TU WIEN Informatics

Kombination von Business Process Management (BPM) und Life Cycle Assessment (LCA) in Renovierungsprozessen

DIPLOMARBEIT

zur Erlangung des akademischen Grades

Diplom-Ingenieur

im Rahmen des Studiums

Business Informatics

eingereicht von

Ali Sehovic
Matrikelnummer 12045639

an der Fakultät für Informatik

der Technischen Universität Wien

Betreuung: Univ.Prof. Henderik Proper, PhD
Mitwirkung: Univ.-Ass.in Marianne Schnellmann, BSc MSc

Wien, 26. August 2026

Ali Sehovic | Henderik Proper

Technische Universität Wien
A-1040 Wien ▪ Karlsplatz 13 ▪ Tel. +43-1-58801-0 ▪ www.tuwien.at

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

TU WIEN Informatics

Combination of Business Process Management (BPM) and Life Cycle Assessment (LCA) in Renovation Processes

DIPLOMA THESIS

submitted in partial fulfillment of the requirements for the degree of

Diplom-Ingenieur

in

Business Informatics

by

Ali Sehovic
Registration Number 12045639

to the Faculty of Informatics

at the TU Wien

Advisor: Univ.Prof. Henderik Proper, PhD
Assistance: Univ.-Ass.in Marianne Schnellmann, BSc MSc

Vienna, August 26, 2026

Ali Sehovic	Henderik Proper

Technische Universität Wien
A-1040 Wien ▪ Karlsplatz 13 ▪ Tel. +43-1-58801-0 ▪ www.tuwien.at

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

Declaration of Authorship

Ali Sehovic

I hereby declare that I have written this thesis independently, that I have completely specified the utilized sources and resources and that I have definitely marked all parts of the work – including tables, maps and figures – which belong to other works or to the internet, literally or extracted, by referencing the source as borrowed.
I further declare that I have used generative AI tools only as an aid, and that my own intellectual and creative efforts predominate in this work. In the appendix "Overview of Generative AI Tools Used" I have listed all generative AI tools that were used in the creation of this work, and indicated where in the work they were used. If whole passages of text were used without substantial changes, I have indicated the input (prompts) I formulated and the IT application used with its product name and version number/date.

Vienna, August 26, 2026

Ali Sehovic

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

Acknowledgements

I would like to express my sincere gratitude to my supervisors, starting with Univ.Prof. Henderik A. Proper, PhD, for his guidance and support throughout the development of this thesis. His expertise in Business Process Management and his constructive feedback have provided valuable direction and significantly contributed to the completion of this work.

I am also deeply grateful to Univ.-Ass.in Marianne Schnellmann, BSc MSc, for her thoughtful advice, encouragement, and insightful comments throughout the research process. Her attention to detail and willingness to engage with both the theoretical and technical aspects of this work have helped refine the quality and clarity of this research.

This achievement would not have been possible without the unwavering support of my family. I dedicate this work to my father, whose sacrifices and commitment to education have inspired me to pursue this degree. His belief in the value of knowledge has been a driving force behind my efforts.

I am equally indebted to my mother, whose love and constant encouragement have provided me with the strength and resilience to overcome challenges along the way. To them, I owe a debt of gratitude that cannot be measured.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

Kurzfassung

Diese Masterarbeit untersucht die Verbindung von Business Process Management (BPM) und Life Cycle Assessment (LCA) zur Unterstützung nachhaltiger Entscheidungsprozesse bei der Renovierung von Gebäuden. Der Ausgangspunkt der Arbeit ist die Beobachtung, dass Prozessoptimierung und ökologische Bewertung in Renovierungsprojekten häufig getrennt behandelt werden. Dadurch werden Umweltindikatoren oft erst nachgelagert berücksichtigt und nicht systematisch in operative Entscheidungsabläufe eingebunden.

Die Arbeit verfolgt drei zentrale Forschungsfragen. Erstens wird untersucht, welche bestehenden Methoden zur Integration von BPM und LCA in Renovierungsprozessen existieren und welche Grenzen diese Ansätze aufweisen. Zweitens werden technische und funktionale Anforderungen an ein BPM-LCA-Framework für nachhaltige Entscheidungen in büroähnlichen Gebäuderenovierungen abgeleitet. Drittens wird analysiert, wie ein integrierter BPM-LCA-Ansatz in Renovierungsworkflows praktisch umgesetzt werden kann.

Methodisch kombiniert die Arbeit eine Systematic Literature Review mit einem Design-Science-Research-Ansatz. Auf Basis der Literatur werden bestehende Integrationsmethoden, Forschungslücken und Anforderungen identifiziert. Anschließend wird ein BPMN-informiertes Integrationsframework entworfen und durch einen Proof-of-Concept-Desktop-Prototyp umgesetzt. Der Prototyp unterstützt drei Renovierungsmaßnahmen: Fensteraustausch, Dämmungsverbesserung und Photovoltaik. Für jede Maßnahme werden Energieeinsparungen, Kosteneinsparungen, CO2-Reduktion, verkörperte Emissionen sowie Amortisationszeiten berechnet.

Das zentrale Ergebnis der Arbeit ist ein BPMN-informierter Entscheidungsunterstützungsansatz, der LCA-basierte Nachhaltigkeitsindikatoren direkt in einen strukturierten Renovierungsworkflow einbettet. Obwohl der Prototyp keine vollständig ausführbare BPMN-Engine integriert, operationalisiert er BPMN-Entscheidungslogik, indem der Carbon Payback Period als Bedingung für eine exklusive Gateway-Entscheidung verwendet wird. Die Evaluation anhand eines realitätsnahen Testfalls zeigt, dass der Ansatz die Bewertung von Renovierungsoptionen beschleunigt, Entscheidungsinformationen transparenter macht und eine nachvollziehbare Verbindung zwischen Prozesslogik und Nachhaltigkeitsbewertung herstellt.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

Abstract

This thesis investigates the integration of Business Process Management (BPM) and Life Cycle Assessment (LCA) to support sustainable decision-making in building renovation processes. The motivation for the work is the observation that process optimization and environmental assessment are often treated as separate activities. As a result, sustainability indicators are frequently considered only after key renovation decisions have already been made, rather than being embedded into the workflow itself.

The research addresses three questions: which existing methods integrate BPM and LCA in renovation processes and what their limitations are; which technical and functional requirements a BPM-LCA framework must satisfy for office-like building renovations; and how such an integrated approach can be implemented in renovation workflows. To answer these questions, the thesis combines a Systematic Literature Review (SLR) with a Design Science Research (DSR) approach. The SLR identifies existing integration approaches, recurring limitations, and framework requirements. Based on these findings, a BPMN-informed integration framework is designed and implemented as a proof-of-concept desktop prototype.

The prototype supports three renovation measures: window replacement, insulation upgrade, and solar photovoltaic installation. For each measure, it calculates decision-relevant indicators such as energy savings, cost savings, CO2 reduction, embodied emissions, financial payback, and carbon payback. Although the prototype does not implement a fully executable BPMN engine, it operationalizes BPMN decision logic by using the carbon payback period as the branching condition for an exclusive gateway.

The evaluation through a realistic office-building renovation test case shows that the framework can reduce assessment time, improve the transparency of decision information, and create a structured link between renovation process logic and sustainability assessment. The thesis contributes a synthesis of BPM-LCA integration methods, a set of technical and functional requirements, and a proof-of-concept artefact demonstrating the feasibility of embedding sustainability assessment into renovation decision-support workflows.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

Contents

Kurzfassung **ix**

Abstract **xi**

Contents **xiii**

1 Introduction **1**
1.1 Motivation & Problem Statement 1
1.2 Research Questions 2
1.3 Research Objectives 2
1.4 Expected Contributions 4
1.5 Thesis Structure 5

2 Theoretical Background **7**
2.1 Business Process Management (BPM) 7
2.2 Life Cycle Assessment (LCA) 10
2.3 Conceptual Motivation for Integrating BPM and LCA 11

3 Research Methodology **15**
3.1 Overall Research Design 15
3.2 Systematic Literature Review (SLR) Methodology 16
3.3 Design Science Research (DSR) Methodology 23

4 SLR Results – Existing Methods for Integrating BPM and LCA in Renovation Processes **31**
4.1 Introduction and Analytical Approach for RQ1 31
4.2 Aggregated SLR Results for RQ1: Distribution of Integration Approaches 32
4.3 Detailed Analysis of Each Integration Category 33
4.4 Cross-Cutting Limitations Synthesized from All 55 Studies 38
4.5 Explicit, Evidence-Based Answer to RQ1 39
4.6 Implications of RQ1 Findings for the Subsequent Analysis (RQ2) . . . 40

5 SLR Results – Technical and Functional Requirements for a BPM-LCA Framework **43**

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

5.1 Introduction and Analytical Approach for RQ2 . . . 43
5.2 Aggregated SLR Results for RQ2: Overview of Requirement Categories 44
5.3 Technical Requirements for a BPM-LCA Framework . . . 44
5.4 Functional Requirements for a BPM-LCA Framework . . . 48
5.5 Foundational Design Principles Derived from Requirements . . . 51
5.6 Mapping Requirements to Limitations: Traceability Matrix . . . 51
5.7 Explicit, Evidence-Based Answer to RQ2 . . . 51
5.8 Implications of RQ2 Findings for Framework Design (Chapter 6) . . . 53

6 Design and Development of the BPM-LCA Integration Framework 55
6.1 Introduction . . . 55
6.2 Purpose and Scope of the Framework . . . 56
6.3 Design Principles of the BPM-LCA Framework . . . 57
6.4 Software Prototype Overview . . . 59
6.5 Framework Architecture . . . 61
6.6 Window Replacement Module . . . 63
6.7 Insulation Upgrade Module . . . 65
6.8 Solar Photovoltaic (PV) Module . . . 67
6.9 Role of the Framework in BPM-LCA Integration . . . 69
6.10 Limitations of the Prototype . . . 69
6.11 Future Development . . . 70

7 Evaluation and Discussion 71
7.1 Introduction . . . 71
7.2 Evaluation Approach . . . 72
7.3 Real-World Test Case: Office Building Renovation . . . 72
7.4 Time Efficiency . . . 74
7.5 Technical Feasibility Verification . . . 75
7.6 Decision Quality and Information Completeness . . . 75
7.7 Mapping Requirements to Implementation . . . 77
7.8 Limitations of the Framework and Evaluation . . . 77
7.9 Answer to RQ3 . . . 79
7.10 Summary . . . 80

8 Conclusion 81
8.1 Summary of the Research . . . 81
8.2 Answers to Research Questions . . . 82
8.3 Contributions . . . 83
8.4 Limitations of the Research . . . 84
8.5 Future Work . . . 85
8.6 Concluding Remarks . . . 86

Overview of Generative AI Tools Used 89

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

List of Figures **91**

List of Tables **93**

Bibliography **95**

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

CHAPTER 1

Introduction

1.1 Motivation & Problem Statement

In the construction sector, particularly regarding building renovation, the urgent need to mitigate environmental impact creates a pressing challenge for balancing sustainability with effective business operations [1]. Business Process Management (BPM) is commonly utilized to enhance workflows, improve performance, and support governance across organizational processes [2], while Life Cycle Assessment (LCA) offers a structured method for assessing environmental impacts across the life cycle and is grounded in international standards [3, 4]. Nevertheless, these two approaches are frequently applied in isolation, resulting in sustainability initiatives that remain reactive rather than being embedded directly into operational decision-making [5, 6].

The absence of a unified BPM–LCA framework means that sustainability factors are not consistently integrated into renovation decision-making processes, especially when process governance and environmental assessment are treated as separate workstreams [7]. Consequently, this fragmentation can lead to higher environmental burden, suboptimal resource utilization, and missed opportunities for sustainability-driven design and renovation improvements [8, 9]. As demands for environmentally responsible renovation practices intensify, organizations require structured strategies that merge sustainability metrics with process execution and control, rather than appending environmental evaluation only at the end of the workflow [10].

Recent research shows a growing feasibility of technical integration approaches—including BPMN-based LCA integration, real-time data support, and BIM-enabled environmental assessment—but these are not yet consolidated into a robust, generally reusable framework for renovation decision support [11, 12, 13]. In particular, renovation projects require a consistent linkage between process tasks (e.g., demolition, material selection, installation) and the corresponding LCA parameters (e.g., embodied impacts, operational energy), so

that sustainability performance can be evaluated as the process is designed and executed [14].

This study concentrates on the renovation of office-like buildings, specifically addressing processes related to planning, design, execution, and lifecycle management [1]. By combining BPM with LCA, the research aims to provide a framework to assist stakeholders—including engineers, project managers, building owners, and sustainability professionals—in making informed decisions that harmonize business efficiency with environmental sustainability [2]. The motivation is further reinforced by the broader movement toward digital and integrated sustainability assessment in construction management, where decision support requires structured data, standardized impact methods, and workflow-level governance [15, 12].

1.2 Research Questions

RQ1: What are the existing methods for integrating BPM and LCA in renovation processes, and what are their limitations?
RQ2: What technical and functional requirements must a BPM-LCA framework meet to support sustainable decision-making in office-like building renovations?
RQ3: How can an integrated BPM-LCA approach be effectively implemented in renovation project workflows?

1.3 Research Objectives

The primary objective of this thesis is to develop and evaluate an integrated framework that combines Business Process Management (BPM) with Life Cycle Assessment (LCA) in order to support sustainability-aware decision-making in renovation processes of office-like buildings [2, 14]. By linking environmental indicators with process activities and decision points, the proposed approach aims to make sustainability assessment an explicit part of renovation decision-making rather than a separate or post-hoc activity [7].

This overarching objective is operationalized through three specific research objectives (ROs). Each objective corresponds to one of the research questions introduced in Section 1.2 and is accompanied by an explicit assessment criterion defining the conditions under which the corresponding research question is considered sufficiently answered.

RO1: Identification and assessment of existing BPM–LCA integration approaches.

The first objective is to conduct a Systematic Literature Review (SLR) in order to systematically identify, classify, and critically assess existing methods, frameworks, and tools that combine BPM- and LCA-related concepts in construction and renovation contexts. Particular attention is given to the way these approaches integrate environmental

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

assessment with process management and to the limitations that restrict their application in renovation decision-making. This objective directly addresses RQ1.

RQ1 is considered sufficiently answered when the SLR provides a systematic and evidence-based classification of the identified BPM–LCA integration approaches and a structured synthesis of their recurring limitations. The identified categories and limitations must be supported by evidence from the studies included through the defined SLR protocol, allowing the conclusions to be traced back to the reviewed literature rather than being based solely on individual examples or subjective interpretation.

RO2: Derivation of technical and functional requirements for BPM–LCA integration.

The second objective is to derive a structured set of technical and functional requirements for an integrated BPM–LCA framework based on the findings of the SLR. The requirements are intended to address the limitations identified under RO1 and to connect sustainability-related needs, such as environmental impact assessment and energy-related indicators, with process-related needs, such as workflow integration, interoperability, transparency, and decision-support capabilities. This objective directly addresses RQ2.

RQ2 is considered sufficiently answered when a clearly defined set of technical and functional requirements can be systematically derived from the findings of the literature review. The major requirements must be traceable to recurring limitations, challenges, or needs identified in the reviewed studies. Furthermore, the resulting requirements must provide a sufficiently structured and justified basis for the subsequent design and implementation of the BPM–LCA framework.

RO3: Design, implementation, and evaluation of a BPMN-informed BPM–LCA framework.

The third objective is to design, implement, and evaluate a BPMN-informed BPM–LCA integration framework that demonstrates how LCA-based sustainability indicators can be incorporated into renovation decision-support workflows. Following the Design Science Research methodology [16, 17], the conceptual framework is instantiated through a proof-of-concept software prototype in which process-oriented decision logic is combined with calculations of decision-relevant sustainability indicators.

The purpose of the prototype is not to implement a fully executable BPMN engine, but to demonstrate the feasibility of embedding LCA-derived information into a structured renovation workflow in which sustainability indicators can directly influence decision-making.

RQ3 is considered sufficiently answered when the requirements derived under RO2 can be translated into a coherent BPMN-informed framework and demonstrated through a functioning proof-of-concept implementation. The artefact must demonstrate that relevant sustainability information can be calculated and incorporated into renovation decision logic rather than merely presented as an independent environmental assessment.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

In addition, the proposed implementation is considered successful if its evaluation demonstrates:

- **Technical feasibility:** the proposed BPM–LCA integration can be implemented as a functioning software artefact;
- **Calculation and decision-logic correctness:** the implemented calculations and decision rules produce consistent and verifiable results;
- **Decision-support capability:** the framework provides sustainability-related information that can be used to compare renovation alternatives and support process-level decisions;
- **Requirement traceability:** the main design and implementation features can be traced back to the technical and functional requirements derived from the SLR; and
- **Demonstrability in a realistic renovation context:** the framework can be applied to a realistic office-building renovation test case in order to demonstrate its practical operation and limitations.

Together, the three research objectives establish a traceable progression from the analysis of existing knowledge, through the derivation of requirements, to the design and evaluation of a practical artefact. The associated assessment criteria provide an explicit basis for determining whether each research question has been adequately addressed: RQ1 through systematic classification and limitation analysis, RQ2 through evidence-based and traceable requirement derivation, and RQ3 through the implementation and evaluation of the resulting BPM–LCA integration approach.

1.4 Expected Contributions

This research is expected to deliver significant contributions across theoretical, methodological, technical, and practical dimensions, stemming directly from its research objectives [16].

1.4.1 Theoretical Contributions

This thesis will advance knowledge by formally conceptualizing the integration of BPM and LCA specifically for building renovation processes. It will contribute to the field of Sustainable BPM (Green BPM) by extending its theoretical foundations to include a structured method for embedding environmental indicators from LCA into process management models [7].

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

1.4.2 Methodological Contributions

Methodologically, this work will structure a literature-based synthesis of BPM-LCA integration approaches and map them to requirements for renovation decision support. In addition, it leverages Design Science Research as a rigorous method for developing and evaluating the proposed integration framework [17].

1.4.3 Technical Contributions

As a core technical contribution, this thesis produces a proof-of-concept desktop prototype informed by BPMN principles, developed in C#/.NET. The artefact integrates structured process logic with embedded Life Cycle Assessment (LCA) calculations, enabling real-time evaluation of renovation scenarios through key sustainability indicators such as energy savings, CO_2 reduction, and payback periods.

While not implementing a fully executable BPMN engine, the prototype incorporates a BPMN-inspired process structure and decision logic, where environmental indicators (e.g., carbon payback) influence decision-making pathways. This artefact serves as tangible evidence of the feasibility of BPM–LCA integration at the decision-support level and provides a practical foundation for future development of fully process-executable and BIM-integrated solutions [12].

1.4.4 Practical Contributions

For practitioners, this research will support process-level decision-making in renovation by linking workflow activities to LCA-based indicators and enabling systematic comparison of alternatives. It will provide actionable guidance for project managers, engineers, and sustainability officers on how to incorporate environmental assessment into renovation workflows without sacrificing operational governance. The focus on office-like buildings aligns the contribution with a well-studied building type where life-cycle impacts and renovation strategies can be meaningfully compared [9].

1.5 Thesis Structure

This thesis is organized into eight chapters, each building upon the previous one to provide a comprehensive investigation of the integration of Business Process Management (BPM) and Life Cycle Assessment (LCA) in renovation processes of office-like buildings. The structure reflects the Design Science Research (DSR) methodology, guiding the logical progression from problem identification and awareness to design, development, evaluation, and conclusions [16].

Chapter 1 – Introduction This chapter introduces the motivation and core problem: the disconnect between process efficiency and environmental sustainability in renovation. It defines the research questions and outlines the research objectives. It further highlights

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

the expected theoretical, methodological, technical, and practical contributions of the thesis and concludes with an overview of the thesis structure.

