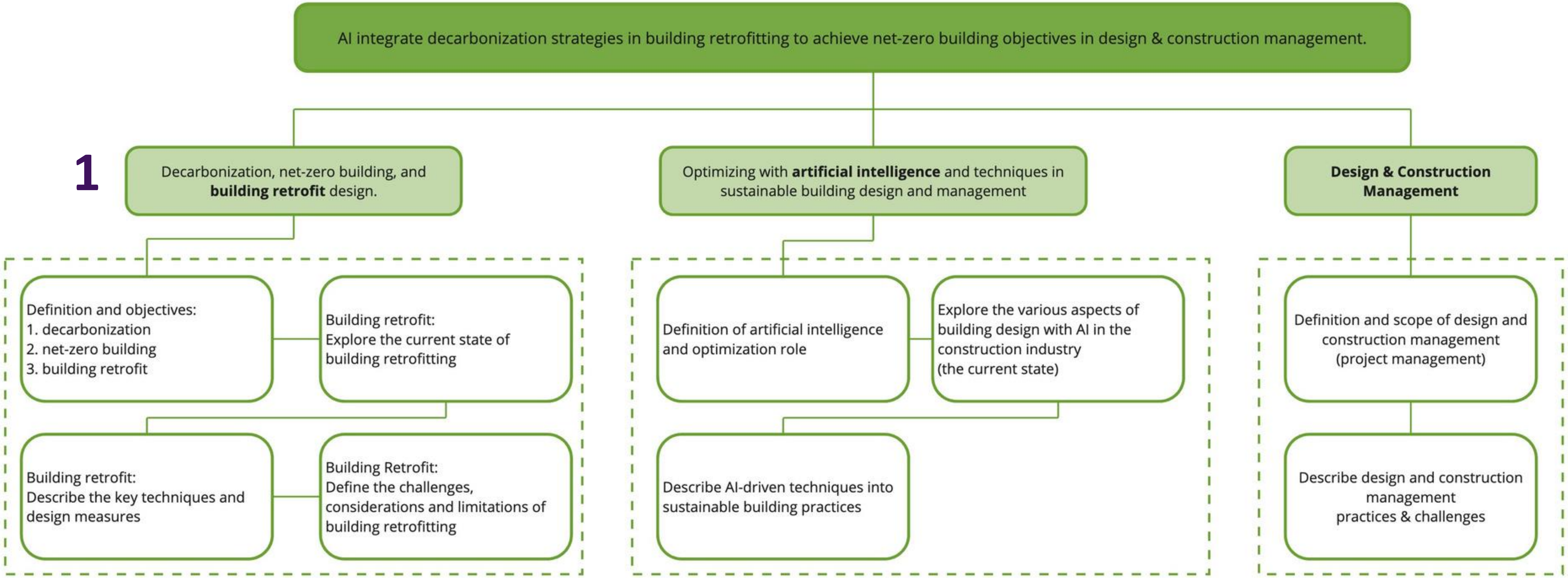
2. What is the current state of AI-driven techniques in sustainable building design?

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

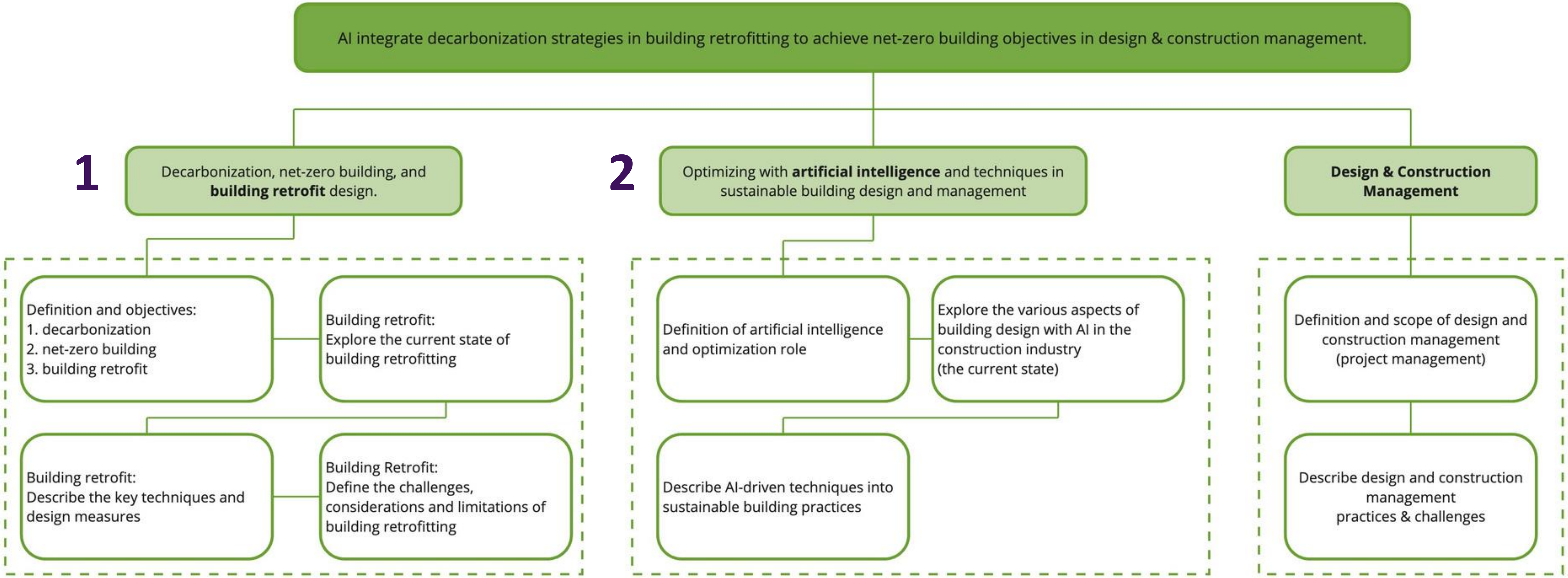
4. How can design and construction management utilize AI in decarbonization strategies?

