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CONSTRUCTION
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Enhancing Sustainable Material Management in Infrastructure Renovation: Strategies for Contractors in the Dutch Construction Sector

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Executive Summary

The construction sector significantly impacts the environment through carbon emissions, resource depletion, and waste generation. In Dutch infrastructure renovation projects, these challenges are compounded by the need to maintain aging structures while enhancing sustainability. Sustainable Material Management (SMM) is an approach that focuses on enhancing material use throughout the entire lifecycle—from extraction and production to usage and end-of-life disposal—to minimize environmental impact and improve economic efficiency. However, implementing SMM in the construction industry faces significant challenges, including limited availability of sustainable materials, higher costs, client resistance, and logistical constraints. The goal of this thesis is to explore how contractors can enhance sustainable material management in Dutch infrastructure renovation projects, identifying key challenges and opportunities for implementing SMM practices and offering actionable strategies to promote sustainable development in the construction industry.

Research Objectives and Questions

The primary objective of this thesis is to determine effective strategies for contractors to enhance SMM in renovation projects. The main research question is: **How do contractors enhance sustainable material management in Dutch infrastructure renovation projects?** This question is explored through four sub-questions, focusing on understanding SMM practices, identifying barriers and drivers, checking current applications by contractors, and exploring strategies for future projects.

Sub-Questions:

SQ1.: What are the barriers and drivers that contractors face in enhancing sustainable material management within infrastructure renovation projects?

SQ2.: What research methodology can be employed to identify challenges and best practices in SMM within infrastructure renovation projects?

SQ3.: How do contractors currently apply SMM strategies in projects, and what are their willingness and ability to enhance sustainability in this area?

SQ4.: What sustainable material management strategies can enhance environmental and economic sustainability in future infrastructure renovation projects?

Methodology

The research was structured into three main phases:

1. **Literature Review:** The first phase involved a review of the existing literature on SMM, particularly within the construction industry. This review established a theoretical foundation for the study, examining the roles of contractors, the importance of sustainable practices, and the various barriers and drivers influencing SMM implementation.

2. **Empirical Research:** In the second phase, semi-structured interviews were conducted with eleven industry professionals, including contractors, engineers, and sustainability experts. These interviews provided practical insights into the current state of SMM practices,

contractor’s willingness and ability to implement these strategies, and the challenges they face in doing so.

3. **Synthesis and Conclusion:** The final phase synthesized the findings from both the literature review and empirical research. This synthesis provided an understanding of SMM in the context of infrastructure renovation, answering the main research question and sub-questions. The study concludes with specific recommendations designed for contractors, clients, and suppliers.

Key Findings

The study found that SMM involves a comprehensive approach to managing materials across their entire lifecycle, from sourcing and procurement to disposal and recycling. Contractors are at the forefront of implementing these practices because they are directly responsible for material selection, procurement processes, and construction methodologies. Their position enables them to make critical decisions about which materials to use, how to optimize resource utilization, and how to manage waste on-site, all of which significantly impact the sustainability of renovation projects. By integrating SMM into their operations, contractors can influence the environmental performance of projects more than any other stakeholder, making their role crucial in driving sustainable practices within the industry.

However, the research also identified several challenges that limit the widespread adoption of SMM practices. Financial constraints are a primary obstacle, since eco-friendly materials and technologies often involve greater initial expenses, straining project budgets and profitability. Client demands and preferences sometimes conflict with sustainability objectives, especially when clients prioritize cost savings or expedited timelines over environmental considerations. Limited access to sustainable materials poses another challenge, with contractors facing difficulties in sourcing eco-friendly materials due to supply chain limitations or lack of availability in the market. Additionally, market barriers such as regulatory hurdles, insufficient industry standards, and a lack of incentives complicate the implementation of SMM strategies. Even when contractors are willing to pursue more sustainable options, these obstacles can hinder their ability to fully integrate SMM into their projects. This underscores the need for a collaborative effort among all stakeholders—including clients, suppliers, and policymakers—to support the transition towards sustainable practices.

Despite these challenges, the study revealed a strong willingness among contractors to adopt SMM, driven by both regulatory requirements and a growing recognition of the importance of sustainability in construction. Through semi-structured interviews with industry professionals, the research gathered valuable insights into current SMM practices and strategies being employed. Contractors are actively exploring innovative approaches, such as using recycled and bio-based materials to reduce reliance on virgin resources and lower carbon emissions. They are enhancing energy efficiency by adopting electric machinery and equipment, which decreases operational emissions and long-term energy costs. Contractors are also optimizing waste management by implementing circular economy principles, such as designing for disassembly and promoting material reuse and recycling. These strategies not only reduce environmental impact but also contribute to economic sustainability by lowering operational costs, improving resource efficiency, and potentially opening new market opportunities for green construction.

The findings show that successfully implementing SMM requires a combination of strategic actions. Early involvement of contractors in project planning and design is crucial, as it allows them to influence key decisions about materials and sustainability assessments before constraints become fixed. By participating from the outset, contractors can advocate for sustainable options and integrate SMM principles effectively. Flexible contracts that accommodate innovative SMM solutions enable contractors to incorporate sustainable practices without being hindered by rigid specifications or traditional procurement models. The integration of digital technologies, such as Building Information Modeling (BIM) and Radio Frequency Identification (RFID), is essential for efficient material management and waste reduction. These tools enhance transparency, enable precise tracking of materials throughout the project lifecycle, and facilitate better decision-making. Additionally, a supportive regulatory framework and market incentives, such as subsidies or tax benefits for sustainable practices, can encourage the adoption of SMM by making it more financially viable and appealing to both contractors and clients. These measures demonstrate the long-term benefits of SMM in both environmental and economic terms, providing a compelling case for its broader implementation in the construction industry.

To consolidate these strategic actions and provide a practical roadmap for contractors, the study developed a structured framework. This framework outlines key strategies for enhancing SMM in renovation projects, integrating the critical components identified in the research. This framework includes Comprehensive Assessments and Lifecycle Calculations, Sustainable Material Integration, Sustainable Design Optimization, Stakeholder Engagement and Collaboration, Electrification of Equipment and Energy Efficiency, and Gradual Technological Integration. This structured approach enables them to overcome obstacles and contribute significantly to both environmental and economic sustainability in their projects.

Recommendations

For Contractors:

- Invest in Training and Technology: Focus on learning about SMM practices and adopting technologies like BIM, RFID, and IoT for better project planning and material management.
- Engage Early in Projects: Get involved early in project planning to influence sustainable material choices and construction methods.
- Adopt Sustainable Practices: Implement recycling programs, reduce waste with efficient material use, and use lean construction techniques.
- Foster Collaboration: Maintain open communication with clients, suppliers, and regulatory bodies to align on sustainability goals.

For Clients:

- Set Clear Sustainability Goals: Define specific sustainability objectives for material use, energy efficiency, and waste reduction in project requirements.
- Provide Contract Flexibility: Allow for innovative solutions by offering flexible contracts that encourage sustainable practices.
- Offer Financial Incentives: Motivate contractors with bonuses, funding for sustainable materials, or sharing costs for green technologies.
- Promote Awareness: Organize workshops and training to highlight the benefits of sustainable construction practices.

For Suppliers:

- Meet Sustainability Standard: Produce materials with low environmental impact and high recyclability.

- Enhance Transparency: Provide detailed information on product sustainability, including lifecycle assessments and certifications.
- Innovate Continuously: Develop new sustainable materials and collaborate with contractors and clients to meet industry needs.
- Optimize Logistics: Improve sustainability in distribution with energy-efficient transport and reduced packaging waste.

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Acronyms

EMM- Effective Material Management

SMM - Sustainable Material Management

BIM - Building Information Modeling

RFID - Radio Frequency Identification

IoT - Internet of Things

COM-B - Capability, Opportunity, Motivation, and Behavior

TPB - Theory of Planned Behavior

LEED - Leadership in Energy and Environmental Design

GSCM - Green Supply Chain Management

LCA - Life Cycle Assessment

ECI - Environmental Cost Indicator

VOC - Volatile Organic Compound

DB - Design-Build

DBM - Design-Build-Maintain

GBM - Green Building Materials

CDW - Construction and Demolition Waste

IBIM - Infrastructure Building Information Modeling

JIT - Just-In-Time

EPD - Environmental Product Declaration

HVAC - Heating, Ventilation, and Air Conditioning

CE - Circular Economy

1. Introduction

1.1. Background of the study

The construction sector significantly impacts environmental sustainability due to its contributions to carbon emissions, resource depletion, and waste generation (Hashoosh, 2023). The industry's heavy reliance on materials like cement and steel results in high greenhouse gas emissions, worsening climate change (Crawford & Cadorel, 2017). Moreover, the extensive use of natural resources such as water, minerals, and raw materials leads to their depletion, endangering the sustainability of future projects (Crawford & Cadorel, 2017). To mitigate these environmental impacts, sustainable construction practices are essential. These practices focus on waste prevention, reuse, and management, aiming to balance economic growth with environmental preservation and social well-being (Mavi et al., 2021; Hashoosh, 2023). By adopting such practices, the construction sector can reduce pollution, conserve resources, and ultimately contribute to a more sustainable future (Hashoosh, 2023).

Given the construction sector's significant impact on the environment, sustainable practices are also important for addressing the challenges of aging infrastructure. As infrastructure ages, particularly in regions like Europe and North America, there is an increasing need to enhance key sectors such as water and roads to improve climate resilience (Kennedy & Corfee-Morlot, 2013). In the Netherlands, for instance, efforts to upgrade and maintain structures built since the 1960s have become necessary due to increased loads from growing car traffic and climate-induced changes, such as higher waves, which exceed these infrastructure's original design capacities (A.N. Bleijenberg, 2021). The urgency of renovating aging infrastructure is driven by climate change and sustainability commitments, requiring strategies that are resilient to environmental threats and adaptable to evolving societal needs (Lim et al., 2023). This involves adjusting the physical characteristics of buildings and adopting construction practices that use materials durable enough to withstand extreme weather conditions while also being environmentally sustainable (Grynning et al., 2020). Thus, addressing aging infrastructures through sustainable practices not only enhances resilience and adaptability but also aligns with broader efforts to mitigate environmental impacts and promote sustainability in the construction sector (Lim et al., 2023).

Building on the need for sustainable practices in aging infrastructure, the construction industry's movement towards sustainable development is increasingly driven by the scarcity of natural resources. This shift encourages the exploration of innovative and sustainable technical solutions (Stanitsas et al., 2021). In sustainable renovation, these solutions must meet environmental, social, and economic sustainability criteria during building modifications (Thuvander et al., 2012). A key focus in renovation projects is the management of material resources, which involves using materials effectively and sustainably through designs that ensure product longevity and energy efficiency, as well as incorporating waste-efficient procurement and planning for deconstruction (Sáez-De-Guinoa et al., 2022). These strategies aim to reduce waste and optimize energy consumption, enhancing the overall sustainability of construction practices (Sáez-De-Guinoa et al., 2022). Central to achieving these objectives is Sustainable Material Management (SMM), a comprehensive approach that manages the lifecycle of materials—from selection and extraction to recycling and disposal—promoting both economic efficiency and environmental sustainability (Fiksel, 2006).

The benefits of these strategies show the importance of material management for achieving sustainability and cost-efficiency in construction projects. Although materials are a subset of resources, they have the most significant impact on project costs, timelines, and overall productivity (Koriom et al., 2019). Effective material management improves planning and control, reduces waste, and optimizes resource use, which is vital for achieving project goals (Da Silva et al., 2023). Given that materials and equipment often account for over 70% of a project's total cost, their efficient management is key to controlling budgets and minimizing cost variances (Gulghane & Khandve, 2015). Construction materials alone can influence up to 80% of a project's costs and timelines, highlighting their critical role in project planning (Koriom et al., 2019). Additionally, material management supports environmental sustainability by reducing greenhouse gas emissions through the use of sustainable materials with lower embodied energy and carbon footprints, contributing to climate change mitigation and the transition to a low-carbon economy (Altaf & Zulfiqar, 2023).

While material management is important for sustainability, collaboration among all project stakeholders is essential for the broader shift towards sustainable construction, as it enables the integration of sustainability goals across all project stages and ensures that each stakeholder's efforts reinforce one another (Larsson & Larsson, 2020). This approach utilizes eco-friendly, resource-efficient processes to minimize environmental impact throughout a building's lifecycle (Zainordin et al., 2023). For example, clients play an important role by setting sustainability goals at the project's inception, incorporating environmental certifications and efficiency standards into procurement documents to embed these priorities from the start (Yang & Qian, 2014). This early commitment not only directs the project’s path but also fosters innovation among contractors and other participants to meet sustainability objectives. Suppliers support these efforts by adhering to circular economy principles, providing environmentally friendly materials, and ensuring that the supply chain aligns with sustainability goals (Tushar et al., 2022). Additionally, contractors maintain the project's schedule and budget by managing effective material use and promoting sustainable practices throughout the project lifecycle (Kar and Jha, 2020; Chong et al., 2023). By working together, these stakeholders collectively advance the construction industry towards more sustainable practices.

1.2. Research Problem

Achieving sustainable construction requires a coordinated approach among main stakeholders (Clients, Contractors, and suppliers), emphasizing the need for efficient and sustainable management of material resources. Despite the growing recognition of the need for SMM, significant gaps remain in understanding how these practices can be effectively implemented, particularly in the context of infrastructure renovation projects.

Previous studies have explored various aspects of SMM. For instance, Kar and Jha (2020) examined improving material management and the challenges it faces. Gulghane and Khandve (2015) highlighted the importance of effective materials management and techniques for minimizing construction waste. Yang and Qian (2014) emphasized specifying clear sustainability requirements in contractor selection to achieve sustainable project goals. Additionally, research in Malaysia's construction industry by Chong et al. (2023) focused on using green materials and the challenges of implementing sustainable materials to reduce carbon emissions and waste. Other studies, such as those by Koriom et al. (2019), have noted the impact of materials management on project costs and timelines, emphasizing that effective materials management can improve productivity and reduce delays, while identifying ongoing challenges such as inadequate implementation practices among contractors. Hashoosh (2023) explored the importance of recycling construction waste for environmental, economic, and social sustainability. Sáez-De-Guinoa et al. (2022) highlighted the need for effective material recovery, energy efficiency improvements, and sustainable practices to meet climate targets.

These studies have contributed valuable insights into the importance of material management in the construction industry and how sustainable materials can reduce environmental footprints and improve project efficiency. However, there remains a critical gap in understanding the specific contributions and challenges faced by contractors in implementing SMM practices (Figure 1). Contractors play an important role in operationalizing sustainability ambitions and driving the industry toward sustainable development, yet their perspectives, particularly in managing materials efficiently to meet environmental standards, are underrepresented in the literature. Empirical evidence on the practical implementation and effectiveness of SMM practices in infrastructure renovation projects is limited. This gap underscores the need for detailed empirical research that focuses on the roles and challenges of contractors.

The Netherlands is selected as the study's focal area due to the urgent need for sustainable construction practices, driven by its extensive and aging infrastructure (Van Baaren et al., 2023). Contractors are the main focus because of their direct role in material management and their significant influence in leading the shift toward sustainability. By integrating sustainable practices into construction projects, contractors play a crucial role in this shift, impacting resource efficiency, environmental performance, and economic outcomes (Tan et al., 2011). Sustainable construction practices enable contractors to minimize negative environmental impacts and enhance economic contributions, fostering a competitive advantage. Through innovation, improved productivity, and better compliance with environmental regulations, contractors drive improved project outcomes and elevate industry standards (Tan et al., 2011).

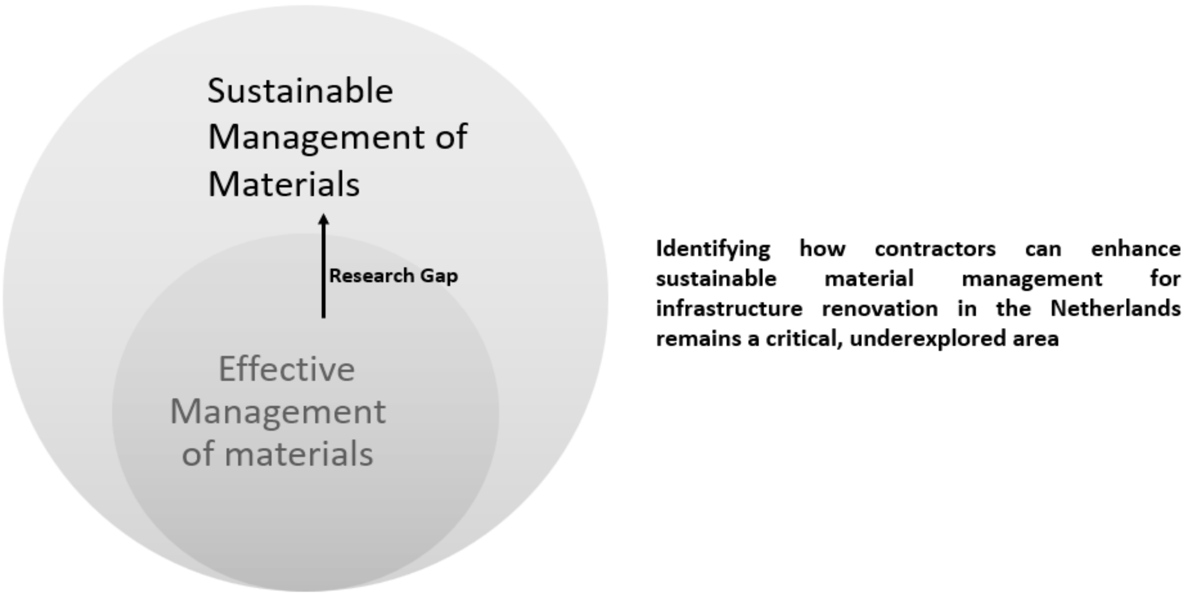

Figure 1 Shift from Effective to Sustainable Material Management in Infrastructure Renovation (Source: Author)

1.3. Objectives and Research Questions

The objective of this study is to fill the previously described gap in sustainable material management by identifying and proposing actionable strategies for contractors. This research will investigate current SMM practices and the challenges contractors face, with a focus on the effectiveness of these practices. By identifying these challenges, the study aims to highlight how overcoming them can lead to reduced waste, lower carbon emissions, and the promotion of recycled and eco-friendly materials, contributing to environmental sustainability. The outcome will include targeted recommendations for enhancing SMM adoption and effectiveness at the contractor level, aiming to improve both sustainability outcomes and operational efficiency in renovation projects.

The main research question is:

How do contractors enhance sustainable material management in Dutch infrastructure renovation projects?

To answer the main research question, the following sub-research questions are developed:

SQ1.: What are the barriers and drivers that contractors face in enhancing sustainable material management within infrastructure renovation projects?

SQ2.: What research methodology can be employed to identify challenges and best practices in SMM within infrastructure renovation projects?

SQ3.: How do contractors currently apply SMM strategies in projects, and what are their willingness and ability to enhance sustainability in this area?

SQ4.: What sustainable material management strategies can enhance environmental and economic sustainability in future infrastructure renovation projects?

1.4. Significance of the study

This study enriches the Dutch construction sector by spotlighting contractor's role in sustainable material management during infrastructure renovations. It bridges the gap between the perceived trade-off of environmental sustainability and economic efficiency, offering practical strategies for harmonizing these goals. Through interviews with experienced professionals to collect and analyze data, and subsequent interviews conducted to validate the results, the research provides contractors with actionable insights to adopt sustainable practices.

Aimed at advancing the integration of sustainability within material management, this research underscores the feasibility of achieving environmental benefits alongside economic viability. It challenges the notion of mutual exclusivity between sustainability and cost-effectiveness. The outcome is envisioned to catalyze the shift towards construction processes that support the Netherland's environmental ambitions without compromising economic growth.

1.5. Research Design

The main research question will be answered by 3 stages as shown in figure 2, first stage will be the literature study which will form the base for the empirical research stage, and finally the synthesis stage.

Figure 2 Research design schematic.

Stage 1. literature Study

The literature study aims to establish a foundational understanding of sustainable material management in renovation projects. This stage will be conducted in chapter 2, addressing SQ1 by exploring existing literature. A traditional literature study will be employed, utilizing academic databases such as Google Scholar, Scopus, ScienceDirect, and the TU Delft online library, with keywords such as sustainable material management in construction, construction and demolition ,waste recycling, circular economy in renovation projects, contractor’s role in sustainable construction, effective material management, challenges in sustainable construction material management.
The literature review is designed to investigate and document the current state of SMM practices within the context of infrastructure renovation projects, with a focus on the role of contractors. It seeks to determine the existing practices adopted by contractors to manage materials sustainably, the environmental and economic implications of these practices, and the primary challenges contractors face in implementing SMM in renovation projects. The review will utilize a variety of academic sources to gather insights that will inform subsequent phases of research, including the formulation of interview questions, thereby ensuring a grounded understanding of SMM within the Dutch construction sector.

Stage 2. Empirical Research

This stage of the research marks a critical transition from theoretical exploration in the literature review to empirical investigation. Chapter 3 delineates the methodology for conducting empirical research, laying the groundwork for the subsequent chapters and address sub-question 2. Chapter 4 delves into interviews that bolster the findings from the literature review.

This stage addresses sub-question 3 by detailing the application of SMM strategies, exploring contractor’s readiness to transition from traditional effective material management to SMM, and assessing their capability to implement these strategies in real-world projects.

Stage 3. Synthesis

This final stage synthesizes the outcomes of the literature review and the empirical study presented through the interviews in Chapter 5. In this chapter, the findings from both the literature and the interviews are discussed in detail, answering sub-question 4. Chapter 6 then presents the conclusion, where the main research question is addressed, bringing together the key insights and recommendations derived from the research.