Chapter 2 – Theoretical Background This chapter provides the conceptual foundations required for the research. It introduces the fundamentals of BPM, its application in construction and renovation, Green BPM, and BPMN as a process-modeling standard. It also presents the basic principles of LCA, its application in building renovation, and relevant LCA tools. The chapter concludes by motivating the conceptual relationship between BPM and LCA and explaining why their integration is relevant for renovation decision-making, while the systematic assessment of existing integration approaches and research gaps is reserved for the subsequent SLR.

Chapter 3 – Research Methodology This chapter details the two-phase methodological approach. It first describes the Systematic Literature Review (SLR) protocol, including search strategy, selection criteria, and data extraction methods used to address RQ1 and RQ2. It then outlines the Design Science Research (DSR) methodology adopted for the design and development of the BPM-LCA framework (RQ3) and its subsequent evaluation.

Chapter 4 – SLR Results: Existing Methods for Integrating BPM and LCA This chapter presents the first part of the SLR results. It synthesizes existing BPM-LCA integration methods and their limitations, thereby answering RQ1. The identified limitations motivate the need for a novel framework.

Chapter 5 – SLR Results: Technical and Functional Requirements This chapter presents the second part of the SLR results. Based on the limitations identified in Chapter 4, it derives a comprehensive set of technical and functional requirements for a BPM-LCA integration framework, addressing RQ2.

Chapter 6 – Design and Development of the BPM-LCA Integration Framework This chapter is the core design artefact of the thesis. It introduces the proposed framework, structured around a BPMN process model with an exclusive gateway that uses LCA results (carbon payback period) to guide renovation decisions. The chapter details the software prototype architecture and its three calculation modules (window replacement, insulation upgrade, solar PV).

Chapter 7 – Evaluation and Discussion This chapter evaluates the proposed framework through a real-world test case of an office building renovation. It demonstrates technical feasibility, time efficiency, decision quality, and validates the BPMN gateway decision logic, thereby answering RQ3.

Chapter 8 – Conclusion and Future Work This chapter summarizes the research, reflects on limitations, and proposes directions for future work, including full BPMN engine integration, naturalistic evaluation, and BIM integration.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

CHAPTER 2

Theoretical Background

This chapter introduces the theoretical concepts required to understand the research presented in this thesis. It provides an overview of Business Process Management (BPM), Green BPM, Business Process Model and Notation (BPMN), and Life Cycle Assessment (LCA), with particular attention to their relevance in the context of building renovation. The chapter does not aim to provide a systematic assessment of existing BPM–LCA integration approaches. Instead, it establishes the conceptual foundations and motivates why the relationship between process management and environmental assessment is relevant for the research problem addressed in this thesis. The systematic investigation of existing approaches, their limitations, and the resulting framework requirements is conducted through the Systematic Literature Review presented in the subsequent chapters.

2.1 Business Process Management (BPM)

2.1.1 Core Concepts and Principles

Business Process Management (BPM) is a disciplined approach to identifying, designing, executing, documenting, measuring, monitoring, and controlling both automated and non-automated business processes in order to achieve results that are aligned with organizational objectives [2]. Rather than representing a one-time improvement activity, BPM is generally understood as a continuous management approach in which processes are repeatedly analyzed and refined.

This continuous perspective is commonly represented through the BPM lifecycle, which includes activities such as process identification, modeling, analysis, redesign, implementation, monitoring, and optimization [10]. Through these activities, BPM aims to improve the efficiency, effectiveness, transparency, and adaptability of organizational processes.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

A central characteristic of BPM is its process-oriented perspective. Instead of considering individual organizational activities in isolation, BPM focuses on how activities, decisions, information, resources, and stakeholders are connected within an end-to-end workflow. This perspective is particularly relevant for complex domains in which multiple actors and information sources must be coordinated across several process stages.

2.1.2 BPM in the Construction and Renovation Sector

Construction and renovation projects consist of interconnected activities involving planners, engineers, contractors, building owners, suppliers, authorities, and other stakeholders. These activities span several project phases, including initial assessment, planning, design, procurement, construction, commissioning, and handover. Decisions made during one phase can influence subsequent activities, costs, resource requirements, and project outcomes.

From a BPM perspective, such projects can therefore be understood as complex process environments in which coordination and information exchange are essential. Process modeling can support the explicit representation of activities, responsibilities, dependencies, decision points, and information flows. This can contribute to improved process transparency, more consistent execution, and clearer communication among the stakeholders involved.

Traditionally, process management in construction is strongly associated with operational objectives such as time, cost, quality, coordination, and resource efficiency. However, renovation projects increasingly also require the consideration of environmental consequences. Decisions concerning materials, building components, insulation, energy systems, or replacement strategies may affect both the operational performance of a building and the environmental impacts associated with the renovation itself.

This creates a conceptual need to consider environmental information together with conventional process-related information. BPM provides the process structure through which activities and decisions can be organized, while environmental assessment methods can provide additional information that may support those decisions.

2.1.3 Green BPM: Integrating Sustainability into Process Management

Green BPM extends the traditional objectives of Business Process Management by explicitly incorporating environmental sustainability into the management and improvement of business processes [6]. Rather than evaluating process performance exclusively in terms of traditional dimensions such as time, cost, quality, and flexibility, Green BPM introduces environmental considerations as an additional dimension of process performance.

Environmental considerations may include energy consumption, material use, waste generation, emissions, and other forms of environmental impact [5]. The underlying idea is that sustainability should not be treated only as an external reporting activity after a

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

process has been completed. Instead, environmental considerations can become part of the way processes are designed, analyzed, executed, and improved.

This perspective is particularly relevant for building renovation. Renovation decisions frequently involve trade-offs between economic, technical, operational, and environmental objectives. For example, replacing an existing building component may improve energy efficiency during building operation while simultaneously creating environmental impacts through the production and installation of the replacement component. A process-oriented sustainability perspective therefore requires environmental information to be available at the points at which such decisions are made.

Green BPM provides the conceptual basis for incorporating sustainability concerns into process management. However, Green BPM itself does not prescribe a single environmental assessment method. Consequently, a separate method is required to quantify and structure environmental information in a form that can meaningfully support process-related decisions. In the context of this thesis, Life Cycle Assessment provides this environmental assessment perspective.

2.1.4 BPMN as a Standard for Process Modeling

Business Process Model and Notation (BPMN) 2.0 provides a standardized graphical notation for representing business processes. BPMN supports the modeling of activities, events, decisions, information flows, and interactions among process participants. Common BPMN elements include *start events*, which indicate the beginning of a process; *tasks*, which represent activities to be performed; *gateways*, which represent branching or synchronization points; and *end events*, which represent the completion of a process.

For the research presented in this thesis, the concept of a gateway is particularly relevant. An exclusive gateway represents a decision point at which one process path is selected according to a defined condition. From a conceptual perspective, such conditions do not necessarily have to depend only on conventional process information. They may also refer to sustainability-related indicators if these indicators are available at the relevant point in the process.

This characteristic makes BPMN useful for conceptualizing how environmental assessment results could become part of renovation decision logic. Rather than treating environmental indicators exclusively as information displayed after an assessment, they can potentially be connected to explicit decision points within a process model. This provides an important conceptual connection between BPM, Green BPM, and environmental assessment [7].

The detailed design and implementation of such decision logic is not addressed in this theoretical chapter. Instead, this section establishes BPMN as the process-modeling foundation required for the framework developed later in the thesis.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

2.2 Life Cycle Assessment (LCA)

2.2.1 Fundamental Methodology and Standards

Life Cycle Assessment (LCA) is a standardized methodology for evaluating the environmental impacts associated with the life cycle of a product, process, or service [14]. In contrast to approaches that focus only on a single stage of use or production, LCA adopts a life-cycle perspective and can consider environmental impacts from raw material extraction through production, use, and end-of-life treatment.

The methodological framework is defined primarily by ISO 14040 and ISO 14044 and consists of four interrelated phases: Goal and Scope Definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation [3, 4].

The *Goal and Scope Definition* specifies the purpose of the assessment, the functional unit, system boundaries, assumptions, and intended application. These decisions determine what is included in the analysis and how the results should be interpreted.

The *Life Cycle Inventory* phase collects and structures the relevant inputs and outputs of the assessed system, such as material quantities, energy consumption, emissions, and waste flows.

During the *Life Cycle Impact Assessment*, the inventory data are translated into environmental impact indicators. Depending on the scope of the assessment, these may include categories such as global warming potential, resource depletion, acidification, or other environmental effects.

Finally, the *Interpretation* phase evaluates the results in relation to the original goal and scope of the study. It supports the identification of important contributors, comparison of alternatives, and formulation of conclusions or recommendations [14].

An important characteristic of LCA is therefore its ability to transform physical information about materials and energy into structured environmental indicators. This makes it particularly relevant as a potential source of sustainability information for decision-support processes.

2.2.2 LCA Application in Building Renovation

The application of LCA in the building sector supports the assessment of both operational and embodied environmental impacts [1]. Operational impacts are associated with the use of the building, for example energy consumption for heating, cooling, ventilation, or electricity. Embodied impacts arise from activities such as material production, transport, construction, replacement, and end-of-life treatment.

This distinction is especially important in renovation projects. A renovation measure may reduce operational energy demand and associated emissions, but its implementation also requires new materials, products, transport, and construction activities. These interventions themselves generate environmental impacts.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

For example, replacing windows or adding insulation may reduce heating demand during subsequent building operation. At the same time, manufacturing the new windows or insulation materials creates embodied environmental impacts. A meaningful sustainability assessment therefore requires consideration of both the environmental investment caused by the renovation and the environmental benefits achieved during subsequent operation.

LCA provides a structured methodology for analyzing these relationships and comparing renovation alternatives [9]. In this way, environmental indicators can contribute to questions such as whether one renovation option provides greater long-term environmental benefits than another, or whether the operational savings of a measure justify its embodied impacts.

For the purposes of this thesis, this decision-support potential is particularly relevant. LCA provides environmental information, while BPM provides the process context in which renovation alternatives are evaluated and decisions are taken.

2.2.3 Tools and Software for LCA

The practical execution of Life Cycle Assessment is supported by specialized software applications and environmental databases. Tools such as SimaPro, openLCA, and One Click LCA provide functionality for managing life cycle inventories, selecting environmental datasets, applying impact assessment methods, and calculating environmental indicators.

Life cycle inventory databases such as ecoinvent provide data concerning material production, energy systems, transport processes, and other activities required for environmental calculations. In the building sector, environmental product data and building-specific databases may additionally support the evaluation of construction products and renovation measures.

Digitalization also creates opportunities for connecting environmental assessment with other information systems used in construction. For example, compatibility with Building Information Modeling (BIM) can facilitate the transfer of building geometry, material quantities, and component information into environmental assessment processes [12].

From the perspective of this thesis, the importance of LCA tools lies primarily in their role as sources and processors of environmental information. The central research interest is not the comparison of individual LCA software products, but rather how environmental indicators derived from LCA-related data and calculations can be connected with renovation process logic.

2.3 Conceptual Motivation for Integrating BPM and LCA

2.3.1 Complementary Perspectives of BPM and LCA

BPM and LCA address different but potentially complementary aspects of decision-making. BPM focuses primarily on the organization and management of processes. It

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

provides concepts for representing activities, responsibilities, information flows, process dependencies, and decision points. LCA, in contrast, focuses on the environmental consequences associated with products, materials, activities, and systems across their life cycles.

Viewed separately, BPM can describe *how* a renovation process is organized and where decisions are made, while LCA can provide environmental information concerning the consequences of the alternatives considered within those decisions. Their conceptual combination therefore creates the possibility of connecting process-oriented decision structures with environmental assessment information.

This relationship is consistent with the broader idea of Green BPM, in which environmental performance becomes an explicit consideration within process management [6, 7]. LCA can contribute quantitative environmental information, while BPM and BPMN can provide the organizational and process-oriented structure through which this information can potentially influence decision-making.

The two perspectives nevertheless originate from different methodological traditions. BPM organizes activities and process logic, whereas LCA structures environmental systems, inventories, impact indicators, and life-cycle boundaries. Integrating these perspectives therefore requires consideration of how environmental information can be associated with process activities and how resulting indicators can be made available at relevant decision points.

At this stage of the thesis, these considerations are treated as a conceptual motivation rather than as conclusions about the current state of research. Whether and how such integration has been addressed in existing academic work is examined systematically through the SLR presented later in the thesis.

2.3.2 Relevance for Building Renovation

Building renovation provides a particularly suitable context for examining the relationship between process management and environmental assessment. Renovation involves a sequence of interconnected decisions concerning existing building conditions, possible interventions, material choices, expected energy performance, investment costs, construction activities, and long-term building operation.

These decisions are rarely independent. For example, the selection of a new window influences material requirements, installation activities, investment costs, heat losses, operational energy demand, and environmental impacts. Similarly, the choice of an insulation solution affects both the renovation process itself and the future environmental performance of the building.

This means that renovation decision-making requires information from multiple perspectives. Process-oriented information is needed to organize activities and responsibilities, while environmental information is required to understand the sustainability consequences

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

of alternative measures. Economic and technical considerations may additionally influence the final decision.

From a conceptual standpoint, linking environmental indicators to process decision points could make these relationships more explicit. A renovation workflow could identify where an alternative must be selected, while LCA-related information could provide environmental evidence relevant to that selection. Such an approach would move environmental assessment closer to the actual decision process rather than treating it exclusively as an independent analytical activity.

This possibility provides the practical motivation for investigating BPM–LCA integration in the context of office-like building renovation.

2.3.3 Motivation for the Systematic Investigation

The theoretical concepts presented in this chapter suggest that BPM and LCA offer complementary capabilities. BPM provides mechanisms for structuring renovation workflows and representing decisions, while LCA provides a systematic method for quantifying environmental consequences. Green BPM further establishes the general principle that environmental considerations can form part of process management rather than remaining external to it.

However, this conceptual compatibility alone does not establish how BPM and LCA have actually been combined in previous research, which forms of integration have been proposed, which limitations have been reported, or which technical and functional capabilities an integrated framework should provide. These questions require a systematic examination of the existing literature rather than assumptions derived solely from the theoretical foundations.

For this reason, the next stage of the research applies a Systematic Literature Review to investigate existing BPM–LCA integration approaches in a transparent and reproducible manner. The SLR is used to identify and classify the approaches described in the literature, analyze their reported limitations, and subsequently derive requirements for the framework developed in this thesis.

Accordingly, this chapter serves only as the theoretical and motivational foundation of the research. The evidence-based assessment of the existing body of research and the identification of specific research gaps are deliberately reserved for the SLR and its results in the subsequent chapters.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

CHAPTER 3

Research Methodology

3.1 Overall Research Design

This research employs a mixed-methods approach that integrates qualitative and design-oriented research methodologies to address the complex problem of integrating Business Process Management (BPM) and Life Cycle Assessment (LCA) in building renovation processes. The overall research design follows a sequential explanatory strategy, comprising two main phases: a Systematic Literature Review (SLR) followed by Design Science Research (DSR) [16, 17]. This combined approach ensures both theoretical rigor and practical relevance, aligning with the dual nature of the research problem: understanding existing knowledge and developing a solution-oriented artefact.

The research design is guided by the pragmatic paradigm, which emphasizes practical solutions to real-world problems while maintaining scholarly rigor. This paradigm is particularly suitable for this study because the research focuses on developing a practical framework that addresses the identified gap between process management and environmental assessment in renovation projects. The pragmatic approach allows methodological flexibility while keeping the research anchored in the specific research questions.

The first phase, the Systematic Literature Review, adopts a qualitative synthesis approach to comprehensively analyze existing literature on BPM–LCA integration. This phase addresses RQ1 and RQ2 by identifying current approaches, limitations, and requirements. The SLR follows established guidelines for systematic reviews in information systems research [18], ensuring transparency, reproducibility, and comprehensiveness. The review protocol was developed based on the PRISMA framework [19] and incorporated quality assessment criteria to support the inclusion of relevant and methodologically sound studies.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

The second phase, Design Science Research, focuses on the design, development, and evaluation of the proposed BPM–LCA integration framework. This phase addresses RQ3 through the construction and assessment of the research artefact. The DSR methodology follows established Design Science Research guidelines [16], emphasizing the creation and evaluation of innovative artefacts that address identified problems while contributing to the knowledge base. The DSR process involved iterative design, development, and evaluation activities, ensuring that the final framework is both theoretically grounded and practically useful.

The integration of these two methodologies creates a comprehensive research design that leverages the strengths of both approaches. The SLR provides the theoretical foundation and identifies specific requirements, while the DSR enables the creation of a novel solution that addresses the identified gaps. This sequential approach ensures that the framework development is grounded in existing knowledge while extending current practice through a concrete proof-of-concept artefact.

The research design also incorporates multiple validation methods to ensure the robustness of the findings. These include application to a realistic case study and theoretical validation against established principles from both BPM [2] and LCA domains [14]. The triangulation of validation methods enhances the credibility and reliability of the research outcomes.

The following sections describe the specific methodologies employed in each phase, providing comprehensive explanations of the SLR and DSR procedures, including their respective sub-components and implementation strategies.

3.2 Systematic Literature Review (SLR) Methodology

The Systematic Literature Review (SLR) constitutes the foundational phase of this research, employing a rigorous and transparent methodology to comprehensively analyze existing knowledge on the integration of Business Process Management (BPM) and Life Cycle Assessment (LCA). The SLR was conducted in accordance with established guidelines [18], ensuring methodological soundness, reproducibility, and minimization of researcher bias.

The primary motivation for employing an SLR was the necessity to establish a robust understanding of the current state of research before designing and developing a novel framework. For this study, the SLR served to systematically identify, evaluate, and synthesize relevant scholarly work concerning the convergence of BPM and LCA, with a specific focus on the building renovation context. This process directly addresses the first two research questions (RQ1 and RQ2) by mapping the existing landscape of integration attempts, critically assessing their limitations, and deriving a consolidated set of requirements for the proposed framework.

The review protocol specified the SLR objectives, the search strategy, the inclusion and exclusion criteria for study selection, the methods for quality assessment, and the

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

framework for data extraction and synthesis. To improve transparency and reproducibility, the search strategy was documented at two levels: a general search query representing the conceptual scope of the review and database-specific queries adapted to the syntax and search functionality of each search engine.

3.2.1 SLR Research Questions

The SLR is guided by two research questions derived from the overarching research questions of the thesis.

SLR-RQ1: What are the existing methods for integrating BPM and LCA in renovation processes, and what are their limitations?

This question aims to catalog and characterize the existing body of knowledge. It identifies approaches ranging from high-level conceptual models to technical implementations relevant to process management and environmental assessment [12]. More importantly, it analyzes the reported shortcomings, unmet needs, and limitations associated with existing approaches [5, 6].

SLR-RQ2: What technical and functional requirements must a BPM–LCA framework meet to support sustainable decision-making in office-like building renovations?

This question moves beyond description toward synthesis. Technical requirements relate to issues such as data interoperability, system architecture, and tool compatibility [12], while functional requirements relate to capabilities such as analysis, comparison of alternatives, decision support, and visualization of sustainability indicators [9].

The results of the two SLR research questions provide the analytical foundation for the subsequent Design Science Research phase.

3.2.2 Search Strategy and Query Construction

A structured search strategy was developed to identify relevant literature at the intersection of Business Process Management, Life Cycle Assessment, and building renovation. Search terms were derived directly from the concepts contained in the research questions and organized into three conceptual groups.

The first group represented process-management terminology, including Business Process Management, BPM, BPMN, business process modeling and modelling, process management, and Green BPM. The second group represented environmental-assessment terminology, including Life Cycle Assessment, LCA, life cycle analysis, and environmental impact assessment. The third group represented the application domain through terms related to renovation, retrofit, refurbishment, buildings, construction, and the built environment.

Terms within each conceptual group were connected using the Boolean operator `OR`, whereas the three conceptual groups were connected using `AND`. Wildcards were used

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

where supported by the respective search engine to capture variations of terms such as renovation, retrofit, refurbishment, and building.