Theoretical research

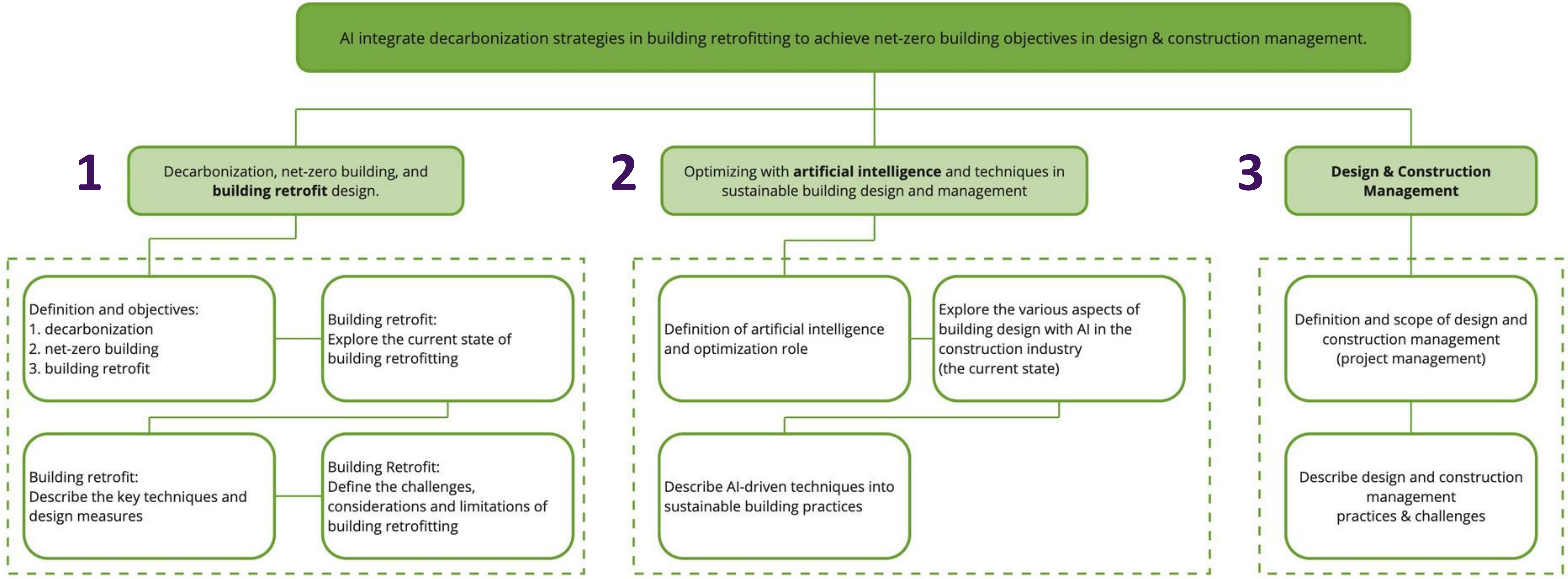
Literature topics



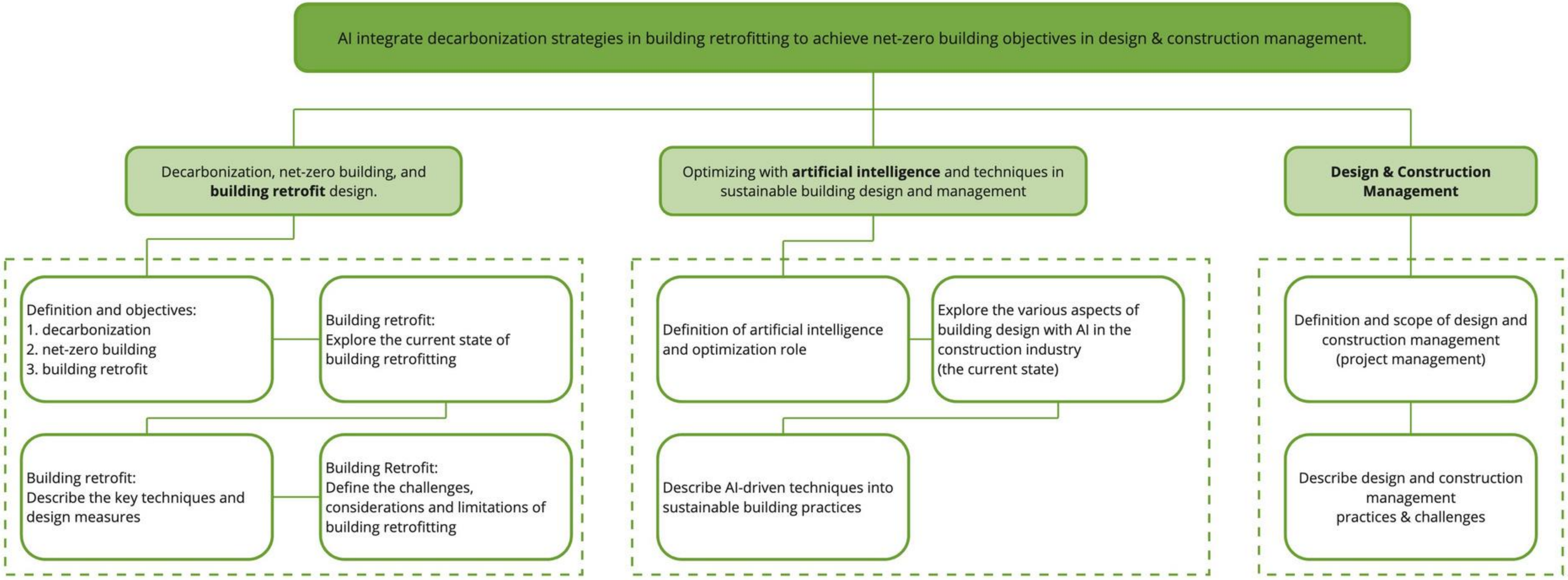
Literature topics



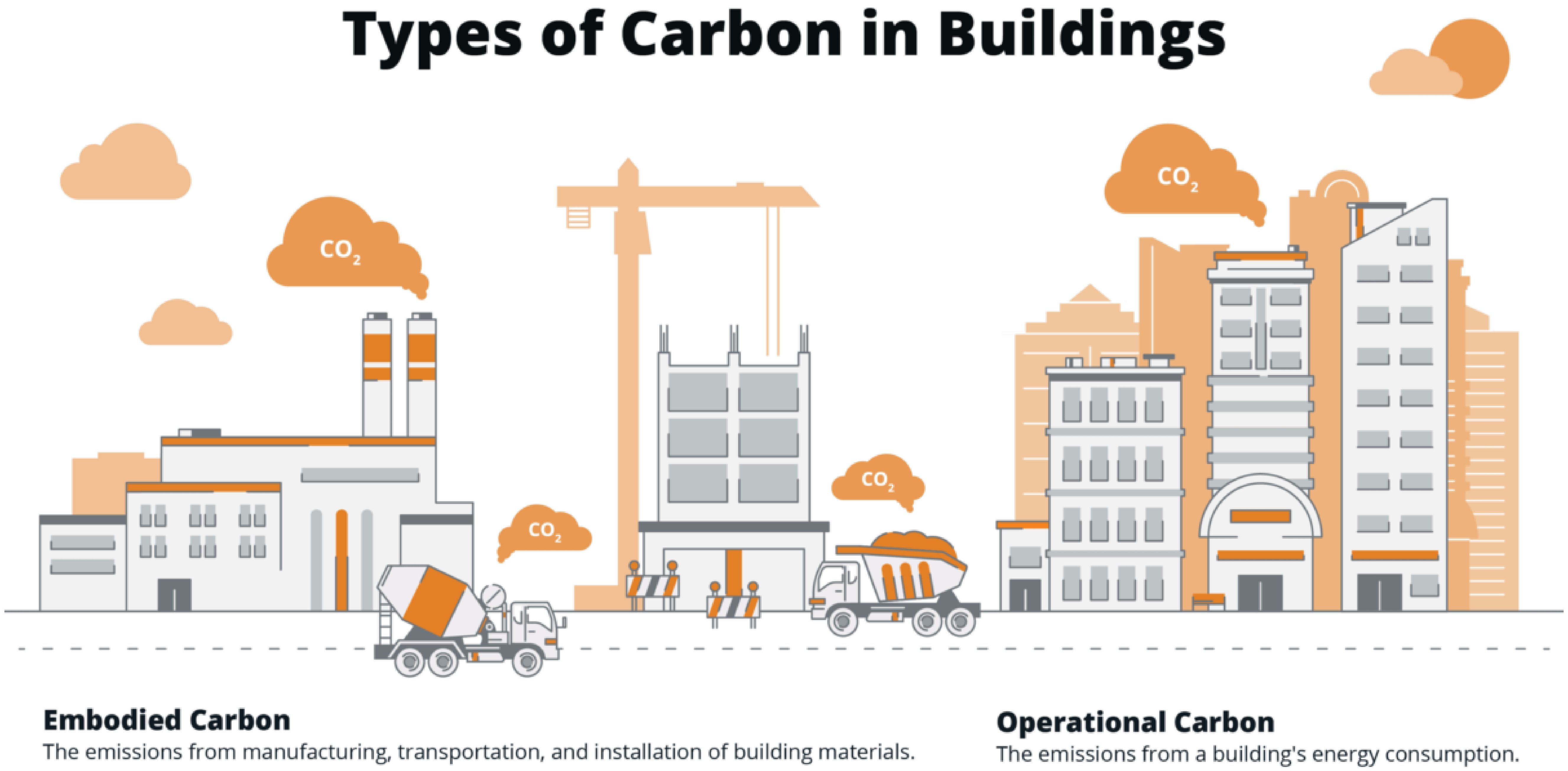
Literature topics



Literature topics



Decarbonization to Net Zero



UK Green Building Council, 2019
Marin et al., 2024; Pastore et al., 2023
World Green Building Council, 2024
Hill et al., n.d

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.

Building retrofitting

Energy efficiency improvements

Operation carbon reduction

Embodied carbon reduction

Renewable energy integration

Smart building technologies

Water efficiency measures

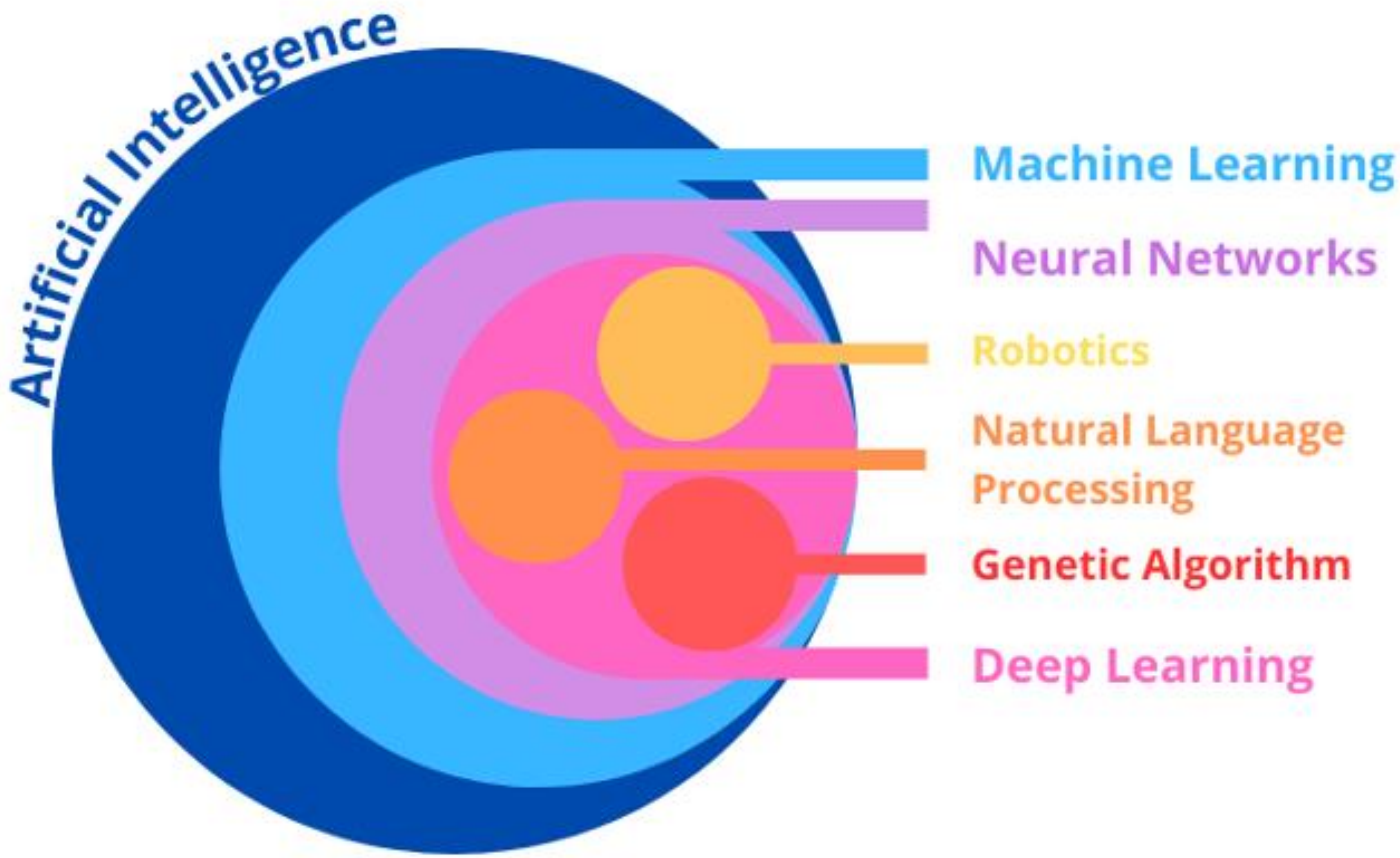
Building Council, 2022
UK Green Building Council, 2022
Hassan et al., 2023
Hill et al., n.d

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.

Artificial Intelligence



Atske, 2022
Hassan et al., 2023
Smolic, 2023
Rocha et al., 2024
Keserer, 2024

Artificial Intelligence

data-driven decision-making	Machine Learning
mimic human brain function	Neural Networks
involves physical automation	Robotics
facilitates language understanding	Natural Language Processing
optimization problems through evolutionary principles	Genetic Algorithm
(complex) data-driven decision-making	Deep Learning

Conway, 2018
Viriato, 2019
Smolic, 2023
Giudici et al., 2024
Keserer, 2024

Artificial Intelligence

Machine Learning

Neural Networks

Robotics

Natural Language Processing

Genetic Algorithm

Deep Learning

Techniques in Sustainable Building Design and Management

- **Design**
- **Building Energy Performance**
- **Automation and Robots**
- **Smart Buildings**
- **Material Database**

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

Conway, 2018
Viriato, 2019
Smolic, 2023
Giudici et al., 2024
Keserer, 2024

AI - Retrofit Technique Table

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.	

Turrin et al., 2011
Begg & Hassan, 2006
Häkkinen et al. 2015
Nagy et al., 2017
Hamidavi et al., 2018
Delgado et al., 2019
Viriato, 2019
Roberts et al. 2020
Von Platten et al., 2020
Abioye et al., 2021
Farzaneh et al., 2021
Adel et al., 2022
Son et al., 2023
Mousavi et al., 2023
Naeem et al., 2023
Tekouabou et al., 2023
Hassan et al., 2023
Monika, 2023
Seagraves, 2023
Rodríguez-Gracia et al., 2023

AI - Retrofit Technique Table

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						
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.	