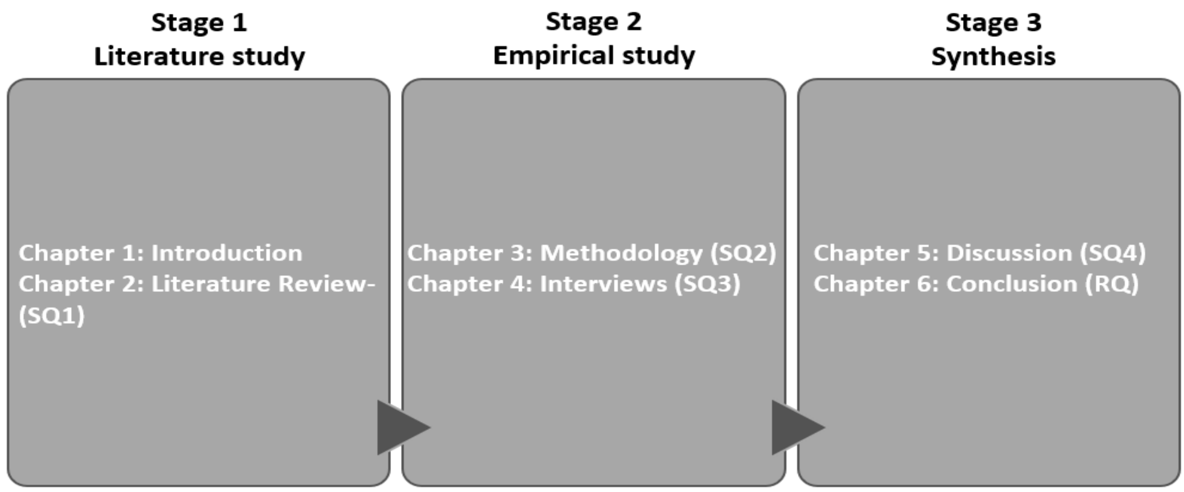

Figure 3 Thesis Outline

2. Literature Review

This chapter aims to explore the existing literature to construct a foundational understanding of SMM in context of renovation projects. The purpose is to situate this study within the broader scholarly landscape, delineating its novel contribution to the field. Additionally, this investigation seeks to explain the concept of SMM, its operational mechanisms, the role of contractors in implementing it, and the barriers and drivers of this implementation, thereby addressing the critical sub-question:

SQ1: What are the barriers and drivers that contractors face in enhancing sustainable material management within infrastructure renovation projects?

Organized into distinct yet interconnected sections, the chapter unfolds as follows: Sections 2.1 (Effective Material Management) and 2.2 (Sustainable Material Management) lay the groundwork by defining SMM, contrasting it with traditional material management practices, and outlining its significance for environmental sustainability and project efficiency. Section 2.3 (Sustainable Materials Management in Construction Projects) delves into the important role contractors play in SMM, examining their responsibilities, challenges, and the strategies they employ from project inception through to completion. Section 2.4 (Barriers and Drivers of Sustainable Material Management Implementation in Construction) further show the specific hurdles encountered in implementing SMM within the renovation sector, offering insights into the complexities of adapting existing practices towards greater sustainability, and the drivers of this implementation. Section 2.5 (Theoretical Framework: Willingness and Ability in Sustainable Material Management) introduces the theoretical underpinnings that highlight the importance of contractors' willingness and ability in implementing SMM strategies. The literature review concludes with Section 2.6 (Summary), which synthesizes the insights garnered from the review, directly addresses the sub-question, and articulates the research gap that this thesis aims to fill, setting the stage for the empirical research that follows.

2.1. Effective Material management

Effective Material Management (EMM) in the construction industry is recognized as a comprehensive and systematic process essential for achieving project success, encompassing planning, procurement, storage, and distribution of materials to meet project demands accurately (Gulghane & Khandve, 2015). This approach is further elaborated by Koriom et al. (2019), necessitates the effective coordination of people, organizations, technology, and procedures, ensuring efficient handling of materials from identification to preservation throughout the project lifecycle (Figure 4). Also, Patel & Vyas (2011) and Donyavi & Flanagan (2009) highlight the importance of material management in ensuring the timely availability of quality materials at the necessary locations, alongside emphasizing cost-effectiveness and efficiency in procurement and on-site management.

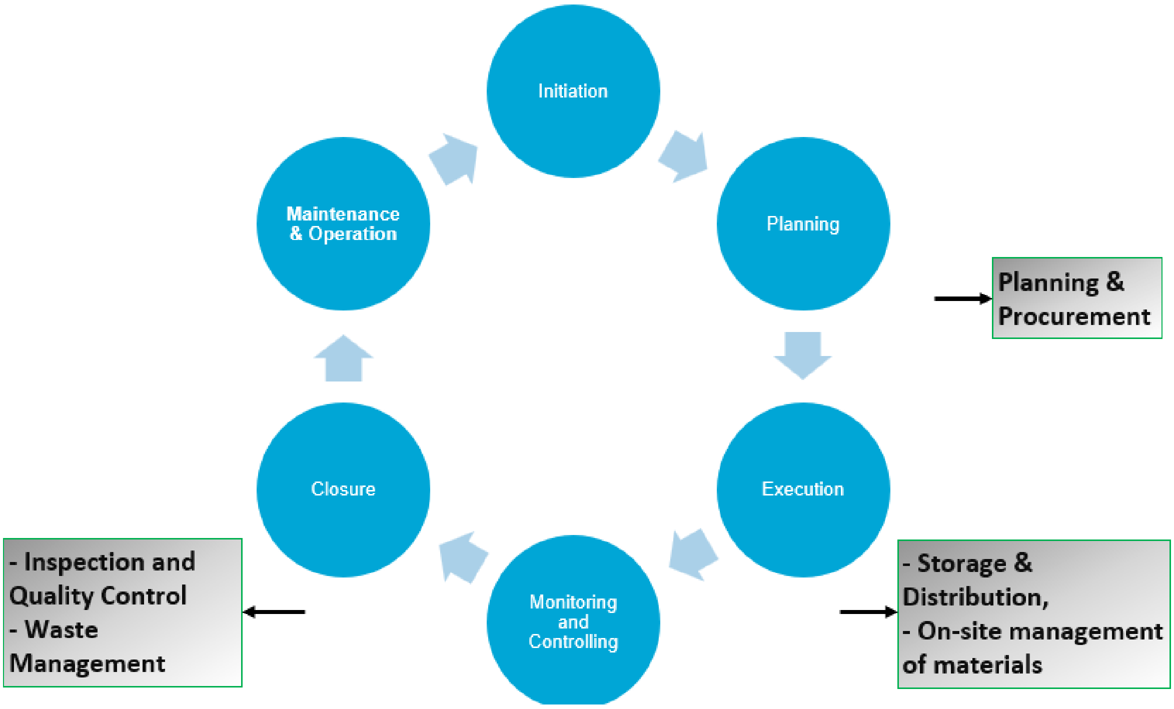

Figure 4 The Integration of Material Management Processes within the Construction Project Lifecycle (Source: Author)

The implementation of EMM within construction projects fosters numerous advantages, including substantial cost reductions, streamlined material handling, minimized order duplications, and elevated labor productivity. These benefits collectively facilitate an optimized project lifecycle, enhance quality control, and strengthen supplier relationships, thereby elevating the efficiency and cost-effectiveness of project execution (Patil & Pataskar, 2013).

The efficacy of EMM lies in its ability to blend theoretical models such as Just-In-Time (JIT) delivery and Lean Construction with practical applications, addressing the unique challenges faced in construction projects. These challenges include resource allocation, time management, cost control, maintaining quality and safety standards, managing project complexity, adapting to changes, dealing with uncertainties, and ensuring effective communication (Alameri et al., 2021). This seamless integration is instrumental in minimizing waste and enhancing delivery timelines, as evidenced by Hussein and Zayed's (2021) exploration of JIT's critical success factors in modular integrated construction. It underscores the transformative potential of bridging theoretical frameworks with practical implementation, marking a significant leap towards operational excellence in the industry.

Moreover, the rise of digitalization and technology has opened new ways to improve EMM. The application of Artificial Intelligence (AI) and Machine Learning (ML) technologies, as discussed by Liu and Lin (2021), is revolutionizing the forecasting of material requirements, refining procurement schedules, and reducing inventory discrepancies. These advancements not only improve the accuracy of material demand predictions but also underscore the growing importance of integrating cutting-edge technologies to enhance material management practices.

In conclusion, EMM is identified within this research as the standard method for managing materials in the construction industry. It encompasses a comprehensive process aimed at the systematic planning, procurement, storage, and distribution of materials to meet the precise demands of construction projects. EMM is characterized by its focus on optimizing operational efficiency, enhancing cost-effectiveness, and ensuring timely availability of materials. This traditional methodology underlines the importance of coordinating people, technology, and procedures to facilitate smooth project execution and achieve project success. As the transition from EMM to explore SMM in the next section, it is crucial to recognize EMM's role in laying the groundwork for introducing more environmentally sustainable practices in the field.

2.2. Sustainable Material Management (SMM)

In 1987, the Brundtland Commission of the United Nations set the foundation for sustainability, defining it as “development that meets present needs without compromising the ability of future generations to meet their own” (United Nations, n.d.-b). Building upon this foundation, SMM adopts a comprehensive approach, aiming to reduce environmental harm and conserve resources throughout a material's lifecycle. This involves minimizing waste generation, reducing carbon emissions, and promoting the efficient use of materials from extraction and manufacturing through to transportation, use, and end-of-life disposal (Van Calster, 2014). Simultaneously, it seeks to ensure economic viability and equity, striving for a balance between ecological preservation and socio-economic benefits (Van Calster, 2014).

Aligned with this approach, SMM is grounded in the three pillars of sustainability (environmental, economic, and social sustainability) which together ensure a balanced strategy for sustainable development (Elkington, 1997). Environmental sustainability focuses on minimizing negative impacts on ecosystems and conserving natural resources (Goodland, 1995). Economic sustainability emphasizes the efficient use of resources and the long-term economic viability of practices without causing harm to the environment or society (Dyllick & Hockerts, 2002). Social sustainability involves promoting social equity, community well-being, and fair labor practices (Colantonio, 2009). By integrating these three pillars, SMM aims to strike a balance between ecological preservation, economic viability, and social responsibility (OECD, 2012).

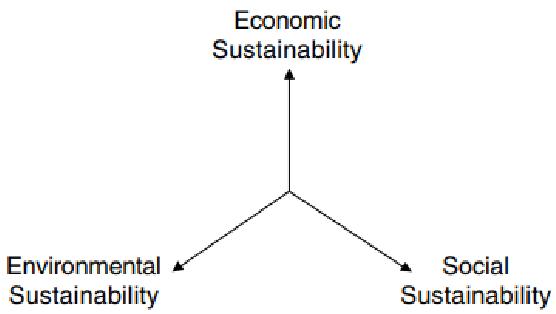

Figure 5 Three pillars of sustainability (Dyllick & Hockerts, 2002).

The prioritization in SMM is on enhancing project sustainability by integrating eco-friendly materials and practices into project execution. This involves selecting materials that minimize ecological footprints, such as those with low embodied energy, sourced from renewable or recycled content, and designed for longevity and recyclability (Bhuiyan & Hammad, 2023). These criteria support the broader goal of a circular economy by reducing waste, enhancing resource efficiency, and promoting the reuse and recycling of materials throughout the project lifecycle (Bhuiyan & Hammad, 2023).

SMM emphasizes the need for integrated strategies across procurement, transportation, and facility management to mitigate impacts on the economy, environment, and society. Key to this integration is the emphasis on sustainable practices from the outset—including sustainable policy implementation, waste minimization, and the promotion of material reuse and recycling. These practices are essential for achieving the objectives of sustainable construction, aligning project goals with broader sustainability targets (Fini & Akbarnezhad, 2019; Aigbavboa et al., 2017).

Metrics in SMM focus on achieving sustainable outcomes that offer long-term value to economy, environment, and society. Economically, these practices can lead to lower operating costs, enhanced productivity, and improved economic performance of buildings, ultimately resulting in better payback periods, faster returns on investment, and higher property values (Emmanuel Eze et al., 2021). Contractors are instrumental in harnessing these economic benefits through their choice and implementation of energy-efficient solutions, such as solar panels or advanced insulation materials. These choices significantly diminish energy expenses, lowering operational costs (Zhuan et al., 2023). The introduction of natural lighting and enhanced air quality into workplaces not only serves to reduce energy use but also improves occupant health and productivity, further demonstrating the economic value of sustainable construction practices (Horr et al., 2016). These improvements are increasingly recognized in the real estate market, where buildings that embody sustainable features often command higher rental rates or sale prices. This market trend underscores a growing demand for sustainability, with green buildings achieving faster investment returns, reflecting the economic viability of integrating SMM principles into construction projects (Leskinen et al., 2020).

Environmentally, the concept of 'green materials' plays an important role, referring to substances with beneficial environmental qualities, produced in accordance with sustainable standards (Emmanuel Eze et al., 2021). Green Building Materials (GBM) are defined as substances that achieve low environmental impact by either partially or entirely substituting conventional building materials. These materials are characterized by their ability to enhance energy efficiency, conserve natural resources, significantly reduce waste, and lower carbon dioxide emissions, thereby presenting an environmentally friendly alternative to traditional construction resources (Sujatha & Sivarethinamohan, 2021). Boosting the demand for GBM in the construction sector is crucial for advancing sustainable construction. This increased demand initiates a positive feedback loop in the market, offering additional environmental, health, and financial advantages (Emmanuel Eze et al., 2021). The environmental advantages of employing green materials, such as ecosystem protection, improved air and water quality, and waste reduction, are integral to achieving SMM goals (Emmanuel Eze et al., 2021). For instance, choosing recycled steel over newly mined ore conserves natural resources and reduces the ecological footprint of construction projects (Yellishetty et al., 2011). Similarly, the use of low-Volatile Organic Compound (VOC) materials enhances indoor air quality, contributing to healthier building environments (Bhoonah et al., 2023), while materials like bamboo which can grow rapidly and absorbs carbon dioxide represent renewable resources that also aid to protect the environment (Chun-Yu et al., 2023).

Socially, the use of sustainable materials has a positive impact on society by enhancing the aesthetic appeal, comfort, and health of building occupants (Nagrath et al., 2013). Additionally, the innovative nature of these materials generates employment opportunities in research, development, and application (Emmanuel Eze et al., 2021). The growing demand for sustainable materials drives extensive research and development efforts, fostering collaboration between universities, private laboratories, and industry. This collaborative environment leads to innovations in construction techniques and building design. During the development phase, activities such as prototyping, testing, and refining materials to meet industry standards are crucial. The subsequent application of these materials in construction projects requires a skilled workforce, creating jobs and promoting ongoing education in sustainable practices (Emmanuel Eze et al., 2021). This holistic approach not only contributes to reducing greenhouse gas emissions but also facilitates the transformation of existing buildings into more sustainable environments. Consequently, these efforts support local economies and reinforce governmental initiatives towards sustainable development (Emmanuel Eze et al., 2021).

This shift from EMM towards SMM in renovation projects not only aligns with global environmental goals but also offers significant socio-economic advantages, marking a crucial step towards a more sustainable future in the construction industry, table 1 summarizes the main features of this shift.

Table 1 Comparison of Effective vs. Sustainable Material Management Practices

Criteria	Effective Material Management	Sustainable Material Management	References
Focus	Time, cost, and scope optimization	Enhancing project sustainability while considering environmental, economic, and social impacts	Patil & Pataskar (2013); Van Calster (2014)
Prioritization	Enhancing operational efficiency and achieving cost-effectiveness	Integrating eco-friendly materials and practices into project execution	Patel & Vyas (2011); Donyavi & Flanagan (2009); Emmanuel Eze et al. (2021)
Key Processes	Efficient procurement, storage, and distribution practices	Implementing strategies for material lifecycle management, including material conservation and resource optimization	Gulghane & Khandve (2015); Aigbavboa et al. (2017)
Project Metrics	Focus on immediate metrics like labor productivity and project scheduling	Emphasis on achieving sustainable outcomes that offer long-term value to society, environment, and economy	Patil & Pataskar (2013); Emmanuel Eze et al., (2021).
Environmental Consideration	May not explicitly focus on sustainability in project planning and execution	Deliberately seeks to mitigate environmental impact, enhancing ecosystem health and promoting sustainability	Patil & Pataskar (2013); Emmanuel Eze et al. (2021)

2.3. Sustainable Materials Management in Construction Projects

Contractors play a major role in promoting sustainable materials management within the construction industry, influencing the entire project lifecycle from planning and design to execution and beyond (Figures 6 and 7). Their decisions to incorporate green materials, such as recycled or locally sourced materials, are important in reducing carbon emissions and enhancing resource efficiency (Chong et al., 2023).

This section will also outline key strategies contractors can adopt to effectively implement SMM throughout project phases.

Depending on the type of contract, contractors may have the authority to make decisions regarding material selection and construction practices. In other cases, while the client retains decision-making power, contractors can still provide valuable advice on incorporating sustainable practices (Mosey, 2009). For instance, they can recommend installing green roofs for better stormwater management (Paithankar & Taji, 2020) or utilizing prefabricated concrete to minimize waste (Jie & Nan, 2020). Contractors not only ensure compliance with sustainability standards but also drive innovation by adopting materials and methods that push the boundaries of traditional construction towards more ecologically responsible practices (Umoh et al., 2024). This includes exploring emerging technologies such as bio-concrete and self-healing materials, which offer enhanced durability and eco-friendly benefits, showcasing the industry's shift towards sustainable building solutions (Umoh et al., 2024).

Figure 6 Contractor's Role in SMM in Construction Projects (Source: Author)

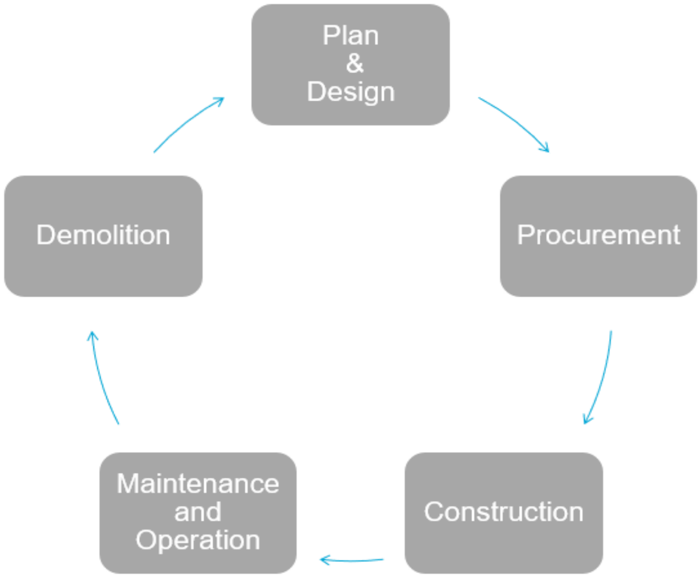

Figure 7 Project lifecycle (Westland, 2006)

2.3.1. Plan & Design

In the Plan and Design phase, contractors play a crucial role in embedding SMM practices, provided the contracts allow it. They actively participate in design charrettes with architects and engineers to develop sustainable design solutions and select materials that minimize greenhouse gas emissions and enhance recyclability (Azouz & Kim, 2015). This early collaboration ensures that sustainable practices are integrated from the outset. Contractors also ensure compliance with green building standards such as LEED, considering the lifecycle impacts of materials. By doing so, they significantly contribute to the project's environmental, economic, and social sustainability (Azouz & Kim, 2015).

A key aspect of SMM during this phase is the selection of sustainable building materials. This process directly contributes to reducing greenhouse gas emissions, lowering embodied energy costs, and enhancing recyclability and safety considerations. Commonly used sustainable materials include recycled plastic, natural clay, and wood timber, reflecting the growing awareness and adoption of sustainable materials in construction projects (Eze et al., 2021).

Adopting circular economy principles during the Plan and Design phase involves prioritizing the reuse, recycling, and recovery of materials throughout the project's lifecycle, rather than relying on the traditional linear model of 'take, make, dispose' (Karstensen et al., 2019). For instance, using recycled concrete aggregate (RCA) in new construction not only reduces the demand for virgin aggregate but also diverts construction and demolition waste from landfills (Han et al., 2023). Similarly, specifying modular components designed for disassembly and reuse enables materials to be repurposed at the end of their current use, leading to reduced waste and conserved resources (O'Grady et al., 2021). The construction industry is also focusing on reducing carbon emissions by using substitute substances in construction materials (Sudarsan et al., 2023). For example, using fly ash, a byproduct of coal combustion, can replace Portland cement, which is a major contributor to CO2 emissions (Nayak et al., 2022).

2.3.2. Procurement

In the procurement phase, integrated contracts such as design-build (DB) or design-build-maintain (DBM) provide contractors with greater control over design choices and supplier selection, thereby directing projects towards sustainability (Mirzadeh et al., 2020). These contracts enable contractors to influence the selection of sustainable materials and ensure that suppliers adhere to green practices, aligning the project with sustainability goals. This strategic position is vital for ensuring supplier integration and quality monitoring, both of which are essential for achieving sustainability objectives (Favié, 2010). Mokhlesian (2014) points out the importance of contractors working with suppliers who share a commitment to green practices. This partnership leverages eco-friendly knowledge, ensuring that the process of choosing suppliers for green and traditional projects aligns. This strategy encourages collaborations that advance sustainable construction efforts.