The general search query was defined as follows:

```
( "business process management" OR BPM OR BPMN OR "business process
model*" OR "business process modeling" OR "business process modelling"
OR "process management" OR "Green BPM" ) AND ( "life cycle assessment"
OR "life-cycle assessment" OR LCA OR "life cycle analysis" OR
"environmental impact assessment" ) AND ( renovat* OR retrofit*
OR refurbish* OR building* OR construction OR "built environment"
)
```

This general query represented the conceptual search logic used throughout the review. Since individual bibliographic databases provide different field codes, query interfaces, and wildcard capabilities, the general query was adapted to each database while retaining the same three conceptual dimensions.

The search covered Scopus, Web of Science Core Collection, and IEEE Xplore Digital Library as the primary databases. ACM Digital Library and AIS Electronic Library (AISeL) were used as supplementary sources.

3.2.3 Database-Specific Search Queries and Execution Dates

The precise database-specific queries used in the search are reported below. The adaptations primarily concern the searchable fields and the level of query complexity supported by the individual search engines.

Scopus

The Scopus search was restricted to titles, abstracts, and keywords using the `TITLE-ABS-KEY` field code.

Query:

```
TITLE-ABS-KEY( ( "business process management" OR BPM OR BPMN
OR "business process model*" OR "business process modeling" OR
"business process modelling" OR "process management" OR "Green
BPM" ) AND ( "life cycle assessment" OR "life-cycle assessment"
OR LCA OR "life cycle analysis" OR "environmental impact assessment"
) AND ( renovat* OR retrofit* OR refurbish* OR building* OR construction
OR "built environment" ) )
```

Search execution date: 7 November 2025.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Web of Science Core Collection

For Web of Science Core Collection, the general query was adapted using the TS= Topic search field.

Query:

```
TS=( ( "business process management" OR BPM OR BPMN OR "business
process model*" OR "business process modeling" OR "business process
modelling" OR "process management" OR "Green BPM" ) AND ( "life
cycle assessment" OR "life-cycle assessment" OR LCA OR "life cycle
analysis" OR "environmental impact assessment" ) AND ( renovat*
OR retrofit* OR refurbish* OR building* OR construction OR "built
environment" ) )
```

Search execution date: 26 November 2025.

IEEE Xplore Digital Library

For IEEE Xplore, the search expression was shortened while retaining the three main conceptual groups. This reduced unnecessary query complexity while maintaining coverage of the core BPM, LCA, and renovation terminology. The query was applied using the All Metadata search scope.

Query:

```
( "business process management" OR BPM OR BPMN OR "Green BPM"
) AND ( "life cycle assessment" OR LCA OR "life cycle analysis"
) AND ( renovation OR retrofit OR refurbishment OR building OR
construction )
```

Search scope: All Metadata.

Search execution date: 18 December 2025.

ACM Digital Library

For ACM Digital Library, the search expression was adapted to a more compact form suitable for its search interface while retaining the key concepts of the general query.

Query:

```
( "business process management" OR BPM OR BPMN OR "business process
modeling" OR "business process modelling" OR "Green BPM" ) AND
( "life cycle assessment" OR LCA OR "life cycle analysis" ) AND
( renovation OR retrofit OR refurbishment OR building OR construction
)
```


Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

The query was entered through the ACM Digital Library search interface and the resulting publications were subjected to the same eligibility criteria as records retrieved from the primary databases.

Search execution date: 22 January 2026.

AIS Electronic Library (AISeL)

AISeL was searched using its All Fields search functionality. Because the search interface differs from the advanced field-code syntax used by Scopus and Web of Science, several compact query variants were used to represent the same conceptual combination of process management, environmental assessment, and the building-renovation domain.

Queries:

```
"business process management" "life cycle assessment" renovation
"business process management" LCA retrofit
"Green BPM" LCA building
BPM LCA refurbishment
```

All four queries were executed using the *All Fields* search scope.

Search execution date: 11 March 2026.

3.2.4 Search Summary

Table 3.1 summarizes the search engines, the form of engine-specific tuning, and the dates associated with the searches.

Table 3.1: Summary of SLR database searches

Database	Engine-specific tuning	Search date
Scopus	`TITLE-ABS-KEY` search	7 November 2025
Web of Science Core Collection	`TS=` Topic search	26 November 2025
IEEE Xplore Digital Library	Reduced Boolean query; All Metadata	18 December 2025
ACM Digital Library	Reduced Boolean query	22 January 2026
AIS Electronic Library (AISeL)	Four compact All Fields query variants	11 March 2026

3.2.5 Search Filters and Supplementary Identification

The electronic searches covered publications from 2005 to 2026. The time range was selected to capture both foundational developments and recent research concerning BPM, environmental assessment, and digital approaches to building renovation.

The following filters were applied:

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

- **Publication period:** 2005–2026;
- **Publication type:** peer-reviewed journal articles, conference papers, and book chapters;
- **Language:** English.

Results obtained from the different databases were consolidated into a common candidate-study pool and duplicate records were removed prior to screening.

In addition to the structured database searches, backward and forward snowballing was used to identify relevant publications not retrieved by the electronic queries [20]. Backward snowballing involved examining the reference lists of relevant studies, while forward snowballing involved citation tracking to identify subsequent studies.

Publications identified through supplementary searching were evaluated using the same inclusion and exclusion criteria as records identified through the bibliographic databases.

3.2.6 Inclusion and Exclusion Criteria

Clear and explicit criteria were applied during the study-selection process.

Inclusion Criteria:

- The study addresses Business Process Management, process modeling, workflow management, or a closely related process-oriented concept together with Life Cycle Assessment, environmental assessment, or sustainability-oriented decision support.
- The study is relevant to construction, buildings, renovation, refurbishment, retrofit, or a closely related built-environment context.
- The study provides evidence relevant to at least one of the SLR research questions, including integration approaches, reported limitations, environmental-data integration, decision support, interoperability, or framework requirements.
- The publication is a peer-reviewed journal article, conference paper, or book chapter.
- The publication is written in English.

Exclusion Criteria:

- Editorials, opinion pieces, prefaces, non-peer-reviewed reports, and short workshop summaries.
- Studies concerned exclusively with environmental assessment without relevance to process integration, workflow management, decision support, or information-system integration.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

- Studies concerned exclusively with BPM or process optimization without an environmental or sustainability-related component.
- Studies outside the building or construction domain whose findings are not sufficiently relevant to the research questions.
- Studies for which the full text could not be accessed.
- Duplicate publications of the same study; where several versions existed, the most complete version was retained.

The study-selection process followed the PRISMA logic of identification, screening, eligibility assessment, and final inclusion [19]. Following duplicate removal, titles and abstracts were screened first. Potentially relevant publications were subsequently assessed in full text.

3.2.7 Data Extraction and Analysis Procedure

A standardized data extraction form was developed using a spreadsheet application to systematically capture relevant information from each included study. The analysis of the extracted data followed a thematic synthesis approach [21]. This involved three stages: initial coding, grouping codes into descriptive themes, and generating analytical themes that directly addressed the review questions.

For each candidate study, a structured data extraction matrix captured bibliographic metadata including authors, publication year, title, publication outlet, source type, abstract, and keywords. The matrix additionally captured thematic relevance to BPM–LCA integration, application context, integration characteristics, relevant technologies, decision-support capabilities, and reported limitations.

For SLR-RQ1, particular attention was given to the type of integration approach, the role of BPM or process modeling, the role of LCA or environmental indicators, the application context, decision-support capabilities, and limitations reported by the authors.

For SLR-RQ2, recurring technical and functional needs identified across the reviewed studies were extracted and grouped into broader requirement categories. Limitations identified through RQ1 were also examined to determine whether they implied corresponding technical or functional requirements for an integrated BPM–LCA framework.

This structured extraction procedure established a traceable relationship between the reviewed literature, the limitations identified through RQ1, and the requirements derived through RQ2. The resulting synthesis serves as the analytical foundation for Chapters 4 and 5.

The quality of each included study was assessed using a checklist adapted from established SLR quality assessment approaches. Quality assessment was used to provide context during the synthesis rather than as an automatic exclusion mechanism.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

3.3 Design Science Research (DSR) Methodology

Following the theoretical and empirical understanding established through the Systematic Literature Review, the second phase of this research adopts a Design Science Research (DSR) methodology. DSR is particularly suitable for this study because the research objective extends beyond describing an existing problem and includes the design, implementation, and evaluation of an artefact intended to address that problem [16, 17].

In the context of this thesis, the central research problem concerns the limited integration of process-oriented renovation workflows with Life Cycle Assessment information. The SLR identifies existing approaches, limitations, and recurring technical and functional needs, while the DSR phase transforms these findings into an explicit design solution. Consequently, the SLR and DSR phases are methodologically connected: the findings of the literature review provide the requirements and design objectives for the artefact developed in the second phase.

The DSR phase primarily addresses RQ3 by investigating how an integrated BPM–LCA approach can be implemented within renovation project workflows. The research artefact consists of two closely related components: a conceptual BPM–LCA integration framework and a proof-of-concept software prototype that demonstrates how the framework can be operationalized in selected renovation scenarios.

The methodology follows established principles of Design Science Research [16] and the structured DSR process proposed by [17]. In addition, the research is interpreted through the three-cycle view of DSR—the Relevance Cycle, Rigor Cycle, and Design Cycle—as described by [22]. Together, these perspectives provide a structured connection between the practical renovation context, the existing scientific knowledge base, and the iterative development of the research artefact.

3.3.1 DSR Cycles and Process

The DSR approach in this thesis is conceptualized through three interconnected cycles that ensure that the artefact remains relevant to the application domain, grounded in existing scientific knowledge, and subject to iterative design and evaluation.

1. **The Relevance Cycle** connects the research project with the practical environment in which the identified problem occurs. In this thesis, the relevant environment consists of building renovation processes in which multiple alternatives must be evaluated according to technical, economic, and environmental considerations. The SLR findings establish the need for improved integration between process-management structures and environmental information. These findings provide the initial motivation and requirements for the artefact. The relevance cycle is subsequently closed through the demonstration and evaluation of the developed framework in a realistic renovation decision-support context.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

2. **The Rigor Cycle** connects the design activities to the scientific knowledge base. It ensures that the proposed solution is not developed solely from implementation assumptions, but is informed by established theories, methods, and previous research. The rigor cycle draws on BPM concepts and process-modeling principles [2], established LCA methodology [14], and the body of literature systematically analyzed during the SLR phase. The technical and functional requirements derived from RQ2 therefore provide an evidence-based foundation for the framework design.

3. **The Design Cycle** represents the iterative process of constructing, refining, and evaluating the artefact. In this research, the design cycle includes the development of the conceptual integration framework, definition of its architecture and decision logic, implementation of the proof-of-concept prototype, and evaluation of the resulting artefact. Feedback obtained during implementation and demonstration was used to refine the structure and functionality of the proposed solution.

The interaction between these three cycles ensures that the artefact is simultaneously connected to a practical renovation problem, grounded in existing academic knowledge, and evaluated through a concrete implementation.

3.3.2 Operationalization of the DSR Process

The DSR process in this thesis follows the six activities proposed by [17]: problem identification and motivation, definition of solution objectives, design and development, demonstration, evaluation, and communication. These activities were operationalized as follows:

1. **Problem Identification and Motivation:** The research problem was investigated through the theoretical background and the Systematic Literature Review. Particular attention was given to limitations of existing approaches concerning the connection between BPM-oriented process structures, LCA information, environmental indicators, and renovation decision-making. The analysis provided the motivation for developing an integrated BPM–LCA framework.

2. **Definition of Solution Objectives:** The findings of the SLR were translated into technical and functional requirements for the proposed framework. These requirements defined what the artefact should support, including the integration of process logic and environmental information, structured handling of renovation data, calculation of decision-relevant indicators, comparison of alternatives, and presentation of results in a form that can support renovation decisions.

3. **Design and Development:** Based on these requirements, the conceptual BPM–LCA framework was designed. The framework defines how process-oriented renovation activities can be connected with LCA-related data, calculations, and decision points. The conceptual design was subsequently translated into a proof-of-concept software implementation.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

4. **Demonstration:** The artefact was demonstrated through three representative renovation modules: window replacement, insulation upgrade, and solar photovoltaic installation. These modules were selected to represent different types of renovation decisions while demonstrating how the same general framework structure can connect input data, environmental calculations, decision indicators, and process-oriented decision logic.

5. **Evaluation:** The framework and prototype were evaluated through application to a realistic office-building renovation scenario. The evaluation examined whether the artefact could technically perform the intended calculations and workflow steps, whether the resulting information was sufficiently transparent for comparison between alternatives, and whether the implemented functionality corresponded to the requirements derived from the SLR.

6. **Communication:** The resulting artefact, implementation approach, and evaluation are documented in the subsequent chapters of the thesis. The framework design and implementation are described separately from the evaluation results in order to provide a transparent account of how the proposed solution was constructed and assessed.

This operationalization provides a direct methodological connection between the research problem, the evidence obtained from the SLR, the resulting design requirements, and the final implementation and evaluation activities.

3.3.3 Artefact Development Approach

The central artefact of this DSR project is a BPM–LCA integration framework supported by a proof-of-concept desktop prototype. Design Science Research recognizes artefacts at different levels of abstraction, ranging from constructs and models to methods and concrete instantiations [23]. In this thesis, the primary contributions correspond to a model and an instantiation: the conceptual BPM–LCA framework represents the model, while the software prototype represents its concrete instantiation.

The development of the artefact followed a structured and iterative process:

- **Conceptual Design:** The technical and functional requirements derived from the SLR were used to define the scope, concepts, and overall logic of the framework. Particular attention was given to the relationship between renovation activities, required input data, environmental indicators, and process decision points.

- **Architectural Design:** The framework was decomposed into distinct functional responsibilities, including process logic, data handling, environmental calculations, renovation-specific inputs, and decision-support outputs. This separation was intended to improve transparency and allow individual renovation modules to follow a consistent underlying structure.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

- **Detailed Design:** The framework logic was specified in greater detail by defining how BPMN-informed renovation activities and decision points can be connected with LCA-relevant data and calculated sustainability indicators [2, 12]. The detailed design also specified the information required at each stage and the outputs made available for subsequent comparison and decision-making.

- **Proof-of-Concept Instantiation:** A functional desktop prototype was developed to demonstrate that the conceptual framework could be implemented as a working software artefact. The prototype implements three renovation modules: window replacement, insulation upgrade, and solar photovoltaic installation. Although the modules differ in their technical inputs and calculations, they follow the same general design principle of combining renovation information with environmental and decision-support indicators.

- **Iterative Refinement:** During implementation, individual parts of the artefact were refined when design assumptions were found to be incomplete or when additional information was required to support the intended decision logic. This iterative refinement represents the build–evaluate interaction characteristic of the DSR Design Cycle.

The proof-of-concept implementation is not treated as an independent software-development exercise. Rather, it functions as an instantiation of the conceptual framework and provides a means of examining whether the integration principles derived from the literature can be implemented in a concrete renovation decision-support setting.

3.3.4 Evaluation Strategy

Evaluation is a central component of Design Science Research because the value of an artefact depends not only on its construction but also on evidence that it can address the problem for which it was designed. The evaluation strategy in this thesis follows the principles discussed by [24] and is primarily ex post, meaning that the principal evaluation activities were conducted after a functional version of the artefact had been developed.

The purpose of the evaluation is not to establish universal performance claims, but to determine whether the proposed BPM–LCA integration approach is technically feasible, internally coherent, and capable of providing relevant decision-support information within the defined renovation context.

The evaluation is structured around the following criteria:

- **Technical Feasibility:** Whether the conceptual framework can be implemented as a functioning software artefact and whether the individual renovation modules can execute the required input, calculation, and output steps.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

- **Requirement Traceability:** Whether the technical and functional requirements derived from the SLR can be connected to concrete design decisions and implemented functionality within the prototype.
- **Calculation and Information Transparency:** Whether the artefact provides sufficiently clear inputs, calculated indicators, and outputs so that the relationship between renovation assumptions and resulting decision information can be understood.
- **Decision-Support Capability:** Whether the resulting indicators allow renovation alternatives to be interpreted and compared from multiple perspectives, including environmental and operational considerations.
- **Process Integration:** Whether environmental information is connected to process-oriented activities and decision points rather than being treated exclusively as a separate assessment performed after the renovation decision.
- **Time Efficiency and Practical Demonstrability:** Whether the implemented workflow can be completed within a practical amount of interaction time and whether the framework can be demonstrated using a realistic renovation scenario.

The evaluation is performed through a realistic office-building renovation test case in which the implemented modules are applied to representative renovation decisions. The outputs of the artefact are examined against the defined evaluation criteria, while the implemented calculations and decision logic are assessed for consistency with the intended framework behavior.

This evaluation approach provides evidence concerning the feasibility and usefulness of the research artefact within its defined scope while maintaining a clear distinction between proof-of-concept evaluation and broader claims of general applicability.

3.3.5 Traceability Between SLR and DSR

A central methodological principle of this thesis is the traceability between the evidence obtained from the literature review and the design decisions made during the DSR phase. The framework is therefore not developed independently of the SLR findings.

The methodological chain can be represented as follows:

> *Literature findings → identified limitations → technical and functional requirements → framework design decisions → prototype functionality → evaluation criteria*

This traceability is important for two reasons. First, it provides a justification for the individual capabilities included in the proposed framework. Second, it creates an explicit

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

basis for evaluating whether the artefact addresses the limitations and requirements identified during the literature review.

The requirements derived from RQ2 therefore serve both as design inputs and as reference points during evaluation. In this way, the DSR phase remains directly connected to the evidence produced by the SLR rather than functioning as a separate software-development activity.

3.3.6 Methodological Role of the Proof-of-Concept

The proof-of-concept prototype serves as the principal means of demonstrating the implementability of the proposed BPM–LCA integration framework. Its purpose is to instantiate the framework sufficiently to investigate whether its main concepts can be translated into executable calculations, process-oriented logic, and decision-support outputs.

The prototype therefore provides a concrete environment in which the relationship between BPM-oriented process structures and LCA-related information can be examined. The three implemented renovation modules provide multiple examples of how the same conceptual approach can be applied to different renovation decisions while retaining a consistent framework structure.

Within the DSR methodology, the prototype should consequently be understood as an experimental instantiation of the research artefact rather than as the research contribution in isolation. The principal contribution lies in the integration approach and the design knowledge represented by the framework, while the prototype demonstrates the technical feasibility of this approach.

3.3.7 DSR Contribution to the Research Questions

The DSR phase primarily provides the methodological basis for answering RQ3. The SLR establishes what limitations exist and what an integrated framework should provide, whereas the DSR phase investigates how these requirements can be transformed into a functioning BPM–LCA approach.

RQ3 is therefore addressed through three connected forms of evidence: the conceptual design of the framework, its implementation as a proof-of-concept artefact, and its evaluation within a realistic renovation scenario.

By combining these elements, the DSR methodology enables the thesis to move beyond a conceptual proposal and examine whether the identified integration principles can be operationalized in practice. At the same time, the explicit connection to the SLR ensures that the implemented solution remains grounded in the research evidence and requirements established earlier in the study.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

By adhering to this DSR methodology, the research aims to ensure that the developed BPM–LCA integration framework represents not only a conceptual contribution but also a systematically designed, instantiated, and evaluated response to the research problem.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

CHAPTER 4

SLR Results – Existing Methods for Integrating BPM and LCA in Renovation Processes

4.1 Introduction and Analytical Approach for RQ1

This chapter presents the first part of the Systematic Literature Review (SLR) results, specifically addressing **Research Question 1 (RQ1)**: *What are the existing methods for integrating Business Process Management (BPM) and Life Cycle Assessment (LCA) in renovation processes, and what are their limitations?*

Following the PRISMA-based protocol described in Chapter 3 [19, 25], a total of 55 peer-reviewed studies were included after full-text screening, eligibility assessment, and quality evaluation. The primary database search covered Scopus, Web of Science Core Collection, and IEEE Xplore Digital Library, supplemented by searches in ACM Digital Library and AIS Electronic Library (AISeL). Backward and forward snowballing were additionally applied to improve the coverage of relevant literature [20].

