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Development of a Decision Support Tool that Improves the Integration of Sustainable Waste Management Practices Using Construction Consolidation Centres (CCCs) in Inner-city Construction Projects

by

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Colophon

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Development of a Decision Support Tool that Improves the Integration of Sustainable Waste Management Practices Using Construction Consolidation Centres (CCCs) in Inner-city Construction Projects

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Ai statement

As the impact of Artificial Intelligence (AI) is currently exponentially growing it is important to state that AI is used in this thesis and explain how it is used. In this thesis AI has always been used critically. This means that the responses were always checked using reliable sources. In this thesis AI has been used to brainstorm ideas, provide chapter frameworks and to refine using language assistance. All the data input and conclusions made in this thesis are the work of the author. As AI has only been used as a tool that aids the author, and all decisions and conclusions have been made by the author himself. The author claims full responsibility and ownership of every part of this thesis.

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Preface

This master thesis marks the end of my double degree in Architecture Building & Planning and Construction Management & Engineering at the Eindhoven University of Technology. Before the start of this thesis my goal was to contribute to a circular construction economy by making both theoretical and more practical contributions. As ensuring the circular economy can be seen as an important step in reducing the impact of the AECO on the climate.

This research was performed in collaboration with VolkerWessels Materieel & Logistiek (VWML). I want to extend a special thanks to Ivo Agricola and all my colleagues at VWML for their insights, support, and willingness to share their extensive practical expertise. Through this collaboration the gap between the theoretical best practices and the current situation became apparent. A primary goal of this research became to aid in closing this gap. The partnership was critical in ensuring that the theoretical models developed in this thesis could be applied and tested on real-world challenges.

The completion of this extensive research project would not have been possible without the invaluable guidance and support of my academic supervisors. I wish to express my sincere gratitude to Dr. Dujuan Yang and Dr. Qi Han from the CME department, and to Dr. Melvin Wong and Prof. dr. Soora Rasouli from the USRE department. Thank you for your time, feedback and insightful discussions throughout this entire process.

Additionally, I want to thank my family and friends who not only helped me through this thesis but also supported me through the entire six-year journey. I can wholeheartedly say that my achievements would not have been possible without them.

T.H.P. (Thijs) Nooijen

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Summary

Traditionally, the construction industry operates using a linear take-make-waste economic model. This model is responsible for the construction sector being a major consumer of raw materials and generating a significant amount of waste. However, the sector is making a shift towards the more sustainable circular economy. The circular economy model aims to keep materials in high-value use for as long as possible, which is critical for reducing the sector's environmental footprint. An important part of ensuring this is ensuring on-site waste separation. However, in inner-city construction projects this is often not feasible due to severe spatial constraints. Resulting in the heterogeneous and highly recyclable waste from the project's finishing stage frequently being combined in a single container. Lacking proper knowledge and tools project managers often use a suboptimal approach. This thesis addresses this problem by developing, designing and validating a Decision Support Tool (DST) to facilitate informed decision making for construction waste in inner-city construction projects.

To achieve this the methodology uses three distinct phases: the establishment of evaluation criteria, the comparative simulation of management scenarios, and the development of a Decision Support Tool (DST). The initial phase is the development of a Key Performance Indicator (KPI) framework. This is used to evaluate both construction waste management scenarios across economic, environmental and social criteria. Following this, two scenarios were simulated for comparison; a baseline case reflecting the current practice of using a single mixed-waste container, and an 'integrated' case that uses coordinated logistics to enable effective on-site waste separation. Finally, these components were synthesized into a Decision Support Tool (DST). By entering basic project data, stakeholders can use the tool to compare the two scenarios based on their KPI scores, facilitating a more informed planning process.