2.3.3. Construction

During the construction phase, contractors are key to using SMM practices, which greatly affect the project's environmental and economic results. Zhuan et al. (2023) highlight that adopting the "reduce method" is an effective strategy for minimizing construction waste and optimizing resource utilization, supporting sustainability goals. This approach not only reduces waste volume but also enhances a contractor's competitiveness by improving their corporate image and expanding business opportunities. Additionally, their commitment to SMM includes compliance with environmental regulations and the adoption of innovations like energy-efficient technologies and effective management of construction-related emissions.

Key strategies identified in recent research include the utilization of lean concepts such as just-in-time delivery and pull systems to streamline material management processes (Daghlas et al., 2023). While these strategies primarily focus on EMM by enhancing operational efficiency, they also provide significant benefits for SMM. By reducing material waste and minimizing the carbon footprint through optimized delivery schedules, these systems enhance both effectiveness and sustainability within construction projects (Daghlas et al., 2023).

However, challenges remain in fully realizing SMM practices. Bakr (2023) highlights that unforeseen client changes, worker mistakes, and ordering errors are significant contributors to waste generation. Addressing these factors is crucial for reducing inefficiencies and promoting more sustainable practices.

Moreover, promoting effective communication and collaboration among project stakeholders from the very beginning of construction has been recognized as a crucial practice for reducing claims and enhancing project performance. This fosters a culture of sustainability and efficiency, ensuring that sustainable management practices are implemented effectively throughout the construction process (Awwad & Thabet, 2022).

In addition, Green Supply Chain Management (GSCM) is emerging as an innovative approach in the construction industry, promoting environmental sustainability through efficient resource use and waste minimization. GSCM integrates eco-friendly practices across the supply chain, from material sourcing to construction and demolition, aiming to minimize the environmental impact of construction activities. By focusing on green materials, sustainable design, and construction processes, GSCM supports the industry's shift towards greater sustainability, enhancing environmental performance and competitive advantage (Baranikumar et al., 2021).

2.3.4. Maintenance & Operation

During the maintenance and operation phase, SMM focuses on extending the lifespan of building materials and optimizing resource use to minimize environmental impact. Contractors and facility managers play an important role in implementing practices that enhance sustainability throughout a building's operational life (Lee & Scott, 2009). Key SMM strategies during this phase include preventive maintenance, where regular inspections and timely repairs prolong the life of building components, reducing the need for replacements and minimizing waste (Flores-Colen & de Brito, 2010). Energy efficiency improvements, such as upgrading to LED lighting and high-efficiency HVAC systems, reduce energy consumption and operational costs (Ma et al., 2012). Additionally, sustainable procurement practices involve selecting environmentally friendly maintenance supplies, ensuring that materials used are non-toxic and responsibly sourced, thus supporting sustainable supply chains (Testa et al., 2014).

2.3.5. *Demolition*

In the demolition phase of construction projects, SMM focuses on strategies such as selective dismantling, material sorting, and recycling to minimize environmental impact and maximize resource recovery (Kamrath, 2013). Contractors play a critical role in planning and executing dismantling operations that facilitate material recovery, emphasizing effective construction waste management to minimize environmental impact and enhance project sustainability (Min et al., 2023)

In the realm of waste management, contractors' strategies focused on minimization, recycling, and reuse are not merely regulatory compliance but a contribution towards a circular economy. (Noor et al., 2023). Zhang et al. (2020) examine the Netherland's transition from downcycling to recycling construction and demolition waste (CDW), specifically end-of-life concrete, spotlighting innovative technologies that support concrete manufacturing's sustainability. This has many environmental benefits, such as reduced landfill use and lower emissions, and economic advantages, including cost savings and value creation from recycled materials. Contractors play an important role in this transition by adopting these recycling technologies. Their proactive engagement in choosing recycling over downcycling not only furthers global sustainability goals but also underscores their vital influence in driving industry practices towards more sustainable alternatives.

Van Den Berg et al. (2023) introduced a practical decision-support tool, exemplifying how SMM can be effectively operationalized in demolition projects. Developed in collaboration with a pioneering demolition contractor in the Netherlands, this tool aids contractors in selecting optimal waste management strategies, such as reuse, recycling, or recovery. It systematically assesses each strategy against criteria including technical feasibility, economic costs, environmental gains, and social impacts. By comparing these aspects, the tool provides a ranked list of strategies, thereby assisting contractors in making choices that enhance sustainability and effectiveness in their projects. This structured approach ensures that waste management decisions align with the broader goals of the circular economy, prioritizing environmental and social benefits alongside economic considerations.

2.3.6. Technology within these phases

Technological advancements in the Architecture, Engineering, and Construction (AEC) sector have become integral to promoting sustainability. Key technologies such as Building Information Modeling (BIM), Infrastructure Building Information Modeling (IBIM), Radio Frequency Identification (RFID), and the Internet of Things (IoT) enhanced how materials are managed across different phases of construction, contributing to both environmental and economic benefits. These technologies are supported by frameworks that evaluate material sustainability, focusing on comparing costs with environmental impacts of construction waste flows. This highlights the need for robust data collection mechanisms and public data provision to ensure the scalability of SMM trends (Schützenhofer et al., 2022, Oreto et al., 2023).

The table below summarizes the implementation of key technologies across various phases of construction and their associated benefits. It outlines the specific technologies used during the design, procurement, construction, and demolition phases, highlighting how each technology contributes to SMM.

Table 2 Implementation of Key Technologies and Their Benefits Across Construction Phases

Project Phases	Technology	Benefits	Source
Design Phase	Infrastructure Building Information Modeling (IBIM)	Integrates sustainability criteria, enables informed decisions on material selection and maintenance, and ensures environmental and economic benefits throughout the lifecycle.	Oreto et al., 2023
	Real Material Databases (ORIS Platform)	Achieves carbon emissions reduction and lifecycle cost savings.	Negishi et al., 2022
Procurement Phase	BIM, RFID	Enhances material efficiency, minimize waste and boost overall project efficiency	Iacovidou et al., 2018
	BIM, RFID, IoT	Enhances material sourcing, improves supply chain management, support accurate forecasting of material needs, facilitate compliance with green procurement standards, reduces unnecessary material orders.	Chen et al., 2020
Construction Phase	BIM	Facilitate better coordination, simulation, visualization, and progress tracking	Toyin & Mewomo, 2023
	RFID, LoT	Tracks construction activities such as stress levels, corrosion, and excavations.	Mijwil et al., 2023
	RFID, IoT	Enables real-time data collection and monitoring, reduces wastage.	Jain et al., 2023; Balar & Shah, 2015
Demolition Phase	BIM-based Web Tool as Material and Component Bank	Facilitates recycling of materials and reuse of components, quantifies waste, assesses design for deconstruction.	Jayasinghe & Waldmann, 2020
	Industry 4.0 Technologies (IoT, Advanced Data Analytics)	Enhances sustainability by addressing waste generation and energy transition challenges.	Zairul & Zaremohzzabieh, 2023

2.4. Barriers and Drivers of SMM Implementation in Construction

Sustainable material management in construction projects, including renovations, faces countless barriers that are important for the success and sustainability of these projects.

These include the need for cost-effective procurement and ecological disposal of materials, the management process encompasses purchasing, inventory control, and transportation (Mehr & Omran, 2013). Barriers often arise from material price fluctuations and procurement issues (Mehr & Omran, 2013). For instance, the sudden increase in steel prices can significantly disrupt budget planning.

Additionally, finding ecologically sound disposal options for construction waste, like concrete recycling, involves logistical and regulatory challenges (Yu et al., 2021). The complexities in material management are further compounded by challenges in information technology, decision modeling, and implementation management (Mehr & Omran, 2013). For example, implementing a new software system for inventory control is a difficult transition that requires training and adjustments to existing workflows. Effective systems for tracking, supplier selection, and adapting to new processes and technologies are essential for maintaining project timelines, quality, and budget. Such adaptation, while potentially disruptive initially, can lead to long-term benefits in sustainable material management (Mehr & Omran, 2013).

Renovation projects face unique barriers compared to new constructions (Mitropoulos & Howell, 2002). Challenges arise from physical limitations associated with the existing facility's condition, such as cramped spaces and the limited capacity of current systems. These issues, coupled with restricted access to work areas and unknowns regarding existing conditions, intensify the project's complexity. This is particularly true in phased construction projects where certain parts of the facility need to remain in operation (Mitropoulos & Howell, 2002). Jowkar et al. (2022) note that there is a general lack of awareness about the economic and social benefits of sustainable building renovation, leading to uncertainty about participation and personal advantages like improved indoor environmental quality and reduced energy costs.

Figure 8 summarizes these barriers by illustrating their impact on key success criteria such as cost savings, project timelines, and sustainability goals. The figure is based on the insights gathered from Mehr & Omran (2013), Mitropoulos & Howell (2002), Jowkar et al. (2022), and Yu et al. (2021), as discussed in the literature review.

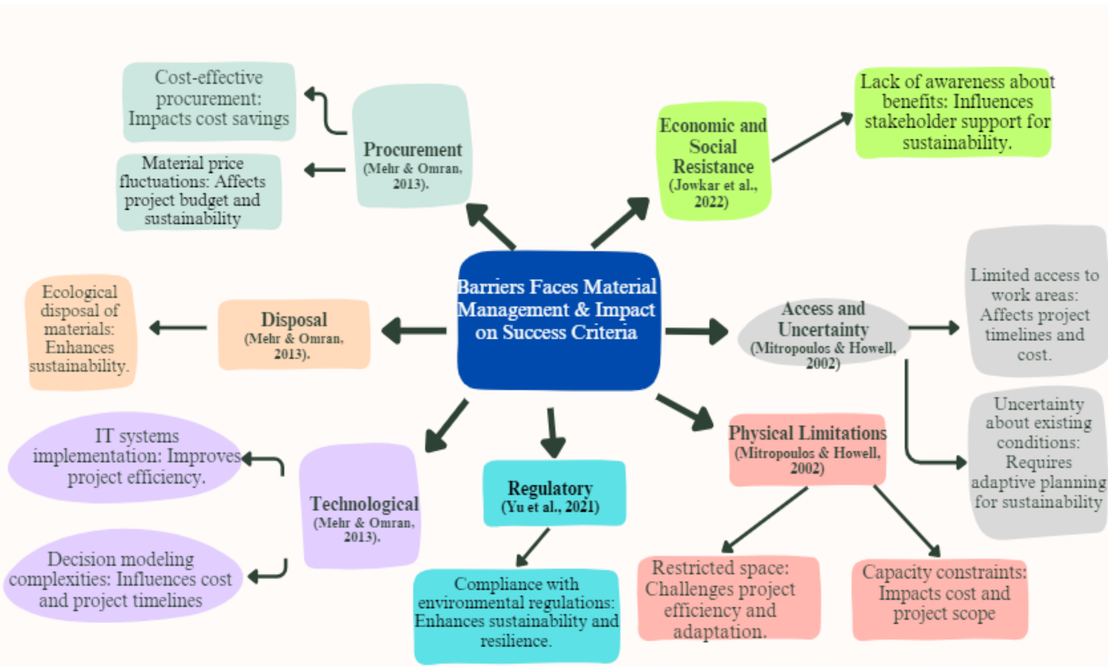

Figure 8 Barriers faces SMM in Renovation Projects

Despite these multifaceted barriers, several key drivers encourage the adoption of SMM practices in the construction industry:

- **Regulatory Compliance**: Governments worldwide are enforcing stricter environmental regulations, prompting construction projects to adopt sustainable practices. Standards such as BREEAM in the UK, LEED in the USA, and HQE in France provide guidelines for managing environmental impacts and enhancing building sustainability (Kamsu-Foguem et al., 2019).

Legislation significantly influences waste management strategies, compelling companies to align with new legal standards to maintain market competitiveness and meet client expectations (Adjei et al., 2015).

- **Economic Benefits**: Cost savings from reduced material use and improved waste management schemes enhance resource efficiency, lowering the cost of goods sold. The adoption of circular business models also improves corporate reputation and stakeholder relations, leading to higher project valuations due to sustainability credentials (Romero-Hernández & Romero, 2018). Economic incentives, such as subsidies and tax reductions, further motivate stakeholders to invest in green building practices, making sustainable projects more affordable and appealing (Fan et al., 2018).

- **Environmental Responsibility**: Given the construction industry's substantial ecological footprint, reducing waste and utilizing eco-friendly materials are essential practices to mitigate environmental damage (Muntean et al., 2023).

- **Stakeholder Pressure**: Investors, customers, and community groups demand adherence to sustainable practices. Pressure from these stakeholders plays a significant role in influencing companies to integrate SMM into their projects. Qi et al. (2010) highlights that stakeholder demands for better environmental performance are critical drivers leading contractors to adopt green construction practices.

- **Client Procurement Strategies:** Clients play a crucial role in driving the adoption of SMM practices through their procurement strategies. By incorporating sustainability requirements into procurement policies, tender documents, and contracts, clients influence contractors to prioritize sustainable materials and methods (Ruparathna & Hewage, 2015). For example, specifying the use of eco-friendly materials or setting targets for waste reduction in contracts motivates contractors to implement SMM practices to meet these criteria. This client-driven demand fosters innovation and sustainability across the supply chain, promoting broader industry adoption of sustainable practices (McMurray et al., 2014).

2.5. Theoretical Framework: Willingness and Ability in SMM

To fully understand the factors influencing contractor's implementation of SMM strategies, it is important to explore the concepts of willingness and ability through established theoretical frameworks. These concepts are critical in explaining why contractors adopt or resist sustainable practices, providing insights into their current practices and the potential for enhancing sustainability in construction projects.

2.5.1. Theory of Planned Behavior

Ajzen's Theory of Planned Behavior (1991) is a well-established psychological model that aims to clarify how people act within certain situations. According to this theory, a person's actions are primarily driven by their intention to engage in the behavior, which is itself shaped by three main influences.

- **Attitude Toward the Behavior**: The degree to which a person has a favorable or unfavorable evaluation of the behavior.

- **Subjective Norms**: The perceived social pressure to perform or not perform the behavior.

- **Perceived Behavioral Control**: The perceived ease or difficulty of performing the behavior, which relates to one's ability.

In the context of SMM, contractor's willingness to implement sustainable practices can be linked to their attitudes toward sustainability and the subjective norms within the industry. If contractors perceive sustainability positively and believe that important stakeholders expect them to adopt such practices, their willingness to engage in SMM increases.

Perceived behavioral control, or the ability, reflects contractor's perceptions of their capacity to implement SMM strategies. This includes having the necessary resources, skills, and opportunities to perform sustainable practices. If contractors feel confident in their ability to execute SMM, they are more likely to do so.

2.5.2. COM-B Model

The Capability, Opportunity, Motivation, and Behavior (COM-B) model, developed by Michie et al. (2011), provides another framework for understanding behavior change. According to this model, behavior (B) is the result of the interaction between:

1. **Capability (C)**: The individual's psychological and physical ability to engage in the activity (similar to ability).
2. **Opportunity (O)**: External factors that make the behavior possible or prompt it.
3. **Motivation (M)**: Brain processes that direct behavior, including habits, emotional responses, and decision-making (aligned with willingness).

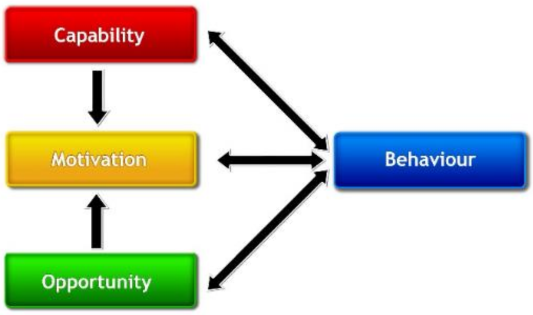

Figure 9 The COM-B system (Michie et al., 2011)

Applying the COM-B model to contractors in SMM:

- **Capability (Ability)**: Contractors must have the technical knowledge, skills, and resources to implement sustainable practices effectively.
- **Opportunity**: The external environment, including regulatory frameworks, market conditions, and client demands, provides opportunities or barriers to SMM adoption.
- **Motivation (Willingness)**: Contractor's desire and intention to adopt SMM practices are influenced by their beliefs, values, and perceived benefits.

Research by Ahn et al. (2013) highlights that both intrinsic motivation (e.g., environmental concern) and extrinsic motivation (e.g., market advantages) influence contractor's adoption of sustainable construction practices.

2.6. Summary:

This literature review has thoroughly explored the first sub question, examining the implementation of SMM within infrastructure renovation projects. The review identified the important role of EMM and highlighted how integrating principles such as JIT delivery and Lean Construction minimizes waste and enhances project sustainability. These strategies are important in addressing the core aspects of EMM, which include planning, procurement, storage, and distribution of materials, ensuring project success by optimizing resource utilization.

Further discussion on SMM emphasized a comprehensive approach aimed at reducing environmental harm and conserving resources throughout the material lifecycle. The focus on 'green materials' advocates for choices that not only minimize ecological footprints but also promote goals of the circular economy, addressing economic, environmental, and social impacts holistically.

The roles of contractors in SMM across various project phases (from planning and design to procurement, construction, and demolition) were detailed, illustrating their critical involvement. The review also highlighted both the barriers and drivers influencing SMM adoption in the construction industry. While barriers such as cost, logistical complexities, and the physical limitations of renovation projects pose significant hurdles, drivers like regulatory compliance, economic incentives, environmental concerns, and stakeholder pressures provide strong motivation for contractors to integrate SMM practices.

Importantly, the integration of theoretical frameworks such as the Theory of Planned Behavior and the COM-B model provided deeper insights into the factors influencing contractor’s implementation of SMM strategies. Understanding the concepts of willingness and ability is essential, as they directly impact contractor’s motivation and capacity to adopt sustainable practices. These theories explain how attitudes, perceived norms, and control beliefs shape contractor’s intentions and behaviors regarding SMM.

Moving forward, the next phase of this research involves conducting interviews with industry professionals to gather empirical data. These interviews aim to provide practical insights and firsthand accounts of how SMM practices are implemented in real-world scenarios. By capturing the experiences and perspectives of practitioners, the interviews will enrich our understanding of SMM and potentially uncover new dimensions of contractor involvement and effectiveness. This qualitative data collection is important for bridging the gap between theoretical frameworks and practical applications, ensuring that the research outcomes are both relevant and actionable. Furthermore, the insights gained from these interviews will contribute to developing targeted recommendations for enhancing SMM adoption and effectiveness in infrastructure renovation projects, thus supporting the broader goals of sustainability in the construction sector.

3. Research Methodology

This research employs a qualitative, exploratory research design to investigate the strategies, challenges, and best practices of SMM in infrastructure renovation projects. A qualitative approach is appropriate because it allows for an in-depth understanding of participant's experiences, perceptions, and practices, which are essential for exploring complex and nuanced phenomena like SMM (Creswell, 2013).

The exploratory nature of the study is relevant due to the limited existing research on SMM practices specifically within the context of infrastructure projects. Exploratory research is used when the subject is relatively new or under-researched, aiming to generate insights and identify patterns that can form the basis for further study (Stebbins, 2001). By using semi-structured interviews with professionals actively involved in the construction and renovation of infrastructure projects, this study seeks to uncover rich, detailed information that may not be accessible through quantitative methods.

To enhance the validity and depth of the findings, the research incorporates expert validation by consulting industry specialists. This mixed-methods approach ensures a robust analysis of SMM practices, combining qualitative data collection with validation techniques to strengthen the reliability and applicability of the results.

The following sections provide a detailed explanation of the methodology employed in this research: Section 3.1 describes the structure and characteristics of the interviews. Section 3.2 presents the individual participants of the interviews, highlighting their unique backgrounds and the similarities and differences in their experiences. Section 3.3 explains the method of processing and using the interview results, including the incorporation of expert validation.

3.1. Semi-Structured Interviews

The primary goal of the semi-structured interviews is to gain in-depth insights into the practical aspects of SMM from professionals involved in infrastructure projects. These interviews aim to uncover current practices, identify challenges, and gather best practices that can enhance SMM.

Semi-structured interviews were chosen due to their flexibility and effectiveness in exploratory research. This method allows for a coherent structure with predetermined questions while providing the opportunity for open-ended discussions (Kallio et al., 2016). Such flexibility is essential for capturing the complexities of SMM practices, as it enables participants to elaborate on their experiences and introduce new topics relevant to the research (Bryman, 2012).

This approach ensures comprehensive coverage of key topics while providing the space to explore new insights as they emerge. According to Saunders et al. (2016), semi-structured interviews are particularly suitable when the research aims to understand the reasons behind participants' attitudes and behaviors, which aligns with the objectives of this study.

Interview Design and Procedure:

The interview process involved eleven professionals, including project managers, CEO, and sustainability experts, selected for their experience and active roles in infrastructure projects. The use of semi-structured interviews enabled the interviewer to probe deeper into specific areas based on the responses, making this method particularly effective for exploring perceptions, experiences, and the rationale behind specific practices (Gill et al., 2008).

All interviews were recorded with the participant's consent and transcribed verbatim to ensure accuracy in capturing the insights. The interview questions were designed to explore several key areas:

the profile of the interviewee, their current SMM practices, the challenges they face, and the best practices and strategies they recommend. This method ensures a rich, detailed set of qualitative data essential for understanding the complex nature of SMM in infrastructure projects.

The interview protocol, including the list of questions, can be found in Appendix 2. The full transcripts of the interviews are provided in a separate document.