Turrin et al., 2011
Begg & Hassan, 2006
Häkkinen et al. 2015
Nagy et al., 2017
Hamidavi et al., 2018
Delgado et al., 2019
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Hassan et al., 2023
Monika, 2023
Seagraves, 2023
Rodríguez-Gracia et al., 2023

Hypothesis 3

“AI (subsets) can reduce operational carbon emissions by optimizing energy efficiency.”

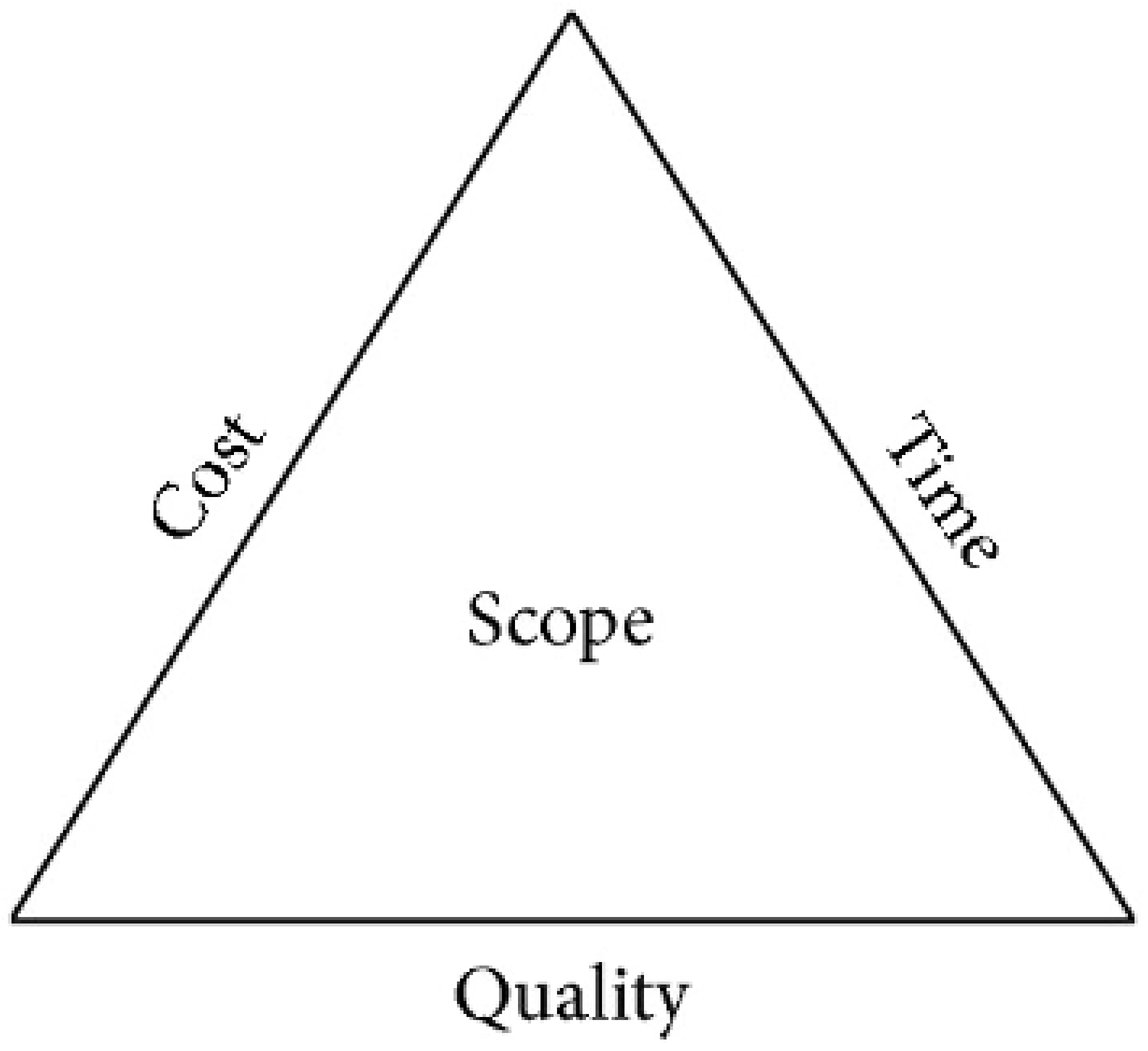
The ability of AI subsets to evaluate building performance in real-time enables precise predictions and adjustments. AI can ensure energy is used efficiently, minimizing waste and reducing operational carbon emissions.

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.

Context: Design and Construction Management (DCM)



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 resource

- Early Design Decision-making
- Project Planning and Scheduling
- Cost Estimation and Budgeting
- Risk Management and Safety

Vahidi & Greenwood, 2009
Silvius et al., 2012
Parsamehr et al., 2022
Shah et al., 2023
Russell et al., 2024
Advances in Construction and Project Management, n.d.

Hypothesis 5

“AI can optimize data-driven insights, enhance accuracy, and reduce human error in design and construction management practices.”

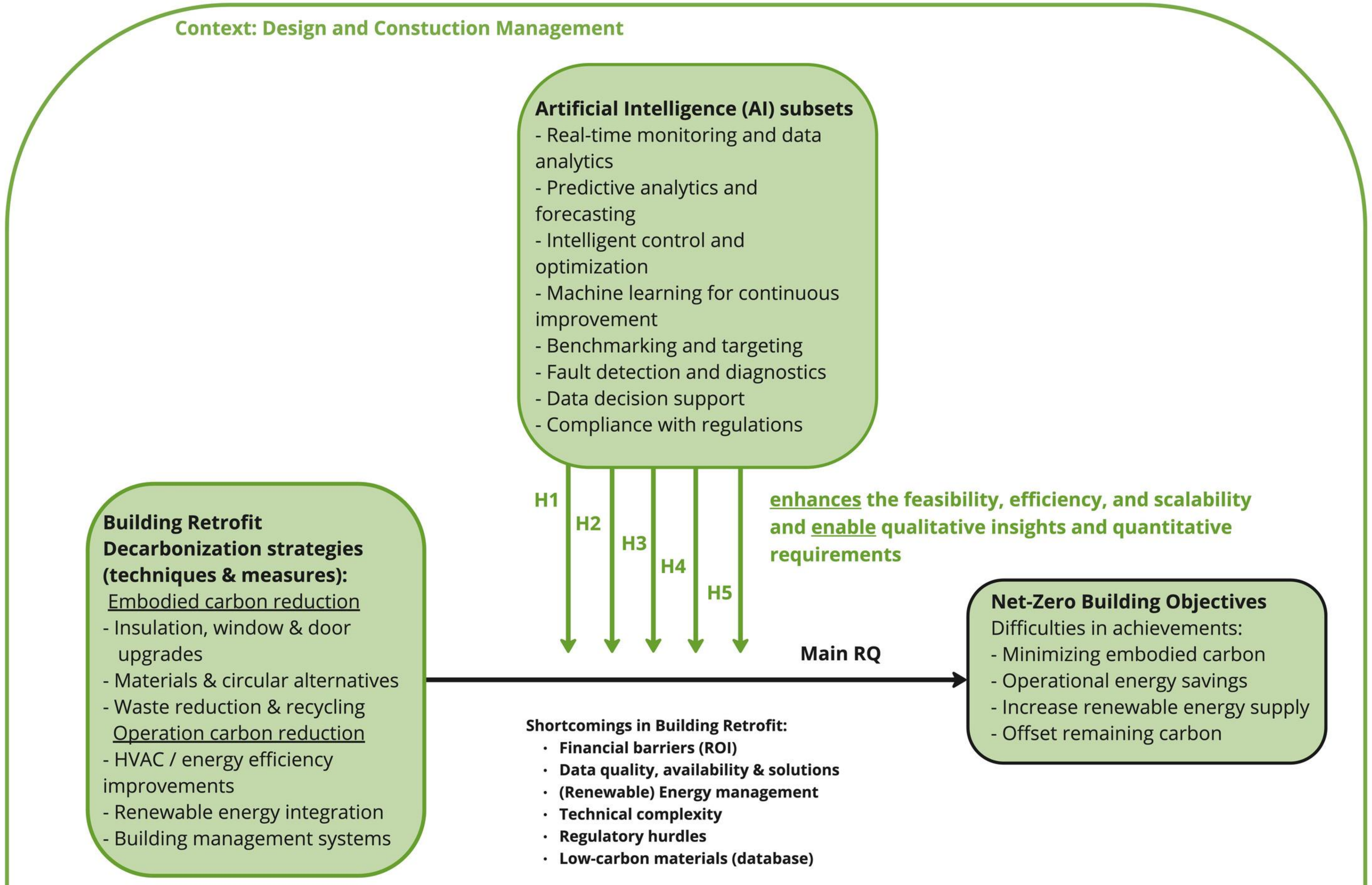
AI can transform traditional design and construction management practices by providing data-driven insights, improving decision-making, and minimizing human error. In conventional processes, managing vast amounts of data and ensuring accuracy is challenging and prone to mistakes. With AI, these tasks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

5 Research Hypothesis

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 research identifies a gap in traditional decarbonization strategies for building retrofitting, which often fail to fully optimize energy efficiency and minimize embodied carbon. Integrating AI-driven technologies offers a solution to these limitations, enabling data-driven decision-making, predictive insights, and real-time adjustments to achieve net-zero building objectives.

Conceptual model



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

Hypotheses:
1. AI can optimize data-driven integration 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.

main research questions

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?