The DST was applied to three real world case studies to evaluate the performance. Economically, the integrated strategy resulted in cost savings of 20% to 37% compared to the baseline. Environmentally, it achieved a CO_2 emission reduction of 85% to 94% compared to the baseline. These benefits are primarily driven by eliminating the expensive and energy-intensive process of sorting mixed waste at a recycling facility. The main trade-off was a minor increase in noise pollution, traffic congestion and a decrease in traffic safety, resulting from an increase in the number of vehicle trips required from 8.45% to 14.63%, compared to the baseline.

This research successfully developed a tool to quantify and compare the economic, environmental, and social impacts of C&DW management strategies. The results demonstrate that coordinating material deliveries with waste removal is a financially and environmentally superior approach. By providing clear, data-driven insights into these trade-offs, the DST empowers project stakeholders to adopt more sustainable and market-driven practices.

Samenvatting

Traditioneel opereert de bouwsector volgens een lineair 'take-make-waste' economisch model. De bouwsector is een grootverbruiker van grondstoffen en is verantwoordelijk voor een aanzienlijke hoeveelheid afval. De sector maakt echter een verschuiving door naar een duurzamere circulaire economie. Het circulaire economiemodel is erop gericht materialen zo lang mogelijk in hoogwaardig gebruik te houden, wat cruciaal is voor het verminderen van de ecologische voetafdruk van de sector. Een belangrijk onderdeel hiervan is bronscheiding van afval op de bouwplaats. Bij binnenstedelijke bouwprojecten is dit echter vaak onhaalbaar door een ernstig gebrek aan ruimte. Het gevolg is dat het heterogene en goed recyclebare afval uit de afbouwfase van een project vaak in één container wordt verzameld. Door een gebrek aan de juiste kennis en hulpmiddelen hanteren projectmanagers vaak een suboptimale aanpak. Dit proefschrift pakt dit probleem aan door een Beslissingsondersteunend Systeem (BOS) te ontwikkelen, ontwerpen en valideren om een weloverwogen besluitvorming voor bouwafval bij binnenstedelijke bouwprojecten te faciliteren.

Om dit te bereiken, hanteert de methodologie drie verschillende fasen: het opstellen van evaluatiecriteria, de vergelijkende simulatie van afvalbeheer scenario’s en de ontwikkeling van een Beslissingsondersteunend Systeem (BOS). De eerste fase is de ontwikkeling van een kader van Key Performance Indicators (KPI's). Dit wordt gebruikt om de scenario's voor bouwafvalbeheer te evalueren op economische, ecologische en sociale criteria. Vervolgens werden de twee scenario's gesimuleerd voor vergelijking: een 'basisscenario' dat de huidige praktijk van het gebruik van één gemengde afvalcontainer weerspiegelt, en een 'geïntegreerd scenario' dat gecoördineerde logistiek gebruikt om effectieve bronscheiding mogelijk te maken. Ten slotte werden deze componenten samengebracht in het BOS. Door basisprojectgegevens in te voeren, kunnen belanghebbenden de tool gebruiken om de twee scenario's te vergelijken op basis van hun KPI-scores, wat een beter onderbouwd planningsproces mogelijk maakt.

Het BOS werd toegepast op drie praktijkcasussen om de prestaties te evalueren. Financieel resulteerde de geïntegreerde strategie in kostenbesparingen van 20% tot 37% ten opzichte van het basisscenario. Op milieugebied behaalde het een CO_2-reductie van 85% tot 94% ten opzichte van het basisscenario. Deze voordelen zijn voornamelijk het gevolg van het elimineren van het dure en energie-intensieve proces van het sorteren van gemengd afval in een recyclinginstallatie. De belangrijkste afweging was een lichte toename in geluidsoverlast, verkeersdrukte en verkeersveiligheid als gevolg van een stijging van het aantal voertuigritten, variërend van 8,45% tot 14,63%, vergeleken met het basisscenario.