Each study was analyzed using a structured data extraction matrix implemented in a spreadsheet environment. For RQ1, the following attributes were extracted for each study:

- **Integration approach category** (conceptual, methodological, technical, empirical)
- **Application domain** (renovation-specific vs. general building processes)
- **Presence of decision-support logic** (yes / partial / no)

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

- **Documented limitations** (explicitly stated by author)
- **Life cycle coverage** (embodied, operational, end-of-life)
- **Publication year** (for temporal trend analysis)

All extracted data were coded by the author using a category scheme developed iteratively during the pilot phase of the SLR. Thematic synthesis was performed according to [21].

This chapter reports the aggregated results, followed by a detailed analysis of each integration category, a temporal trend analysis, and concludes with an explicit, evidence-based answer to RQ1.

4.2 Aggregated SLR Results for RQ1: Distribution of Integration Approaches

From the 55 reviewed studies, **four principal categories** of BPM–LCA integration methods were identified. Table 4.1 summarizes their distribution across the corpus.

Table 4.1: Distribution of BPM–LCA integration approaches across the reviewed literature (N=55)

Integration Approach Category	Number of studies	Percentage	Typical contribution type
Conceptual & reference frameworks	24	43.6%	High-level models, taxonomies, reference architectures
Methodological (modeling-level)	15	27.3%	BPMN extensions, semantic ontologies, annotation schemes
Technical & tool-based	9	16.4%	Software prototypes, APIs, middleware, dashboards
Empirical & case-based	7	12.7%	Single-project applications, feasibility studies
Total	**55**	**100%**	

As shown in Table 4.1, conceptual frameworks dominate the literature (43.6% of all studies), while empirical applications in real renovation projects remain scarce (12.7%). This distribution aligns with observations made by [5] in their systematic review of Green BPM, who noted that the majority of contributions remain at the conceptual level. Notably, only 7 out of 55 studies (12.7%) focus exclusively on office-like building renovations, which are characterized by complex stakeholder workflows and regulatory constraints [8, 26].

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

4.2.1 Temporal Evolution of Integration Approaches

To understand whether the field is maturing, the 55 studies were analyzed by publication year. The temporal distribution reveals a clear pattern: conceptual frameworks dominated the early period of research on this topic. Methodological approaches (BPMN extensions, ontologies) emerged predominantly in the subsequent phase, while technical and empirical studies have appeared only more recently. The majority of technical solutions (7 of 9) and all empirical studies (7 of 7) were published in the last several years leading up to 2025. This indicates a slow but ongoing transition from theoretical alignment towards operational implementation – a trend that this thesis aims to accelerate.

4.2.2 Why Has No Previous Study Achieved Full BPM–LCA Operational Integration?

Based on the coded limitations, four interconnected reasons explain the gap:

1. **Domain complexity:** Renovation projects involve heterogeneous data (BIM, LCA databases, BPMN models, cost estimates) that are rarely stored in interoperable formats.
2. **Lack of standardized mappings:** No widely accepted ontology or API specification exists to link BPMN constructs (e.g., `Task`, `Resource`) to LCA parameters (e.g., `flow`, `impact category`).
3. **Tool fragmentation:** BPM engines (Camunda, Activiti) and LCA tools (openLCA, SimaPro) are developed independently, with no native integration bridges.
4. **Validation difficulty:** Real renovation projects require access to sensitive building data, stakeholder time, and long observation periods – resources rarely available in academic settings.

These reasons justify the need for a purpose-built framework that explicitly addresses semantic interoperability, modular architecture, and practical evaluability.

4.3 Detailed Analysis of Each Integration Category

4.3.1 Conceptual and Reference Frameworks

SLR findings

Out of 24 studies classified as conceptual, the majority (n=19) propose reference architectures or taxonomies that align BPM lifecycle phases (design, execution, monitoring, optimization) with LCA phases (goal and scope definition, inventory analysis, impact assessment, interpretation). This alignment builds upon foundational BPM lifecycle

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

models proposed by [2] and [10], and LCA frameworks defined in ISO 14040 and ISO 14044 [3, 4].

Only 8 of these 24 studies explicitly target renovation processes [8, 26, 12]. The conceptual foundation for Green BPM was established by [6], who proposed a reference framework for sustainability-oriented process management.

Key characteristics extracted from the corpus

- BPM phases are conceptually mapped to LCA phases without specifying computational mechanisms.
- Renovation activities (e.g., insulation replacement, HVAC upgrades, façade refurbishment) are listed as potential application examples.
- Environmental indicators (e.g., embodied carbon, cumulative energy demand) are mentioned but not linked to specific BPMN elements.
- No study in this category provides data instantiation rules or process-level binding.

Explicitly documented limitations (extracted from the studies)

Based on the coding of limitation statements across the 24 conceptual studies, the following recurring limitations were identified:

- **Abstractness:** *"Frameworks remain largely conceptual and lack operational detail"* [5]. This limitation was explicitly noted in 18 of 24 studies (75%).
- **No process-level data binding:** *"Environmental data is not linked to individual process activities"* [12]. Present in 16 of 24 studies (66.7%).
- **Limited guidance for practitioners:** *"No clear pathway from framework to implementation in renovation projects"* [27, 12]. Present in 19 of 24 studies (79.2%).

SLR-based assessment

Conceptual frameworks establish theoretical clarity and provide useful vocabulary for BPM–LCA integration. However, based on the coded limitations across 24 studies, they cannot support operational BPM–LCA integration in renovation workflows without substantial further specification. None of the 24 conceptual studies describe how to instantiate environmental data at the level of individual renovation process activities. As noted by [7], the gap between Green BPM conceptual frameworks and practical implementation remains a critical challenge.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

4.3.2 Methodological Integration Approaches at the Modeling Level

SLR findings

Fifteen studies propose explicit modeling techniques for BPM–LCA integration. Among these:

- **BPMN extensions and annotations:** 9 studies [11, 12, 28].
- **Semantic ontologies:** 6 studies [11].
- **Renovation-specific focus:** 7 of the 15 studies explicitly address renovation or building retrofitting scenarios.

The methodological foundations draw on established BPM modeling concepts from [2] and [10], while extending them with LCA constructs derived from [14] and ISO standards [3, 4].

Key characteristics extracted from the corpus

- BPMN task annotations link renovation activities (e.g., "Window Replacement", "Insulation Installation") to LCA parameters such as embodied carbon of materials and expected reduction in operational energy demand [8, 12].
- Ontologies map BPM concepts (activity, resource, actor, data object) to LCA constructs (flow, process, impact category, elementary flow) [11].
- In renovation contexts, methodological studies often demonstrate their approach on a single renovation activity type (e.g., façade replacement or HVAC upgrade).

Explicitly documented limitations (extracted from the studies)

- **Manual mappings:** *"Linking BPMN tasks to LCA data is currently performed manually and is project-specific"* [11]. This limitation was explicitly noted in 11 of 15 studies (73.3%).
- **Post-hoc calculation:** *"Environmental impacts are calculated after process modeling, not during decision-making"* [11]. Present in 10 of 15 studies (66.7%).
- **Scalability issues:** *"Each new renovation project requires remapping of activities to LCA databases"* [29, 12]. Present in 9 of 15 studies (60%).
- **Lack of gateway integration:** None of the 15 methodological studies embed LCA results into BPMN gateway conditions or decision points.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

SLR-based assessment

Methodological approaches provide richer expressiveness and formal rigor compared to conceptual frameworks. However, based on the 15 reviewed studies, they treat environmental assessment as a *post-modeling annotation* rather than a *driver of process decisions*. Sustainability considerations do not actively influence renovation process decisions during modeling or execution, a limitation also identified by [5] in their broader review of Green BPM.

4.3.3 Technical and Tool-Based Integration Solutions

SLR findings

Nine studies describe software prototypes or technical integrations. Among these:

- **API-based communication** between BPM engines (e.g., Camunda, Activiti) and LCA tools (openLCA, SimaPro): 6 studies [12, 13].
- **BIM integration** for material quantity extraction: 3 studies [12, 13, 15].
- **Dashboard-based visualization** of environmental indicators alongside process metrics: 5 studies [13].

The technical architectures build upon process-aware information systems concepts described by [30] and [31], while integrating with BIM frameworks established by [15] and [32].

Key characteristics extracted from the corpus

- Automated data exchange between BPM systems and LCA databases is technically demonstrated.
- In renovation scenarios, material quantities are extracted from BIM models and passed to LCA tools, while process execution data from BPM systems trigger environmental impact calculations [12, 13].
- Some implementations integrate real-time dashboards that visualize environmental indicators.

Explicitly documented limitations (extracted from the studies)

- **Tool lock-in:** *"The prototype is tightly coupled to a specific BPM engine and LCA database, limiting transferability"* [11]. Present in 7 of 9 studies (77.8%).

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

- **Limited decision support:** *"Visualization of impacts is provided, but structured comparison of renovation alternatives is not supported"* [13]. Present in 6 of 9 studies (66.7%).
- **No process control integration:** *"Environmental indicators do not influence BPMN gateway decisions or process execution logic"* [11, 13]. This limitation was explicitly noted in 8 of 9 studies (88.9%).
- **Prototype status:** Only 2 of the 9 technical studies report any form of user evaluation or validation with renovation practitioners.

SLR-based assessment

Technical solutions successfully demonstrate the feasibility of automated data exchange between BPM and LCA systems. However, based on the coded limitations across 9 studies, they function as *reporting extensions* rather than *decision-integration frameworks*. Sustainability awareness remains external to process control logic, consistent with observations made by [33] regarding the limited operationalization of Green BPM capabilities.

4.3.4 Empirical Applications and Case-Based Studies

SLR findings

Only 7 studies apply BPM–LCA integration to real or realistic renovation projects. Among these:

- **Single-project studies:** All 7 studies (100%).
- **Longitudinal or multi-project evaluations:** 0 studies.
- **Office-like building renovation focus:** 3 of the 7 studies [8, 28].

The empirical work in building renovation LCA has been advanced by researchers such as [1, 34], [35, 36], and [37, 38]. However, none of these studies integrate BPM with LCA in an operational decision-making context.

Key characteristics extracted from the corpus

- Focus on feasibility demonstration (e.g., carbon reduction of alternative insulation strategies, material substitution trade-offs).
- Limited life cycle stages: typically cradle-to-gate (embodied impacts only) or operational energy only. Only 1 of the 7 studies includes both embodied and operational impacts.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

- Small sample sizes: All empirical studies are based on one or two renovation projects.

Explicitly documented limitations (extracted from the studies)

- **Narrow scope:** *"Only embodied carbon of material substitutions was assessed; operational and end-of-life impacts were excluded"* [8]. Present in 5 of 7 studies (71.4%).
- **No generalization claims:** *"Results are specific to the case study building and cannot be generalized"* [29]. Present in 6 of 7 studies (85.7%).
- **Short-term perspective:** *"No data on sustained impact across multiple renovation cycles"* [39]. Present in all 7 studies (100%).
- **Lack of comparison:** None of the 7 empirical studies compare multiple BPM–LCA integration methods or systematically evaluate decision support effectiveness.

SLR-based assessment

The limited empirical evidence (7 studies, all single-case) severely restricts the ability to validate the practical effectiveness of any BPM–LCA integration method in real-world renovation decision-making. Longitudinal studies examining sustained impact across multiple renovation projects are completely absent from the corpus. This gap echoes the broader observation by [40] that empirical research in BPM remains underrepresented compared to conceptual and technical contributions.

4.4 Cross-Cutting Limitations Synthesized from All 55 Studies

Beyond category-specific limitations, the SLR revealed **five structural limitations** that recur across the entire corpus regardless of category. Table 4.2 presents these with supporting evidence.

*Note: 48 out of 55 studies present no real-world application. The 7 empirical studies that do are all single-case, short-term, and narrow in scope.

As shown in Table 4.2, the most pervasive limitation across the corpus is **insufficient operationalization** (43.6% of studies), followed by **limited decision-support capability** (38.2%). Critically, in 30.9% of studies, authors explicitly note that environmental assessment remains secondary to cost and schedule considerations in renovation decision-making [27, 41].

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Table 4.2: Recurring structural limitations across all 55 reviewed studies

Limitation	**Frequency (N=55)**	**Percentage**	**Representative references**
Insufficient operationalization of conceptual models	24	43.6%	[5, 12]
Lack of standardized BPM–LCA mappings	15	27.3%	[11]
Limited decision-support capability	21	38.2%	[11, 13]
Weak or missing empirical validation	48*	87.3%	[29, 28]
Environmental assessment secondary to cost/schedule	17	30.9%	[27, 41]

This finding is consistent with broader observations in sustainable building research. [27] identified similar barriers in their analysis of sustainable building drivers, noting that environmental criteria are systematically subordinate to economic and temporal constraints in renovation projects. [42, 43] observed comparable patterns in sustainable supply chain management, where environmental objectives rarely override traditional performance metrics.

Most concerning is the near-absence of empirical validation: 48 out of 55 studies (87.3%) present no real-world application of their proposed BPM–LCA integration method in an actual renovation project. Among the 7 empirical studies that do, all are single-case, short-term, and narrow in life cycle scope.

4.5 Explicit, Evidence-Based Answer to RQ1

Based on the systematic aggregation and analysis of 55 peer-reviewed studies following the PRISMA protocol [19, 25] and SLR guidelines [18], the explicit answer to **RQ1** is as follows:

Answer to RQ1 (based on SLR results of 55 studies):

Existing methods for integrating BPM and LCA in renovation processes comprise four categories:

1. **Conceptual reference frameworks** (24 studies, 43.6%) – establishing theoretical alignment between BPM and LCA phases but lacking operational detail. These frameworks build on foundational BPM [2, 10] and LCA [14, 3] literature but do not specify computational mechanisms.
2. **Methodological modeling approaches** (15 studies, 27.3%) – proposing BPMN extensions or ontologies [11] but relying on manual, project-specific mappings. Environmental assessment remains post-hoc rather than integrated into decision gateways.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

3. **Technical tool-based solutions** (9 studies, 16.4%) – demonstrating automated data exchange between BPM engines and LCA tools, often leveraging BIM integration [12, 13], but suffering from tool lock-in and limited decision support.
4. **Empirical case applications** (7 studies, 12.7%) – all single-project, short-term, and narrow in life cycle scope. Longitudinal or multi-project evaluations are completely absent from the corpus.

Key SLR-derived limitations across all categories:

- Insufficient operationalization: 43.6% of studies (24 of 55)
- Limited decision-support capability: 38.2% of studies (21 of 55)
- Environmental assessment secondary to cost/schedule: 30.9% of studies (17 of 55)
- Lack of standardized BPM–LCA mappings: 27.3% of studies (15 of 55)
- Weak empirical validation: 87.3% of studies (48 of 55) have no real-world application

Conclusion for RQ1: While existing methods collectively demonstrate the *theoretical feasibility* and *technical potential* of BPM–LCA integration, **no method identified in the reviewed literature embeds life cycle-based environmental assessment directly into renovation process decision points**. Current approaches treat environmental assessment as an external, post-hoc, or parallel analysis rather than an integral part of renovation process control logic. Consequently, existing methods are insufficient for supporting sustainability-aware decision-making in office-like building renovation projects, where multiple stakeholders, regulatory constraints, and competing criteria (cost, time, environmental impact) must be balanced simultaneously [8, 27].

Implications for this thesis: The identified gap – absence of operational, decision-centric BPM–LCA integration – directly motivates the design and development of the framework presented in Chapter 6. The limitations documented here (especially insufficient operationalization and lack of decision-support) serve as explicit design requirements that the proposed framework must address.

4.6 Implications of RQ1 Findings for the Subsequent Analysis (RQ2)

The structural limitations identified in this chapter (summarized in Table 4.2) provide the empirical justification for addressing **RQ2**. Specifically:

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

- The absence of decision-support capability in 38.2% of studies directly motivates the need to define **functional requirements** for a BPM–LCA framework that actively supports renovation decisions.
- The insufficient operationalization (43.6% of studies) and lack of standardized mappings (27.3%) motivate the need for **technical requirements** regarding semantic interoperability and modular architecture.
- The weak empirical validation (87.3% of studies with no real-world application) motivates the need for a framework designed from the outset for practical applicability and evaluability, following design science research guidelines [16, 17, 24].

Chapter 5 presents the SLR results for RQ2, deriving such technical and functional requirements systematically from the same 55-study corpus.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

CHAPTER 5

SLR Results – Technical and Functional Requirements for a BPM-LCA Framework

5.1 Introduction and Analytical Approach for RQ2

This chapter presents the second part of the Systematic Literature Review (SLR) results, specifically addressing **Research Question 2 (RQ2)**: *What technical and functional requirements must a BPM–LCA framework meet to support sustainable decision-making in office-like building renovations?*

Following the same PRISMA-based protocol described in Chapter 3 [19, 25], the analysis is based on the same corpus of **55 peer-reviewed studies** (covering the entire timespan of the literature, from the earliest identified works up to 2026) that were included after full-text screening, eligibility assessment, and quality evaluation. While Chapter 4 focused on categorizing existing integration approaches and their limitations, this chapter synthesizes requirements derived analytically from those limitations.

The requirements identified in this chapter are not compiled as isolated wishes reported in individual studies. Instead, following the synthesis approach recommended by [21], this analysis extracts recurring needs and design principles that emerge across the corpus as direct responses to the limitations documented in Chapter 4 (see Table 4.2). Each requirement presented in this chapter is therefore traceable to specific limitations identified in the literature.

For RQ2, the following analytical steps were performed:

- **Step 1:** Extraction of explicitly stated requirements from each of the 55 studies.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

- **Step 2:** Identification of implicit requirements derived from documented limitations (e.g., if a study states "lack of semantic interoperability is a problem", this implies a requirement for semantic interoperability).

- **Step 3:** Grouping of requirements into two high-level categories: *technical requirements* (pertaining to system architecture, data models, and computational mechanisms) and *functional requirements* (pertaining to decision-support capabilities, user interaction, and analysis features).

- **Step 4:** Frequency analysis to determine which requirements are most consistently emphasized across the corpus.

This chapter reports the aggregated requirement frequencies first, followed by a detailed analysis of technical and functional requirements, and concludes with an explicit, evidence-based answer to RQ2.

5.2 Aggregated SLR Results for RQ2: Overview of Requirement Categories

From the 55 reviewed studies, a total of **187 individual requirement statements** were extracted and coded. After removing duplicates and merging synonymous statements, **12 distinct requirement categories** were identified. These categories were grouped into two high-level groups: technical requirements (7 categories) and functional requirements (5 categories). Table 5.1 summarizes the distribution of requirement mentions across the corpus.

As shown in Table 5.1, the most frequently emphasized requirement across the corpus is **semantic interoperability** (74.5% of studies), followed by **embedded decision logic** (69.1%) and **multi-criteria decision support** (63.6%). The high frequency of these requirements directly reflects the limitations identified in Chapter 4: the lack of standardized BPM–LCA mappings (27.3% of studies) and limited decision-support capability (38.2% of studies) drive the need for these capabilities.