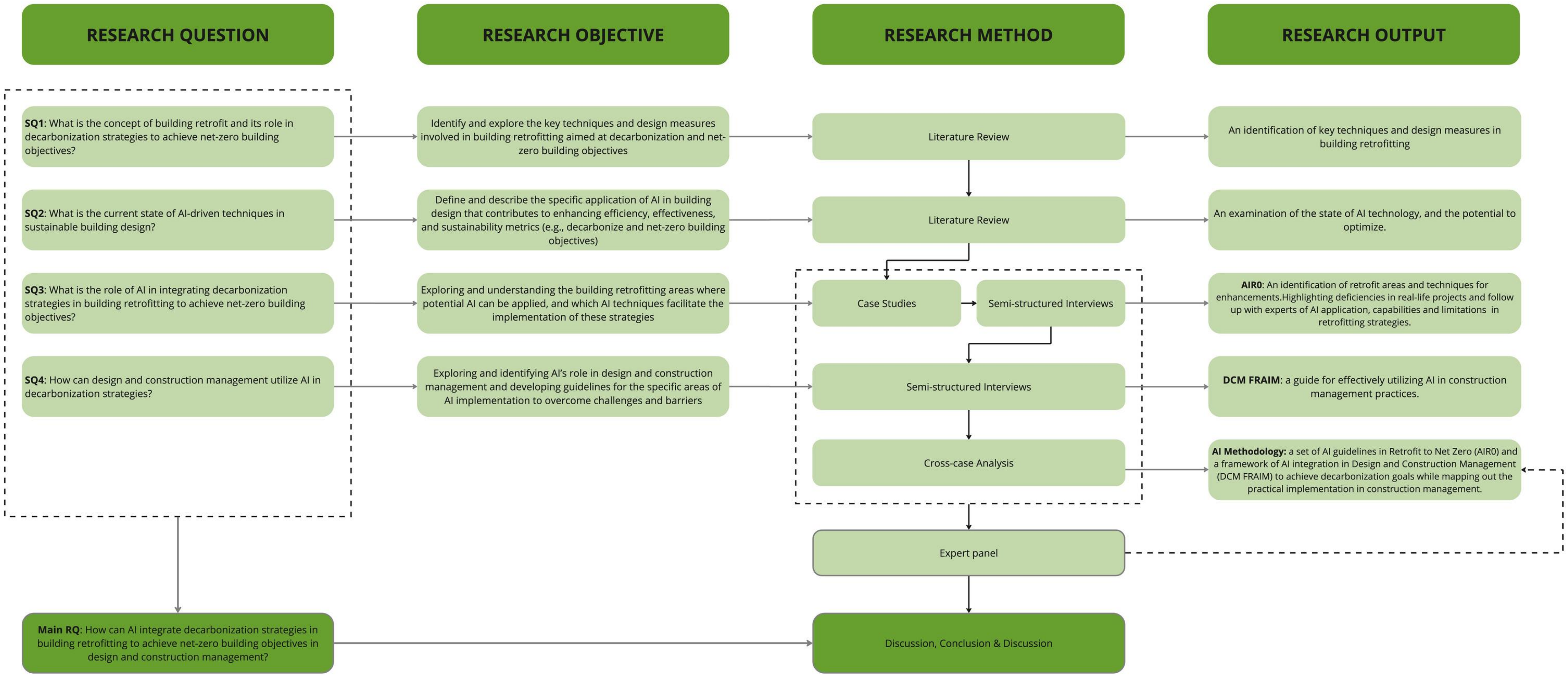
2. What is the current state of AI-driven techniques in sustainable building design?

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?

Research design & method

Methods and Instruments



Case study

2 case study: Building Retrofit Deficiencies
10 documents and 5 semi-structured interviews)

Case selection 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).

Semi-structured interviews

13 one-on-one interviews

Selection criteria:
1.Expertise in AI or digitalization and/or;

2.Expertise in retrofit/net zero building and/or;

3. In Design and Construction Management firm.

Closed coding (ATLAS.ti) for Case Studies

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

Closed coding (ATLAS.ti) for One-on-one Interviews

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

Empirical research

SQ3: What is the role of AI in decarbonization strategies to achieve net-zero building objectives?

SQ3: What is the role of AI in decarbonization strategies to achieve net-zero building objectives?

Chapter 4: Case Studies

Analysis of two retrofit projects: Hotels and Campus Buildings.

Identifying deficiencies and challenges in achieving net-zero objectives.

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Retrofit Deficiencies

Chapter 5: Experts Interviews

What Experts Believe AI Can Realistically Do

What Experts Believe AI Cannot Yet Do

What Needs to Change for AI to Succeed

=

8 AI Capabilities

Chapter 6: Cross-case analysis

Chapter 4 <=> Chapter 5

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AI Strategies in Retrofit Application

Chapter 4: Case Study Projects

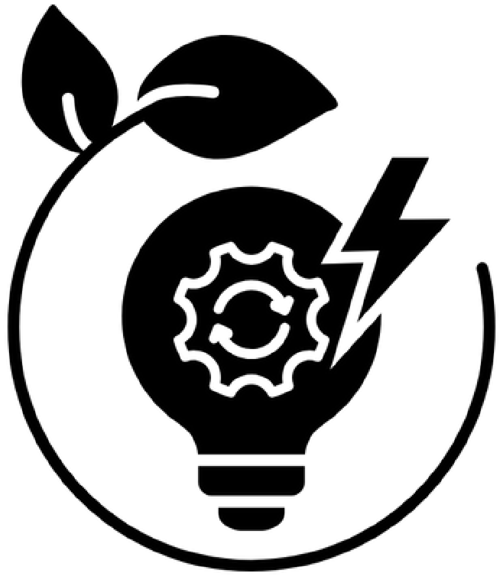
Project 1: Hotel Buildings Decarbonization

Focus: Four hotels across Europe (Spain, Italy, Netherlands).
Objective: Achieve A+ energy labels and BREEAM ‘Very Good’ certifications.
Challenges: High carbon footprints, limited renewable energy integration.

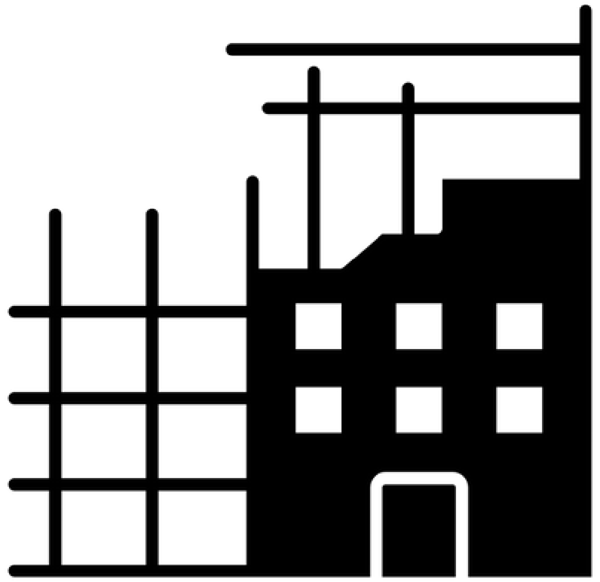
Project 2: Campus Buildings Decarbonization

Scope: Seven interconnected buildings (office, lab, data centers).
Target: Carbon neutrality by 2030.
Challenges: Aging infrastructure, shared energy systems, lack of metering.

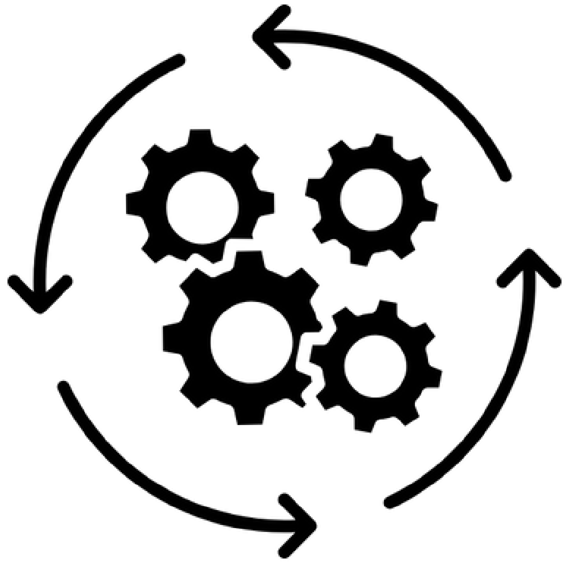
Chapter 4: Key Challenges Identified



Energy Efficiency & Installations

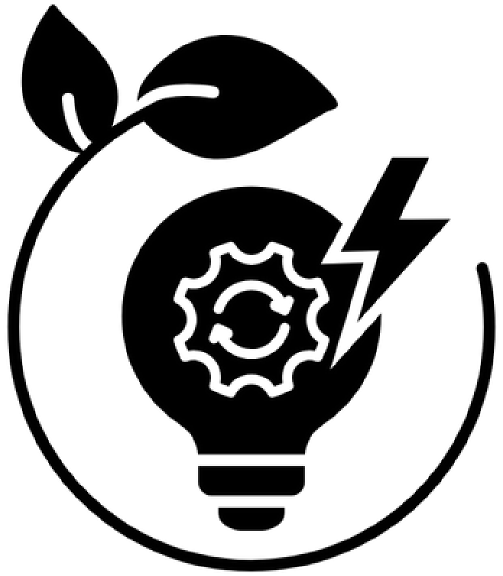


Building Envelope



Operational Deficiencies

Chapter 4: Key Challenges Identified

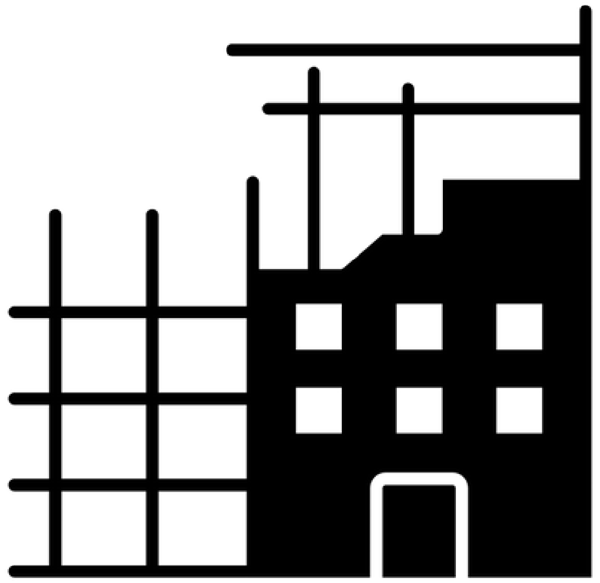


Issues with renewable energy procurement and outdated systems.

Barriers to heat pumps and sub-metering due to costs and shared energy systems.

Energy Efficiency & Installations

Chapter 4: Key Challenges Identified

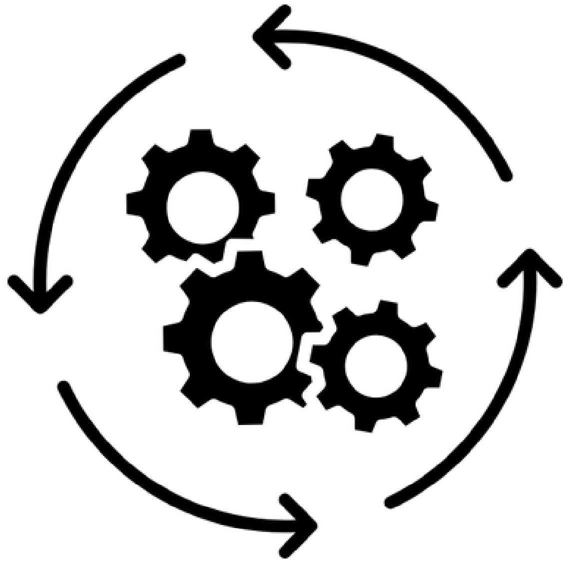


Building Envelope

Minimal insulation in older buildings.