Dit onderzoek heeft met succes een instrument ontwikkeld om de economische, ecologische en sociale effecten van strategieën voor bouw- en sloopafvalbeheer te kwantificeren en te vergelijken. De resultaten tonen aan dat het coördineren van materiaalleveringen met afvalinzameling een financieel en ecologisch superieure aanpak is. Door duidelijke, dat gestuurde inzichten in deze afwegingen te bieden, stelt het BOS, projectbelanghebbenden in staat om duurzamere en markt gedreven praktijken te hanteren.

Abstract

The construction industry's linear economic model is a primary consumer of raw materials and contributor of waste generation. In inner-city construction projects, spatial constraints during the critical finishing stage often prevent on-site waste separation. Resulting in the use of a single mixed-waste container which results in materials not being high-quality recycled. This practice stems from a lack of an integrated tool that can be used to holistically evaluate alternative Construction and Demolition Waste Management (C&DWM) strategies, leading to decisions that prioritize initial costs over long-term sustainability. This thesis addresses this gap by developing and validating a Decision Support Tool (DST) that quantifies and compares the economic, environmental, and social impacts of two different C&DW strategies. The methodology simulates two scenarios: a baseline scenario representing current industry practice and an integrated scenario that uses a Construction Consolidation Centre (CCC) to coordinate reverse logistics and enable on-site source separation. Each scenario is assessed using Key Performance Indicators (KPIs) derived from Life Cycle Costing (LCC), Life Cycle Assessment (LCA), and Social Impact Assessment (SIA). Application of the DST to three case studies demonstrates that the integrated scenario yields substantial economic cost savings of 20-37% and reduces CO_2 emissions by 85-94% compared to the baseline. These improvements are mainly driven by eliminating expensive and energy-intensive mechanical sorting of mixed waste. The downside is an 8-15% increase in vehicle trips for the integrated model, which results in increased traffic and noise pollution. In conclusion, this research delivers a validated decision support framework that quantifies the trade-offs between competing C&DW strategies. The tool provides stakeholders with a data-driven methodology to make informed, sustainability-oriented decisions.

Keywords: Construction and Demolition Waste Management, Circular Economy, Decision Support Tool, Construction Consolidation Centre, Inner-city Construction.

List of Abbreviations

Abbreviations	Meaning
AECO	Architecture, Engineering, Construction and Operation
AI	Artificial Intelligence
APB	Architecture, Building and Planning
API	Application Programming Interface
BIM	Building Information Modelling
BREEAM	Building Research Establishment Environmental Assessment Method
CCC	Construction Consolidation Centre
CE	Circular Economy
C&DW	Construction and Demolition Waste
C&DWM	Construction and Demolition Waste Management
CLA	Collective Labour Agreement
CME	Construction Management Engineering
CP	Carbon Price
DfD	Designing for Disassembly
DST	Decision Support Tool
EC	Economic Costs
ELCC	Environment Life Cycle Costing
EU	European Union
GVW	Gross Vehicle Weight
HDV	Heavy Duty Vehicle
HTTP	HyperText Transfer Protocol
LCA	Life Cycle Analysis
LCC	Life Cycle Cost
LP	Linear Programming
PESTLE	Political, Economic, Social, Technological, Legal and Environmental
RE	Recycling Emissions
REC	Rental Costs
RC	Recycling Costs
SIA	Social Impact Assessment
SC	Sorting Costs
SUS	System Usability Scale
TC	Total Costs
TE	Transportation Emissions
TRC	Transportation Costs
USRE	Urban System and Real Estate

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1. Introduction

The construction industry is one of the largest consumers of energy and raw materials globally. Within the EU, it contributes to nearly 40% of emissions and accounts for almost a third of all waste generated (European commission, 2024). Therefore, it is more crucial than ever for the industry to adopt sustainable practices and minimize its environmental impact. Reducing pollution to the lowest possible levels should be the goal for the industry. In addition to this, The Netherlands has proposed an agenda that states that all materials should be 100% reusable, and no fossil energy should be used in construction in 2050. Furthermore, 50% of this goal should already be reached in 2030 (Nelissen et al, 2018). The Netherlands is one of the frontrunners regarding recycling in the construction industry. Due to a landfill ban, a recycling rate of 88% has been reached. When taken at face value, this recycling rate of 88% is quite high. However, it is important to note that 85% of the total C&DW that is recycled, is downcycled into road foundations and site elevations for roads (Heijnen et al., 2022) (figure 1). This downcycling does classify as recycling but is a practice needs to become more sustainable.