Achieving Data Saturation:

Saturation was considered an essential criterion for determining the adequacy of the sample size. According to Guest et al. (2006), data saturation occurs when no new information or themes are observed in the data. In this study, saturation was reached when the answers provided by the interviewees started to become repetitive, indicating that no new significant information was being uncovered. This repetition of themes and concepts across multiple interviews highlights the reliability and validity of the findings, demonstrating that the data accurately represents the broader population's experiences and perspectives on SMM in infrastructure projects.

3.2. Participants

Participant Selection:

Eleven interviews were conducted with a targeted group of professionals to gather the necessary data. The participants are professionals actively involved in the construction and renovation of infrastructure projects, specifically focusing on sustainable material management. Selecting participants with direct experience in SMM ensures that the data collected is relevant and grounded in practical knowledge (Marshall, 1996).

To ensure the reliability and relevance of the information, participants were selected based on the following criteria:

- **Experience:** Having worked in their respective roles for a minimum of two years within the past three years. This criterion ensures that participants have sufficient recent experience to provide meaningful insights.
- **Diversity of Roles:** Including a variety of roles such as CEOs, project managers, material specialists, and sustainability experts to capture a broad range of perspectives within the industry.
- **Organizational Representation:** Participants were distinguished based on the organizations they represent, all of whom work for contractors or engineering firms. This diversity ensures a comprehensive representation of the sector.

Ensuring Representativeness and Comparability:

During the selection process, careful attention was given to ensure that the group of participants was representative of the broader industry, while still being similar enough to allow for meaningful comparisons. The goal was to include a variety of perspectives from different types of projects and organizational contexts within the same overall field. This targeted sampling approach is suitable for qualitative research, where the goal is to achieve an in-depth understanding of a specific phenomenon rather than to produce findings that apply broadly to a larger population. (Palinkas et al., 2013).

Participant Profiles:

Participants hold roles such as CEO, project managers, material specialists, and sustainability experts. They are responsible for various aspects of sustainable material management in infrastructure projects. Their exact job descriptions vary based on different contracts, organizational structures, and project phases.

The specific contexts of their work, such as the types of projects they handle and their roles within their organizations, provide varied insights into the practices and challenges of sustainable material management. Here is an overview of the participant profiles (Table 3):

Table 3 List of Participants

Participant Number	Date of Interview	Organization	Experience (years)	Project phases	Specific Role Details	Experience with SMM
EXP1	21/05/24	Contractor	> 2	Planning	Specialist Material Technology	Yes
EXP2	30/05/24	Contractor	> 18	All	Program manager of sustainability- Team Leader for Structural Engineers	Yes
EXP3	02/05/24	Contractor	> 40	All	CEO	Yes
EXP4	28/05/24	Engineering Company	> 14	All	Project leader- Sustainability Consultant	Yes
EXP5	29/05/24	Engineering Company	> 2	Planning	Structure Engineer	Yes
EXP6	31/05/24	Contractor	> 10	All	Sustainability Manager	Yes
EXP7	13/06/24	Contractor	> 3	Planning	Sustainability Advisor	Yes
EXP8	19/06/24	Contractor	> 8	All	Structural Designer, Project Leader	Yes
EXP9	07/06/24	Contractor	> 25	All	Head of Sustainability NL- Business Director Circular Economy	Yes
EXP10	21/06/24	Engineering Company	> 24	All	Design Manager	Yes
EXP11	21/06/24	Engineering Company	> 17	All	Design Manager	Yes

3.3. Data Analysis

The interviews conducted for this research were recorded and transcribed verbatim to ensure the accuracy and reliability of the data collected. This process was essential for preserving the richness of the qualitative data and facilitating a thorough analysis. The analysis of the interview data is done using ATLAS.ti, a qualitative data analysis software. This software facilitates the organization and coding of large amounts of qualitative data, making it easier to identify patterns and themes (Friese, 2019).

Initially, each interview was transcribed to convert the audio recordings into written text, ensuring that all details were accurately captured. Transcription is a critical step in qualitative research as it preserves the integrity of the data and allows for detailed analysis (Halcomb & Davidson, 2006). Following transcription, the data was imported into ATLAS.ti for coding and thematic analysis.

Coding involved categorizing segments of text based on themes or concepts that emerged from the data. Both predefined codes, derived from the literature review and research questions, and emergent codes, identified during the analysis, were utilized. This combination of deductive and inductive coding enhances the richness of the analysis and allows for the discovery of new insights (Fereday & Muir-Cochrane, 2006). The following steps outline the coding process workflow:

1. Transcription and Review: Interviews were recorded and transcribed using Microsoft Teams. After transcription, the text was reviewed for accuracy and grammar to ensure precision before proceeding.
2. Data Preparation in ATLAS.ti: Final transcripts were uploaded into ATLAS.ti for organizing and coding.
3. Reading and Coding: The transcripts were read to identify key insights on SMM. The data was then coded, starting with theoretical frameworks, but additional themes emerged as the review continued, and the coding structure was adjusted accordingly. Themes and codes are recorded on excel sheet for keep editing clear.
4. Continuous Refinement: The coding was revisited regularly to ensure it accurately captured the core themes and insights, improving the overall understanding of the data.
5. Data Interpretation: The final stage involved analyzing the coded data to extract key findings and address the research questions. These insights were then applied to the broader context of SMM in infrastructure renovation.

Thematic analysis is conducted to identify and explore the main themes and sub-themes. This method is appropriate for qualitative research aiming to understand participants' perspectives and experiences (Braun & Clarke, 2006). The process involved reviewing the coded data to find connections and relationships between the themes. Thematic analysis provides a systematic approach to identifying patterns within qualitative data, allowing for an in-depth understanding of complex issues like SMM practices (Nowell et al., 2017). It is particularly suitable for this research as it helps in synthesizing participants' experiences to identify common challenges and best practices.

To further validate these findings, expert validation is incorporated into the analysis process. Expert validation enhances the credibility and trustworthiness of the research by ensuring that the findings are grounded in practical expertise (Andrew & Halcomb, 2009). After the initial thematic analysis, the identified themes and conclusions were reviewed by two industry experts. The first expert EXP13, a Company Director with over 26 years of experience working as a contractor across all project phases, provided feedback during an interview conducted on October 4, 2024. The second expert EXP14, a Senior Project Coordinator with more than 7 years of experience in the contractor sector, contributed additional insights in an interview held on October 9, 2024. Both experts have extensive experience with SMM, confirming the relevance and applicability of the research conclusions. Their feedback was used to refine and enhance the analysis, ensuring that the identified themes are not only theoretically sound but also practically applicable. The validation process confirmed the robustness of the themes and their implications for SMM practices.

The insights from the interviews, combined with expert validation, provide a comprehensive understanding of SMM practices in infrastructure projects. These results are important for identifying current practices, understanding the challenges faced by professionals, and documenting successful strategies and approaches that can enhance SMM. The detailed analysis of the interview data, supported by expert validation, forms a solid foundation for the research findings, ensuring that they are grounded in the real-world experiences and validated by industry experts.

4. Current Practices and Willingness of Contractors in SMM

This chapter is a part of the Empirical Research section, presenting the findings from the conducted interviews answering sub-questions three (SQ3). The interviews were designed to gain insights into the current application of SMM strategies by contractors and to explore their willingness and capability to enhance sustainability in their projects.

This chapter addresses the third sub-question of the research:

SQ3: How do contractors currently apply SMM strategies in projects, and what are their willingness and ability to enhance sustainability in this area?

To effectively present the findings, this chapter is organized into two main sections. Section 4.1 discusses the results from the interviews, including a detailed analysis of the key themes and patterns that emerged. Then, Section 4.2 provides the main insights and their implications based on the analysis.

The results from the interviews were coded, resulting in a total of 44 codes. These codes were grouped into 8 themes. Each code has various quotes from the interviews, providing a rich narrative of the data collected (Table 4). To provide a detailed overview of the interview findings, each code is substantiated with representative quotes from the interviews. These quotes are supported by the participant numbers, ensuring the diversity of perspectives and the consistency of themes across different interviews. A comprehensive table categorizing the interview results into themes, codes, and occurrence frequencies is available in Table 4.

Table 4 Interview's Themes and Codes

Themes	Codes	# Quotations
SMM Characteristics	Prioritizing Sustainability	5
	Aligning with Client Requirements	3
	Awareness of Environmental Implications	4
	Balancing Short-Term and Long-Term Sustainability	3
	Integrating Sustainability with Economic and Functional Performance	4
	Comprehensive Approach and Innovation	2
	Differences from Traditional Material Management	6
SMM Practices	Sustainable Design	37
	Sustainable Material Use	14
	Electrification and Energy Use	5
	Assessments and Calculations	8
	Recycling and Waste Reduction	9
	Sustainable Sourcing and Materials	1
Influential Factors	Organizational Culture and Leadership	12
	Economic Considerations and Cost-Benefit Analysis	5
	Regulatory and Market Pressures	6
	Documentation and Standardization	9
	Material and Worker Resistance	4
	Client Limitations and Knowledge	10

Challenges	Technical Knowledge and Experience	10
	Contractual and Specification Issues	11
	External and Competitive Pressures	6
	Cost and Financial Issues	9
	Logistical and Supply Challenges	4
Contractor Influence Phase	Planning and Procurement	17
	Construction	1
Contractor Willingness and Ability	Willingness	16
	Ability: can do it	15
	Ability: cannot do it	5
Contractors Needs	Client Responsibility and Collaboration	23
	Training and Education	10
	Marketplaces and Platforms	3
	More Time	2
	Incremental Changes and Regulations	2
	Communication and Mindset Change	6
	Political and Regulatory Support	2
	Financial Incentives	7
	Standardization and Certification	3
Future Directions	Influence of Young People and Educational Shifts	3
	Continued Research, Technological, and Material Innovation	10
	Client Demand, Market Pressure, and Regulatory Influence	6
	Development of Bio-based and Alternative Materials	2
	Future state of SMM	13
	Systemic and Cultural Changes in Sustainable Practices	2

4.1. Current Application of SMM Strategies in Contractor Projects

Based on SMM Characteristics theme, all participants describe SMM as a broad approach that focuses on sustainability over traditional concerns. It highlights the environmental impact, long-term use, and innovation. SMM combines sustainability with economic and functional goals, balancing short and long-term environmental effects. Unlike traditional material management, which focuses on cost and efficiency, SMM looks at the full lifecycle of materials and promotes more sustainable options.

This section addresses the first half of research question 3: "How do contractors currently apply SMM strategies in projects?" It is organized around two key aspects. The first explores the main SMM practices implemented in construction projects, while the second examines the influential factors

affecting their application (Figure 10). Together, these aspects provide insight into how contractors adopt SMM and the factors shaping their implementation.

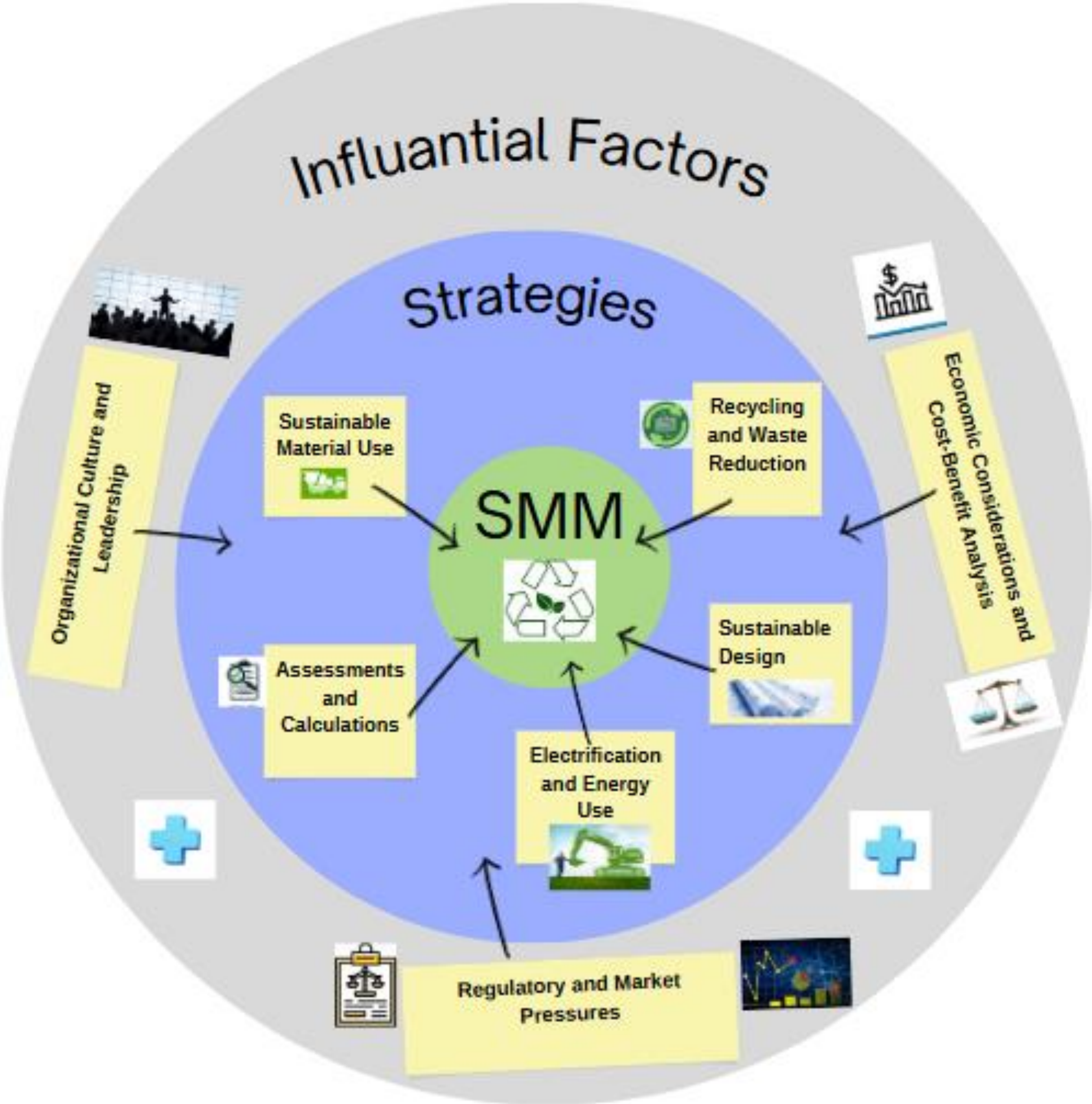

Figure 10 Overview of Key Practices and Influential Factors in SMM Implementation in Projects

4.1.1. Strategies

The interviews reveals key practices that the contractors applied in their projects to implement SMM. These findings were coded under the **SMM_Practices** theme, which includes categories such as Assessments and Calculations, Sustainable Material Use, Sustainable Design, Electrification and Energy Use, and Recycling and Waste Reduction.

1- Assessments and Calculations

Assessments and calculations of environmental impacts, such as Life Cycle Assessments (LCAs), carbon footprint analyses, and Environmental Product Declarations (EPDs), are essential for selecting sustainable materials and processes in construction. Tools like the Environmental Cost Indicator (ECI) allow contractors to measure the environmental impact of materials such as sand, concrete and steel, helping them make choices that reduce emissions and resource consumption. Circularity assessments are also used to determine how well materials can be reused or recycled at the end of a project's life, promoting a more circular economy in construction.

> "We are currently developing several tools to address these aspects. For instance, we are piloting a circularity assessment that we intend to introduce for all projects." – *EXP2*

These evaluations provide the benefit of optimizing material use, lowering environmental impact, and making smarter, long-term decisions that balance sustainability and cost. Training staff to use these tools ensures that sustainable choices are applied consistently across all projects. EXP-6 mentioned that training staff to use these tools ensures that sustainable choices are applied consistently across all projects.

> "If a project has high environmental criteria, we might choose a more expensive material with a lower footprint because it's worth it. We focus on big components because they make the most difference." – *EXP6*

2- Sustainable Material Use

Sustainable material use aims to reduce the environmental impact of construction by using more eco-friendly materials. One way to do this is by using recycled concrete aggregates, which replace some of the natural materials in concrete with recycled ones. This helps cut down on waste and the need for new resources. Another important method is using green concrete, which has less cement. Since cement production creates a lot of CO2, reducing its use helps lower emissions.

> "The Groote Wielenbrug project used green concrete with less cement, reducing CO2 emissions in the process." – EXP1

Innovative materials, such as biobased products and geopolymer concrete, are gaining traction. Geopolymer concrete incorporates industrial by-products like fly ash or slag as a substitute for conventional cement, helping to reduce CO2 emissions without compromising durability. Meanwhile, biobased products, derived from renewable sources like plants, provide a lightweight and eco-friendly option with reduced environmental impact.

> "In the N69 project, we used geopolymer concrete and biobased materials to reduce cement and lower environmental impact, while optimizing the design to use less material overall." – EXP11

These alternatives are better for the environment but still provide the strength needed for building projects. By improving concrete mixtures with these materials, the industry can reduce its environmental impact without sacrificing quality.

3- Sustainable Design

Sustainable design focuses on reducing the environmental impact of construction by using fewer materials, reusing existing ones, and designing for future recyclability. One important strategy is modular design, so materials can be reused instead of discarded. This design for disassembly approach helps cut down on waste and ensures materials have a longer life. Another key practice is optimizing material use within a project, such as reusing materials excavated from one part of a site in another, which reduces waste and transportation costs. For example, when a construction project involves digging up soil to create a foundation, that excavated material can be reused elsewhere on the same site, such as for landscaping or filling low-lying areas. This practice reduces waste by repurposing materials that would otherwise be discarded and cuts down on transportation costs by eliminating the need to haul materials away or bring new ones in. Strategic design choices, like building a bridge instead of a tunnel, can also help save materials and minimize environmental disruption. Though sustainable design can require higher upfront planning and costs, the long-term benefits include reduced waste, lower material costs, and a smaller environmental footprint, making it a valuable approach for more sustainable construction.

> "We had a choice between building a bridge or a tunnel in the N69 project. The tunnel required a lot of concrete and excavation, so we opted for a bridge instead. This used fewer materials and created an ecological passage, making it a better design choice." –EXP11

4- Electrification and Energy Use

Switching to electric equipment and vehicles in construction helps reduce emissions and create cleaner worksites.

> "Electric equipment and electric vehicles are a big part—we are trying to electrify the equipment that we use." *–EXP1*

Although the initial costs of moving to electric machinery and renewable energy are high, contractors understand the long-term savings. Energy consumption is reduced over time, and reliance on fluctuating fossil fuel prices is minimized. For example, a contractor might replace diesel-powered equipment like excavators and forklifts with electric versions. Although the initial cost of electric machinery is greater, it offers long-term savings by decreasing fuel costs and requiring less maintenance. This switch also cuts down emissions, resulting in cleaner and more environmentally friendly worksites. Moreover, electric vehicles and machines produce less noise and vibrations, which can be especially important in urban construction sites where minimizing disturbance to surrounding areas is a priority.

In addition to machinery, contractors are also focusing on saving energy in the production of materials like concrete, steel, and asphalt, which traditionally require high energy.

> "Asphalt was produced at 160 degrees Celsius, which requires a lot of gas. And we came up with a solution in the asphalt plant to do it in a different way. So we could limit the temperature up to 100 degrees. So that saves 60 degrees. Saves a lot of energy." – EXP3

By adopting green energy sources or developing innovative techniques to lower energy use in production, they further reduce costs and environmental impact. With increasing environmental regulations, companies that adopt these practices early will save money and gain a competitive advantage in the future.

5- Recycling and Waste Reduction

According to EXP3 ,in many projects, old materials like asphalt, concrete, and steel are reused instead of discarded. For instance, asphalt removed from old roads can be taken back to the plant, mixed with new materials, and used again in new layers. This approach has improved over time, with some projects now reusing up to 100% of old asphalt, which helps reduce the need for new resources.

Another key strategy is recovering materials from demolished structures, such as beams or building facades, to be reused in new projects. This not only cuts down on waste but also lowers the environmental footprint. However, one challenge is ensuring the quality of recovered materials and tracking available resources for future projects. For example, Rijkswaterstaat reused concrete girders from the decommissioned A9 motorway in the construction of a new viaduct on the A44. This practice reduces waste and environmental impact by repurposing existing materials instead of producing new ones. (*Liggers A9 Krijgen Tweede Leven in A44*, n.d.)

In some projects, contractors also find ways to reuse materials directly on-site. For example, stones, curbs, or other items can be harvested, checked for quality, and reused in the same project, reducing the need for transportation and lowering costs. These practices not only reduce the demand for new materials but also help minimize the environmental impact by cutting down on emissions related to material production and transport.

The benefits of recycling and waste reduction are clear: they save costs, reduce the environmental burden, and make construction projects more efficient. However, it requires careful planning and coordination to ensure materials can be recovered and reused effectively.

> "In infrastructure, there's no waste. We use everything where we find. For example, if we set up for a new road, we have to deconstruct the old road. The material we deconstruct will go directly to the place where they can reuse the materials. Asphalt goes to asphalt factory. The lower parts, which are concrete or steel, they go directly to the steel factory. The concrete goes to a recycling plant." – *EXP6*

4.1.2. Influential factors for implementing SMM practices

The extent of SMM implementation varies significantly across different projects and organizations. While the industry is moving towards sustainability, the adoption of these practices is influenced by three interrelated factors: Organizational Culture and Leadership, Economic Considerations and Cost-Benefit Analysis, and Regulatory and Market Pressures. These factors were derived from four key themes identified through the thematic analysis: challenges, contractor's needs, contractor's willingness and ability, and future directions.