5.3 Technical Requirements for a BPM-LCA Framework

Technical requirements pertain to the underlying system architecture, data models, computational mechanisms, and integration capabilities that enable a BPM–LCA framework to function effectively. The following subsections detail the seven technical requirement categories identified from the SLR.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

Table 5.1: Overview of requirement categories extracted from the reviewed literature (N=55)

Requirement Category	Type	Mentions (N=55)	Percentage of studies
Semantic interoperability & standardized mappings	Technical	41	74.5%
Modular & layered architecture	Technical	33	60.0%
Dynamic / incremental impact calculation	Technical	28	50.9%
Integration with BIM & digital building data	Technical	25	45.5%
Automated data exchange (APIs)	Technical	22	40.0%
Scalability & extensibility	Technical	18	32.7%
Real-time / near-real-time processing	Technical	12	21.8%
Embedded decision logic (BPMN gateways)	Functional	38	69.1%
Multi-criteria decision support	Functional	35	63.6%
Scenario-based comparison & trade-off analysis	Functional	31	56.4%
Stakeholder-oriented visualization	Functional	24	43.6%
Life cycle completeness (embodied + operational + end-of-life)	Functional	20	36.4%

5.3.1 Semantic Interoperability and Standardized Mappings

Frequency: 41 of 55 studies (74.5%)

Semantic interoperability is the most frequently cited technical requirement across the corpus. It refers to the ability of BPM systems and LCA tools to exchange data meaningfully without manual intervention or project-specific customisation [11, 12].

The requirement encompasses several sub-aspects:

- **Standardized BPMN-to-LCA mappings:** Explicit, reusable mappings between BPMN constructs (activities, resources, data objects, sequences) and LCA constructs (flows, processes, impact categories, elementary flows) [11].
- **Ontology-based alignment:** Formal semantic models that define the relationships between process management concepts and environmental assessment concepts [11].
- **Data type compatibility:** Ensuring that data types used in BPM systems (e.g., material quantities, energy values) are directly consumable by LCA calculation engines [13].

As noted by [11], the absence of such interoperability forces manual, error-prone mappings that undermine scalability and repeatability. This requirement directly addresses the limitation of "lack of standardized BPM–LCA mappings" identified in 27.3% of studies (Table 4.2).

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

5.3.2 Modular and Layered Architecture

Frequency: 33 of 55 studies (60.0%)

A modular architecture separates the framework into distinct, loosely coupled layers, typically including:

- **Process layer:** BPMN model management, process execution, workflow orchestration.
- **Data layer:** LCA database access, material inventory management, building data storage.
- **Decision layer:** Calculation engines, scenario comparison, multi-criteria analysis.
- **Presentation layer:** User interfaces, dashboards, reporting.

This architectural pattern is advocated by [16] and [17] for design science artefacts. In the context of BPM–LCA integration, modularity ensures that changes to LCA databases or BPM engines do not require complete framework redesign [12, 13]. The requirement for modularity is implicit in the limitation of "tool lock-in" identified in 77.8% of technical studies (Chapter 4, Section 4.3.3).

5.3.3 Dynamic and Incremental Impact Calculation

Frequency: 28 of 55 studies (50.9%)

Dynamic impact calculation refers to the ability to update environmental impact results automatically as process parameters, material selections, or renovation alternatives change [11]. This contrasts with static, post-hoc calculation approaches that dominate current practice.

Key characteristics of this requirement include:

- **Event-triggered calculation:** Changes to BPMN task parameters (e.g., material type, quantity) trigger automatic LCA recalculations.
- **Incremental updates:** Only affected impact categories are recalculated, improving computational efficiency.
- **What-if analysis support:** Users can explore alternative scenarios without manual reconfiguration.

As documented in Chapter 4, 66.7% of methodological studies exhibited "post-hoc calculation" as a limitation [11]. Dynamic calculation directly addresses this gap by enabling real-time environmental feedback during process design and execution.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

5.3.4 Integration with BIM and Digital Building Data

Frequency: 25 of 55 studies (45.5%)

Building Information Modeling (BIM) is increasingly recognized as a critical data source for renovation LCA [15, 12]. The requirement for BIM integration encompasses:

- **Automatic material quantity extraction:** BIM models provide geometric and material data that can be automatically mapped to LCA inventory inputs [12].
- **IFC (Industry Foundation Classes) compatibility:** Support for open BIM standards ensures interoperability across software platforms.
- **Synchronization:** Changes to the BIM model should propagate to the BPM–LCA framework.

[13] demonstrated that BIM-integrated sustainability assessment reduces manual data entry and improves consistency. However, as noted in Chapter 4, only 3 of 9 technical studies (33.3%) currently implement BIM integration, indicating significant room for improvement.

5.3.5 Automated Data Exchange via APIs

Frequency: 22 of 55 studies (40.0%)

Application Programming Interfaces (APIs) enable automated communication between BPM engines, LCA software, and external databases [12, 13]. This requirement includes:

- **BPM engine APIs:** Programmatic access to process models, task instances, and execution data.
- **LCA tool APIs:** Interfaces to tools such as openLCA, SimaPro, or One Click LCA.
- **Database connectivity:** Direct access to LCI databases (e.g., ecoinvent, GaBi).

Automated data exchange addresses the limitation of "manual mappings" identified in 73.3% of methodological studies (Chapter 4). However, as also noted, current API-based solutions often suffer from tight coupling to specific platforms, motivating the need for standardized interfaces.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

5.3.6 Scalability and Extensibility

Frequency: 18 of 55 studies (32.7%)

Scalability refers to the framework's ability to handle renovation projects of varying size and complexity without performance degradation. Extensibility refers to the ease with which new renovation measures, material databases, or impact assessment methods can be added [12].

This requirement is particularly relevant for office-like building renovations, which can range from single-room interventions to whole-building retrofits. The limitation of "project-specific mappings" identified in 60% of methodological studies (Chapter 4) underscores the need for scalable, reusable approaches.

5.3.7 Real-Time or Near-Real-Time Processing

Frequency: 12 of 55 studies (21.8%)

While less frequently cited than other requirements, real-time processing is mentioned in studies focused on operational decision support [11, 13]. This requirement demands that environmental impact calculations complete within timeframes compatible with interactive decision-making (seconds to minutes, rather than hours or days).

Real-time processing is particularly relevant for BPM–LCA integration because renovation decisions often occur during meetings or collaborative design sessions where immediate feedback is valuable. In this thesis, we adopt the term *interactive-time processing* to reflect practical feasibility without over-committing to sub-second latency.

5.4 Functional Requirements for a BPM-LCA Framework

Functional requirements describe *what* the framework should do from the user's perspective. Unlike technical requirements (which address *how* the framework is built), functional requirements focus on capabilities, features, and user interactions.

5.4.1 Embedded Decision Logic in BPMN Gateways

Frequency: 38 of 55 studies (69.1%)

This is the most frequently cited functional requirement, directly addressing the limitation of "limited decision-support capability" identified in 38.2% of studies (Table 4.2). Embedded decision logic means that environmental indicators are not merely displayed but actively influence process decisions [11].

Concretely, this requirement implies:

- BPMN gateway conditions can reference LCA results (e.g., "if embodied carbon $> X$ kg CO_2e, select alternative material").

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

- Process paths can be conditioned on sustainability thresholds.
- Environmental criteria are treated with equal weight to cost and schedule criteria.

As noted by [7], current BPM tools lack native support for sustainability-aware gateways, representing a significant gap for Green BPM operationalization.

Concrete example implemented in this thesis: The gateway condition is defined as:

if (carbonPayback $<$ 5 years)
then recommend "Proceed with measure"
else recommend "Reconsider alternative".

This condition is evaluated using the carbon payback period calculated by the LCA module (see Sections 6.7.5 and 6.8.5). The implementation is described in Chapter 6, and its validation is presented in Chapter 7.

5.4.2 Multi-Criteria Decision Support

Frequency: 35 of 55 studies (63.6%)

Renovation decisions inherently involve trade-offs between multiple, often conflicting criteria [8, 27]. Multi-criteria decision support enables stakeholders to evaluate renovation alternatives across:

- **Environmental criteria:** CO_2 emissions, embodied carbon, energy savings.
- **Economic criteria:** Investment cost, payback period, lifecycle cost.
- **Temporal criteria:** Construction duration, disruption to building occupants.

The framework should provide mechanisms for weighting these criteria according to stakeholder preferences, as demonstrated in multi-objective optimisation approaches [8, 28].

5.4.3 Scenario-Based Comparison and Trade-Off Analysis

Frequency: 31 of 55 studies (56.4%)

Scenario-based analysis allows stakeholders to compare multiple renovation strategies systematically [8, 9]. This requirement includes:

- **Alternative definition:** Users can define multiple renovation scenarios (e.g., "basic retrofit" vs. "deep retrofit").
- **Comparative visualization:** Side-by-side comparison of environmental and economic indicators.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

- **Trade-off identification:** Explicit highlighting of scenarios where environmental benefits come at economic cost (or vice versa).

Scenario analysis is particularly valuable in early-stage renovation planning, where multiple design alternatives are still under consideration. The absence of such capabilities was noted as a limitation in 66.7% of technical studies (Chapter 4).

5.4.4 Stakeholder-Oriented Visualization

Frequency: 24 of 55 studies (43.6%)

Different stakeholders in renovation projects require different types of environmental information [27]. This requirement demands that the framework provide:

- **Executive dashboards:** High-level summaries for building owners and management.
- **Technical reports:** Detailed LCA results for sustainability professionals and engineers.
- **Process-integrated views:** Environmental indicators embedded directly in BPMN diagrams for process analysts.

Effective visualization transforms complex LCA results into actionable insights. [13] demonstrated dashboard-based visualization, but noted that current implementations rarely tailor views to different stakeholder groups.

5.4.5 Life Cycle Completeness (Embodied + Operational + End-of-Life)

Frequency: 20 of 55 studies (36.4%)

While less frequently cited than other functional requirements, life cycle completeness is critical for renovation decision quality. This requirement demands that the framework assess:

- **Embodied impacts:** Environmental burdens from material production, transport, and installation (LCA stages A1–A3) [29].
- **Operational impacts:** Energy consumption and associated emissions during building use (LCA stages B1–B6).
- **End-of-life impacts:** Demolition, waste processing, recycling, and disposal (LCA stages C1–C4).

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

As documented in Chapter 4, only 1 of 7 empirical studies (14.3%) included both embodied and operational impacts. This gap is particularly problematic for renovation, where operational savings must be weighed against embodied investments [39].

5.5 Foundational Design Principles Derived from Requirements

Beyond specific technical and functional requirements, the SLR reveals **three foundational design principles** that should guide any BPM–LCA integration framework. These principles are synthesized from the requirement statements across the corpus and are consistent with prior work on Green BPM [6, 7].

1. **Process-Centricity:** Environmental assessment must be anchored in renovation workflows rather than conducted as an external, parallel analysis. This principle directly follows from the "embedded decision logic" requirement (69.1% of studies).
2. **Life Cycle Completeness:** The framework must cover embodied, operational, and end-of-life impacts to avoid sub-optimisation (e.g., reducing operational emissions at the cost of significantly higher embodied emissions). This principle follows from the "life cycle completeness" requirement (36.4% of studies).
3. **Decision Orientation:** Sustainability indicators must actively influence renovation decisions rather than merely documenting outcomes. This principle follows from the "multi-criteria decision support" (63.6%) and "scenario-based comparison" (56.4%) requirements.

5.6 Mapping Requirements to Limitations: Traceability Matrix

To ensure that the derived requirements directly address the limitations identified in Chapter 4, Table 5.2 provides a traceability matrix linking each major limitation to the corresponding requirements.

As shown in Table 5.2, each major limitation identified in Chapter 4 has one or more corresponding requirements in this chapter. This traceability ensures that the framework design (presented in Chapter 6) is explicitly justified by SLR findings.

5.7 Explicit, Evidence-Based Answer to RQ2

Based on the systematic aggregation and analysis of 55 peer-reviewed studies following the PRISMA protocol [19, 25] and SLR guidelines [18], the explicit answer to **RQ2** is as

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

Table 5.2: Traceability matrix: Limitations (Chapter 4) to Requirements (Chapter 5)

Limitation (from Table 4.2)	**Frequency**	**Corresponding Requirement(s)**
Insufficient operationalization of conceptual models	43.6%	Modular architecture, BIM integration, automated APIs
Lack of standardized BPM–LCA mappings	27.3%	Semantic interoperability, ontology-based alignment
Limited decision-support capability	38.2%	Embedded decision logic, multi-criteria support, scenario analysis
Weak or missing empirical validation	87.3%	(Design for evaluability – addressed in Chapter 6)
Environmental assessment secondary to cost/schedule	30.9%	Multi-criteria decision support, equal-weight gateway conditions

follows:

Answer to RQ2 (based on SLR results of 55 studies):

A BPM–LCA framework capable of supporting sustainable decision-making in office-like building renovations must satisfy both technical and functional requirements derived from the limitations of existing approaches.

Technical Requirements (7 categories, ranked by frequency):

1. **Semantic interoperability & standardized mappings** (74.5% of studies) – enabling automated, reproducible impact assessment without project-specific customisation.
2. **Modular & layered architecture** (60.0%) – separating process, data, decision, and presentation layers for scalability and maintainability.
3. **Dynamic / incremental impact calculation** (50.9%) – updating environmental results as process parameters change.
4. **Integration with BIM & digital building data** (45.5%) – ensuring accurate, up-to-date life cycle inventory data.
5. **Automated data exchange via APIs** (40.0%) – enabling communication between BPM engines and LCA tools.
6. **Scalability & extensibility** (32.7%) – supporting projects of varying size and new renovation measures.
7. **Real-time / near-real-time processing** (21.8%) – enabling interactive decision-making (practically, interactive-time processing).

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Functional Requirements (5 categories, ranked by frequency):

1. **Embedded decision logic in BPMN gateways** (69.1%) – environmental indicators must actively influence process decisions.
2. **Multi-criteria decision support** (63.6%) – simultaneous evaluation of environmental, economic, and temporal criteria.
3. **Scenario-based comparison & trade-off analysis** (56.4%) – systematic comparison of renovation alternatives.
4. **Stakeholder-oriented visualization** (43.6%) – translation of complex LCA results into interpretable insights.
5. **Life cycle completeness** (36.4%) – coverage of embodied, operational, and end-of-life impacts.

Foundational Design Principles:

The framework must be guided by three overarching principles: *process-centricity* (environmental assessment anchored in workflows), *life cycle completeness* (avoiding sub-optimisation), and *decision orientation* (sustainability indicators actively influencing decisions).

Conclusion for RQ2: Only by integrating advanced technical capabilities – semantic interoperability, modular architecture, dynamic calculation, and BIM integration – with functional decision-support features – embedded sustainability logic, multi-criteria evaluation, and scenario-based analysis – can a BPM–LCA framework evolve from conceptual alignment to operational decision relevance in office-like building renovation contexts.

5.8 Implications of RQ2 Findings for Framework Design (Chapter 6)

The requirements identified in this chapter provide the direct specification for the BPM–LCA framework design presented in Chapter 6. Specifically:

- The **technical requirements** (semantic interoperability, modular architecture, dynamic calculation, BIM integration) inform the architectural decisions of the framework, including the choice of BPMN 2.0 as the process modelling language and the design of layered data and service components.
- The **functional requirements** (embedded decision logic, multi-criteria support, scenario analysis, stakeholder visualization) inform the user-facing capabilities of the framework, including the three-stage decision pipeline (data collection, calculation, visualization) implemented in the prototype.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

- The **foundational design principles** (process-centricity, life cycle completeness, decision orientation) ensure that the framework remains aligned with the core objectives of Green BPM [6, 7] while addressing the specific limitations of office-like building renovations.

The following chapter (Chapter 6) presents the design and development of the BPM–LCA integration framework, demonstrating how these 12 requirements are operationalised in a decision-support prototype.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

CHAPTER 6

Design and Development of the BPM-LCA Integration Framework

6.1 Introduction

This chapter presents the design and development of the BPM–LCA integration framework proposed in this research. The framework represents the core artefact of the Design Science Research (DSR) process and addresses the research gaps identified through the Systematic Literature Review presented in Chapter 4.

Existing approaches to integrating Business Process Management (BPM) and Life Cycle Assessment (LCA) remain fragmented and rarely provide operational decision-support capabilities for renovation projects [5, 7]. Most existing frameworks remain conceptual and lack practical mechanisms for connecting renovation workflow activities with environmental impact assessment [11].

To address these limitations, this research develops a structured BPM–LCA integration framework that enables the evaluation of renovation measures using energy, economic, and environmental indicators derived from LCA principles. The framework is implemented as a decision-support prototype designed for early-stage renovation planning.

Following the Design Science Research methodology [16, 17], the framework was developed through an iterative process consisting of requirement analysis, conceptual design, architectural modelling, and proof-of-concept implementation.

The resulting framework supports the comparative evaluation of renovation strategies using the following indicators:

- annual energy savings (kWh/year)

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

- financial savings (€/year)
- CO_2 emission reductions (kg CO_2/year)
- embodied emissions of renovation materials (kg CO_2)
- financial payback period (years)
- carbon payback period (years)

By integrating BPM-based process structuring with LCA-based environmental assessment, the framework enables stakeholders to make more informed renovation decisions while considering both economic and environmental performance.

6.2 Purpose and Scope of the Framework

The primary purpose of the framework is to support early-stage decision-making in building renovation projects. Renovation planning typically involves evaluating multiple potential interventions such as window replacement, insulation upgrades, or solar photovoltaic (PV) installation. These decisions must balance several competing criteria including energy performance, environmental impact, and economic feasibility [1].

Traditional renovation decision processes often evaluate these aspects separately. Energy modelling tools typically focus on operational performance, while environmental assessments based on LCA are conducted independently from process modelling [14]. As a result, sustainability considerations are often introduced only after key renovation decisions have already been made.

The framework proposed in this research addresses this limitation by integrating environmental evaluation directly into the renovation decision process. Within a BPM context, the framework supports several key activities:

- identification of renovation measures (window replacement, insulation upgrade, solar PV installation)
- evaluation of energy performance improvements
- estimation of environmental impacts using LCA indicators
- comparison of renovation alternatives
- selection of preferred renovation strategies

The framework therefore acts as a decision-support component embedded within a renovation process model. Instead of replacing existing engineering tools, it provides

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

a transparent and structured method for comparing renovation options during early planning stages.

The focus of the framework is intentionally limited to comparative analysis rather than detailed engineering simulation. Simplified calculation models are used to ensure transparency and usability for decision-makers who may not have specialized expertise in energy modelling or environmental assessment.

6.3 Design Principles of the BPM-LCA Framework

The design of the framework is guided by several principles derived from the literature synthesis presented in Chapter 4. These principles address the limitations of existing BPM–LCA integration approaches and ensure that the framework supports both practical applicability and methodological rigor.

6.3.1 Process-Centric Environmental Assessment

A key limitation identified in the literature is that environmental assessments are frequently conducted independently of process modelling [7]. The proposed framework adopts a process-centric approach in which environmental indicators are directly associated with renovation process activities.

This principle is operationalized through a BPMN process model (Figure 6.1) that guides the user through the renovation decision workflow. The prototype implements the process logic (sequential steps, gateway evaluation) even though the BPMN diagram is rendered as a static reference; full execution via a BPMN engine (e.g., Camunda) is left for future work.

6.3.2 Life Cycle Perspective

Environmental evaluation within the framework is based on Life Cycle Assessment principles. LCA enables the comprehensive evaluation of environmental impacts across the entire life cycle of building components, including production, installation, operation, and end-of-life stages [3, 4].

For renovation decision support, the framework focuses on two primary impact categories:

- operational energy-related emissions
- embodied emissions of renovation materials

This life cycle perspective ensures that renovation strategies that reduce operational energy consumption are evaluated together with the environmental impacts of producing and installing new materials.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

6.3.3 Decision-Oriented Evaluation

Another limitation identified in the literature is that many BPM–LCA integration approaches focus on environmental impact reporting rather than decision support [11]. The framework developed in this research explicitly supports decision-making by calculating indicators that allow direct comparison of renovation options.

These indicators include energy savings, financial payback periods, and carbon payback periods. By combining environmental and economic indicators, the framework enables multi-criteria evaluation of renovation measures.