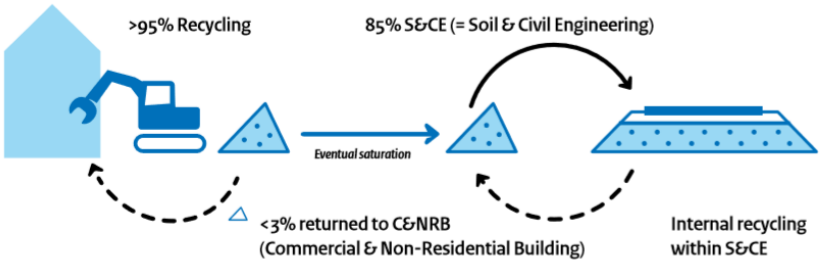


Figure 1 Recycled materials used in construction, (Heijnen et al, 2022)

To decrease the significant emissions and raw material usage of the construction sector a shift with regards to using materials is underway, moving from the traditional linear take-make-dispose model towards a more sustainable circular economy (Hossain & Ng 2018). To achieve higher quality recycling and reduce the number of materials that get downcycled, closed loop material flows should be enforced. Closed loop material flows describe the concept of recycling everything that is used. The goal is to transform waste streams into resource streams through systematic reuse, recycling, and recovery, thereby closing material loops and reducing the reliance on virgin resources (Gálvez-Martos et al., 2018).

Figure 2 Linear- and circular economy. (Foster, 2023)

Despite this goal, there is still a significant number of construction projects that do not adhere to this new shift, particularly in inner-city construction projects. While frameworks like BREEAM advocate for separating waste into multiple streams, projects in inner-city locations often do not have sufficient

space for the seven different large containers that facilitate waste separation. In these projects, the common practice is to only use one large container for all mixed waste, which results in waste being sent in an unseparated state to the recycling centre where high-value materials are often downcycled (Wang et al., 2010).

This issue is particularly pronounced during the construction finishing stage. While the total volume of waste often declines near the end of a project, the complexity of the waste streams increases significantly. Unlike the structural phase, which produces large volumes of relatively homogenous waste like concrete, the finishing stage is characterized by a highly diverse mix of materials, including wood off-cuts, drywall, insulation, plastics, packaging, and various metals. This heterogeneity complicates waste management, as separating a multitude of smaller, mixed waste streams is inherently more difficult than handling a few large, uniform ones (Villoria Sáez et al., 2012). The complexity of this stage, combined with the spatial constraints of inner-city projects, transforms waste management into a difficult logistical puzzle.

The logistical complexities of inner-city projects extend beyond waste management to include site constraints such as limited storage space, restricted accessibility hours, and vehicle size limitations. These challenges are particularly acute in the finishing stage, where a high number of subcontractors require frequent and varied material deliveries. In these cases, Construction Consolidation Centres (CCCs) have been found to be an effective solution. A CCC is a shared distribution facility, typically located on the outskirts of an urban area near major transport networks, that channels material deliveries for one or multiple construction projects. Instead of multiple suppliers making individual, often inefficient, deliveries directly to a congested inner-city construction site, materials are sent to the CCC. There, they can be sorted, bundled into work-packages (kitting), and loaded onto a single, fully utilized vehicle for a coordinated delivery at a specific time (Guerlain et al., 2021).