1- Organizational Culture and Leadership

Interviews shows that companies that prioritize sustainability tend to have strong leadership actively promoting these practices across their projects. This leadership often translates into setting clear sustainability goals, such as reducing carbon emissions or minimizing material waste, and embedding these goals into daily operations.

> "In interviews, our CEO has said we don't want to work for the diesel client anymore. That summarizes a bit how we look at it." – *EXP2*

These companies don't treat sustainability as a separate effort but rather integrate it into every decision-making process, ensuring that all projects align with sustainable practices. Leaders play a key role in driving these initiatives by shaping the company's values and commitment to environmental responsibility.

> "Sustainability is a really, really important part of the company." *– EXP1*

Externally, they are motivated by regulations, market demands, and stakeholder expectations to act in environmentally responsible ways. Governments, investors, and customers increasingly expect firms to adopt sustainable practices, making it not just an ethical obligation but also a competitive necessity. For example, government contracts increasingly require firms to have the CO_2 Performance Ladder certification, making sustainable practices a competitive necessity (*What Is the Ladder*, n.d.). Internally, leaders often view sustainability as both a smart business decision and an ethical commitment to reducing environmental harm. This can lead to growth opportunities and efficiency improvements as companies that adopt sustainability early often gain a competitive edge in winning new projects.

> "Adopting sustainable practices can actually be advantageous in the long run. Clients are increasingly looking for companies that can deliver environmentally friendly solutions. By positioning themselves as leaders in sustainability, contractors can enhance their reputation and become more competitive in the procurement of future projects." *– EXP5*

In organizations with strong leadership, sustainability is embedded into the company culture. For instance, some companies create internal sustainability committees or dedicate teams specifically to review and ensure project plans adhere to SMM principles. These efforts ensure that sustainability is a core part of the company's operations rather than an afterthought. On the other hand, companies with weaker leadership on sustainability often struggle to fully integrate these practices, leading to more fragmented and inconsistent efforts across projects.

> "As a company, we have more than 25 persons full-time on sustainability, which is a huge number. So we know how it works. But not all contractors know it." – EXP6

Having 25 full-time employees focused solely on sustainability is a substantial commitment for any company, especially in the construction industry. This number is huge because most contractors typically have much smaller teams, or even just a few individuals dedicated to sustainability efforts. Such a large team indicates that the company prioritizes sustainability at a high level, integrating it deeply into their operations and decision-making processes.

2- Economic Considerations and Cost-Benefit Analysis

Contractors often need to balance sustainability goals with project budgets, and cost remains a key driver in many decisions. In projects where the upfront cost of sustainable materials or methods is higher than traditional alternatives, contractors may hesitate to adopt them if the long-term benefits are not immediately clear. As a result, some companies may prioritize short-term financial savings over environmental considerations, especially when project margins are tight.

> *"The other one is that sometimes you can have the best solution for sustainability. But it can be more expensive than the other one*." – EXP3

However, when contractors can clearly see the financial benefits of SMM—such as cost savings from reduced material waste, increased energy efficiency, or longer-lasting materials—they are more likely to implement these practices. For example, contractors have found that using electric equipment's like electric excavators, wheel loaders, and forklifts consumes significantly less energy than fuel-powered machinery, leading to reduced operating costs. The challenge lies in quantifying these benefits in a way that encourages wider adoption. Traditional cost analysis methods often overlook long-term savings, which can make sustainable options seem more expensive upfront.

This highlights the need for better cost-benefit analysis tools that factor in long-term economic gains from sustainability. Life-cycle costing methods evaluate all costs associated with a project from inception to disposal, including capital, operation, maintenance, and end-of-life expenses. Incorporating these methods into project planning allows contractors to assess the full economic impact of sustainable practices over a project's lifespan. For example, while sustainable materials may have higher upfront costs, they often reduce operating expenses through lower energy consumption, less frequent maintenance, longer service life, and minimized disposal costs due to recyclability. This comprehensive assessment makes SMM a more financially attractive option.

> "Demonstrating the long-term cost savings of sustainable materials through life-cycle assessments can help convince clients of their value." – EXP5

3- Regulatory and Market Pressures

Contractors working in regions with strict environmental regulations are more likely to integrate sustainable methods to comply with legal requirements. Governments, especially within the European Union, enforce regulations that push large companies in industries such as steel, cement, and construction to adopt greener practices. Mechanisms like the EU Emissions Trading System (EU ETS) and directives such as the Industrial Emissions Directive (Directive 2010/75/EU) create financial and legal incentives for companies to reduce their environmental impact and meet sustainability targets. In the Netherlands, laws like the Climate Act (Klimaatwet) and the Environmental Management Act (Wet Milieubeheer) set stringent national goals for emission reductions and environmental protection

> "Pressure from the EU, especially on large companies like ArcelorMittal, ThyssenKrupp, Holcim, and Dyckerhoff, drives them to adopt sustainable practices. These big companies are significantly influenced by European regulations and the CO2 payment system." – EXP6

Market pressures also play a role, as clients increasingly demand green certifications or proof of sustainable practices. Contractors who can demonstrate their commitment to sustainability may gain a competitive edge when bidding for projects, especially those funded by government agencies or environmentally-conscious clients.

> *"Clients are also asking for sustainable practices."* – EXP1

However, the extent to which these pressures drive change depends largely on the strength of enforcement and the financial support provided. In markets where regulations are weak or not strictly enforced, contractors may have less motivation to adopt SMM practices. For example, within the European Union, countries like the Netherlands have stringent enforcement of environmental regulations, motivating contractors to adopt SMM practices, whereas in some newer EU member states, weaker enforcement leads to lower adoption rates. This underscores the need for robust regulatory frameworks that not only mandate sustainability but also offer financial incentives, such as tax breaks, subsidies for renewable energy adoption, or grants for sustainable technology investments—to ease the transition to greener practices.

4.2. Overcoming Challenges: Contractor Willingness and Ability to Implement SMM

This section addresses the second half of research question 3: "What are contractor's willingness and ability to enhance sustainability in this area?". To assess this, it is essential to identify the challenges they face and determine the optimal timing for their involvement to maximize their influence on project outcomes. Understanding this will provide deeper insights into their overall willingness and ability to improve sustainability (see Figure 11).

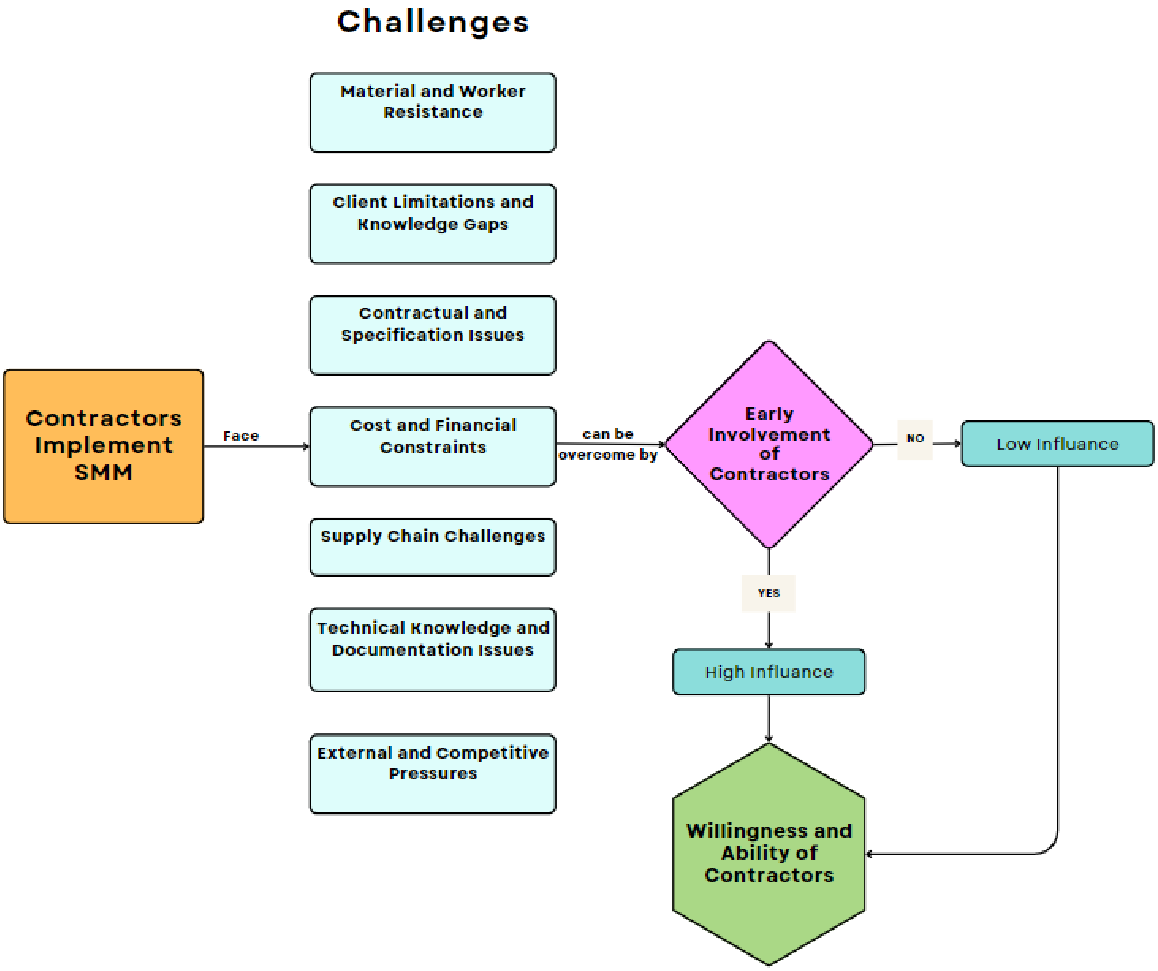

Figure 11 Overview of discovering Willingness and Ability of Contractors to Implement SMM

4.2.1. Challenge of Implementing SMM

Interviews reveal a set of challenges that contractors face when trying to implement SMM in their projects, all of which fall under the Challenges theme. These barriers stem from various areas, including resistance from workers, limitations imposed by clients, financial constraints, supply chain issues, technical knowledge gaps, and external pressures. Each of these challenges makes it difficult for contractors to fully adopt sustainable materials and practices.

1- Material and Worker Resistance

One of the significant challenges in implementing SMM practices is the resistance from workers who are accustomed to traditional materials and methods. Workers often prefer to stick with familiar processes and materials, as they have developed expertise and comfort over years of practice. Introducing new sustainable materials, such as eco-friendly asphalt or alternative concrete mixes, can disrupt these established workflows. Workers may resist adopting new materials because they require different handling or techniques, leading to a slowdown in adoption and efficiency.

This reluctance is not only about technical changes but also cultural resistance within the workforce. Cultural resistance refers to worker's attachment to familiar materials and methods, making them hesitant to adopt new sustainable practices. The challenge lies in overcoming this resistance, as it can slow down the shift towards more sustainable practices in construction.

> "Workers tend to prefer sticking with familiar materials and methods. When we introduce new ones, there's resistance because people prefer to work with what they're used to." – EXP1

2- Client Limitations and Knowledge Gaps

According to all participants, clients play a major role in the implementation of sustainable practices. However, many clients are hesitant to adopt new materials and methods due to concerns about cost, reliability, and unfamiliarity with sustainable options. As a result, they often prioritize traditional, proven materials, which restricts contractors from proposing more innovative and sustainable solutions.

> *"Often, it's the client, which gives limited room to propose different things."* – EXP2

Additionally, there are knowledge gaps among clients when it comes to understanding the long-term benefits of SMM. Many clients are unaware of how sustainable practices can lead to cost savings, improved project durability, and enhanced environmental performance. This lack of understanding often results in clients choosing traditional methods, leaving little room for contractors to implement more sustainable approaches. Moreover, in some cases, clients lack the flexibility to consider sustainable options due to strict budget constraints or tight timeframes, making it difficult for them to accommodate changes or innovations.

> "For clients, it's also difficult. Often, they have limited capacity. The capacity at municipalities or government institutions is limited." – EXP2

3- Contractual and Specification Issues

Many contracts lock in the use of specific, traditional materials and methods, leaving contractors with little flexibility to suggest more sustainable alternatives. These rigid specifications, often dictated by clients or regulatory bodies, can prevent contractors from proposing innovative solutions that could reduce the environmental impact of the project.

For instance, a contract may require the use of traditional C40/50 concrete, which has a compressive strength of 40 MPa for cylinders and 50 MPa for cubes. While this type of concrete is widely accepted and used, the contractor might want to propose a more sustainable alternative, such as concrete with recycled aggregates or geopolymer concrete, which can offer similar strength but with a lower carbon footprint. However, because the contract is rigidly bound to specific material requirements, the contractor is unable to substitute the greener alternative, even if it meets or exceeds the required performance standards. This lack of flexibility hinders the opportunity for contractors to introduce more environmentally friendly materials into the project.

> “The client writes only methods or materials can be used that are known. So it's forbidden to use new materials, new methodologies. You have to only use materials and products and work methods that are well known.” –EXP3

4- Cost and Financial Constraints

Sustainable materials, such as recycled aggregates or biobased products, typically come with a higher price than traditional options. This cost difference makes it challenging for contractors and clients to justify their use, especially in projects operating under tight budgets. The pressure to minimize immediate project costs often leads to sustainable materials being perceived as too expensive to fit within financial constraints.

> *“The other one is that sometimes you can have the best solution for sustainability. But it can be more expensive than* the other one.” –EXP3

As a result, many opt for cheaper, conventional materials, even if they have a higher environmental impact. For example, contractors frequently opt for traditional Portland cement instead of lower-carbon alternatives like geopolymer cement, as the latter is often more costly.

In addition to the higher costs of materials, sustainable design also requires more time and effort. Creating environmentally friendly structures often involves more complex calculations, specialized designs, and innovative techniques.

> "The costs of making a thin structure are higher than a standard one, both for construction and engineering, due to the more complex calculations and execution."
> – EXP10

5- Supply Chain Challenges

Many sustainable materials are not yet widely available, which poses a challenge for contractors trying to implement SMM practices. For large-scale projects, contractors need reliable sources that can deliver these materials in sufficient quantities and within tight deadlines. Unfortunately, the supply chain for many sustainable materials, such as recycled concrete or biobased products, is still developing, and contractors often struggle to find suppliers that can meet their demands for both quality and volume.

For example, recycled concrete aggregates are in high demand, but finding suppliers that can consistently produce the required amount for large infrastructure projects is challenging. This lack of availability can lead to project delays or force contractors to revert to traditional materials. In sustainable construction using certified timber, sourcing large quantities of timber that meets strict environmental standards often involves importing from far regions, which extends lead times and increases costs.

> "In some cases, sustainable materials are limited in availability, especially newer or innovative options that have not yet been widely adopted." – EXP5

6- Technical Knowledge and Documentation Issues

Sustainable materials often demand different techniques and approaches than traditional construction methods, and contractors may lack the experience needed to work with them effectively. For example, geopolymer concrete, a sustainable alternative to traditional Portland cement, requires controlled curing conditions to prevent cracking and ensure durability. This contrasts with traditional concrete, which can be poured and left to cure naturally. Similarly, recycled concrete aggregates need additional screening and cleaning to ensure they meet structural standards, whereas traditional materials typically have more predictable properties and require less preparation.

This lack of knowledge makes it more challenging for contractors to confidently adopt and integrate new, sustainable materials into their projects, slowing down the overall transition to greener practices.

Moreover, the absence of standardized documentation and environmental tracking systems further complicates the process. Contractors often struggle to assess the true environmental impact of the materials and methods they use due to inconsistent data and the lack of a unified system for tracking sustainability metrics. This makes it difficult to evaluate the long-term effectiveness of sustainable practices and hinders efforts to improve and refine their implementation over time.

> “As a Dutch company, we work with both local and international suppliers. While Dutch suppliers understand our ECI system, international suppliers often don’t. A unified European system, like the EPD standard, would make comparing environmental footprints much easier and ensure fair comparisons across all bids.” – EXP6

7- External and Competitive Pressures

In bidding processes, contractors proposing greener, more expensive solutions are often at a disadvantage compared to those offering cheaper, traditional methods. For instance, a contractor suggesting low-carbon concrete might lose a bid to one using conventional concrete, which is less sustainable but more cost-effective. This disincentivizes contractors from prioritizing sustainability, as they risk losing contracts to competitors focused on minimizing costs.

> "Even big companies like Boskalis tried using geopolymer concrete for a cycle bridge but stopped because it was too costly. Companies are willing to adopt sustainable methods, but their main goal is still to earn money." – EXP11

Smaller firms are particularly impacted by this pressure. While larger companies may have the resources to absorb higher sustainability costs, smaller firms with tighter budgets struggle to compete when sustainability increases project expenses.

> “But it can be a competitor, which is less far in the developments who can also block the situation. This can be the case that the client is willing to change, but it is blocked by one of the other competitors.” – EXP3

In addition, EXP-6 explain about evolving environmental regulations, such as the EN15804 standard for environmental product declarations (EPDs), are becoming more complex, there are already 10 environmental indicators and they are planning to add something like 10 more factors. While these regulations promote sustainability, they also add administrative burdens and costs, especially for smaller contractors. For example, firms must now provide detailed environmental impact data, which can be time-consuming and expensive to compile. These additional requirements make it harder for some contractors, particularly smaller ones, to stay compliant while adopting sustainable practices.

"The European standard is already a complex system, and adding more environmental factors will only make it more complicated." –EXP6

4.2.2. Impact of Early Involvement

This section is based on the insights gathered from "Contractor Influence Phase" theme. Most participants agree that early contractor involvement is essential for maximizing sustainability in construction projects. When contractors are involved from the start, they can influence key decisions, such as selecting sustainable materials and suggesting design modifications that reduce waste. For example, contractors can advocate for using materials like recycled concrete aggregates, geopolymer concrete, or biobased options like timber, which have a much lower environmental impact compared to traditional materials.

"from the theory I've learned, the most influence is at the early stages. So, I would even say early contractor involvement. So, in making already the first decisions on what kind of project do we need? What kind of infrastructure, what kind of structure do we need? Because there you can make decisions such as, okay, I'm not going to build anything new. I'm just going to extend maybe the lifetime of this structure." –EXP2

Contractors can also propose practical design changes that enhance sustainability. One example is designing for disassembly, where buildings are constructed in a way that allows materials to be reused at the end of their life. They might also suggest optimizing a building's layout to improve energy efficiency, such as maximizing natural light to reduce energy consumption for lighting and heating.

"If you really want to build sustainably, you have to involve a contractor as early as possible. Especially if you talk about reuse of materials… Having a contractor is quite crucial." – EXP8

Late involvement of contractors, particularly during the construction phase, limits their ability to influence sustainability. By this stage, critical decisions such as material choices and design elements are already locked in, leaving little room for changes. For example, if traditional concrete has already been chosen over more sustainable options, the opportunity to lower the project's carbon footprint is lost.

Similarly, if the design doesn't consider methods like modular construction, contractors can't introduce more sustainable practices. While they may still reduce waste or improve resource efficiency on-site, their overall influence is reduced by the time the project reaches construction.

"If the contractor is brought in towards the end of the design phase or just before construction, most material decisions have already been made. Their ability to influence sustainability is limited." –EXP5

4.2.3. Contractor’s Willingness and Ability to Implement SMM

Based on “Contractor’s Willingness and Ability” theme, all participants agreed that there is a strong willingness among contractors to implement SMM and incorporate sustainable practices into their projects. Contractors understand the long-term benefits of sustainability, not only for the environment but also for staying competitive and meeting client expectations.

> "Our strategy, recently renewed for another three years, continues with the slogan ‘Building a Sustainable Tomorrow.’ This approach reflects our commitment: we either build sustainably or we don’t build at all, aiming to set an example as a contractor dedicated to building differently." – EXP2

Despite the bad name that contractors may have for lacking sustainability efforts, in practice and especially in the Netherlands, they are emerging as leaders in this area.

> *“I know we as contractors have a bad name, but we are already busy with it before even clients thought about it*.” – EXP3

This is evident through their daily work, ambitious sustainability goals, and investments in innovations like green concrete and geopolymer concrete.

> “we are a construction company who set up a net zero goal. We're committed on the SPTI, the net zero goal.” – EXP6

However, while the desire to implement SMM is evident, the ability to do so is not entirely within their control. Contractors possess the expertise to integrate sustainability into projects through material selection and sustainable design. Many contractors are adept at using tools like Environmental Product Declarations (EPDs) to assess material impacts and recommend greener alternatives. However, their ability to implement these alternatives depends on client approval and contracts flexibility.

Additionally, contractors are increasingly experienced in sustainable construction techniques. Techniques like modular construction and design for disassembly allow them to reduce material waste and improve efficiency. Contractors are capable of proposing these approaches early in the design phase, but their implementation hinges on the client’s willingness to adapt project specifications.

> "There's been a big shift in the contractor's role. In the Dutch market, major contractors are now actively contributing to sustainable solutions like timber and building technologies. They've realized they can't rely on old methods anymore." – EXP8

As EXP8 explained, contractors have realized they can't rely on old methods anymore due to increasing material scarcity, rising environmental concerns, regulatory pressures, and client demand for sustainable solutions. These factors have driven contractors to adopt more sustainable practices and explore innovative construction methods.

Contractors also demonstrate strong operational efficiency in managing waste reduction and material reuse on-site. Many have successfully implemented lean construction methods to minimize waste and recycle materials like concrete and asphalt. However, their ability to expand these practices can be limited by project constraints, including budget and timelines imposed by clients.