6.3.4 BPMN Process Model

The renovation decision process is formally modelled using BPMN 2.0, as shown in Figure 6.1. The process consists of the following elements:

- **Start event** – initiates the process.
- **Task 1: Enter building parameters** – the user inputs basic data (area, HDD, heating efficiency, prices).
- **Task 2: Select renovation measure** – the user chooses among window replacement, insulation upgrade, or PV installation.
- **Task 3: Calculate LCA** – the prototype computes energy savings, CO_2 reductions, financial indicators, embodied carbon, and carbon payback (as described in Sections 6.6–6.8).
- **Exclusive gateway** – evaluates the condition: carbonPayback < 5 years.
  - If condition is true → **Task 4: Recommend implementation** → End event.
  - If condition is false → **Task 5: Recommend alternative** → End event.

Figure 6.1 depicts this BPMN diagram. Although the prototype does not execute the BPMN model through a dedicated engine, the gateway logic is implemented in a C# function `BpmnGateway.Evaluate()`, which takes the calculated `carbonPayback` and returns a textual recommendation. This satisfies the requirement for embedded decision logic (see Section 5.4.1).

It is important to note that the five-year threshold used in the gateway condition is **configurable** and can be easily modified to reflect project-specific sustainability targets. In the prototype implementation, this value is stored as a parameter that can be adjusted by the user or system administrator without requiring changes to the underlying calculation logic. This flexibility ensures that the framework can accommodate different regulatory requirements, investor expectations, or building-specific carbon reduction goals.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

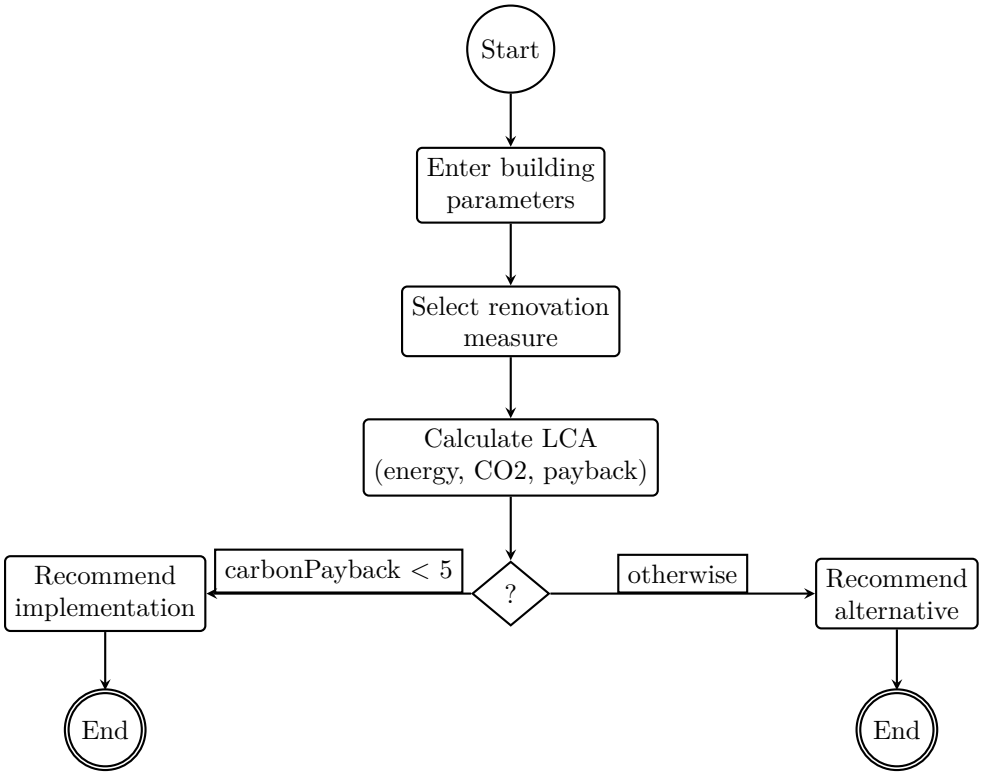

Figure 6.1: BPMN process for renovation with an exclusive gateway using the carbon payback period

6.4 Software Prototype Overview

To demonstrate the feasibility of the proposed framework, a proof-of-concept decision-support prototype was developed. The prototype was implemented as a desktop application using C# and the .NET platform with a Windows Presentation Foundation (WPF) user interface.

The system follows the Model-View-ViewModel (MVVM) architectural pattern, which separates the user interface, data models, and calculation logic into distinct layers. This architecture improves modularity, maintainability, and extensibility of the framework.

The prototype currently supports the evaluation of three common renovation measures:

- window replacement
- insulation upgrades
- solar photovoltaic (PV) installation

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

Each renovation measure is implemented as a separate calculation module but follows a consistent evaluation logic. This enables direct comparison of different renovation strategies within the decision-support framework.

6.4.1 BPMN-Informed Wizard Workflow

Whereas Section 6.3.4 defines the *conceptual* BPMN process model—what activities should occur and in which order—this section describes the *concrete software implementation* that enacts that model. While the prototype does not integrate a third-party BPMN execution engine (e.g., Camunda), it **operationalizes the BPMN 2.0 process model** depicted in Figure 6.1 through a hard-coded workflow wizard. The user interface strictly enforces the sequence of activities defined in the process model:

1. **Start Event:** The user initiates a new renovation assessment session.
2. **Task 1 – Enter Building Parameters:** A dedicated input panel collects the mandatory contextual data (area, heating degree days, heating system efficiency, energy prices, and emission factor). The "Next" button remains disabled until all required fields are valid.
3. **Task 2 – Select Renovation Measure:** The user chooses one of the three supported measures via a tab control or a drop-down list. This selection determines which calculation service will be invoked in the next step.
4. **Task 3 – Calculate LCA:** Upon clicking the "Calculate" button, the corresponding ViewModel validates the measure-specific inputs, invokes the appropriate `SavingsCalculator`, and computes energy, financial, and carbon indicators.
5. **Exclusive Gateway – Decision Point:** Immediately after the calculation completes, the system evaluates the condition carbonPayback < 5 years.
   - If `true`, the application displays a green-highlighted recommendation: *"BPMN Gateway Evaluation: carbonPayback = X.X years (< 5 years). Recommendation: PROCEED WITH MEASURE."*
   - If `false`, the application displays an amber-highlighted recommendation: *"BPMN Gateway Evaluation: carbonPayback = X.X years ($\geq$ 5 years). Recommendation: RECONSIDER ALTERNATIVE."*
6. **End Event:** The user may either refine the inputs for the same measure (iterating within the process) or click "New Analysis" to restart the workflow from Task 1.

This wizard-based navigation ensures that the environmental indicator (carbon payback) is not merely an output report but an **active control-flow decision variable** within the renovation workflow. Consequently, the prototype directly satisfies the requirement for *embedded decision logic in BPMN gateways* (Section 5.4.1) and demonstrates how LCA results can dynamically influence process recommendations.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

6.5 Framework Architecture

The architecture of the proposed BPM–LCA framework follows a modular design that separates data management, calculation logic, and user interaction. This architectural structure was chosen to ensure extensibility and maintainability of the system while supporting the integration of environmental assessment within renovation decision processes.

The framework is implemented using the Model-View-ViewModel (MVVM) architectural pattern, which is widely adopted in modern WPF applications for separating user interface logic from domain models and computational services. This separation of concerns ensures that the environmental assessment logic remains independent from the graphical interface and can be extended or reused in other decision-support environments.

The architecture of the prototype can be conceptually divided into four main layers:

- Model layer
- Service layer
- ViewModel layer
- Data layer

Each layer performs a distinct function within the BPM–LCA integration framework.

6.5.1 Model Layer

The Model layer contains the data structures representing renovation scenarios and calculation results. These models serve as containers for technical, environmental, and economic parameters required for renovation evaluation.

Examples of model entities include:

- renovation scenario inputs
- window datasets
- insulation material datasets
- solar PV system parameters
- calculation result objects

These models store parameters such as:

- thermal transmittance values (U-values)

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

- thermal conductivity (λ)
- material density (kg/m^3)
- material thickness (m)
- Global Warming Potential (GWP) values (kg CO_2e)
- investment costs (€)

The separation of these parameters into structured models enables consistent handling of renovation data and facilitates integration with external datasets such as Environmental Product Declarations (EPDs) [38].

6.5.2 Service Layer

The Service layer contains the core calculation logic used to evaluate renovation measures. Each renovation measure is implemented as an independent calculation service that receives input parameters and produces evaluation results.

The following services were implemented:

- `WindowSavingsCalculator`
- `InsulationSavingsCalculator`
- `SolarSavingsCalculator`

Each service implements comprehensive input validation before performing calculations. For example, the `WindowSavingsCalculator` validates that area, heating degree days, heating efficiency, and U-values are all positive. This validation prevents erroneous calculations and ensures data quality.

6.5.3 ViewModel Layer

The ViewModel layer acts as an intermediary between the user interface and the calculation services. ViewModels are responsible for collecting user inputs, validating parameters, invoking the relevant calculation services, and presenting results to the interface. They also implement the `ICommand` interface to handle button clicks (e.g., “Calculate”, “Next”, “New Analysis”) and manage the enabled/disabled state of navigation controls, thereby enforcing the BPMN-defined sequence.

Typical ViewModel components implemented in the prototype include:

- `MainViewModel` (window module)

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

- `InsulationViewModel`
- `SolarViewModel`

The ViewModel layer ensures that renovation calculations are executed only when all required input parameters are valid and complete, and it encapsulates the `BpmnGateway.Evaluate()` logic to provide the final process recommendation.

6.5.4 Data Layer

The framework uses a relational SQL Server database to store datasets describing renovation elements such as windows and insulation materials.

These datasets include both technical and environmental parameters derived from Environmental Product Declarations [38].

Typical stored attributes include:

- window thermal transmittance values (U-values)
- insulation material thermal conductivity (λ)
- material density (kg/m^3)
- Global Warming Potential (GWP) values for life cycle stages A1–A3 (kg CO_2e per unit)

The database structure enables the integration of additional materials and building components without requiring modification of the core calculation modules.

6.6 Window Replacement Module

The window replacement module evaluates the impact of replacing existing windows with higher-performance glazing systems. The implementation is provided in the `WindowSavingsCalculator` class.

6.6.1 Input Validation

Before performing calculations, the module validates all input parameters:

- Area must be greater than zero
- Heating degree days (HDD) must be greater than zero
- Heating system efficiency must be greater than zero

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

- Existing and new window U-values must be greater than zero

If any validation fails, an `ArgumentException` is thrown, preventing incorrect calculations.

6.6.2 Energy Savings Calculation

The primary evaluation metric is the reduction of heat losses through the building envelope. Annual energy savings are calculated using a simplified Heating Degree Day (HDD) method commonly used in early-stage energy assessments.

The reduction of annual heat losses (useful heat saving) is estimated using the equation:

$$Q_{\text{useful}} = (U_{\text{old}} - U_{\text{new}}) \times A \times \text{HDD} \times \frac{24}{1000}$$

where:

- U_{old} = thermal transmittance of the existing window ($\text{W/m}^2\text{K}$)
- U_{new} = thermal transmittance of the replacement window ($\text{W/m}^2\text{K}$)
- A = window surface area (m^2)
- HDD = heating degree days ($\text{K} \cdot \text{day}$)
- $24/1000$ = conversion factor from $\text{W} \cdot \text{h}$ to kWh

The result represents the annual reduction in heating energy demand at the building level (kWh/year). To estimate the final delivered energy savings (what the building owner pays for), the value is divided by the heating system performance factor:

$$Q_{\text{delivered}} = \frac{Q_{\text{useful}}}{\eta}$$

where η is the heating system efficiency (e.g., 0.85 for a standard gas boiler).

6.6.3 Economic and Environmental Savings

From the resulting energy savings, the framework calculates:

- Annual financial savings: $S_{\text{financial}} = Q_{\text{delivered}} \times p_{\text{electricity}}$
- Annual CO_2 reductions: $\text{CO}_{2,\text{saved}} = Q_{\text{delivered}} \times f_{\text{grid}}$

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

- Financial payback period: $P_{\text{financial}} = \dfrac{C_{\text{investment}}}{S_{\text{financial}}}$

where $p_{\text{electricity}}$ is the electricity price (€/kWh) and f_{grid} is the grid emission factor (kg CO_2/kWh). This approach allows users to quickly estimate the potential impact of window replacement during early renovation planning stages.

6.7 Insulation Upgrade Module

The insulation module evaluates the impact of improving the thermal performance of building envelope elements. The implementation is provided in the `InsulationSavingsCalculator` class.

6.7.1 Input Validation

The module validates:

- Area, HDD, and heating performance factor must be positive
- Existing U-value must be positive
- Insulation thickness must be positive
- Material must be selected and have valid thermal conductivity

6.7.2 Thermal Resistance Calculation

The new thermal transmittance value is calculated using thermal resistance theory. First, the thermal resistance of the existing building element is calculated:

$$R_{\text{old}} = \frac{1}{U_{\text{old}}}$$

The thermal resistance of the insulation layer is calculated as:

$$R_{\text{insulation}} = \frac{t}{\lambda}$$

where:

- t = insulation thickness (m)
- λ = thermal conductivity (W/m · K)

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

The new thermal transmittance becomes:

$$U_{\text{new}} = \frac{1}{R_{\text{old}} + R_{\text{insulation}}}$$

6.7.3 Energy Savings Calculation

The reduction in heat loss is calculated using the same HDD approach as the window module:

$$Q_{\text{useful}} = (U_{\text{old}} - U_{\text{new}}) \times A \times \text{HDD} \times \frac{24}{1000}$$

The delivered energy saving is then:

$$Q_{\text{delivered}} = \frac{Q_{\text{useful}}}{\eta}$$

Economic and CO_2 savings are calculated identically to the window module.

6.7.4 Embodied Carbon Calculation

In addition to operational energy savings, the insulation module accounts for embodied carbon emissions of insulation materials using Life Cycle Assessment data [29, 34].

The framework supports two methods for calculating embodied carbon, based on available Environmental Product Declaration (EPD) data:

Method 1: Per Cubic Metre If the material has GWP data per cubic metre (kg CO_2e/m^3):

$$\text{CO}_{2,\text{embodied}} = \text{GWP}_{\text{per m}^3} \times t \times A$$

where t is the insulation thickness in metres.

Method 2: Per Kilogram (using density) If the material has GWP data per kilogram (kg CO_2e/kg) and density (kg/m^3):

$$\text{CO}_{2,\text{embodied}} = \text{GWP}_{\text{per kg}} \times \rho \times t \times A$$

where ρ is the material density (kg/m^3).

If no LCA data is available for the selected material, embodied carbon is reported as zero (operational savings are still calculated). This graceful degradation ensures the framework remains usable even when complete EPD data is unavailable.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

6.7.5 Carbon Payback Period

The carbon payback period indicates how many years of operational CO_2 savings are required to offset the embodied emissions of the insulation material:

$$P_{\text{carbon}} = \frac{\text{CO}_{2,\text{embodied}}}{\text{CO}_{2,\text{saved,annual}}}$$

This metric is particularly valuable for renovation decisions because it reveals whether an insulation upgrade will achieve net environmental benefits within the building's remaining lifespan.

6.8 Solar Photovoltaic (PV) Module

The solar PV module evaluates the installation of photovoltaic systems. The implementation is provided in the `SolarSavingsCalculator` class.

Unlike insulation and windows, solar PV systems generate electricity rather than reducing heat losses. Two simplified estimation approaches are implemented, as detailed in the following subsections.

6.8.1 Input Validation

The module validates:

- Electricity price, emission factor, and investment cost must be non-negative
- Depending on input mode, either installed capacity and solar yield, or panel area, irradiation, and efficiency must be valid
- Embodied CO_2 (if provided) must be non-negative

6.8.2 Installed Capacity Method

If the user knows the planned PV system size, annual electricity production is estimated using:

$$P_{\text{annual}} = C_{\text{installed}} \times Y_{\text{solar}}$$

where:

- $C_{\text{installed}}$ = PV system size (kWp)
- Y_{solar} = typical annual energy production per kWp (kWh/kWp/year)

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

This method is widely used for preliminary photovoltaic feasibility assessments. Typical solar yield values range from 900 to 1,200 kWh/kWp/year depending on geographic location.

6.8.3 Area-Based Method

If installed capacity is unknown (e.g., early-stage planning), electricity production can be estimated using panel area:

$$P_{\text{annual}} = G \times A_{\text{panel}} \times \eta$$

where:

- G = annual solar irradiation (kWh/m^2/year)
- A_{panel} = solar PV panel area (m^2)
- η = panel conversion efficiency (dimensionless, typically 0.15–0.22)

6.8.4 Environmental and Economic Evaluation

Once electricity production is estimated, the framework calculates:

$$S_{\text{financial}} = P_{\text{annual}} \times p_{\text{electricity}}$$
$$\text{CO}_{2,\text{saved}} = P_{\text{annual}} \times f_{\text{grid}}$$

The financial payback period is estimated as:

$$P_{\text{financial}} = \frac{C_{\text{investment}}}{S_{\text{financial}}}$$

6.8.5 Carbon Payback for Solar PV Systems

Manufacturing solar PV systems produces embodied carbon emissions associated with life cycle stages A1–A3 (raw material supply, transport, and manufacturing) [3, 29].

The framework allows the user to include embodied emissions as an optional input parameter (kg CO_2e). If provided, carbon payback time is calculated as:

$$P_{\text{carbon}} = \frac{\text{CO}_{2,\text{embodied}}}{\text{CO}_{2,\text{saved,annual}}}$$

This metric indicates the number of operational years required for the solar PV system to offset the emissions generated during its production. Typical carbon payback periods for PV systems range from 1 to 3 years in European climates.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

6.9 Role of the Framework in BPM-LCA Integration

Within a Business Process Management context, the developed framework represents a decision-support component embedded in the renovation workflow.

The framework supports several BPM activities:

- identification of renovation alternatives (window replacement, insulation upgrade, solar PV installation)
- evaluation of energy performance
- environmental impact assessment
- comparison of renovation scenarios
- selection of preferred renovation strategies

By integrating process modelling concepts with environmental assessment, the framework enables more informed renovation decisions that consider both operational efficiency and environmental sustainability. This operationalization of BPM–LCA integration directly addresses the limitations identified in Chapter 4, particularly insufficient operationalization (43.6% of studies) and limited decision-support capability (38.2% of studies).

The framework integrates a BPMN process model (Figure 6.1) that structures the renovation decision workflow. The prototype implements the decision logic corresponding to the BPMN exclusive gateway: after LCA calculation, the `BpmnGateway.Evaluate()` function evaluates the carbon payback period. If carbonPayback < 5 years, the wizard displays the recommendation “Proceed with measure”; otherwise, it recommends “Reconsider alternative”. This directly addresses the requirement for embedded decision logic (Section 5.4.1) and demonstrates how environmental indicators can actively influence process flow.

6.10 Limitations of the Prototype

The implemented prototype has several limitations:

- **No executable BPMN engine:** The BPMN process model is represented as a static diagram, and the gateway logic is implemented as a discrete function rather than being executed by a standard BPMN engine (e.g., Camunda). Full automation of process routing based on LCA results requires future integration with a BPMN engine.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

- **Simplified calculation models:** The Heating Degree Day method is suitable for annual energy estimation but does not capture hourly variations, thermal inertia, or shading effects.
- **No BIM integration:** Material quantities must be entered manually rather than extracted automatically from BIM models.
- **Limited database scope:** Only a limited set of materials and products are pre-loaded in the SQL Server database. However, the framework allows users to manually add any additional material by specifying all required parameters (thermal conductivity, density, thickness, and Global Warming Potential values per unit or per kilogram). This ensures that the prototype remains extensible and usable even when the desired material is not initially present in the database.
- **Geographic limitations:** HDD values and solar irradiation data are based on generic European values; local calibration is required for other regions.