While the effectiveness of CCCs has been proven for inbound material logistics, their potential to integrate reverse logistics has yet been researched. By using the same coordinated trips to backhaul waste, a CCC can provide the mechanism needed to make on-site separation possible in inner-city construction projects. This creates a theoretical solution for improving circularity. However, the adoption of this promising circular strategy is difficult as C&DW management strategies are frequently selected based on fragmented and limited information, which results in the objective of minimizing the initial direct costs. (Yuan, 2012). This narrow economic focus systematically ignores the significant external costs imposed on society and the environment. These externalities include the long-term environmental damage from greenhouse gas emissions and resource depletion, as well as the immediate social costs associated with construction logistics, such as increased traffic congestion, noise pollution, public health issues, and compromised traffic safety (Yuan, 2012; Brusselaers et al., 2022). It often concerns projects that have additional complexities in which the goal of circular practices falls out of scope. Inner-city construction projects often do not have the space for traditional on-site recycling centres. Resulting in, no on-site waste separation and lower recycling potential for materials. In many cases, project managers are forced to plan future scenarios based on economic grounds due to the absence of a structured and holistic assessment framework (Tafesse et al., 2022).

This shows a gap between the ambition of implementing circular economy principles and the practical tools available to decision-makers. The literature shows that while individual assessment tools like life cycle assessment (LCA) and life cycle costing (LCC) are well-established, there is a lack of studies that have defined methodological tools for the integration of circular practices in the C&DW context (Yazdani et al., 2021). Previous studies have mostly looked at the economic viability or the environmental impact in isolation. In addition, the social dimension is often being overlooked due to difficulties in quantification. (Yuan, 2012; Sobotka & Sagan, 2021).

Therefore, the primary objective of this thesis is to develop and validate a quantitative decision support tool that holistically evaluates and compares C&DW management strategies by integrating economic,

environmental, and social performance indicators into a unified, actionable framework. This research aims to provide a robust and adaptable methodology that empowers stakeholders to make informed decisions that align with the principles of sustainability.

To address the problem defined above, this research uses a primary research question in combination with a set of sub questions. These questions are designed to deconstruct the problems and guide the development of the proposed decision support framework.

RQ: "*How can the economic, environmental and social impacts of different C&DW management strategies in urban construction projects in the finishing stage be quantified and integrated in a decision-making framework that is used to support the selection of the preferred option?"*

SQ1: What are the most critical key performance indicators (KPIs) required for a comprehensive assessment of economic, environmental and social C&DW management?

SQ2: How can a simulation be structured to quantify the specific waste streams produced during the construction finishing stage, utilizing project-specific data?

SQ3: How can a decision support tool be structured to help stakeholders navigate the performance trade-offs between economic cost, environmental impact, and social impacts when selecting a C&DW management strategy?

To address these questions, this research will follow a quantitative methodology to construct and test a decision support tool (DST). The DST will be built on an assessment framework that uses principles from life cycle costing (LCC), life cycle assessment (LCA) and social impact assessment (SIA) (Yazdani et al., 2021). In this tool the environmental impact will be transformed into a monetary unit using carbon pricing principles. This thesis provides multiple contributions to the field of C&DW management practices. First it provides the theoretical framework that demonstrates how to assess economic and environmental impact using the same unit. This is achieved by applying the carbon pricing concept within a project-level tool. In the practical sense, this thesis delivers a DST that can be used by stakeholders to make evidence-based decisions that are backed by data evaluating the economic, environmental and social impact.

To present the research in a clear manner, the following chapters will be used:

Chapter 1: Introduction. This chapter has established the research problem, highlighting the environmental, economic, and social burdens of C&DW and identifying the critical gap in integrated decision-making tools for stakeholders. It concludes by presenting the guiding research questions and the overall approach of this study.

Chapter 2: Literature Review: This chapter provides an overview of the literature regarding current C&DW developments. It examines the current landscape while focussing on the challenges of inner-city construction and the role of construction consolidation centres (CCCs). It then covers explaining LCC, LCA and SIA while mentioning how they can be integrated.

Chapter 3: Methodology. This chapter details the construction of the Decision Support Tool. It will meticulously define the two comparative models (baseline and integrated), outline the quantification of the selected economic, environmental, and social Key Performance Indicators (KPIs), and explain the data collection and analysis procedures. The scope and limitations of the research will also be clearly defined.