Limited data on structural conditions.

Chapter 4: Key Challenges Identified



Incomplete or outdated data (e.g., post-COVID anomalies).

Over-reliance on assumptions.

Operational Deficiencies

Chapter 4: Summary of Deficiencies in Retrofit (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.

Chapter 5: AI Insights from Interviews

Benchmarking & Targeting.

Predictive Analytics.

Real-Time Monitoring.

Data Decision Support.

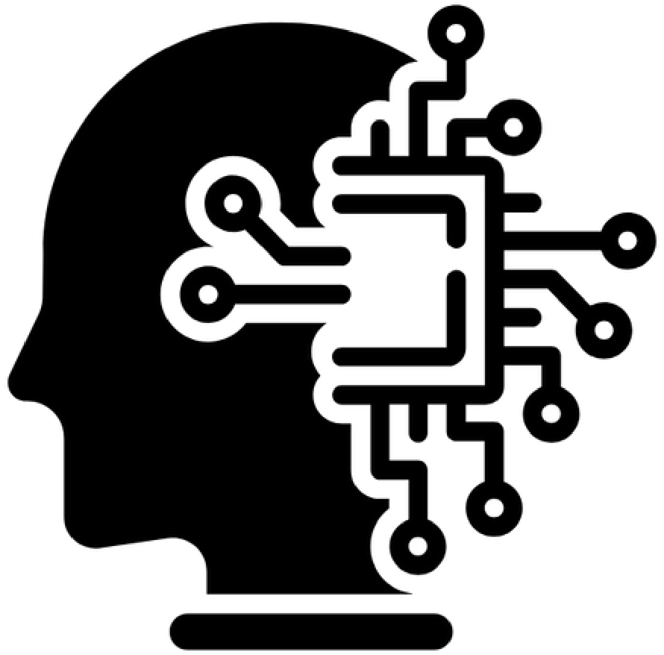
Compliance with Regulations.

Fault Detection.

Intelligent Optimization.

Continuous Learning.

Chapter 5: AI Insights from Interviews



AI Can Do

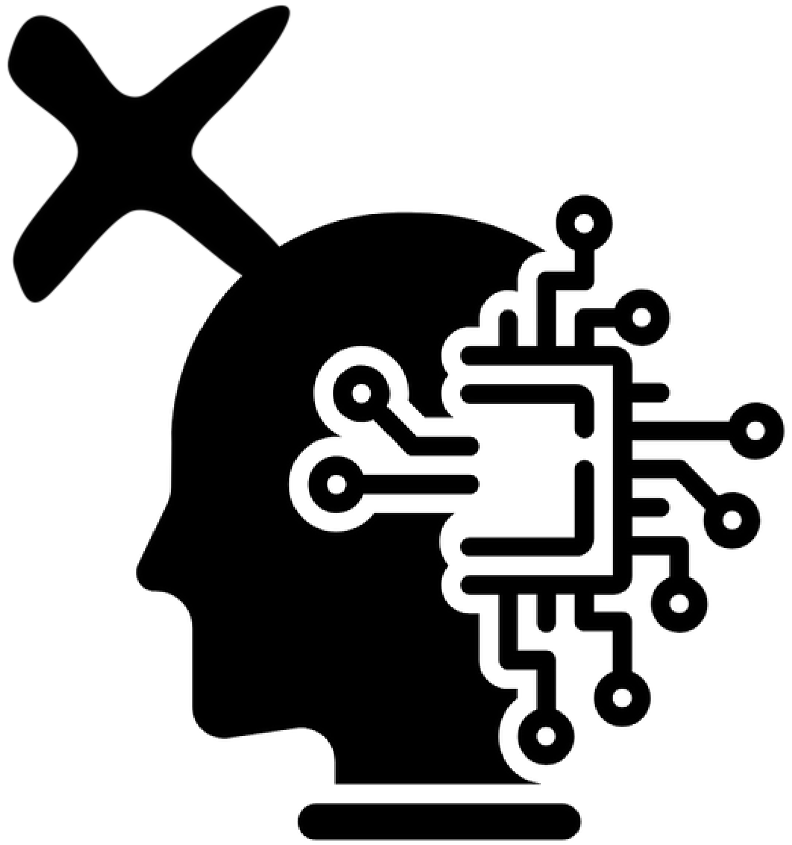
Energy Optimization:
- **Real-time adjustments for HVAC, lighting.**

Carbon Footprint Reduction:

- **Identifying low-carbon materials and renewable energy sources.**

Operational Efficiency:
- **Reducing energy intensity (EUI) via AI-driven monitoring.**

Chapter 5: AI Insights from Interviews



AI Can Not Yet Do

Data Challenges:

- Incomplete or poor-quality data limits AI accuracy.
- Structuring legacy data is resource-intensive.

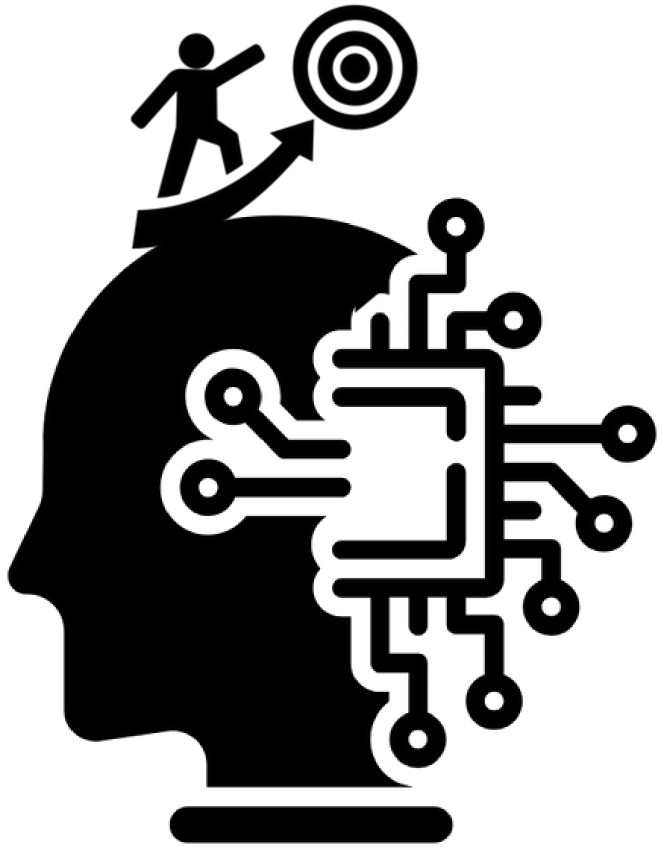
Stakeholder Skepticism:

- Trust issues with AI as a "black box."

Technological Barriers:

- High implementation costs and lack of standardization.

Chapter 5: AI Insights from Interviews



Focus on Measurable Objectives:
- **Energy savings, carbon reduction, operational efficiency.**

Enhance Data Infrastructure:
- **Invest in real-time metering and structured datasets.**

Stakeholder Collaboration:
- **Build trust and align goals across project teams.**

Gradual Implementation:
- **Begin with simpler applications and scale over time.**

Needs to Change for AI

Chapter 5: Further Recommendations by experts

1. Advocate for Industry-Wide Digitalization
   - Standardize and structure data collection and sharing across projects.
   - Integrate IoT devices and sensors for real-time data collection.
   - Facilitate collaboration between stakeholders to aggregate data insights.

2. Adopt a Phased Implementation Approach
   - Begin with simpler AI applications in new builds before tackling legacy structures.
   - Gradually integrate AI tools, starting with data analytics and progressing to advanced optimization.
   - Demonstrate incremental value to increase acceptance and reduce resistance.

3. Foster Supply Chain Collaboration
   - Promote transparency and data sharing across suppliers, manufacturers, and contractors.
   - Align AI applications with shared sustainability goals within the supply chain.

4. Strengthen Stakeholder Engagement
   - Build trust by educating stakeholders on AI benefits and addressing skepticism.
   - Ensure AI tools are transparent and provide measurable outcomes.
   - Engage policymakers to support AI adoption with incentives and clear regulations.

5. Emphasize Measurement and Verification
   - Establish clear metrics to validate AI's impact on energy and carbon reduction.
   - Implement a feedback loop for continuous improvement of AI tools.
   - Ensure human oversight to verify AI outputs and mitigate errors or biases.

Chapter 5: Role of AI summary (Case studies)

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.

SQ4: How can design and construction management utilize AI in decarbonization strategies?

Early-Stage Design and Scenario Planning

Project Planning and Scheduling

Risk Management

Cost Estimation and Accuracy

Automate Routine Task

Procurement and Supply Chain Management

Quality Control and Assurance

Data Security & Privacy

People and Ethics (Human Intelligence)

Accountability

Chapter 5: Key Contributions of DCM with AI

Strategic Planning and Coordination

- Aligns decarbonization goals with AI capabilities for optimal outcomes.
- Facilitates collaboration among stakeholders (designers, contractors, AI experts).

Data-Driven Decision Making

- Leverages AI tools to analyze energy performance, material use, and operational inefficiencies.
- Supports data-backed decisions to prioritize retrofit interventions.

Risk Management

- Identifies technical, financial, and regulatory risks.
- Uses AI for predictive analytics to mitigate risks proactively.

Compliance with Standards

- Ensures retrofit measures meet certifications like LEED and BREEAM.
- Adapts projects to evolving sustainability policies and regulations.

Chapter 5: Challenges for DCM with AI

Limited access to structured and real-time data.

High upfront costs of integrating AI technologies.

Resistance to adopting AI within traditional construction practices.

Chapter 5: AI-Driven Strategies in DCM

1. Optimizing Project Design
   - AI tools assist in:
     - Generating sustainable design alternatives.
     - Simulating energy performance and carbon impacts of various designs.