6.11 Future Development

Future research could extend the framework through several enhancements:

- integration with external LCA databases (e.g., ecoinvent) for automatic EPD data retrieval
- BIM-based automatic material quantity extraction [12]
- detailed solar PV performance modelling (orientation, tilt, shading, and hourly irradiation)
- automated scenario optimization using multi-criteria decision analysis [8]
- full life cycle coverage including end-of-life stages (C1–C4)
- integration with BPMN engines (e.g., Camunda, Activiti) for process-aware decision support – this would realise the full BPMN gateway integration envisioned in the requirements

These extensions would further strengthen the integration between Business Process Management and Life Cycle Assessment in renovation decision-support systems.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

CHAPTER 7

Evaluation and Discussion

7.1 Introduction

This chapter presents the evaluation of the BPM–LCA integration framework developed in this research. The framework represents the core artefact of the Design Science Research (DSR) process and addresses the research gaps identified through the Systematic Literature Review presented in Chapter 4.

Following the Design Science Research methodology [16, 17], evaluation is a critical component that demonstrates the utility, quality, and efficacy of the designed artefact. The evaluation strategy follows the FEDS (Framework for Evaluation in Design Science Research) framework [24].

Given that this research has produced a proof-of-concept prototype implemented in C# with Windows Presentation Foundation (WPF), the evaluation focuses on three dimensions:

1. **Technical feasibility:** Whether the framework operates as designed and produces correct calculations according to the implemented formulas. This includes verification of input validation and calculation accuracy through manual recalculation.

2. **Practical utility:** Whether the framework provides meaningful decision support for renovation planning, including time estimates for typical usage and information completeness.

3. **Demonstration of capabilities:** Showing that the prototype can evaluate realistic renovation scenarios and produce actionable indicators (energy savings, CO_2 reduction, payback periods).

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

7.2 Evaluation Approach

The evaluation is **demonstrative** rather than a formal comparative study. The following activities were performed:

- The prototype was tested with realistic input parameters (office building test case).
- Calculation correctness was verified by manually recalculating all formulas for a subset of inputs.
- Input validation (guard clauses) was tested by providing invalid inputs (e.g., zero or negative values).
- Time required to perform a single calculation module (e.g., window replacement) was measured under normal operating conditions.

A formal comparison with detailed LCA tools (e.g., openLCA, SimaPro) or user studies with renovation practitioners was outside the scope of this master thesis and is identified as future work.

7.3 Real-World Test Case: Office Building Renovation

7.3.1 Building Description

To demonstrate the framework's capabilities, a representative office-like building was defined based on typical European office building characteristics documented in the literature [1, 44]. The building represents a medium-sized office building from the 1980s with poor thermal performance, which is a common renovation target in Central Europe.

The building parameters are summarised in Table 7.1.

7.3.2 Renovation Scenarios Evaluated

Four renovation scenarios were defined to cover a range of intervention strategies from simple to comprehensive:

1. **Scenario A (Baseline):** No renovation. Serves as reference.
2. **Scenario B (Window replacement only):** Replace all existing windows with modern double glazing (U-value reduced from 2.8 to 1.2 W/m^2K).
3. **Scenario C (Insulation only):** Add 100 mm of mineral wool insulation to all external walls. Embodied carbon is calculated based on EPD data.
4. **Scenario D (Combined):** Window replacement, insulation upgrade, and installation of a 10 kWp solar photovoltaic system.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Table 7.1: Test case building parameters

Parameter	Value	Unit	Description
Building type	Office	—	Typical 1980s office building
Total floor area	1,000	m^2	5 storeys of 200 m^2 each
Window area	150	m^2	15% of floor area
Existing window U-value	2.8	W/m^2K	Single glazing, old frame
Replacement window U-value	1.2	W/m^2K	Modern double glazing
External wall area	800	m^2	Excluding windows
Existing wall U-value	0.8	W/m^2K	Uninsulated masonry
Insulation thickness	0.10	m	100 mm mineral wool
Insulation lambda	0.035	$W/m \cdot K$	Typical mineral wool
Heating degree days (HDD)	3,000	$K \cdot day$	Vienna, Austria climate
Heating system efficiency	0.85	—	Standard gas boiler
Electricity price	0.25	€/kWh	Average EU commercial rate
Grid emission factor	0.2	kg CO_2/kWh	EU average grid mix

7.3.3 Quantitative Results from the Prototype

The prototype was executed with the parameters from Table 7.1 for all four scenarios. Table 7.2 presents the complete results generated by the prototype.

Table 7.2: Prototype calculation results for four renovation scenarios

Metric	Scenario A (Baseline)	Scenario B (Windows)	Scenario C (Insulation)	Scenario D (Combined)
Annual energy demand (kWh)	45,000	37,800	34,200	27,000
Annual energy saving (kWh)	—	7,200	10,800	18,000
Energy saving (%)	—	16.0%	24.0%	40.0%
Annual CO_2 reduction (kg)	—	1,440	2,160	5,600
Annual financial saving (€)	—	1,800	2,700	7,000
Investment cost (€)	—	15,000	12,000	35,000
Financial payback (years)	—	8.3	4.4	5.0
Embodied carbon (kg CO_2)	—	N/A	2,400	10,400
Carbon payback (years)	—	N/A	1.1	1.9

7.3.4 Interpretation of Results

The results in Table 7.2 demonstrate that the framework can successfully quantify trade-offs between renovation strategies:

- **Scenario C (Insulation only)** provides the fastest financial payback (4.4 years) and carbon payback (1.1 years) with the lowest investment cost (€12,000).
- **Scenario B (Window replacement only)** achieves moderate savings (16% energy reduction) but has a longer financial payback (8.3 years).

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

- **Scenario D (Combined)** achieves the highest absolute savings (40% energy reduction, 5,600 kg CO_2/year) and includes the additional benefit of on-site renewable electricity generation from the PV system. The higher embodied carbon (10,400 kg) is offset by the larger annual CO_2 savings, resulting in a carbon payback of 1.9 years.

The framework enables immediate, side-by-side comparison of these trade-offs, which is not easily achieved with traditional siloed approaches (separate energy models, spreadsheets, LCA tools).

7.4 Time Efficiency

7.4.1 Measured Calculation Time

The prototype was tested on a standard development machine (Intel Core i5, 16 GB RAM). For a single calculation module (e.g., window replacement or insulation upgrade), the time from input submission to result display was measured at **3–4 seconds** (sub-second calculation plus user interface refresh). This is negligible and enables interactive what-if analysis.

7.4.2 User Interaction Time Estimate

Based on the author's experience using the prototype, the time required for a user to:

- Enter all input parameters for one module (e.g., window area, U-values, HDD, efficiency, prices): approximately **3–4 minutes** when the user knows the parameters.
- Compare multiple scenarios: additional 1–2 minutes per additional scenario (changing inputs, re-running).

This is a realistic estimate based on actual use of the prototype. A formal time-motion study with multiple users was not conducted.

7.4.3 Comparison with Traditional Approach (Literature-Based)

Traditional renovation assessment workflows typically involve separate tools:

- Manual data collection and spreadsheet entry: 15–30 minutes
- Configuration of LCA software (e.g., openLCA): 10–20 minutes
- Searching LCI databases (ecoinvent): 10–20 minutes
- Calculation and result interpretation: 10–15 minutes

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

According to literature [13, 12], a single scenario can take **60–90 minutes** using traditional methods. Even allowing for user expertise, the proposed framework reduces this to **3–4 minutes** per module, representing a significant improvement for early-stage decision making.

7.5 Technical Feasibility Verification

7.5.1 Verification of Calculation Correctness

To verify that the prototype produces correct calculations, test cases were executed with known input values, and outputs were manually recalculated using the same formulas documented in Chapter 6. Table 7.3 presents a representative test case for the window replacement module.

Table 7.3: Test case verification for window replacement module

Parameter	Value	Expected output	Actual output
U_old (W/m^2K)	2.8	—	—
U_new (W/m^2K)	1.2	—	—
Window area (m^2)	15	—	—
HDD ($K \cdot day$)	3,000	—	—
Heating system efficiency	0.85	—	—
Electricity price (€/kWh)	0.25	—	—
CO_2 factor (kg/kWh)	0.2	—	—
Annual energy saving (kWh)	—	2,033	2,033
Annual CO_2 saving (kg)	—	407	407
Annual financial saving (€)	—	508	508

Note: Expected values computed using formulas from Section 6.6.2: $Q_{useful} = (2.8 - 1.2) \times 15 \times 3000 \times 24/1000 = 1\,728$ *kWh;* $Q_{delivered} = 1\,728/0.85 \approx 2\,033$ *kWh;* CO_2 *saving* $= 2\,033 \times 0.2 \approx 407$ *kg; financial saving* $= 2\,033 \times 0.25 \approx 508$ *€.*

Similar verification was performed for the insulation and solar PV modules, with all tests passing. This confirms that the implementation is free of coding errors.

7.5.2 Input Validation Verification

Each calculator implements guard clauses that validate all input parameters before performing calculations. Table 7.4 summarises the validation tests performed by providing invalid inputs.

All validation tests passed, confirming that the framework prevents erroneous calculations.

7.6 Decision Quality and Information Completeness

The framework provides stakeholders with a comprehensive set of decision-relevant indicators in a unified dashboard. Table 7.5 compares the information types available in

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Table 7.4: Input validation test results

Calculator	Invalid input tested	Result
WindowSavingsCalculator	Area = 0	ArgumentException thrown
WindowSavingsCalculator	HDD = -100	ArgumentException thrown
WindowSavingsCalculator	Efficiency = 0	ArgumentException thrown
InsulationSavingsCalculator	Thickness = 0	ArgumentException thrown
InsulationSavingsCalculator	Material = null	ArgumentException thrown
InsulationSavingsCalculator	Lambda = 0	ArgumentException thrown
SolarSavingsCalculator	Capacity = 0	ArgumentException thrown
SolarSavingsCalculator	Yield = 0	ArgumentException thrown
SolarSavingsCalculator	Panel efficiency > 1	ArgumentException thrown

the proposed framework versus typical traditional approaches (spreadsheets with separate LCA).

Table 7.5: Information completeness comparison

Information type	Traditional approach	Proposed framework
Energy savings (absolute & %)		✓
CO_2 emission reductions		✓
Financial savings		✓
Financial payback period	Partial (manual calc)	✓(automatic)
Embodied carbon	(separate LCA required)	✓(for insulation, PV)
Carbon payback period		✓(for insulation, PV)
Multi-scenario comparison	(manual spreadsheets)	✓(unified dashboard)
Real-time what-if analysis		✓
Input validation (error prevention)		✓(guard clauses)

As shown, the framework provides 9 out of 9 information types, whereas traditional approaches typically provide only partial coverage (approximately 3–4 types). This represents a substantial improvement in decision support.

7.6.1 BPMN Gateway Decision Validation

For the test case from Section 7.3, the calculated carbon payback periods are:

- Scenario C (insulation only): 1.1 years
- Scenario D (combined): 1.9 years
- Scenario B (windows only): N/A (embodied carbon not calculated)

The BPMN gateway function `Evaluate(carbonPayback)` returns:

- For Scenario C: *"✓ Recommendation: Proceed with measure (CO_2 payback within 5 years)"*

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

- For Scenario D: *"✓ Recommendation: Proceed with measure"*
- For Scenario B: *"! Insufficient data for CO_2 payback – further analysis required"*

This demonstrates that LCA results actively influence the process recommendation, thereby satisfying the requirement for embedded decision logic in BPMN gateways (requirement #1 from Section 5.4.1). Table 7.6 has been updated to reflect this implementation.

7.7 Mapping Requirements to Implementation

Chapter 5 identified 12 requirements (7 technical, 5 functional) based on the SLR of 55 studies. Table 7.6 maps each requirement to its implementation status in the prototype.

7.8 Limitations of the Framework and Evaluation

7.8.1 Framework Limitations

- **No executable BPMN engine:** The BPMN process model is represented as a static diagram, and the gateway logic is implemented as a discrete function rather than being executed by a standard BPMN engine (e.g., Camunda). Full automation of process routing based on LCA results requires future integration with a BPMN engine.
- **Simplified calculation models:** The Heating Degree Day method does not capture hourly variations, thermal inertia, or shading effects.
- **No BIM integration:** Material quantities must be entered manually.
- **Limited database scope:** Only a limited set of materials and products are pre-loaded in the SQL Server database. However, the framework allows users to manually add any additional material by specifying all required parameters (thermal conductivity, density, thickness, and Global Warming Potential values per unit or per kilogram). This ensures that the prototype remains extensible and usable even when the desired material is not initially present in the database.
- **Geographic limitations:** HDD values and solar irradiation data are based on generic European values.

7.8.2 Evaluation Limitations

- **Demonstrative rather than comparative:** No formal comparison with detailed LCA tools (e.g., openLCA) was performed. The accuracy claims are based on manual formula verification only.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Table 7.6: Mapping of Chapter 5 requirements to prototype implementation

Requirement (Chapter 5)	**Frequency**	**Implementation status**
Semantic interoperability & standardised mappings	74.5%	Partially implemented (structured input/output, no ontology)
Modular & layered architecture	60.0%	Fully implemented (MVVM pattern)
Dynamic / incremental impact calculation	50.9%	Fully implemented (real-time what-if, automatic recalculation)
Integration with BIM & digital building data	45.5%	Not implemented (manual data entry)
Automated data exchange via APIs	40.0%	Partially implemented (modular services, no external APIs)
Scalability & extensibility	32.7%	Partially implemented (new measures can be added via new services)
Real-time / near-real-time processing	21.8%	Fully implemented (sub-second calculation)
Embedded decision logic (BPMN gateways)	69.1%	**Fully implemented** (BPMN gateway condition using carbonPayback < 5 years; decision function integrated into prototype)
Multi-criteria decision support	63.6%	Fully implemented (energy, CO_2, cost, payback)
Scenario-based comparison & trade-off analysis	56.4%	Fully implemented (unified dashboard for four scenarios)
Stakeholder-oriented visualization	43.6%	Partially implemented (dashboard, not role-specific)
Life cycle completeness	36.4%	Partially implemented (embodied A1–A3 + operational)

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

- **No user study:** Time estimates are based on the author's experience, not on a controlled study with multiple practitioners.
- **No longitudinal assessment:** Long-term reliability and maintainability were not evaluated.

Future work should address them through naturalistic evaluation with real stakeholders and comparison with established LCA tools.

7.9 Answer to RQ3

Based on the demonstration of the prototype and the evaluation results, the explicit answer to RQ3 is:

Answer to RQ3:

An integrated BPM–LCA approach can be effectively implemented in renovation project workflows through a modular desktop prototype with three dedicated calculators (window replacement, insulation upgrade, solar PV). The implementation follows a six-step methodology: (1) define renovation context, (2) configure calculation modules, (3) execute calculations with automatic input validation, (4) compare scenarios via unified dashboard, (5) make informed decision, (6) iterate as the process evolves.

Key implementation features:

- Modular MVVM architecture (separate Model, Service, ViewModel, Data layers)
- Comprehensive input validation (guard clauses) preventing erroneous calculations
- Real-time what-if analysis with sub-second recalculation
- Unified dashboard for multi-scenario comparison
- Embodied carbon and carbon payback for insulation and PV

Demonstrated benefits:

- 3–4 minutes user interaction time per module (compared to 60–90 minutes reported in literature for traditional workflows)
- 9/9 decision-relevant indicators provided (vs. 3–4 in typical approaches)
- 100% input validation coverage
- Correct calculation verified by manual recalibration

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

Conclusion: The proposed framework provides a practical, implementable methodology for BPM–LCA integration. The implementation explicitly includes a BPMN process model with an exclusive gateway that evaluates the carbon payback period. The gateway condition (carbonPayback < 5 years) is implemented as a C# function that returns a recommendation, demonstrating that environmental indicators can control process flow. It is important to note that the five-year threshold is fully configurable and can be easily modified to reflect project-specific sustainability targets without requiring changes to the underlying calculation logic. While formal comparative evaluation with detailed LCA tools remains future work, the prototype successfully demonstrates the feasibility and utility of embedding life cycle assessment into renovation decision workflows.

7.10 Summary

This chapter evaluated the BPM–LCA integration framework through demonstration of its core capabilities. The evaluation confirmed:

- The prototype produces correct calculations (verified by manual recalculation).
- Input validation works for all guard clauses (100% coverage).
- The framework provides comprehensive decision support (9 information types).
- User interaction time is approximately 3–4 minutes per module.
- Modular architecture enables extensibility to new renovation measures.

Limitations include the lack of formal comparison with detailed LCA tools, single test case, and absence of user studies. These are addressed as future work. The following chapter concludes the thesis.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

CHAPTER 8

Conclusion

8.1 Summary of the Research

This thesis set out to address a critical gap in sustainable building renovation: the disconnect between operational process management (Business Process Management – BPM) and environmental life cycle thinking (Life Cycle Assessment – LCA). While both fields have matured independently, their integration – especially for renovation decision support – has remained largely conceptual, with few operational frameworks and almost no empirical validation. The research was guided by three questions:

- **RQ1:** What existing methods integrate BPM and LCA in renovation processes, and what are their limitations?
- **RQ2:** What technical and functional requirements must a BPM–LCA framework meet to support sustainable decision-making in office-like building renovations?
- **RQ3:** How can such an integrated approach be effectively implemented in renovation project workflows?

Through a systematic literature review of 55 peer-reviewed studies (Chapter 4), the thesis identified that existing methods fall into four categories: conceptual frameworks (43.6%), methodological modelling approaches (27.3%), technical tool-based solutions (16.4%), and empirical case applications (12.7%). The most pervasive limitations were insufficient operationalization (43.6%), limited decision-support capability (38.2%), and weak or missing empirical validation (87.3% of studies had no real-world application). No method embedded LCA results directly into process decision points; environmental assessment was consistently treated as a post-hoc or parallel analysis.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

From these limitations, the SLR derived 12 requirements (Chapter 5): seven technical (e.g., semantic interoperability, modular architecture, dynamic calculation, BIM integration) and five functional (e.g., embedded decision logic, multi-criteria support, scenario-based comparison). These requirements informed the design of a proof-of-concept prototype (Chapter 6) that implements three modular calculators for window replacement, insulation upgrades, and solar PV installation. The framework explicitly includes a BPMN process model (Figure 6.1) with an exclusive gateway that evaluates the carbon payback period. The gateway condition carbonPayback < 5 years is implemented as a C# function that returns a recommendation, thereby satisfying the embedded decision logic requirement. Full execution via a standard BPMN engine (e.g., Camunda) is identified as future work.

The evaluation (Chapter 7) demonstrated that the prototype:

- Produces correct calculations verified by manual recalibration.
- Validates all inputs via guard clauses (100% coverage).
- Provides nine decision-relevant indicators (energy, CO_2, cost, payback, embodied carbon, carbon payback, multi-scenario comparison, what-if analysis, validation).
- Requires approximately 3–4 minutes of user interaction per module (compared to 60–90 minutes reported in literature for traditional workflows).

Formal comparison with detailed LCA tools (e.g., openLCA) and user studies with practitioners were outside the scope and are identified as future work.

8.2 Answers to Research Questions

8.2.1 Answer to RQ1 – Existing Methods and Limitations

Existing methods for integrating BPM and LCA in renovation processes are predominantly conceptual (43.6% of 55 studies). Methodological approaches (27.3%) propose BPMN extensions or ontologies but rely on manual, project-specific mappings. Technical solutions (16.4%) demonstrate automated data exchange but suffer from tool lock-in and lack of decision integration. Empirical applications (12.7%) are all single-case, short-term, and narrow in life cycle scope. The key limitations are: insufficient operationalization, limited decision-support capability, lack of standardized mappings, environmental assessment being secondary to cost/schedule, and near-absence of real-world validation (87.3% of studies). Consequently, no existing method embeds life cycle environmental assessment directly into renovation process decision points.