Chapter 4: Case Studies. This chapter will provide the case studies that will be used to test the DST. It will explain the project data and notable observations

Chapter 5: Results. This chapter presents the findings from the application of the DST. It will provide a detailed, data-driven comparison of the baseline and integrated scenarios across all performance

indicators, highlighting the trade-offs between the different strategies. In addition, it will provide a sensitivity analysis that tests the model's robustness against key variables.

Chapter 6: Validation. This chapter will validate the tool itself. It will do this by interviewing potential users. In addition, this section shows a storybook of the tool itself

Chapter 7: Conclusion & Discussion. The final chapter will summarize the key findings of the research, explicitly answer the research question and offer recommendations for both stakeholders in the context of C&DW management and future academic research in this domain.

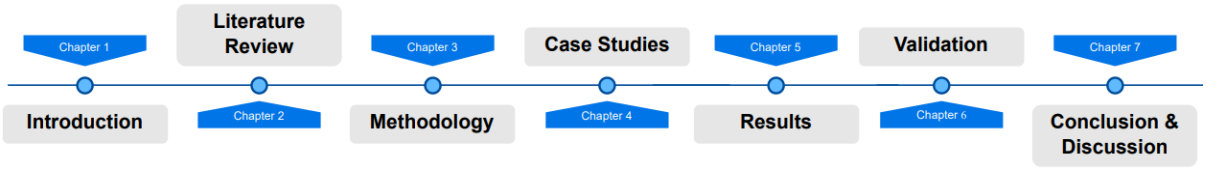


Figure 3 Chapter overview

2. Literature Review

This chapter provides a comprehensive review of the current literature on Construction and Demolition Waste Management, while focussing on the challenges and opportunities of inner-city construction projects. The review begins by examining the global shift from a linear to a circular economy, establishing the context and impact of sustainable construction waste management practices. The chapter details the specific complexities of C&DWM, analysing the barriers to effective recycling in the construction finishing stage. The review then provides insight into Construction Consolidation Centres and how they can be used for C&DWM. Finally, the chapter examines the components of an integrated decision framework, reviewing the principles of Life Cycle Assessment, Life Cycle Costing, and Social Impact Assessment as essential tools for holistically evaluating C&DW management strategies.

2.1 Global Framework

2.1.1 Linear Economy

The housing crisis that has been prevalent in the Netherlands over the last few years will result in an increase of new construction projects. However, this increase in the housing stock will come at a significant environmental cost. The sector is one of the largest consumers of energy and virgin materials on the planet (Haradhan Kumar Mohajan, 2025). The result of this increase in new construction projects will be the generation of large quantities of construction and demolition waste (C&DW). The impact of the C&DW problem is more than significant. Within the European Union, C&DW is the largest single waste stream, accounting for more than a third of all waste generated (European commission, 2024). In addition, C&DW is a highly heterogeneous mix of materials, it includes inert substances: concrete, bricks and masonry, as well as non-inert materials: wood, plastic, insulation, gypsum and glass (European commission, 2024). This heterogeneous mix makes it difficult to manage as different waste streams require different handling, sorting and processing techniques (CMiC, 2024).

The reason that the construction industry has such a large impact on the environment is partly due to the linear “take, make waste” model (Hossain & Ng, 2018). This model makes the flawed assumption that materials are infinitely available and have no value after being used in construction. The process begins with the energy-intensive extraction of raw materials; this is then followed by the energy-intensive manufacturing of building components and transportation to sites. At the end-of-life stage of these buildings these components are treated as valueless and downcycled into road fill. This linear model does not only have a negative impact on the environment it is also a fragile and inefficient economic model. It creates long supply chains by being dependent on finite and increasingly scarce resources (Reconomy, 2025). Furthermore, the practice of landfilling construction and demolition waste represents a significant loss of value as recoverable materials are sent to waste disposals.