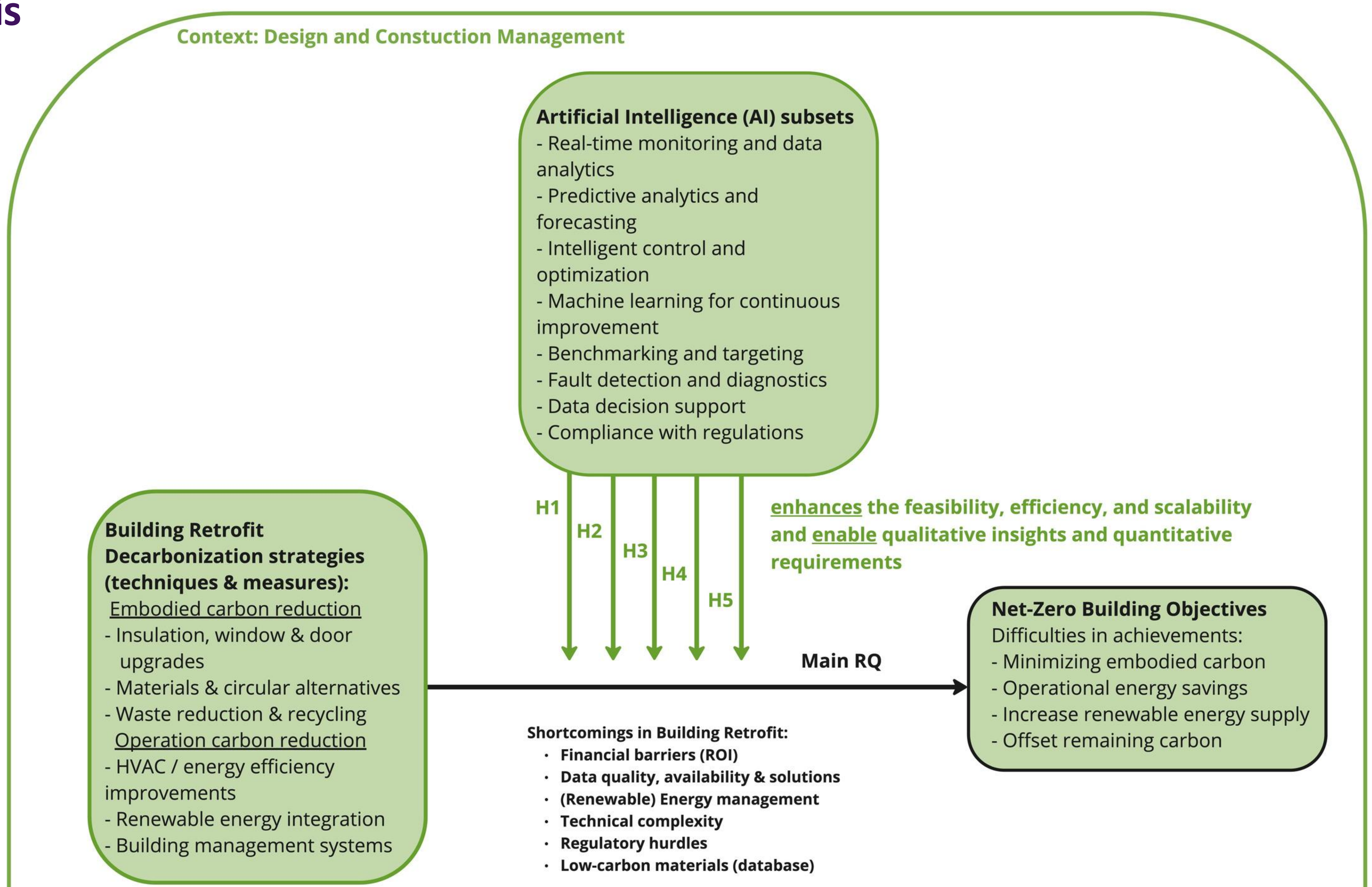
2. Enhancing Construction Processes
   - Real-time monitoring and intelligent control systems reduce energy waste during construction.
   - AI identifies opportunities for improving material efficiency and minimizing embodied carbon.

3. Improving Operational Efficiencies
   - AI-backed systems like Building Management Systems (BMS) optimize energy use post-retrofit.
   - Predictive maintenance ensures building systems operate efficiently and sustainably.

4. Promoting Stakeholder Collaboration
   - DCM frameworks integrate AI insights to align stakeholder goals.
   - Facilitates transparent communication using AI dashboards for progress tracking.

5. Scaling for Net-Zero Objectives
   - Gradual implementation of AI solutions across building portfolios.
   - Aligns with long-term decarbonization targets through continuous learning and adaptation.

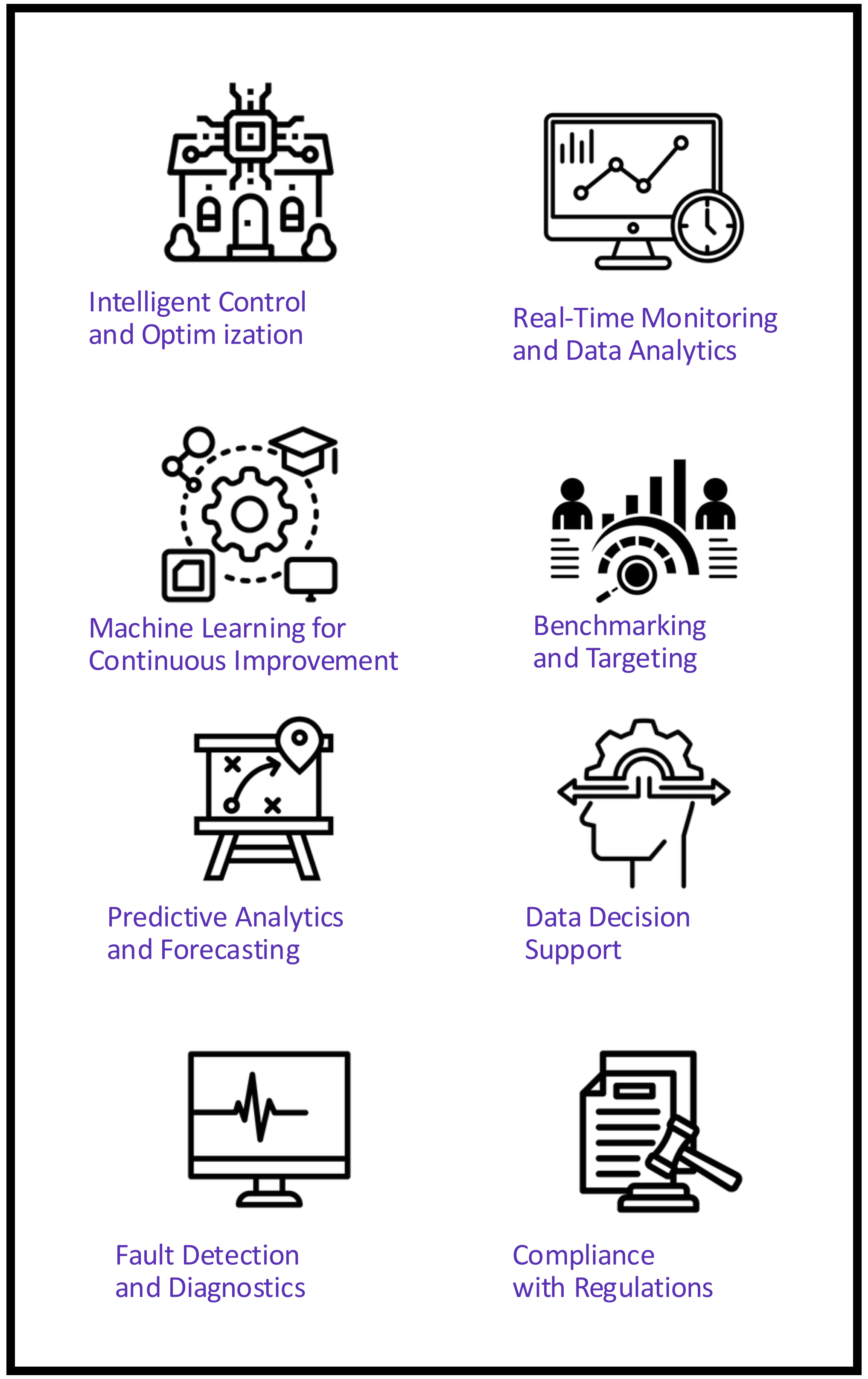
Chapter 6: Cross-case Analysis
Conceptual model



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

Hypotheses:
1. AI can optimize data-driven integration 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.

Chapter 6: Cross-case Analysis



Chapter 6: Cross-case Analysis

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

Validation

2 expert panel (validate findings)

Expert Panel	Participants	Discussion	Take away
1	1.AI consultant 2.Digitalization consultant	two frameworks are the same? Risk and risk management of applying AI	Explain the different framework and how both are part of the AI methodology. Human intelligence and accountability. AI subset is sometimes unclear to define and apply to an specific AI capability (defining based on literature review).
2	1.Retrofit/ Net Zero consultant 2. Project manager	AIR0: Business case for AI to detec (CSF0) DCM FRAIM => RIBA framework Sustainable procurement Risk management (priority) Stakeholder engagement	AIR0: Make it clear of how to use the AIR0 matrix. AIR0: Synergestic retrofit measure for integrating all the individual components DCM FRAIM: Stakeholder engagement in people & ethics. Not all the AI core components are connected to the iron triangle. Define the compont to the direct and intended outcome.

Chapter 6: Hypothesis

- 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.

Conclusion

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

Key Conclusions

SQ1: Concept of Building Retrofitting
- **Retrofitting reduces carbon emissions and operational inefficiencies through insulation, renewable energy integration, and advanced HVAC systems.**

SQ2: AI in current Sustainable Design
- **AI tools like machine learning and neural networks enable energy modeling, predictive maintenance, and decision-making optimization.**

SQ3: Role of AI in Decarbonization
- **AI unifies fragmented data, models energy scenarios, and supports low-carbon material selection.**

SQ4: Design and Construction Management
- **AI enhances early-stage planning, risk assessment, and performance monitoring, aligning construction management with decarbonization goals.**

Embodied Carbon reduction:
- Insulation, window and door upgrade
- Materials and circular alternatives
- Waste reduction and recycling

Net Zero Building Objectives

Operational Carbon efficiency:
- Light upgrades
- HVAC system improvements
- Building Management Systems
- Renewable energy integration

+ CARBON OFFSETTING (DISCUSSION)