Another ability contractors hold is their power to influence supply chains. Contractors can negotiate with suppliers to source sustainable materials, such as recycled aggregates or low-carbon concrete. However, the availability of these materials and their associated costs often require client buy-in, limiting how far contractors can push sustainable alternatives on their own.

> "We recently studied the CO_2 production of our suppliers and subcontractors and realized they were not as advanced as we thought. Now, we're not only focusing on our own activities but also working to improve our suppliers or switch to more sustainable ones." – EXP3

Collaboration is key to contractors' ability to implement SMM effectively, but it involves multiple stakeholders and comes with its own set of challenges. Contractors can more easily collaborate with architects and engineers, as these teams typically share a focus on project efficiency and innovation. By working together, they can align technical plans and sustainability goals early in the design phase. However, collaboration with clients can be more challenging, as clients often prioritize budget constraints or project timelines over sustainability. Contractors may also face resistance when collaborating with suppliers if sustainable materials are not readily available or cost-effective.

To initiate collaboration, contractors can start by discussing sustainability goals with each stakeholder at the project's outset. Proposing regular meetings and transparent communication channels can help align everyone's priorities. However, several challenges may arise, such as differing objectives, varying levels of commitment to sustainability, and contractual limitations that restrict flexibility in materials and methods. For collaboration to succeed, all parties must be willing to compromise, adopt a long-term perspective, and integrate sustainability as a shared goal rather than a secondary priority.

> "While contractors can push for sustainable practices and lead by example, we need the support and cooperation of clients to make a significant impact." *–EXP7*

4.3. Summary

This chapter set out to answer sub-question three:

How do contractors currently apply SMM strategies in projects, and what are their willingness and ability to enhance sustainability in this area?

To answer this question, the interview findings are organized into two main sections, with each section addressing a specific part of sub-research question 3:

- **A.** Current Application of SMM Strategies in Contractor Projects.
- **B.** Overcoming Challenges: Contractor Willingness and Ability to Implement SMM

A. Current Application of SMM Strategies in Contractor Projects

The findings show that contractors are already applying a range of SMM strategies across their projects. These include sustainable material use, environmental assessments, waste reduction, electrification of equipment, and sustainable design practices. Contractors are leveraging innovative materials such as recycled aggregates, geopolymer concrete, and biobased products to minimize their environmental impact. Additionally, assessments and tools like the environmental cost indicator allow for smarter material choices that prioritize sustainability.

However, these practices do not happen in isolation. The influential factors for implementing SMM, such as organizational culture, leadership, and economic considerations, were found to impact the degree to which contractors can successfully adopt these practices. Companies with strong leadership and a commitment to sustainability have made significant progress by embedding SMM into their operations. Economic considerations, including the ability to demonstrate long-term cost savings, further drive these initiatives, while regulatory and market pressures also push contractors toward greener solutions.

B. Overcoming Challenges: Contractor Willingness and Ability to Implement SMM

The second half of the research question examines contractor's willingness and ability to enhance sustainability in construction. While the interviews revealed a clear willingness to implement SMM, the ability to do so is often constrained by various challenges. These include worker resistance to new materials, client limitations, and strict contractual specifications, financial constraints, supply chain limitations, and gaps in technical knowledge also hinder the widespread adoption of SMM practices.

Early contractor involvement emerged as a key factor in maximizing sustainability outcomes. When contractors are involved at the initial stages of a project, they have greater influence over material selection, design adjustments, and lifecycle considerations, which are essential for implementing SMM strategies effectively. Late involvement reduces their ability to make sustainable changes, limiting their influence to more traditional practices.

Despite these challenges, contractors remain committed to enhancing sustainability in their projects, because they recognize the long-term benefits of sustainable practices, including cost savings, enhanced reputation, and compliance with regulatory requirements. They understand that investing in sustainability can lead to competitive advantages and align with their corporate social responsibility goals. Their willingness is evident in the proactive steps they are taking, such as establishing dedicated sustainability teams and setting ambitious targets like achieving net-zero emissions. For example, some contractors have formed internal sustainability teams to monitor and enforce the use of green materials across projects. Others are investing in innovative construction techniques like modular building and designing for disassembly, which allow them to reduce waste and extend the lifecycle of materials.

In addition, contractors are taking specific actions to influence their supply chains. For instance, they are actively seeking suppliers that provide low-carbon materials, such as recycled aggregates and green concrete. In some cases, they are collaborating with suppliers to improve their environmental performance, ensuring that subcontractors and material suppliers align with their sustainability goals. One contractor reported conducting a CO2 analysis of their suppliers to better understand and address the emissions in their supply chain, showing a hands-on approach to improving sustainability beyond their immediate operations.

However, their ability to fully implement SMM is often tied to external factors such as client support, regulatory frameworks, and market conditions. Contractors can propose innovative solutions, but these solutions can only be realized with the cooperation of clients and flexibility in project specifications. Collaboration among all stakeholders is the key to overcome these barriers and enable contractors to fully capitalize on their willingness and ability to drive sustainability in construction.

In summary, the findings indicate that while contractors are currently applying various SMM strategies and show strong willingness to enhance sustainability, their ability to do so is influenced by a combination of internal and external factors. Addressing these challenges through collaborative efforts and early involvement can significantly enhance the implementation of SMM practices in the construction industry.

5. Discussion

The concepts of willingness and ability, as framed in the theoretical discussion using the Theory of Planned Behavior and the COM-B model, offer essential insights into contractor behavior and decision-making in SMM. These frameworks highlight how attitudes, norms, and perceived capabilities influence contractor's choices to adopt and implement SMM practices. This section synthesizes the empirical findings with these theoretical constructs, examining how practical applications align with theoretical expectations and exploring strategies to overcome barriers to SMM implementation effectively.

This section synthesizes findings from the literature review and interviews to answer Sub-Question 4:

What sustainable material management strategies can enhance environmental and economic sustainability in future infrastructure renovation projects?

By comparing theoretical frameworks with practical insights, this synthesis focuses specifically on SMM strategies that have the potential to improve renovation projects, thereby contributing to both environmental and economic sustainability. The discussion presents a framework for applying these SMM strategies, outlining practical steps that can be taken while addressing the barriers identified in the findings.

5.1. SMM Strategies

Based on the findings from the literature (Section 2) and practical insights gathered from interviews (Section 4), Table 6 below provides a comparative overview of the strategies identified. The table highlights how these strategies align or differ between theoretical perspectives and practical applications, emphasizing their role in promoting sustainability in the projects.

Table 5 Comparative Overview of the strategies in Theory and Practice

Strategies	Source	Reference
Integration of Green Materials, Sustainable Material Use	Theory/Practice	Emmanuel Eze et al., 2021 EXP1, EXP2, EXP8
Circular Economy Approaches, Recycling and Waste Reduction	Theory/Practice	Karstensen et al., 2019 EXP4, EXP6, EXP7
Energy Efficiency and Low-Carbon Practices, Electrification and Energy Use	Theory/Practice	Zhuan et al., 2023 EXP1, EXP2, EXP3
Technological Integration	Theory	Schützenhofer et al., 2022
Lean Construction and Waste Minimization	Theory	Daghlas et al., 2023
Assessments and Calculations	Practice	EXP2, EXP6
Sustainable Design	Practice	EXP2, EXP4, EXP9
Contractor's Early Involvement	Practice	EXP1, EXP6, EXP9

5.1.1. SMM Strategies: Aligning Theory and Practice

Both the literature and interview data emphasize that SMM strategies are important for balancing environmental goals with economic sustainability in infrastructure renovation projects. Several strategies, including the use of sustainable materials, waste minimization and energy efficiency, were highlighted in theory and observed in practice.

The theoretical literature emphasizes the importance of green materials such as geopolymer concrete and biobased products. These materials are recognized for reducing CO2 emissions and promoting resource efficiency (Emmanuel Eze et al., 2021). However, practical application revealed that contractors often face challenges, particularly related to the availability of these materials, cost considerations, and client approval. For example, one contractor shared an experience where they proposed several innovations for a project with an allocated innovation budget of €250,000. The innovation involving geopolymer concrete exceeded this budget, requiring additional funds. Although the client invested in the innovation, they were not willing to cover the full cost. The contractor noted:

> *"Because the client offered five innovations for a budget of €250,000, but the innovation of geopolymer concrete itself was above that amount. So yes, the client invested in the innovation, but not 100%"* -EXP11

In another instance, a major construction firm utilized geopolymer concrete for a cycling bridge project. Despite the successful application, they chose not to use this material in subsequent projects due to the higher costs involved. These examples illustrate that even when contractors are willing to adopt sustainable materials, factors such as increased costs and limited client support can hinder their ability to implement these innovations fully.

As a result, contractors adapt theoretical strategies to the realities of the project environment by using more readily available and cost-effective alternatives, such as recycled aggregates or low-carbon materials where feasible. Wider adoption of cutting-edge sustainable materials like geopolymer concrete remains hindered by financial constraints and the need for client approval, highlighting the gap between theoretical potential and practical implementation.

Similarly, the circular economy approach, which promotes recycling and waste reduction, is central to both theoretical frameworks and practice. In theory, the circular economy approach emphasizes reusing materials at the end of their lifecycle to minimize waste and promote a closed-loop system (Karstensen et al., 2019). However, in practice, while contractors have made significant strides in incorporating recycled materials like asphalt and concrete into new projects, they encounter real-world challenges. These include rigid contractual specifications that limit flexibility in material choices and concerns about the quality of recycled materials. As a result, the full implementation of circular economy principles is often constrained, preventing seamless recycling as envisioned in theory.

Figure 12 illustrates the circular economy lifecycle in the construction sector, emphasizing the closed-loop system intended to minimize waste through continuous reuse of materials. However, constraints such as rigid contractual specifications, especially at the design phase, limit flexibility in material choices and hinder full implementation of circular economy.

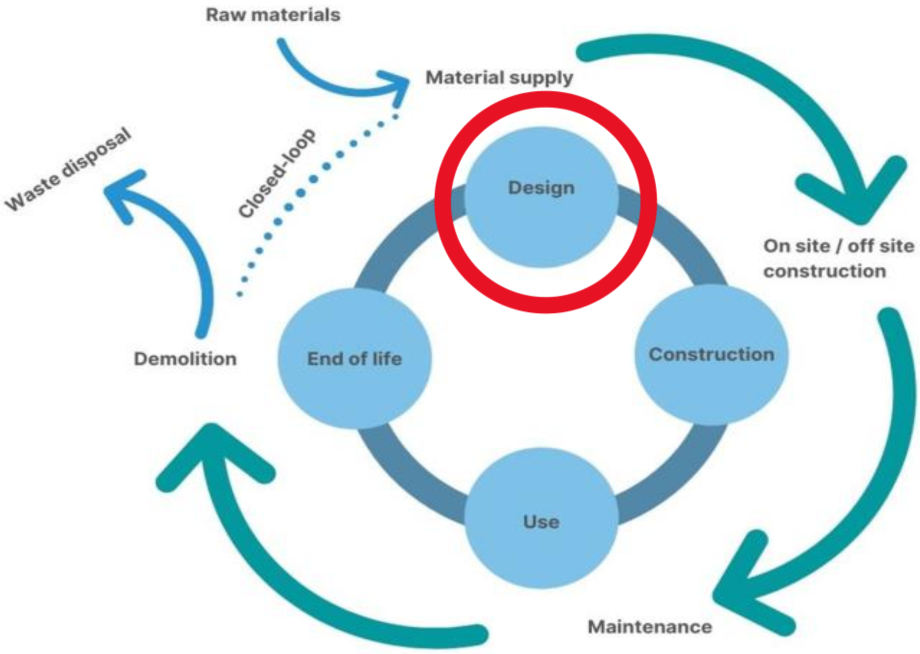

Figure 12 Circular Economy in Building lifecycle (Spišáková et al., 2022)

Additionally, energy efficiency and low-carbon practices are important for reducing energy use and lowering carbon emissions. Theoretical discussions often focus on how using more sustainable materials, like advanced insulation materials, can help lower energy expenses, decrease operational costs (Zhuan et al., 2023). In practice, however, contractors take more direct actions, such as electrifying equipment and improving production processes to save energy. For example, contractors are lowering the production temperatures of asphalt and incorporating renewable energy sources into manufacturing. They are also adopting electric vehicles and machinery to reduce emissions and energy consumption on-site, focusing on immediate and tangible steps to achieve sustainability goals.

The alignment between theory and practice suggests that while the goals of SMM are consistent across both domains, the practical application of these strategies requires flexibility, particularly in navigating project constraints like budget, timelines, and stakeholder expectations.

Also, technological Integration is given attention in the theoretical literature, where it is often emphasized as a key enabler for enhancing sustainability through tools like BIM and advanced material tracking systems (Schützenhofer et al., 2022). However, in practice, the interviews reveal that contractors do not face major technological challenges. In fact, contractors report having access to more technology than they currently need, with the ability to effectively use available tools for implementing sustainable material management. This reveals two key insights: first, it highlights a disparity between larger and smaller contractors, with the former facing fewer technological challenges compared to the latter. Second, while technology remains a key enabler, the primary obstacles to implementing SMM appear to lie elsewhere, such as in client demands or material availability, rather than in technological constraints.

Additionally, there are more strategies observed in practice that are not mentioned in the literature on SMM. For example, sustainable design and strategic material use have emerged as key priorities in practical applications. The interviews showed that contractors are implementing strategies that extend beyond the basic sustainability principles of reducing, reusing, and recycling. These advanced strategies include designing structures for disassembly, allowing for future material reuse, and making strategic design changes to minimize material consumption. A notable example mentioned in the findings is the decision to build a bridge instead of a tunnel, resulting in significant material savings while still meeting the project's sustainability goals.

Moreover, in practice, contractors conduct comprehensive assessments and lifecycle calculations to evaluate the environmental and economic impacts of material choices. This approach enables them to make informed decisions that balance sustainability goals with project constraints, by having a data about all the materials available in the market.

The final strategy emphasizes the early involvement of contractors in decision-making and planning, which participants agree provides the greatest influence on project outcomes. This aligns with the principles of Front-End Loading (FEL), which stress that early-stage decisions have the most significant impact on a project's success (Nyaminani, 2021). FEL is a project management approach that advocates for dedicating time and resources to the initial planning and design phases to improve outcomes and minimize risks. At this early stage, contractors can implement resource-efficient construction methods, such as reusing excavated materials or employing modular construction techniques. These strategies reduce material usage, lower project costs, and enhance overall sustainability, making early contractor involvement essential for achieving long-term environmental and economic benefits (Nyaminani, 2021).

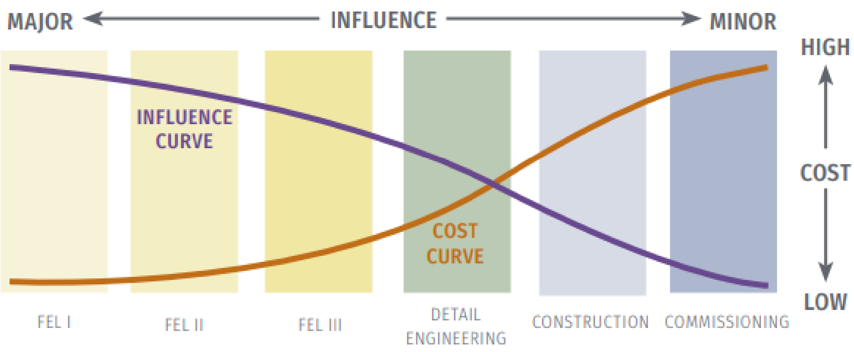

Figure 13 Change and cost curve (SSOE, n.d.).

In summary, while there is a strong alignment between theoretical SMM strategies and practical applications, notable gaps exist due to real-world constraints. Theoretical models advocate for the use of cutting-edge sustainable materials and comprehensive circular economy practices. However, in practice, contractors face challenges such as higher costs, limited material availability, client approval hurdles, and rigid contractual specifications. As a result, they adapt by implementing more feasible alternatives and innovative approaches tailored to project-specific challenges. Additionally, contractors often extend beyond theoretical frameworks by adopting strategies like designing for disassembly and strategic material use. Overall, the comparison reveals that while the goals of SMM are consistent in both theory and practice, successful implementation requires flexibility, innovation, and collaboration to overcome practical obstacles.

5.1.2. Framework for Applying SMM Strategies

To advance the adoption of SMM strategies in future projects, a structured framework is essential. The framework adds significant value by providing a clear, organized approach that helps contractors incorporate sustainable practices into their projects. The framework offers a practical roadmap that ensures comprehensive coverage of key aspects such as material selection, energy efficiency, and stakeholder engagement. It bridges the gap between theoretical recommendations and the real-world challenges contractors face, making sustainability feasible and actionable.

Grounded in the Theory of Planned Behavior (TPB) and the COM-B model discussed in Section 2.5, the framework emphasizes contractors' willingness and ability to adopt SMM strategies. By addressing capability, external opportunities, and motivation, it connects theoretical insights to practical actions. This alignment ensures that the framework tackles both the psychological and operational dimensions of SMM adoption, making it both realistic and impactful.

The framework is presented to guide contractors through the implementation of SMM. The steps ensure that most critical areas of SMM are addressed, from initial assessments to gradual technological integration. They are not meant to be followed in a strict sequence. Each step can be applied individually, depending on the specific requirements and context of the project.

The structured approach enables contractors to implement these strategies progressively, adapting to specific project requirements while fostering long-term sustainability. Moreover, the framework can be used as a reference tool, helping contractors navigate both technical and operational challenges, ultimately improving both environmental and economic outcomes in future projects.

Step 1: Comprehensive Assessments and Lifecycle Calculations

In Chapter 4, contractors highlighted in the theme “SMM Practices” the critical need for comprehensive assessments and lifecycle calculations as a foundational step in a broader framework for implementing SMM. Although theoretical literature may not emphasize this aspect heavily, its significance in practice is undeniable. Conducting thorough evaluations of material choices through tools such as LCAs and EPDs allows contractors to quantify the environmental impacts of various materials and processes. These tools provide essential data for making informed sustainability decisions.

Training project teams to use these tools ensures that sustainability is integrated from the early design stages. By selecting materials and processes with lower environmental impacts, contractors can significantly reduce a project's ecological footprint. This approach serves as the foundation for the entire framework, promoting long-term cost savings through resource optimization while enhancing both environmental and economic sustainability.

Step 2: Sustainable Material Integration:

Contractors should prioritize the use of sustainable options, such as recycled concrete aggregates and low-carbon alternatives like geopolymer concrete. The literature emphasizes the significance of these materials, with Emmanuel Eze et al. (2021) highlighting their role in reducing CO2 emissions and improving resource efficiency. Interviews with industry professionals echo these advantages but also point to challenges regarding the availability of sustainable materials, as discussed in the theme "Challenges."

To address these availability issues, contractors should establish long-term partnerships with suppliers who can reliably provide such materials. Early collaboration with suppliers and clients is essential to ensure sustainable materials are feasible within the project's scope. Incorporating these materials will have a positive environmental impact and deliver long-term economic benefits through reduced resource consumption and enhanced sustainability.

Step 3: Sustainable Design Optimization

This strategy was strongly emphasized in the interview findings under the theme "SMM Practices" where participants highlighted the importance of integrating sustainability into the design phase as a critical success factor. Once contractors identify available sustainable materials, they have the opportunity to influence project outcomes by advocating for designs that minimize material use and maximize resource efficiency. Key strategies such as designing for disassembly, modular construction, and optimizing material usage promote future reuse or recycling of materials, significantly enhancing sustainability.

These design approaches not only reduce waste but also extend the lifecycle of materials, leading to a reduced environmental footprint and long-term cost savings through lower material consumption and reduced waste management expenses. However, interviewees noted that these strategies often come with higher upfront costs due to specialized planning and materials. Additionally, their adoption remains limited, as clients and contractors may perceive them as financially risky or lack familiarity with these methods.

> *The costs for making a very thin structure is higher than making a easy structure. So the costs in executing will become higher for the construction company. And for the engineering company, the costs are also higher because their calculation work is much more.*-EXP10

Despite these challenges, the long-term benefits of sustainability and cost efficiency are clear when implemented effectively.

Step 4: Stakeholder Engagement and Collaboration

A critical step is the early involvement of contractors, as all participants agreed that this has the greatest influence on the successful implementation of SMM, as highlighted in Chapter 4 under the theme "Contractors Influence Phase." Early collaboration with other stakeholders, including clients and suppliers, helps address many of the challenges contractors face, ensuring a smoother and more effective integration of sustainability practices into projects.

Contractors should actively communicate the long-term benefits of sustainable practices, emphasizing not only the positive environmental impact but also the cost savings throughout the project's lifecycle. Collaborative decision-making ensures that sustainability goals are shared and aligned across the project team by establishing clear objectives early on and maintaining regular communication among stakeholders. This approach allows for coordinated actions and quick adjustments, helping the team stay focused on shared sustainability outcomes throughout the project. By bringing stakeholders together around common sustainability objectives, projects can achieve greater efficiency, reduce delays caused by miscommunication, and implement cost-effective sustainable solutions. This approach enhances both environmental outcomes and economic performance in future projects.

Step 5: Electrification of Equipment and Energy Efficiency

The transition to electrification of equipment and energy efficiency emerged as a key step in the sustainability framework, informed by both theoretical research and practical findings. Theoretical discussions, such as those by Zhuan et al. (2023), highlight the potential of sustainable materials and advanced technologies in reducing energy consumption and operational costs. Similarly, interviews with contractors under theme "SMM practices" emphasized the importance of electrifying equipment, utilizing renewable energy, and innovating material production processes to achieve greater energy efficiency.