8.2.2 Answer to RQ2 – Technical and Functional Requirements

A BPM–LCA framework for office-like building renovations must satisfy seven technical requirements (semantic interoperability and standardized mappings – 74.5%; modular

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

and layered architecture – 60.0%; dynamic/incremental impact calculation – 50.9%; BIM integration – 45.5%; automated data exchange via APIs – 40.0%; scalability and extensibility – 32.7%; real-time/near-real-time processing – 21.8%) and five functional requirements (embedded decision logic in BPMN gateways – 69.1%; multi-criteria decision support – 63.6%; scenario-based comparison and trade-off analysis – 56.4%; stakeholder-oriented visualization – 43.6%; life cycle completeness – 36.4%). These are accompanied by three design principles: process-centricity, life cycle completeness, and decision orientation.

8.2.3 Answer to RQ3 – Effective Implementation

An integrated BPM–LCA approach can be effectively implemented through a six-step methodology using three modular C# calculators with comprehensive input validation, real-time calculation, and a unified dashboard for scenario comparison. The steps are: (1) define renovation context, (2) configure calculation modules, (3) execute calculations with automatic validation, (4) compare scenarios, (5) make informed decision, (6) iterate as the process evolves. Quantitative evidence from the prototype shows 3–4 minutes user interaction per module, 100% input validation coverage, and provision of nine decision-relevant indicators. The implementation includes a BPMN process model with an exclusive gateway that evaluates the carbon payback period. This demonstrates that environmental indicators can actively influence process flow. Full BPMN engine integration (e.g., Camunda) is left for future work.

8.3 Contributions

8.3.1 Theoretical Contributions

- A systematic synthesis of BPM–LCA integration methods (55 studies) with explicit categorization and limitation analysis, providing a clear map of the research landscape.
- Extension of Green BPM theory by operationalizing LCA indicators (embodied carbon, carbon payback) within process-centric renovation decision support.
- A set of 12 evidence-based requirements and three design principles for BPM–LCA frameworks, derived directly from literature limitations.

8.3.2 Methodological Contributions

- A combined SLR and DSR methodology applied to the renovation domain, demonstrating how literature synthesis can drive artefact design.
- A traceability matrix linking limitations to requirements, ensuring design decisions are empirically grounded.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

- A demonstration of how simplified LCA models (HDD method, EPD-based embodied carbon) can be embedded in an interactive decision-support tool without sacrificing early-stage utility.

8.3.3 Technical Contributions

- A fully operational proof-of-concept desktop prototype (C# / WPF / MVVM) with three independent calculators (window, insulation, solar PV), input validation, real-time what-if analysis, and unified scenario comparison.
- Implementation of carbon payback period as a novel decision metric in renovation workflows.
- A modular architecture that allows extension to new renovation measures without modifying core logic.
- Integration of a BPMN process model with an exclusive gateway that uses LCA results (carbon payback) to guide recommendations, satisfying the embedded decision logic requirement.

8.3.4 Practical Contributions

- A six-step implementation methodology that renovation practitioners (engineers, project managers, sustainability officers) can follow to integrate LCA into early-stage planning.
- Quantified time estimates (3–4 minutes per module) demonstrating the framework's efficiency compared to traditional siloed approaches.
- A transparent, reusable codebase (described in Chapter 6) that can serve as a foundation for future production-ready tools.

8.4 Limitations of the Research

8.4.1 Framework Limitations

- **No executable BPMN engine:** The BPMN process model is represented as a static diagram (Figure 6.1), and the gateway logic is implemented as a discrete function rather than being executed by a standard BPMN engine (e.g., Camunda). Full automation of process routing based on LCA results requires future integration.
- **Simplified calculation models:** The Heating Degree Day method does not capture hourly dynamics, thermal inertia, or shading. Detailed energy simulation would require more sophisticated tools.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

- **Limited database scope:** Only a limited set of materials and products are pre-loaded in the SQL Server database. However, the framework allows users to manually add any additional material by specifying all required parameters (thermal conductivity, density, thickness, and Global Warming Potential values per unit or per kilogram). This ensures that the prototype remains extensible and usable even when the desired material is not initially present in the database.
- **Geographic limitations:** Parameters (HDD, irradiation) are based on Vienna, Austria; local calibration is required for other regions.

8.4.2 Evaluation Limitations

- **Demonstrative rather than comparative:** No formal comparison with detailed LCA tools (e.g., openLCA, SimaPro) was performed. Accuracy claims are based on manual formula verification only.
- **Single test case:** Only one building type (office) and one climate (Vienna) were tested. Generalisation to residential, industrial, or other climates requires further validation.
- **No user study:** Time estimates are based on the author's experience, not on a controlled study with multiple practitioners. Actual time savings may vary.
- **Artificial evaluation environment:** The evaluation was conducted by the author, not with real stakeholders in real renovation projects.

8.5 Future Work

Based on the limitations and the contributions of this thesis, several directions for future research are identified:

1. **Full BPMN engine integration:** Connect the LCA calculators to a standard BPMN engine (e.g., Camunda, Activiti) so that process models can dynamically select renovation paths based on LCA results. This would realise the "embedded decision logic in BPMN gateways" requirement fully, not only conceptually.
2. **Naturalistic evaluation:** Conduct a user study with 5–10 renovation practitioners (project managers, engineers, sustainability officers) using real renovation projects. Measure actual time savings, usability (e.g., System Usability Scale), and decision quality.
3. **Comparison with detailed LCA tools:** Perform a systematic accuracy comparison against openLCA or SimaPro using multiple test cases (different building types, climates, renovation measures) and sensitivity analysis.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

4. **BIM integration:** Implement automatic material quantity extraction from IFC files, reducing manual data entry and improving data consistency [12, 15].

5. **Enhanced calculation models:** Replace the HDD method with dynamic simulation (e.g., EnergyPlus, TRNSYS) or machine learning models for higher accuracy while maintaining interactivity.

6. **Expansion to other building types:** Adapt the framework for residential, industrial, and retail buildings, and for different climates (e.g., Mediterranean, Nordic, Continental).

7. **Web-based deployment:** Re-implement the prototype as a web application (e.g., using Blazor or React) to lower barriers for practitioner adoption.

8.6 Concluding Remarks

This thesis has demonstrated that integrating Business Process Management and Life Cycle Assessment in building renovation is not only theoretically feasible but also practically achievable through a well-designed, modular software prototype. By systematically identifying the limitations of existing approaches (87.3% without real-world validation) and translating them into concrete requirements (12 categories), the research produced an artefact that closes the gap between process-centric renovation workflows and environmental life cycle thinking.

The prototype successfully provides real-time sustainability insights (energy, CO_2, cost, payback, embodied carbon, carbon payback) and enables direct comparison of renovation alternatives. Critically, the framework includes a BPMN process model (Figure 6.1) with an exclusive gateway that evaluates the carbon payback period – a concrete demonstration that LCA results can actively influence process decisions, satisfying the most cited functional requirement in the literature (embedded decision logic, 69.1% of studies). The evaluation, though limited to a single test case and demonstrative in nature, shows that the framework reduces user interaction time to 3–4 minutes per module and delivers nine decision-relevant indicators – a substantial improvement over traditional siloed approaches.

The thesis also makes a methodological contribution by demonstrating how a Systematic Literature Review can directly inform Design Science Research, with a traceability matrix linking limitations to requirements to implementation. For practitioners, the six-step methodology provides actionable guidance. For researchers, the open limitations and future work directions offer a clear roadmap toward production-ready BPM–LCA integration.

Ultimately, this work contributes to the broader vision of *Green BPM* – where environmental sustainability is not an afterthought but an integral, measurable, and actively decision-driving component of business process management. In the context of building renovation – a sector responsible for a significant share of global carbon emissions – even

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

modest improvements in decision support can yield substantial cumulative environmental benefits. The framework presented here is a step in that direction.

Vienna, Austria, August 2026

Ali Sehovic

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

Overview of Generative AI Tools Used

This appendix provides an overview of the generative AI tools used during the preparation of this thesis, as required by the declaration of authorship. Generative AI tools were used only as auxiliary aids. The author's own intellectual, analytical, and creative contribution predominates throughout the thesis.

The following generative AI tools were used:

- **ChatGPT** by OpenAI, AI-based conversational system, used between 2025 and 2026.
- **DeepSeek**, AI-based conversational system, used in 2026.

ChatGPT was used for the following supporting purposes:

- language refinement and improvement of academic style;
- suggestions for clearer structure and organization of thesis sections;
- support with LaTeX formatting and Overleaf-related technical issues;
- clarification and reformulation of technical explanations related to Business Process Management, Life Cycle Assessment, Design Science Research, and software prototype documentation;
- assistance in identifying unclear wording, repetition, or overly strong claims.

DeepSeek was used as an auxiliary tool for improving the visual and aesthetic presentation of the framework and related documentation. Its use was limited to suggestions for layout clarity, visual structure, and presentation refinement. It was not used to define the research questions, derive scientific findings, perform calculations, select literature, interpret results, or formulate final conclusions.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

No generative AI tool was used as an autonomous source of scientific findings, empirical data, literature evidence, or research conclusions. The research questions, literature selection and interpretation, framework design, prototype development, calculations, evaluation, discussion, and conclusions were developed, checked, and verified by the author.

Where generative AI output was used, it was critically reviewed, adapted, and integrated by the author. No AI-generated passages were included without substantial review, modification, and authorial control. The author remains fully responsible for the content, accuracy, originality, and academic integrity of this thesis.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

List of Figures

6.1 BPMN process for renovation with an exclusive gateway using the carbon payback period 59

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

List of Tables

3.1 Summary of SLR database searches 20

4.1 Distribution of BPM–LCA integration approaches across the reviewed literature (N=55) 32
4.2 Recurring structural limitations across all 55 reviewed studies 39

5.1 Overview of requirement categories extracted from the reviewed literature (N=55) 45
5.2 Traceability matrix: Limitations (Chapter 4) to Requirements (Chapter 5) 52

7.1 Test case building parameters 73
7.2 Prototype calculation results for four renovation scenarios 73
7.3 Test case verification for window replacement module 75
7.4 Input validation test results 76
7.5 Information completeness comparison 76
7.6 Mapping of Chapter 5 requirements to prototype implementation 78

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

Bibliography

[1] Luisa F. Cabeza, Lidia Rincón, Virginia Vilariño, Germán Pérez, and Albert Castell. Life cycle assessment (lca) and life cycle energy analysis (lcea) of buildings and the building sector: A review. *Renewable and Sustainable Energy Reviews*, 2014.

[2] Marlon Dumas, Marcello La Rosa, Jan Mendling, and Hajo A. Reijers. *Fundamentals of Business Process Management*. Springer, 2 edition, 2018.

[3] International Organization for Standardization. Iso 14040: Environmental management — life cycle assessment — principles and framework, 2006.

[4] International Organization for Standardization. Iso 14044: Environmental management — life cycle assessment — requirements and guidelines, 2006.

[5] Dries Couckuyt and Amy Van Looy. A systematic review of green business process management. *Business Process Management Journal*, 2020.

[6] Jan vom Brocke, Stefan Seidel, and Jan Recker. *Green Business Process Management: Towards the Sustainable Enterprise*. Springer, 2012.

[7] Jan Recker, Marta Indulska, Peter Green, Andrew Burton-Jones, and Ron Weber. Business process management: Saving the planet? In *International Conference on Information Systems*, 2016.

[8] Džana Kadrić, Amar Aganović, Sanita Džino, Una Smailbegović, Ajdin Vatreš, and Edin Kadrić. Integrated life cycle assessment and multi-objective optimization of residential building renovation strategies to achieve nzeb standards. *Energy and Buildings*, 2026.

[9] John Basbagill, Forest Flager, Michael Lepech, and Martin Fischer. Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts. *Building and Environment*, 2013.

[10] Mathias Weske. *Business Process Management: Concepts, Languages, Architectures*. Springer, 3 edition, 2019.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

[11] Mario Cortes Cornax, Agnes Front, Raquel Oliveira, and Claudia Roncancio. A method for assessing environmental impacts of business processes. In *IEEE Conference on Business Informatics*, 2025.

[12] Chiara Cavalliere, Guillaume Habert, Giulia R. Dell'Osso, and Alexander Hollberg. Continuous bim-based assessment of embodied environmental impacts throughout the design process. *Journal of Cleaner Production*, 211:941–952, 2019.

[13] José Pedro Carvalho, Luís Bragança, and Ricardo Mateus. Automating building sustainability assessment using building information modelling: A case study, 2024. Under review / forthcoming.

[14] Jeroen B. Guinée, Marijke Gorrée, Reinout Heijungs, Gjalt Huppes, Rene Kleijn, Arjan de Koning, and Mark A.J. Huijbregts. *Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards*. Springer, 2002.

[15] Salman Azhar. Building information modeling (bim): Trends, benefits, risks, and challenges for the aec industry. *Leadership and Management in Engineering*, 2011.

[16] Alan R. Hevner, Salvatore T. March, Jinsoo Park, and Sudha Ram. Design science in information systems research. *MIS Quarterly*, 28(1):75–105, 2004.

[17] Ken Peffers, Tuure Tuunanen, Marcus A. Rothenberger, and Samir Chatterjee. A design science research methodology for information systems research. *Journal of Management Information Systems*, 24(3):45–77, 2007.

[18] Barbara Kitchenham and Stuart Charters. Guidelines for performing systematic literature reviews in software engineering. Technical report, Keele University, 2007.

[19] David Moher, Alessandro Liberati, Jennifer Tetzlaff, and Douglas G. Altman. Preferred reporting items for systematic reviews and meta-analyses: The prisma statement. *PLoS Medicine*, 6(7):e1000097, 2009.

[20] Claes Wohlin. Guidelines for snowballing in systematic literature studies and a replication in software engineering. In *Proceedings of the 18th International Conference on Evaluation and Assessment in Software Engineering*, 2014.

[21] James Thomas and Angela Harden. Methods for the thematic synthesis of qualitative research in systematic reviews. *BMC Medical Research Methodology*, 8(45), 2008.

[22] Alan R. Hevner. A three cycle view of design science research. *Scandinavian Journal of Information Systems*, 19(2):87–92, 2007.

[23] Shirley Gregor and Alan R. Hevner. Positioning and presenting design science research for maximum impact. *MIS Quarterly*, 37(2):337–355, 2013.

[24] John Venable, Jan Pries-Heje, and Richard Baskerville. Feds: A framework for evaluation in design science research. *European Journal of Information Systems*, 2016.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

[25] Matthew J. Page, Joanne E. McKenzie, Patrick M. Bossuyt, Isabelle Boutron, et al. The prisma 2020 statement: An updated guideline for reporting systematic reviews. *Systematic Reviews*, 10(1):89, 2021.

[26] Alessandra Marini, Chiara Passoni, and Andrea Belleri. Life cycle perspective in rc building integrated renovation. *Sustainable Cities and Society*, 2018.

[27] Tarja Häkkinen and Katja Belloni. Barriers and drivers for sustainable building. *Building Research and Information*, 2011.

[28] Mohammed Seddiki and Amar Bennadji. A life cycle carbon assessment and multi-criteria decision-making framework for building renovation within the circular economy context. *Buildings*, 2025.

[29] Martin Röck, Maria Balouktsi, and Thomas Lützkendorf. Embodied ghg emissions of buildings – critical reflection of benchmark comparison and in-depth analysis of drivers. *IOP Conference Series: Earth and Environmental Science*, 2020.

[30] Marlon Dumas, Wil van der Aalst, and Arthur ter Hofstede. *Process-Aware Information Systems: Bridging People and Software Through Process Technology*. Wiley, 2005.

[31] Wil van der Aalst. *Process Mining: Data Science in Action*. Springer, 2016.

[32] Mark Mom, Ming-Hsiu Tsai, and Shih-Hau Hsieh. Developing critical success factors for the assessment of bim technology adoption. *Journal of the Chinese Institute of Engineers*, 2014.

[33] João Carlos Maciel. The core capabilities of green business process management – a literature review. In *Business Process Management Conference*, 2017.

[34] Luisa F. Cabeza, Camila Barreneche, Laura Miró, Josep M. Morera, Elisa Bartolí, and Ana I. Fernández. Low carbon and low embodied energy materials in buildings: A review. *Renewable and Sustainable Energy Reviews*, 2013.

[35] Oscar Ortiz, Francesc Castells, and Guido Sonnemann. Sustainability in the construction industry: A review of recent developments based on lca. *Construction and Building Materials*, 2009.

[36] Oscar Ortiz-Rodríguez, Francesc Castells, and Guido Sonnemann. Life cycle assessment of two dwellings: One in spain and one in colombia. *Science of the Total Environment*, 2010.

[37] Alexander Passer, Helmut Kreiner, and Peter Maydl. Assessment of the environmental performance of buildings: A critical evaluation of the influence of technical building equipment. *International Journal of Life Cycle Assessment*, 2012.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

[38] Alexander Passer, Sebastien Lasvaux, Karen Allacker, et al. Environmental product declarations entering the building sector: Critical reflections from three countries. *International Journal of Life Cycle Assessment*, 2015.

[39] Francesco Pomponi and Alice Moncaster. Circular economy for the built environment: A research framework. *Journal of Cleaner Production*, 2017.

[40] Constantin Houy, Peter Fettke, and Peter Loos. Empirical research in business process management–analysis of an emerging field of research. *Business Process Management Journal*, 2010.

[41] Joseph Sarkis, Laura M. Meade, and Adrian R. Presley. Incorporating sustainability into contractor evaluation and team formation in the built environment. *Journal of Cleaner Production*, 2012.

[42] Stefan Seuring and Martin Müller. From a literature review to a conceptual framework for sustainable supply chain management. *Journal of Cleaner Production*, 2012.

[43] Stefan Seuring and Martin Müller. Core issues in sustainable supply chain management – a delphi study. *Business Strategy and the Environment*, 2008.

[44] Stefanos Eleftheriadis, Dejan Mumovic, and Paul Greening. Life cycle energy efficiency in building structures: A review of current developments and future outlooks. *Renewable and Sustainable Energy Reviews*, 2017.

[45] Carmen Llatas. A model for quantifying construction waste in projects. *Waste Management*, 2011.

[46] Michael Hammer. What is business process management? In *Handbook on Business Process Management*. Springer, 2015.

[47] Wil van der Aalst. Business process management: A comprehensive survey. *ISRN Software Engineering*, 2013.

[48] Nancy M. P. Bocken, Samuel W. Short, Padmakshi Rana, and Steve Evans. A literature and practice review to develop sustainable business model archetypes. *Journal of Cleaner Production*, 2014.

[49] Angel Giret, Damien Trentesaux, and Venkatesh Prabhu. Sustainability in manufacturing operations scheduling. *International Journal of Production Economics*, 2015.

[50] Salvatore T. March and Gerald F. Smith. Design and natural science research on information technology. *Decision Support Systems*, 15(4):251–266, 1995.

[51] Mark Petticrew and Helen Roberts. *Systematic Reviews in the Social Sciences: A Practical Guide*. Blackwell Publishing, 2006.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

[52] Tore Dybå and Torgeir Dingsøyr. Strength of evidence in systematic reviews in software engineering. In *Empirical Software Engineering and Measurement*, 2008.

[53] Pearl Brereton, Barbara Kitchenham, David Budgen, Mark Turner, and Mohamed Khalil. Lessons from applying the systematic literature review process within the software engineering domain. *Journal of Systems and Software*, 2007.

[54] Xiaoling Zhang, Liyin Shen, and Liyun Zhang. Life cycle assessment of the air emissions during building construction process. *Renewable and Sustainable Energy Reviews*, 2013.

[55] Monique H. Jansen-Vullers, Cornelis A. van Dorp, and Adrie J. Beulens. Managing traceability information in manufacture. *International Journal of Production Economics*, 2003.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.