• Conclusion: AI as a Transformative Tool

Building retrofitting measure	Challenge and/or limitation	AI's capabilities (role)	Subset of AI	Retrofit to Net-Zero Goal(s)
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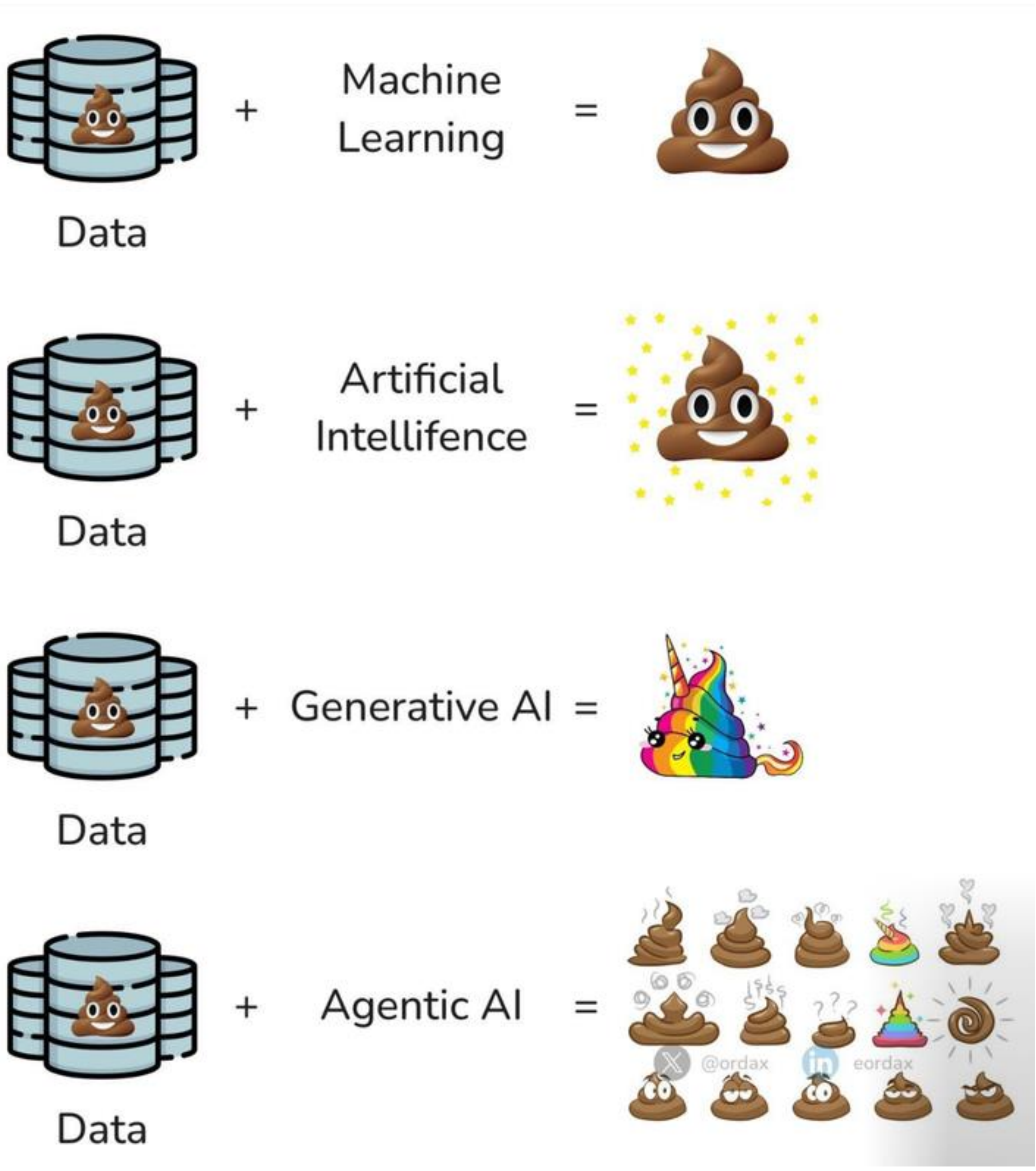
Assumptions - Energy consumption data; - PV panels energy productions; and creating assumptions in general instead of concrete data.	Pose potential challenges, and the project data outcome. Risks and uncertainties, as they may not accurately reflect the actual conditions or requirements of the buildings, 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

to address deficiencies in current retrofitting practices by optimizing energy performance, reducing embodied and operational carbon, and enhancing decision-making processes in design and construction management.


Data
+
Machine Learning
=
Data
+
Artificial Intellifence
=
Data
+
Generative AI
=
Data
+
Agentic AI
=

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

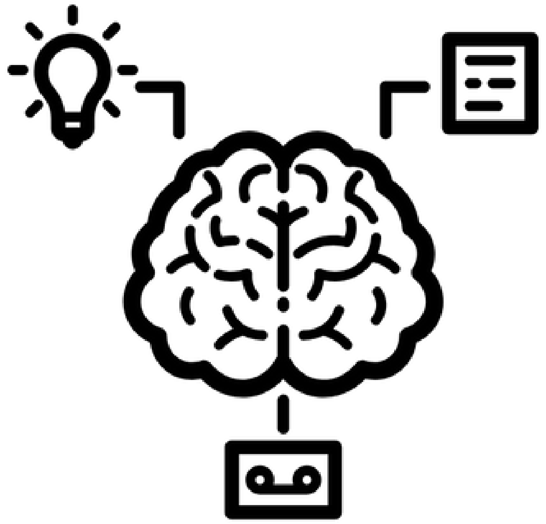

TU Delft
Turner & Townsend

Appendix

Synthesis (AIR0)

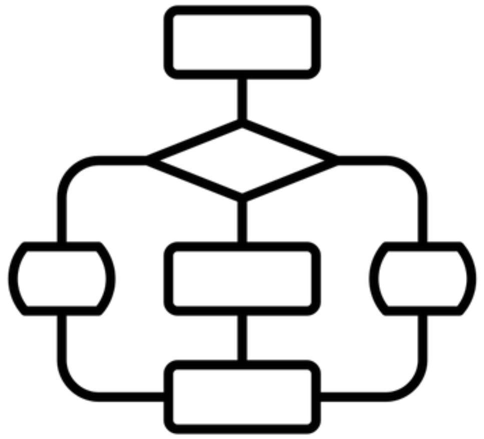
Retrofit Technique
Operational carbon (heatpump)

+



AI capability
Data decision support
+ AI subset (Neural Networks)

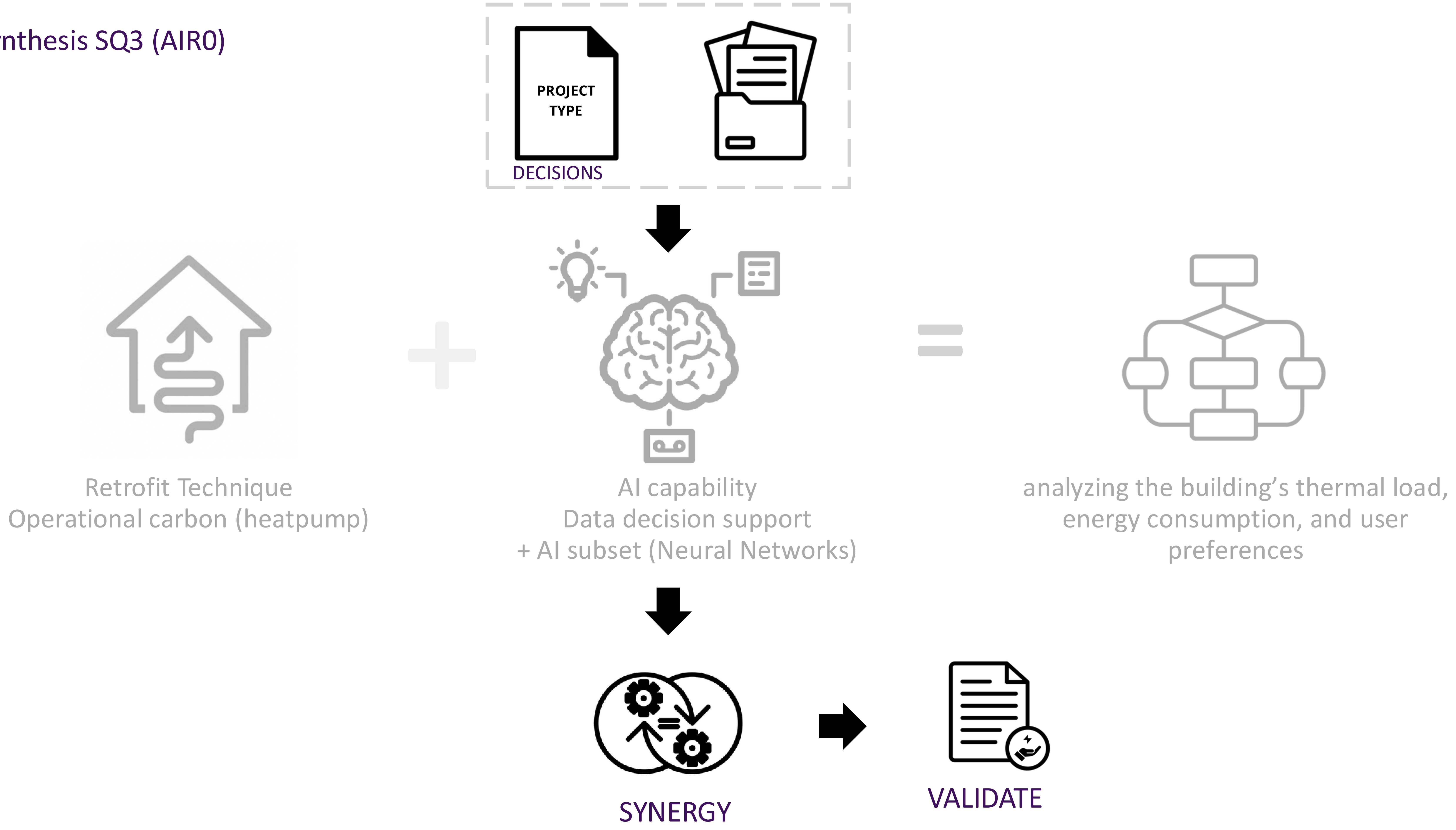
=



analyzing the building’s thermal load, energy consumption, and user preferences

example 1

Synthesis SQ3 (AIR0)



Synthesis SQ4 (DCM FRAIM)

Risk Management

1.Risk assessment

2.Predictive Analytics for Risk Mitigation

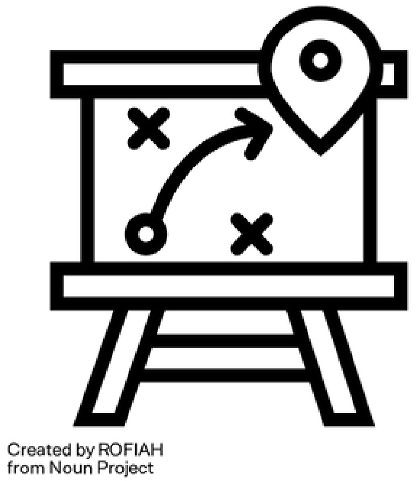
3.Mitigation of Design-Related Risks

AI Core component

Cost saving (Iron triangle)

example 1

Synthesis (DCM FRAIM)



Early-stage design
and scenario planning

1.AI scenario planning

2.Material selection and reuse

3.Client and stakeholder engagement

AI Core component

Carbon reduction (+Iron triangle)

example 2

Discussion

Discussion

- Net-Zero Goals: carbon offsetting (step 5)
- Operational vs Embodied Carbon: financial constraints
- AI's Role: limitations such as fragmented data, outdated infrastructure, and financial constraints
- Robotics and Automation: traditional labor dominating
- Data and Material Selection: incomplete databases and lack of integration with existing systems
- Regulatory Compliance: frequent changes
- Technological Gaps in Older Buildings: lacked infrastructure (sub-meters, sensors)