Given the financial challenges, this transition should be gradual. Contractors can start by electrifying smaller machines, expanding to larger equipment as technology advances and costs become more manageable. Incorporating renewable energy sources, like solar or wind, to power electric machinery on-site will further reduce environmental impact.

Moreover, enhancing energy efficiency through innovations in material production such as lowering production temperatures for asphalt or using green energy in manufacturing can significantly cut energy use. Collaboration with suppliers to adopt these methods and phase out energy-intensive processes will lower emissions and operating costs, delivering both environmental and economic benefits in the long run.

Step 6: Gradual Technological Integration

In the literature, Schützenhofer et al. (2022) highlight tools such as BIM and material tracking systems as important for improving SMM. These tools assist contractors in tracking resources, minimizing waste, and improving efficiency. However, interviews with contractors revealed that technology is not the primary challenge they face. Larger contractors reported having more tools than they currently need, while smaller contractors cited financial barriers to adopting these technologies.

To overcome these challenges, a gradual approach is recommended. Contractors can begin by implementing pilot programs or using technology on smaller-scale projects to refine their methods before expanding to larger initiatives. Furthermore, sharing knowledge and best practices between contractors will be essential for broader industry adoption of these tools. By strategically integrating technology, contractors can enhance project efficiency, reduce errors, and optimize resource management, leading to cost savings and minimized environmental impacts. This approach contributes to both environmental and economic sustainability in future projects.

Step 1: Comprehensive Assessments and Lifecycle Calculations

Targeted party: Sustainability Manager / Project Manager

1. **Train Teams on LCAs and EPDs:** Build internal capabilities to assess sustainability early in the project.
2. **Conduct Lifecycle Assessments (LCAs):** Evaluate environmental impact from material extraction to disposal.
3. **Use Environmental Product Declarations (EPDs):** Make data-driven material selections based on sustainability targets.

Step 2: Sustainable Material Integration

Targeted Party: Procurement Manager / Sustainability Advisor

1. **Collaborate with Suppliers:** Source sustainable materials like recycled concrete aggregates and geopolymer concrete.
2. **Establish Long-Term Partnerships:** Ensure consistent supply of green materials through partnerships with sustainable suppliers.
3. **Negotiate with Clients Early:** Integrate sustainable materials into project scope and contracts to overcome client knowledge gaps.

Step 3: Sustainable Design Optimization

Targeted Party: Design Engineer / Project Architect

1. **Advocate for Reduced Material Use:** Promote design for disassembly and modular construction.
2. **Optimize Material Usage:** Plan for future reuse and recycling of materials.
3. **Coordinate with Stakeholders:** Create designs minimizing environmental impact without compromising project quality.

Step 4: Stakeholder Engagement and Collaboration

Targeted Party: Project Manager / Client Engagement Team

1. **Early Stakeholder Engagement:** Engage stakeholders early to emphasize long-term benefits of sustainable materials.
2. **Collaborative Decision-Making:** Align stakeholder's sustainability goals through open collaboration.
3. **Support Flexibility:** Ensure contracts and material selections are flexible to meet sustainability targets.

Step 5: Electrification of Equipment and Energy Efficiency

Targeted Party: Operations Manager / Procurement Manager

1. **Gradually Electrify Equipment:** Transition to electric-powered machinery to reduce emissions, starting with smaller pilot programs.
2. **Invest in Energy-Efficient Production:** Incorporate innovative production techniques (e.g., lowering asphalt production temperature) to save energy and reduce CO_2 emissions.
3. **Use Renewable Energy Sources:** Leverage renewable energy in production facilities to meet sustainability targets.

Step 6: Gradual Technological Integration

Targeted Party: Project Manager / Technology Manager

1. **Integrate Technology Slowly:** Adopt BIM and material tracking systems gradually, based on project scale and complexity.
2. **Pilot Programs for New Technologies:** Test new technological solutions on smaller-scale projects before full implementation.
3. **Knowledge Sharing:** Encourage inter-company knowledge exchange on successful technological integration to improve industry practices.

Figure 14 Framework Guidelines for the Sustainable Strategies

5.1.3. Addressing Barriers to SMM Implementation

While contractors have shown a strong willingness to adopt SMM strategies, several barriers persist as previously mentioned in section 4.1.2. These challenges include material and worker resistance, client limitations and knowledge gaps, contractual and specification issues, cost and financial constraints, supply chain challenges, technical knowledge and documentation issues, and external and competitive pressures.

Figure 15 illustrates how the proposed framework's innovative strategies tackle these barriers. The figure lists the six steps of the framework on the right side, and the challenges on the left side, with arrows indicating which strategies address each specific barrier.

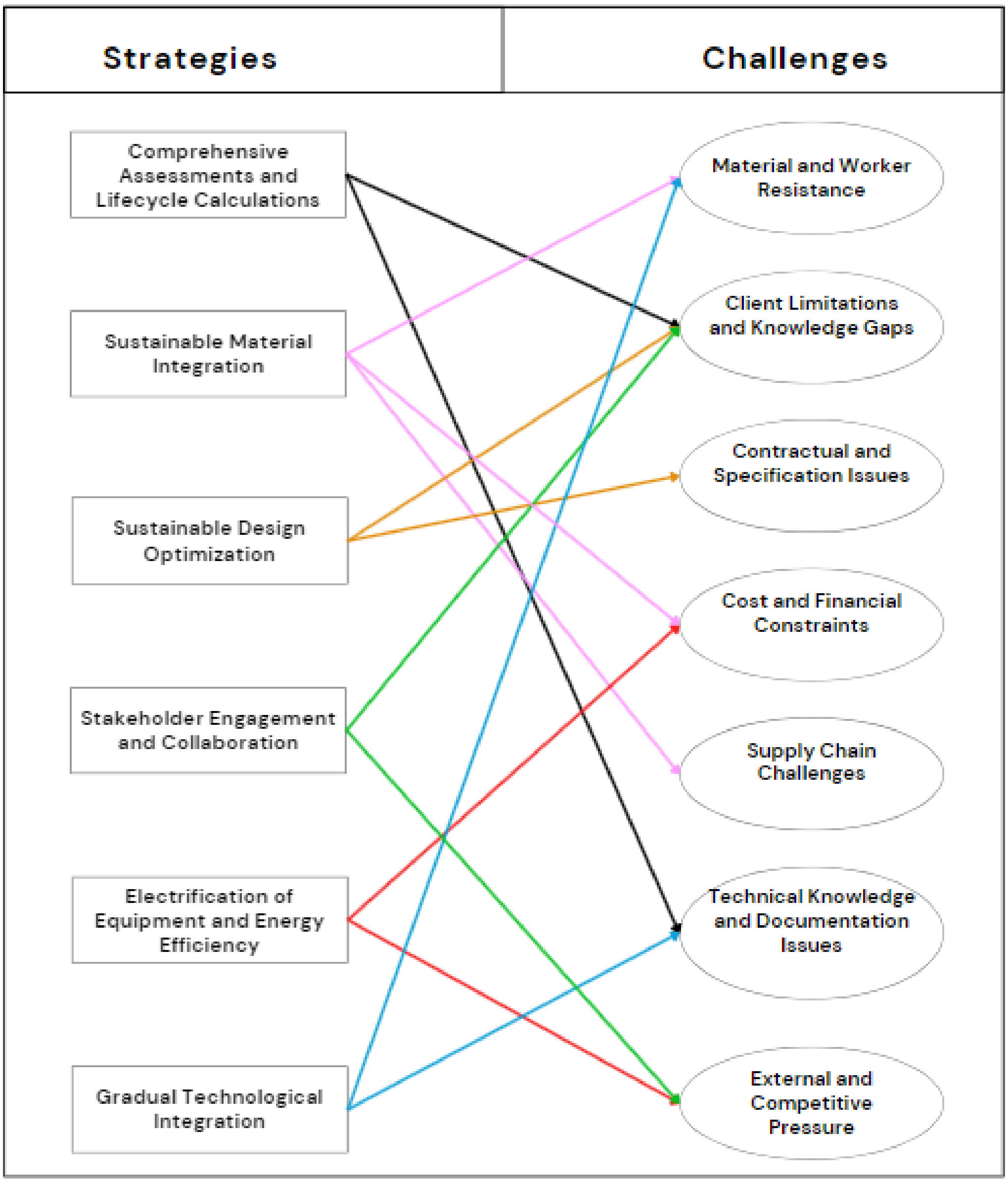

Figure 15 Linking Innovative strategies and Challenges (Source: Author)

5.1.3.1. Explanation of How the Framework Addresses the Barriers:

Step 1: Comprehensive Assessments and Lifecycle Calculations

- **Addresses:** Technical Knowledge and Documentation Issues; Client Limitations and Knowledge Gaps

By training project teams on LCAs and EPDs, contractors enhance their technical expertise and documentation capabilities. This empowers them to provide clients with detailed, data-driven insights into the environmental impacts and long-term benefits of sustainable materials. As a result, client knowledge gaps are bridged, and informed decisions can be made collaboratively, overcoming hesitations due to unfamiliarity with sustainable options.

Step 2: Sustainable Material Integration

- **Addresses:** Material and Worker Resistance; Supply Chain Challenges; Cost and Financial Constraints

Prioritizing sustainable materials involves collaborating with suppliers to secure reliable sources of eco-friendly products like recycled aggregates and geopolymer concrete. Establishing long-term partnerships mitigates supply chain challenges by ensuring consistent availability. Early negotiation with clients to integrate these materials into project scopes helps address cost concerns by highlighting potential long-term savings. Involving workers in the selection and implementation process reduces resistance by increasing familiarity and demonstrating the practicality of new materials.

Step 3: Sustainable Design Optimization

- **Addresses:** Contractual and Specification Issues; Client Limitations and Knowledge Gaps

Incorporating sustainability into the design phase allows contractors to advocate for flexible designs that accommodate innovative materials and methods. By promoting concepts like design for disassembly and modular construction, contractors can work with clients to adjust contractual specifications that may have previously limited material choices. This collaborative approach helps overcome rigid contracts and aligns project goals with sustainable practices.

Step 4: Stakeholder Engagement and Collaboration

- **Addresses:** Client Limitations and Knowledge Gaps; External and Competitive Pressures

Early engagement with clients and stakeholders fosters open communication about the benefits of sustainability, both environmentally and economically. By aligning sustainability goals and encouraging collaborative decision-making, contractors can mitigate client limitations due to knowledge gaps. Additionally, presenting unified sustainability commitments can enhance competitiveness in the market, addressing external pressures by meeting the growing demand for environmentally responsible construction practices.

Step 5: Electrification of Equipment and Energy Efficiency

- **Addresses:** Cost and Financial Constraints; External and Competitive Pressures

Gradually transitioning to electric equipment and investing in energy-efficient production techniques address cost concerns by reducing long-term operational expenses. While the initial investment may be significant, the decrease in fuel consumption and maintenance costs over time provides economic benefits. Demonstrating these savings to clients and stakeholders can justify the upfront costs. Moreover, adopting energy-efficient practices enhances the contractor's reputation for innovation and environmental stewardship, improving competitive positioning.

Step 6: Gradual Technological Integration

- **Addresses:** Technical Knowledge and Documentation Issues; Material and Worker Resistance

Implementing technology solutions like BIM and material tracking systems on a gradual basis allows contractors and their workforce to adapt without being overwhelmed. Starting with pilot programs enables teams to build technical proficiency incrementally. Knowledge sharing and training reduce resistance among workers by demonstrating the practical advantages of new technologies, such as increased efficiency and reduced errors. Improved documentation practices also result from better technological integration.

5.2. Expert Validation

To ensure the practical relevance of the findings and assess the feasibility of the proposed strategies for enhancing SMM in infrastructure renovation projects, expert validation was conducted through semi-structured interviews with industry professionals. This validation focused first on confirming the real-world challenges contractors face, as these challenges form the basis of the framework. Then experts evaluated each framework step to ensure its feasibility for practical implementation. The experts provided valuable insights, which helped refine both the framework and the study's conclusions.

5.2.1. Validation of Challenges

The experts confirmed that the challenges identified in the study accurately reflect those encountered in practice. A primary challenge highlighted was the lack of client demand for sustainability. In recent years, clients have become less inclined to request environmental impact reductions, placing the responsibility on contractors to initiate sustainable practices without explicit support. This shift creates a significant barrier, as contractors risk losing bids if they propose sustainable solutions that may increase costs. Proposals are often evaluated primarily on cost, with little consideration for environmental benefits. The experts emphasized that when environmental criteria are not included in tender evaluations, proposing materials with lower environmental impact becomes financially unviable. Contractors face the dilemma of either incorporating sustainable materials and potentially losing the bid due to higher costs or adhering to traditional methods to remain competitive.

Financial constraints were also highlighted as a critical challenge. Sustainable materials and technologies often come with higher upfront costs, making it difficult for contractors to integrate them without client support or incentives. Without explicit demand from clients, the additional expenses associated with sustainable options cannot be justified within tight project budgets.

Contractual and specification issues further compound the problem. Clients often provide rigid specifications that leave little room for innovation or the introduction of sustainable alternatives. When tenders require specific materials or methods, contractors are constrained from proposing more environmentally friendly options. The experts noted that clients typically expect all bidders to adhere strictly to the specified requirements to maintain a level playing field. Deviating from these specifications, even with more sustainable solutions, could result in disqualification or rejection of the proposal.

Supply chain challenges were acknowledged as well. While the expert's company is reusing materials in some projects—such as harvesting concrete elements from previous constructions—scaling up these practices is challenging. The availability of sustainable materials in the necessary quantities and within project timelines can be a significant obstacle. Implementing such practices requires specialized engineering expertise to assess and certify reused materials, which may not be readily available in all companies.

Technical knowledge and documentation issues were confirmed as challenges, especially regarding new materials like geopolymer concrete. The company relies on specialists to handle assessment and integration, and training all employees is not practical. The experts mentioned that while they have employees who understand the complexities of these materials, disseminating this knowledge across the entire organization is challenging due to resource constraints and the specialized nature of the expertise required.

An additional challenge pertains to emerging environmental regulations, specifically nitrogen emissions and water quality legislation. These new regulatory concerns add complexity to project planning and material selection, creating further obstacles for contractors. The experts pointed out that clients are increasingly concerned about compliance with these regulations, which can influence decision-making processes and priorities.

Worker resistance to new materials and methods was acknowledged but appeared less significant for the expert's company. The primary challenges with new materials lie more with engineering assessments and approval processes than with worker acceptance. This suggests that while workforce adaptability is important, the more pressing issues relate to technical validation and regulatory compliance.

Overall, the expert's insights validate the study's identified challenges, emphasizing that client limitations, financial constraints, and contractual rigidity are significant barriers to implementing SMM practices. The lack of client demand was highlighted as the most difficult challenge to overcome, as it directly influences the feasibility of incorporating sustainable materials and methods. Without client support or incentives, contractors face a dilemma between proposing environmentally friendly solutions and remaining competitive in the market.

The experts stressed the importance of aligning goals between clients and contractors to promote sustainability effectively. Early engagement and collaboration are essential but only effective if clients share the commitment to environmental objectives. If clients do not prioritize environmental impact, efforts by contractors may yield limited results. This underscores the need for a collaborative approach where all stakeholders are committed to sustainability objectives.

5.2.2. Validation of the Framework

The proposed framework offers a structured approach for contractors to implement SMM strategies in infrastructure renovation projects. The experts provided valuable feedback on each step of the framework, highlighting both feasibility and potential obstacles.

Step 1: Comprehensive Assessments and Lifecycle Calculations

Conducting thorough evaluations using tools like LCAs and EPDs is emphasized in the framework. The experts confirmed that this step is feasible and already integrated into their company's practices through the Environmental Cost Indicator (ECI), which is managed by specialists within the organization. While these assessments are essential for quantifying environmental impacts, training all project teams to use these tools is challenging. The company relies on dedicated experts rather than training all staff, indicating that specialized personnel handle these assessments effectively without overextending resources.

> "We have a team focused on sustainability from a broad perspective, with one specialist managing key materials like concrete and basalt reinforcement. However, we rely on a single expert rather than training everyone on these assessments."-EXP13

Step 2: Sustainable Material Integration

The experts affirmed that integrating sustainable materials is both feasible and already occurring in their projects. For example, their company reuses concrete elements from previous constructions, demonstrating practical application of material reuse. While construction workers may not require extensive knowledge about these materials, engineers must assess and certify them to ensure structural integrity. This highlights the need for specialized engineering knowledge to safely integrate sustainable materials. The expert's experience suggests that with the right expertise, sustainable material integration can be successfully implemented, although scaling up such practices may require additional resources and planning.

> “This step is feasible and already happening in practice. For instance, in the A44 project, we’re reusing concrete parts from the A9 project, where materials are harvested and repurposed in a new setting.”-EXP13

Step 3: Sustainable Design Optimization

While acknowledging the value of sustainable design practices, the experts pointed out significant barriers related to client acceptance and contractual limitations. Clients often have rigid specifications and may not accept alternative designs unless specified in advance. This rigidity limits contractor’s ability to propose innovative solutions that deviate from the prescribed requirements. The experts shared that gaining approval for using alternative materials can be a lengthy and complex process, as evidenced by their experience with geopolymer concrete, which took over a year to get accepted. These challenges indicate that while sustainable design optimization is beneficial in theory, practical implementation is hindered by contractual constraints and the time-consuming nature of approval processes.

Step 4: Stakeholder Engagement and Collaboration

Early involvement and collaboration are critical components of the framework. The experts emphasized that this step is effective only when clients share the same sustainability goals. Without client commitment to environmental objectives, efforts to engage stakeholders early may not lead to meaningful adoption of SMM practices. The experts suggested that contractors may need to focus on educating clients and aligning objectives to make this step more effective. Building awareness about the long-term benefits of sustainability could encourage clients to be more receptive to collaborative efforts.

Step 5: Electrification of Equipment and Energy Efficiency

The experts agreed that transitioning to electric equipment and enhancing energy efficiency is important for sustainability. They noted that with current technology, electrification is possible for about 50-60% of their operations. However, they highlighted significant challenges related to infrastructure and costs. The overstretched power grid in the Netherlands poses a substantial obstacle, as connecting to the grid with sufficient power capacity can take several years. To mitigate this, their company is experimenting with charging power packs overnight to supplement limited grid capacity, although this approach incurs additional costs. These insights indicate that while electrification is feasible, practical limitations such as grid capacity and financial implications must be carefully considered. The expert's experience suggests that a gradual approach, as proposed in the framework, is appropriate but requires strategic planning and investment.

Step 6: Gradual Technological Integration

The framework recommends a gradual adoption of technologies like BIM and material tracking systems. The experts confirmed that their company is already integrating such technologies and does not face significant challenges in this area. They mentioned that technological implementation is ongoing and manageable for their organization. However, the experts acknowledged that smaller contractors might face financial barriers in adopting new technologies, aligning with findings from other interviews. This suggests that while technological integration is feasible for larger firms, tailored strategies may be needed to support smaller contractors.

Overall Validation and Suggested Modifications

When discussing the ease of implementing the framework's steps, the experts identified client collaboration as both the most challenging and most critical component. Despite having the necessary technology, materials, and expertise, the lack of client demand and support significantly hinders the implementation of SMM practices. The experts suggested that the framework should place greater emphasis on client engagement and the development of flexible contractual arrangements that allow for innovation. Enabling contractors to propose sustainable alternatives within their bids and have them recognized and rewarded by clients could significantly enhance the adoption of SMM practices.

5.2.3. Sub-Conclusion

The expert validation confirms that the proposed framework is largely feasible and reflects practices occurring within the industry. However, practical implementation of certain steps, particularly sustainable design optimization and stakeholder engagement, depends heavily on client willingness and regulatory environments. The main challenges are not technological but revolve around client acceptance, contractual flexibility, and infrastructural constraints.

To improve the framework's effectiveness, the following modifications are suggested:

- **Enhanced Focus on Client Engagement:** Emphasize strategies for educating and persuading clients about the long-term benefits of sustainability to align goals and objectives. This could involve developing compelling business cases that demonstrate the economic and environmental advantages of SMM practices over the project's lifecycle.
- **Advocacy for Flexible Contractual Arrangements:** Encourage the development of procurement processes that allow contractors to propose innovative, sustainable solutions without being disadvantaged in competitive bidding. This might include advocating for contract provisions that reward sustainability initiatives or allow for alternative proposals that meet or exceed performance specifications.
- **Consideration of Infrastructural Limitations:** Acknowledge external constraints such as power grid capacity in planning for electrification and energy efficiency. Exploring alternative solutions, such as on-site renewable energy generation or energy storage systems, could mitigate some of these limitations.

By addressing these areas, the framework can better guide contractors in overcoming real-world obstacles and enhancing SMM in infrastructure renovation projects. The expert's insights underscore the importance of collaboration and client engagement as important factors in successfully implementing sustainable practices.

6. Conclusion

This chapter concludes the research by revisiting the objectives and questions established at the outset and connecting them with the findings. Section 6.1 outlines the research approach and provides a summary of the answers to sub-questions one through four. Section 6.2 addresses the main research question, drawing conclusions based on the research outcomes. Section 6.3 discusses the limitations encountered during the study, highlighting areas where further investigation is needed. Section 6.4 and 6.5 illustrates the practical and theoretical implications of the research. Finally, Section 6.6 offers recommendations for the contractors, clients, and the suppliers.