Limitations

- Selection of Case Study Projects and Interviewees: the initial phases of retrofitting projects, AI case studies not available,
- Interview Participants Bias: graduation internship, not a broader field of construction management
- Rapid Evolution of AI technologies: current state of technologies, outdated study in the future
- Lack of Quantitative Data: exact metrics of energy savings or carbon reduction
- Technological Readiness: older buildings, technological infrastructure

Recommendations

Recommendation

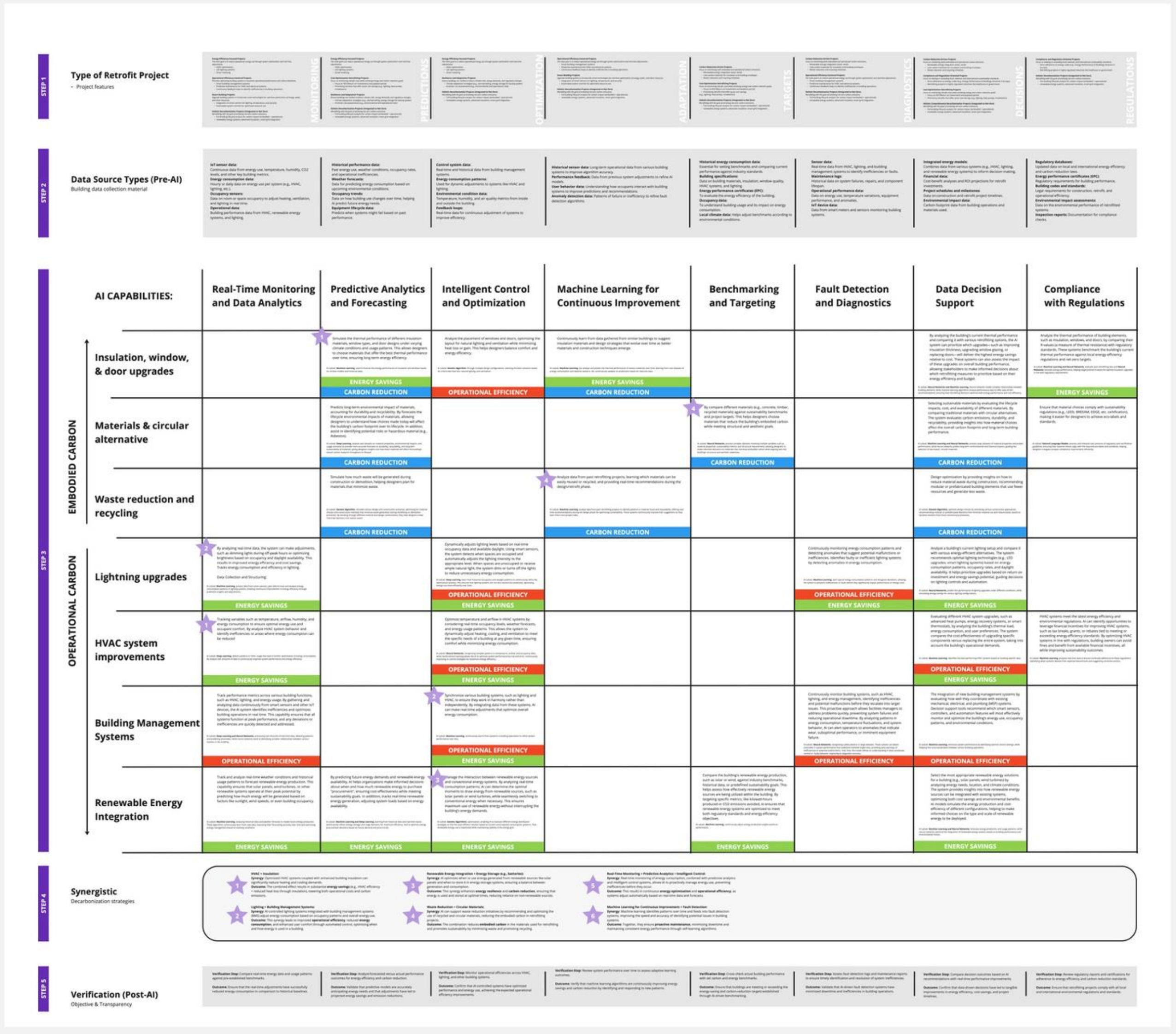
AI Methodology: Continuously update the AI framework to reflect advancements, focusing on integrating AI earlier in retrofitting for better carbon reductions. Expand AI application across different building types and regions to assess scalability.

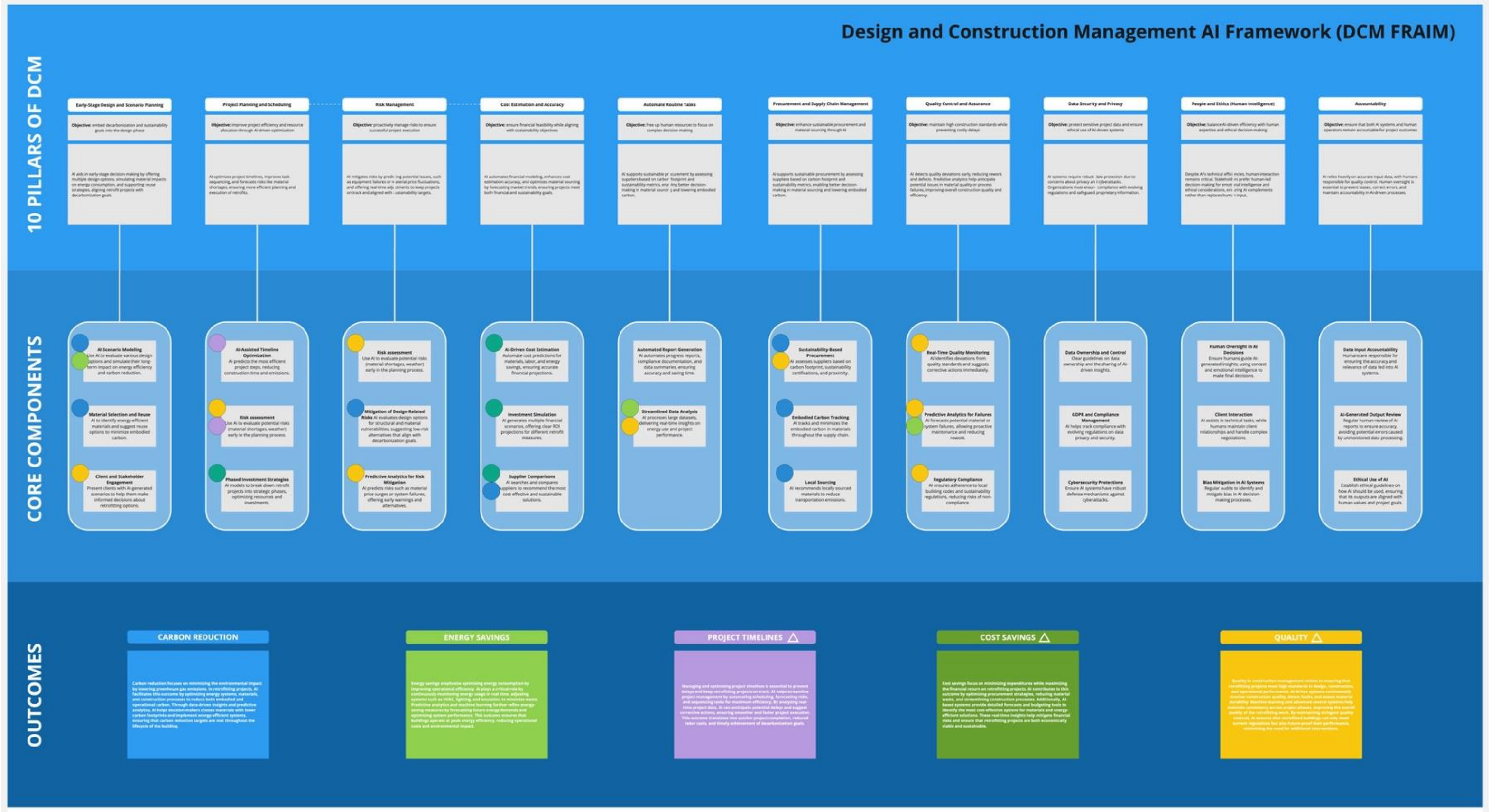
New Buildings: Research should explore how AI can fully optimize energy efficiency and carbon reduction in new building designs, where fewer constraints exist compared to retrofits.

Stakeholder Involvement: Investigate the influence of stakeholders (developers, owners, policymakers) in AI-driven decarbonization strategies, focusing on their role in AI adoption for sustainability goals.

AI in Carbon Tracking: Explore the role of AI in carbon monitoring and offsetting, particularly when AI-powered systems will significantly influence decision-making and prioritize projects based on environmental and financial benefits.

AIR0 Guidelines & DCM FRAIM





Data management

Triangulation

Shention, 2004

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'

Table 3.3: The implementation in this research to ensure trustworthiness (own illustration, adopted from Shenton, 2004)

Data Management Plan

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.

Data Management Plan

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

8B. Will you work with any other types of confidential or classified data or code as listed below? (tick all that apply)

If you are not sure which option to select, ask your Faculty Data Steward for advice.

- Yes, confidential data received from commercial, or other external partners

Internship organization with project-specific data and client-sensitive information. These will be confidential and completely pseudonymised.

9. How will ownership of the data and intellectual property rights to the data be managed?

For projects involving commercially-sensitive research or research involving third parties, seek advice of your Faculty Contract Manager when answering this question. If this is not the case, you can use the example below.

The datasets underlying the published papers will be publicly released following the TU Delft Research Data Framework Policy. During the active phase of research, the project leader from TU Delft will oversee the access rights to data (and other outputs), as well as any requests for access from external parties. They will be released publicly no later than at the time of publication of corresponding research papers.

In my internship agreement, Me and the TU Delft project team own the data related to my graduation project.

10. Which personal data will you process? Tick all that apply

- Photographs, video materials, performance appraisals or student results
- Other types of personal data - please explain below
- Data collected in Informed Consent form (names and email addresses)
- Signed consent forms

-opinions/beliefs/experience in projects

-video and audio recordings

11. Please list the categories of data subjects

Participants in the internship organization (construction management: consultants, project managers, cost managers, digitalization team, R&D AI team members) from different departments.

12. Will you be sharing personal data with individuals/organisations outside of the EEA (European Economic Area)?

- No

15. What is the legal ground for personal data processing?

- Informed consent

16. Please describe the informed consent procedure you will follow:

All study participants will be asked for their written consent for taking part in the study and for data processing before the start of the interview or expert panel session.

17. Where will you store the signed consent forms?

- Same storage solutions as explained in question 6