6.1. Research Summary

This research aimed to explore effective strategies for enhancing SMM in Dutch infrastructure renovation projects, focusing on the role of contractors. The study was conducted in three distinct stages. First, a literature review was undertaken to establish a foundational understanding of current SMM practices and the challenges faced by contractors. The second stage involved empirical research, where insights were gathered through semi-structured interviews with industry professionals. These interviews provided a detailed perspective on the practical application of SMM strategies and the barriers encountered in real-world scenarios. The final stage synthesized findings from the literature and empirical data, forming the basis for the conclusions and recommendations presented in this thesis. Throughout these stages, four sub-questions were addressed, each contributing to answering the main research question regarding the strategies that can enable contractors to improve SMM in renovation projects in the Netherlands.

SQ 1: What are the barriers and drivers that contractors face in enhancing sustainable material management within infrastructure renovation projects?

SMM is a comprehensive approach to handling materials throughout their entire lifecycle—from sourcing to disposal. The goal is to reduce environmental impact, conserve resources, and enhance economic efficiency. In infrastructure renovation projects, contractors play a key role in putting SMM into practice. They are responsible for important decisions about material selection, optimizing resources, and managing waste, which directly affects the sustainability of a project.

There are several barriers to implementing SMM. These include price fluctuation of sustainable materials, procurement issues, and regulatory challenges. On the other hand, there are also drivers that encourage the adoption of SMM. These include government regulations, market demand for sustainability certifications, and the competitive edge gained from adopting green practices. Contractors who understand these challenges and opportunities are better prepared to navigate the complexities of sustainable practices and promote more sustainable solutions in their projects.

SQ2: What research methodology can be employed to identify challenges and best practices in SMM within infrastructure renovation projects?

The empirical methods used in this research, particularly semi-structured interviews with industry professionals, provide a rich understanding of how SMM strategies are currently applied in real-world scenarios. These interviews reveal practical insights into the experiences, challenges, and strategies of contractors, which help to bridge the gap between theory and practice. Empirical methods facilitate actionable improvements by highlighting specific areas where contractors face difficulties and where there is potential for enhancement.

SQ 3: How do contractors currently apply SMM strategies in projects, and what are their willingness and ability to enhance sustainability in this area?

Contractors are actively using a variety of strategies to manage materials sustainably, including sustainable material use, environmental assessments, waste reduction, electrification of equipment, and sustainable design practices. However, their ability to fully implement these strategies is often constrained by factors such as financial limitations, client demands, and the availability of sustainable materials.

Despite these challenges, there is a strong willingness among contractors to enhance sustainability in their projects. Many are proactively seeking ways to incorporate sustainable practices, driven by both regulatory requirements and corporate sustainability goals. The research found that there is a need for a wide collaboration among contractors, clients, and policymakers to make develop and encourage the sustainable practices.

SQ 4: What sustainable material management strategies can enhance environmental and economic sustainability in future infrastructure renovation projects?

This research identified several key strategies for SMM that can improve both environmental and economic outcomes in future projects:

- **Comprehensive Assessments and Lifecycle Calculations:** Using tools like LCAs and EPDs helps contractors choose materials and methods with lower environmental impact, leading to long-term cost savings and reduced resource use.
- **Sustainable Material Integration:** Prioritizing materials such as recycled aggregates and low-carbon options like geopolymer concrete reduces carbon emissions and resource consumption, while establishing partnerships with suppliers ensures a reliable supply of these materials, benefiting both the environment and the project's budget.
- **Sustainable Design Optimization:** Designing for disassembly, modular construction, and efficient material use reduces waste and extends material lifecycles, which lowers environmental impact and cuts material and waste disposal costs.
- **Stakeholder Engagement and Collaboration:** Involving clients, suppliers, and contractors early ensures that sustainability goals are aligned, reducing delays and costs while improving project outcomes.
- **Electrification of Equipment and Energy Efficiency:** Shifting to electric equipment and more energy-efficient production methods reduces emissions and fuel costs. Using renewable energy sources further supports both environmental and economic goals.
- **Gradual Technological Integration:** Slowly adopting technologies like BIM and material tracking systems helps improve project efficiency and resource management, reducing waste and costs over time.

These strategies provide a practical way to enhance sustainability in construction, addressing both environmental and financial challenges.

6.2. Answering the Main Research Question

RQ: How do contractors enhance sustainable material management in Dutch infrastructure renovation projects?

Contractors in Dutch infrastructure renovation projects enhance SMM by acting as key facilitators in integrating innovative practices that balance environmental, economic, and social sustainability. However, achieving this balance presents several challenges that require contractors to adopt a strategic and critical approach. To effectively enhance SMM, contractors must navigate practical constraints such as budget limitations, material availability, client expectations, and regulatory requirements, prioritizing actions that offer the most significant impact.

From an environmental perspective, contractors contribute to reducing the carbon footprint of projects by adopting materials with lower embodied energy, such as geopolymer concrete and recycled aggregates. While these materials offer substantial environmental benefits, their implementation is often hindered by higher costs and limited availability. Contractors can address these challenges by engaging in early collaboration with suppliers to secure sustainable materials and by advocating for their use with clients. By highlighting the long-term environmental advantages and potential operational savings, contractors can make a compelling case for investing in these materials. Additionally, they can prioritize the incorporation of circular economy principles by designing projects that facilitate recycling and reuse. Techniques such as design-for-disassembly and modular construction enable materials to be repurposed, extending their lifecycle and minimizing waste. To achieve this, contractors may need to invest in training and capacity building within their organizations to develop expertise in sustainable design practices.

Economically, contractors enhance SMM by aligning sustainability goals with long-term cost efficiencies. Although sustainable materials and methods may involve higher initial expenditures, contractors can conduct comprehensive life-cycle assessments and cost-benefit analyses to demonstrate potential savings over time. These analyses can reveal reductions in maintenance costs, improvements in energy efficiency, and enhancements in infrastructure durability. By presenting this data to clients, contractors can justify the adoption of sustainable practices from a financial standpoint. Furthermore, collaborating with suppliers and clients allows contractors to negotiate contracts that reflect the financial benefits of sustainability, such as sharing savings from reduced material waste or energy-efficient construction processes. Prioritizing investments in areas with the highest return on investment enables contractors to balance immediate project costs with future economic gains, ensuring the financial sustainability of infrastructure renovation projects.

The social dimension of SMM, while often overlooked, is a critical aspect of how contractors contribute to sustainability in Dutch infrastructure projects. Contractors enhance social sustainability by engaging with local communities and stakeholders early in the project lifecycle. This engagement ensures that projects reflect community needs and values, fostering social inclusion and transparency. However, meaningful community involvement requires time, resources, and a genuine commitment, which can be challenging in a competitive industry focused on efficiency. To overcome this, contractors should prioritize stakeholder engagement by integrating it into project planning and allocating dedicated personnel to manage these relationships. By creating job opportunities within the local population and supporting social equity, contractors contribute to regional economic development and build trust with the community. Additionally, by prioritizing safety and health considerations—such as minimizing emissions on-site through the electrification of equipment—they contribute to the well-being of communities surrounding the project sites. Achieving social sustainability necessitates balancing project demands with community interests, requiring contractors to embrace corporate social responsibility as a core value.

6.3. Implications and Limitations

6.3.1. Practical Implications

The findings of this study have significant practical implications for both contractors and policymakers, emphasizing the importance of flexibility, collaboration, and innovation in adopting Sustainable Material Management (SMM) strategies.

For contractors, the study highlights the need for tailored approaches that align with the unique contexts and constraints of individual projects. This includes investing in training and capacity building to enhance the adoption of advanced technologies and practices, such as Building Information Modeling (BIM) and Radio Frequency Identification (RFID). Contractors must also explore innovative strategies, such as modular construction and circular economy principles, to address challenges related to material availability, cost, and waste management.

Policymakers, on the other hand, play important role in fostering an environment conducive to the adoption of SMM practices. This involves providing financial incentives such as tax breaks or subsidies for sustainable projects, establishing clear and enforceable sustainability standards, and promoting collaboration among key stakeholders. Initiatives to raise awareness about the benefits of SMM and encourage shared accountability between contractors, clients, and suppliers are also essential. By addressing barriers such as cost pressures, resource limitations, and insufficient industry standards, policymakers can drive the systemic change required to mainstream sustainable practices in the construction industry.

6.3.2. Theoretical Implications

The findings suggest several theoretical implications for the field of sustainable construction. First, there is a need to refine existing theoretical models to better reflect the realities of practical implementation. This includes recognizing the variability in contractor's capacities and the influence of external factors such as market conditions and regulatory environments. Also, how the sustainable practices must tackle the barriers to succeed.

Additionally, the study suggests that theoretical frameworks should place greater emphasis on the role of stakeholders, particularly clients, in driving the adoption of SMM practices. The interviews revealed that client requirements and willingness to invest in sustainability significantly impact contractor's ability to implement these practices, highlighting the need for theories that account for these dynamics.

6.3.3. Limitations and Future Research

This study has several limitations that open pathways for future research. First, the research relies on a limited number of interviews with contractors, which may not fully represent the diversity of experiences and perspectives within the industry. Future studies could expand the sample to include a broader range of stakeholders, such as clients, suppliers, and regulatory bodies, to develop a more comprehensive understanding of the challenges and opportunities associated with SMM.

Second, while the research provides actionable insights into the economic and environmental dimensions of SMM, it does not delve into the social pillar. This omission highlights an opportunity for future investigations to explore the social implications of SMM, including labor practices, community engagement, and worker safety. Addressing these aspects would contribute to a more holistic understanding of sustainability in construction projects.

Finally, future research could examine the long-term impacts of SMM practices on project outcomes and sustainability performance. Longitudinal studies could provide valuable insights into the evolution of these practices over time and their effectiveness in achieving environmental, economic, and potentially social goals.

6.4. Recommendations

6.4.1. Recommendations for Contractors

Seek Early Involvement in Projects: Contractors should aim to participate as early as possible in the project planning and design phases. Early involvement enables them to influence key decisions on material selection and construction methods that prioritize sustainability.

Adopt Sustainable Material Management Practices: It's crucial for contractors to integrate sustainable material management practices into their daily operations. This involves implementing recycling programs, reducing waste through efficient material use, and optimizing resources. By employing lean construction techniques and just-in-time delivery, contractors can minimize waste, enhance material efficiency, and contribute to both environmental sustainability and cost savings.

Invest in Advanced Technology and Innovation: Contractors should invest in technologies like BIM, RFID, and LoT to enhance project planning, optimize material use, and reduce waste, positioning themselves as leaders in sustainable practices and gaining a competitive advantage.

Promote Collaboration and Communication: Contractors should maintain clear communication channels with all project stakeholders, including clients, suppliers, and regulatory bodies to ensure that sustainability goals and practices are well-understood and shared by everyone involved.

Encourage Continuous Learning and Training: Contractors should regularly update their teams on new materials, construction methods, and environmental regulations. By fostering a culture of continuous learning, contractors can ensure that their workforce is equipped with the knowledge and skills needed to implement sustainable material management effectively.

6.4.2. Recommendations for Clients

Set Clear Sustainability Goals: Clients should clearly define their sustainability objectives in project requirements, including criteria for sustainable material use, energy efficiency, waste reduction, and minimizing environmental impact.

Provide Flexibility in Contracts to Encourage Innovation: Clients should design contracts that allow for greater flexibility and freedom, enabling contractors to innovate and explore new sustainable materials and methods. By moving away from overly rigid specifications, clients can create an environment where contractors are encouraged to think creatively and develop innovative solutions that enhance project sustainability.

Provide Financial Incentives for Sustainability: To encourage contractors to prioritize sustainability, clients can offer financial incentives such as bonuses for meeting sustainability milestones, funding for sustainable material purchases, or sharing the costs of implementing green technologies.

Invest in Education and Awareness: Clients should promote awareness of the long-term benefits of sustainable construction practices. By organizing educational workshops, seminars, and training programs, clients can help their teams understand the value of sustainable material management and its positive impact on project outcomes.

6.4.3. Recommendations for Suppliers

Ensure Products Meet Sustainability Standards: Suppliers should provide materials that meet high sustainability standards, such as low embodied energy, high recyclability, and minimal environmental impact.

Enhance Transparency and Communication: Suppliers should offer detailed information on the sustainability attributes of their products, including lifecycle assessments, environmental certifications, and sourcing practices. Transparent communication helps clients and contractors make informed decisions about material choices and fosters trust and collaboration throughout the supply chain.

Innovate and Develop Sustainable Materials: Continuous innovation in creating more sustainable materials is vital. Suppliers should collaborate with contractors, clients, and research institutions to develop and test new materials that meet the evolving needs of the construction industry.

Optimize Sustainable Logistics and Distribution: Suppliers should focus on enhancing the sustainability of their logistics and distribution processes. This includes using energy-efficient transportation, reducing packaging waste, and optimizing delivery routes to minimize carbon footprints.

Reflection

As I reach the end of this research, I find it important to reflect on the process and the experiences that have shaped this thesis. My interest in sustainability and its application in the construction industry has been a guiding force throughout this project. This research enabled me to explore these areas in greater depth, enhancing my understanding and commitment to promoting sustainable practices in infrastructure renovation.

At the beginning of my thesis work, I faced the significant challenge of securing an internship within a company to conduct my research. This search was a source of considerable stress, as I was eager to gain practical experience and insights from within the industry. However, when this opportunity did not materialize, I was fortunate to find an alternative path through the university. Conducting my research within the academic setting provided me with a different perspective, and I am grateful for the support from my university, which allowed me to pursue this project under their guidance.

Connecting with professionals for interviews was another hurdle I encountered. Initially, I struggled to find the right contacts and secure the interviews needed to gather valuable insights. Thanks to the support of my committee and several university professors, I was able to connect with experts in the field who were willing to share their knowledge. Their willingness to help was important in overcoming this challenge and significantly enriched the quality of my research.

Throughout this process, I also worked on improving my writing skills, which was another area of growth for me. I utilized paraphrasing tools to enhance my grammar and writing style, which helped me convey my ideas more clearly and professionally. This experience taught me the importance of continually developing my skills and being open to using various resources to improve.

Conducting the interviews presented its own set of challenges. I found it difficult at times to control the duration of the interviews and steer the conversation toward the specific topics I needed to cover. However, these experiences taught me valuable lessons in communication and time management. I learned how to better direct discussions and ensure that the necessary points were addressed, which has strengthened my ability to conduct effective research.

Working on this thesis has been a lesson in balancing ambition with practicality. My deep engagement with the topic often made me want to explore more than the scope and timeframe would allow. Nonetheless, I am proud of the research I have conducted and the findings I have presented. I believe that this work can contribute positively to reducing the environmental impact of the construction industry and promoting more sustainable practices.

I also learned the importance of connecting theoretical knowledge with practical application. Bridging the gap between academia and industry is crucial for driving meaningful change. By focusing on strategies that contractors, clients, and suppliers can implement, I aimed to create a practical guide that aligns with real-world needs while being grounded in solid theoretical understanding. My personal interest in sustainability undoubtedly added depth to my research, motivating me to explore the topic thoroughly and produce comprehensive findings.

This research has taught me several valuable lessons:

1. **Balancing Personal Beliefs with Feedback:** Initially, I struggled to balance my own ideas with the feedback from others. Over time, I learned the importance of considering different perspectives while still trusting my judgment. This balance has been important in refining my research and ensuring it remains both innovative and grounded.

2. **Problem-Solving through Reflection:** Throughout the research, I encountered various challenges. I learned that every problem can be addressed by understanding its root cause and breaking it down into manageable tasks. This approach not only helped me overcome obstacles but also enhanced my problem-solving skills in both professional and personal contexts.
3. **Effective Communication and Management:** Coordinating with my committee, each with different levels of involvement, taught me the importance of clear communication and managing expectations. I have grown in my ability to align everyone's expectations and ensure a smooth research process.

Finally, I hope that sustainability becomes an integral part of all processes in the future. It should be a standard practice, not a choice, and I am optimistic that continued research and practical application can lead us in that direction. I am grateful for the opportunity to contribute to this important field and look forward to seeing how these insights can help shape a more sustainable future.

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Appendix 1

Opening Statement (Interview)

You are being invited to participate in a Master research study titled "Managing Material Resources in Renovation Projects: Strategies for Sustainable and Efficient Management". This study is being done by Mohamad Taha from the TU Delft. The purpose of this research study is to identify and evaluate sustainable material management practices in Dutch infrastructure renovation projects, aiming to enhance contractors' approaches towards environmental sustainability and cost efficiency, and will take you approximately *45* minutes to complete. The data will be used for supporting the literature review in the master thesis. We will be asking you open question about the current situation of the sustainable material practices within the industry. Your participation in this study is entirely voluntary and you can withdraw at any time. You are free to omit any questions.

Below you can find the informed consent form of the research. Please tick the boxes to indicate your consent.

Corresponding Researcher: Mohamad Taha

Responsible Researcher: Dr. Yirang Lim

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICPANT TASKS AND VOLUNTARY PARTICIPATION		
1. I have read and understood the study information above or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
3. I understand that taking part in the study involves: • **The interview will be semi-structured with open-ended questions related to the sustainable material management within dutch renovation infrastructure projects.** • **A recorded interview that will be conducted via Microsoft Teams or Face-to-Face.** • **If via Microsoft Teams, the recording will be transcribed as a text directly from MicrosoftTeams and the researcher will edit the text by listening to the interview recording and adjusting the written transcription to the original spoken text.** • **The interview recording will be stored on the personal storage of Mohamad Taha on the TU Delft OneDrive and will be destroyed the maximum of two years after the study has been completed.**	☐	☐
4. I understand that the study will end September 2024		
B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)		
5. I understand that taking part in the study involves the following risks n • The risk of leaked business/organisation strategies. • The risk of leaked information. • The risk of reputation damage from leaked information. I understand that these risks will be mitigated by storing the important data, such as personal information and original interviews securely, will not be made available publicly and only available to the thesis supervisors, and will be removed after the research is finished. The interview results that will be published on the thesis only in the form of aggregated data (e.g., coded interviews, codebook, and combination of analysis of all the interviews). Furthermore, I can choose how to respond to each question that may be detrimental to me or my organisation. I may choose not to respond to any of them and I have an option to end the interview at any time.	☐	☐
6. I understand that taking part in the study also involves collecting specific personally identifiable information (PII) (name, occupation, contact information) and associated personally identifiable research data (PIRD), with the potential risk of my identity being revealed, the risk of reidentification and the subsequent risk of affecting my public or professional reputation.	☐	☐
7. I understand that some of this PIRD is considered as sensitive data within GDPR legislation, specifically job position and political, economic, social, technological, or environmental view	☐	☐
8. I understand that the following steps will be taken to minimise the threat of a data breach, and protect my identity in the event of such a breach. The interview will be conducted anonymously.	☐	☐

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
Personal information of the interviewees will not be published to anyone who is not involved in the research. After the research is completed, the personal data will be deleted		
9. I understand that personal information collected about me that can identify me, such as my name and contact information, will not be shared beyond the study team.	☐	☐
10. I understand that the (identifiable) personal data I provide will be destroyed after the research has ended, which will be conducted the maximum of two years after the graduation of the researcher.	☐	☐
C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION		
11. I understand that after the research study the de-identified information I provide will be used for the following purposes. The anonymise interview results will be published along with the master thesis on the TU Delft Repository, including the anonymised coding of the interviews.	☐	☐
12. I agree that my responses, views or other input can be quoted anonymously in research outputs.	☐	☐
D: (LONGTERM) DATA STORAGE, ACCESS AND REUSE		
13. I give permission for the de-identified interview results that I provide to be archived in the TU Delft repository (https://repository.tudelft.nl/) in the form of anonymous coded interviews so it can be used for future research and learning. The original transcribed interviews will not be made available to the public or be stored on the TU Delft repository	☐	☐
14. I understand that access to the repository where the master thesis is stored is openly available on the internet.	☐	☐
15. I understand that the collected data may be reused for future scientific publication and educational activities on the topic of Sustainable Material Management.	☐	☐

Signatures

__________________________ _________________________ ________

Name of participant [printed] Signature Date

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

Mohamad Taha

Researcher name [printed] Signature Date

Study contact details for further information:

Mohamad Taha

Appendix 2

Interview Guide for Exploring SMM in Renovation Projects

Introduction:

- **Greeting**: a friendly greeting and introduce myself and my role.

- Purpose of the Interview: gather insights on the practical aspects of implementing sustainable material management in construction projects.

- Consent: Confirm that the interviewee has received the consent form, understands it, and agrees to proceed. Reiterate that the interview will be recorded for accuracy but will remain confidential.

Warm-up Questions:

1. **Can you describe your role and experience in the construction industry?**
2. **Do you have experience with construction projects that emphasize sustainability? If yes, for how long have you been involved in such projects?**

Main Questions:

1. How do you describe sustainable Material Management (SMM), and how do you differentiate it from traditional material management practices in construction?

2. What are the key sustainable material management practices implemented in your projects?

3.In which phase do you see the major role of contractors in SMM? (Planning, procurement, construction, demolition)

4. What challenges have you encountered while implementing SMM practices in your projects?

5. How do you address these challenges , and what additional solutions do you suggest could be effective?

6. What role can contractors play for SMM? (contributing/hampering)

7. What can you do as a contractor to lead this shift in material management from EMM to SMM? (can/cannot)

Deep Dive Questions:

1. Can you provide an example where SMM was applied in project? How did the project outcome turn out? Do you see the causality between SMM and the result?

2. How do you see the future of SMM in the construction industry evolving?

Wrap-up Questions:

1. **What do you think is essential for contractors to successfully transition to and enhance SMM practices in their construction projects?**

2. **Is there anything else you think is important to mention about SMM that we haven't covered?**

Closing:

- **Thank You:** Express gratitude for the participant's time and insights.

- **Open the Floor:** if they have any questions for me or additional comments they would like to add.