2.1.2 Circular Economy

In response to the unsustainable current practices of the linear economic model, the circular economy has emerged. According to Ghisellini et al. (2015) “circular economy implies the adoption of cleaner production patterns at company level, an increase of producers and consumers responsibility and awareness, the use of renewable technologies and materials (wherever possible) as well as the adoption of suitable, clear and stable policies and tools”. It tries to achieve this by eliminating the “end-of-life” concept from the traditional “take-make-dispose” model. Instead, it replaces this with a closed-loop system where materials are used in a high level/value for as long as possible. Ensuring that materials can be reused after they are extracted from a building can minimize waste, optimize resource utility, and discourage the mining of new virgin materials.

To lower the waste generation and resource consumption the European Union is making efforts to move from the traditional linear model to the circular model. Based on the circular economy, it created a new

paradigm called waste hierarchy into the EU Waste Framework Directive (Zhang et al., 2021). This hierarchy establishes a clear order of preference for waste management strategies prioritizing actions with the greatest environmental benefits. This is as followed, starting with the most preferred option:

1. Prevention: focusses on measures that avoid the generation of waste in the first place. Prevention occurs during different phases of the building's life cycle. (1) During the design phase, design principles can be used to limit the environmental impact of the building. Such principles are modular construction and an emphasis on adaptability; these strategies make it easier to disassemble reassemble and reuse building components. (2) In the use phase, enhancing the durability of buildings, components, and materials is a universally acceptable way of minimizing waste generation. Extending the life span means that it will take a longer time to replace them with newer ones and thus less waste is produced (Zhang et al., 2021). (3) After the end-of-life phase of the building the prevention method can still be applied. Choosing smart dismantling and selective demolition over demolition can reduce the number of materials that end up as waste.

2. Reuse: focusses on reusing materials from other projects over the use of virgin materials. This mainly consists of two components, the first one is choosing to use these reused materials over virgin materials, and the second components is preparing this material for reuse by checking, cleaning or repairing.

3. Recycling: recycling ensures that waste will be turned into a new product. The focus in this component is to turn it into the material with the highest value. To ensure a high level of recycling this starts by providing the separate waste streams to the recycling plant, this allows for a higher level of recycling and will be explained in more detail later.

4. Recovery: this considers a lower level of recycling that is often present when waste is delivered not separated. As landfilling is illegal in the Netherlands the common practices is downcycling or incineration for energy recovery. Downcycling is turning waste into a material of a lower quality. With the bulk of the construction waste this occurs as backfilling concrete waste to be used as foundations for new roads.

5. Disposal: this considers the landfilling or incineration without energy recovery (European commission, 2024).

While this hierarchy has been used as a guiding principle, the practical application of CE has expanded into the more sophisticated 10R framework, as shows in table 1. This offers a more nuanced ladder of circularity as it adds more in-between steps (Kirchherr et al., 2017). The ladder is again order from most desirable at the top and least desirable at the bottom.

Table 1 The 10 Rs of the circular economy (Kirchherr et al., 2017)

R1 - Refuse	Making products redundant by abandoning their function
R2 - Rethink	Making products use more intensive
R3 – Reduce	Increase efficiency in products by using fewer virgin materials
R4 – Reuse	Reuse another material
R5 – Repair	Repair and maintain so it can fulfill its original function
R6 – Refurbish	Restore an old product and bring it up to date
R7 – Remanufacture	Use parts of a discarded product in a new product with the same function
R8 – Repurpose	Use parts of a discarded product in a new product with a different function
R9 – Recycle	Process materials to obtain the same or lower grade quality
R10 - Recover	Incineration with energy recovery

This expanded framework is critical for assessing the true circularity of a C&DW management strategy, as it distinguishes between high-value actions like reuse and lower-value actions like material recycling or energy recovery. This framework is of high importance when examining the current state of C&DW

management. Many countries, including the Netherlands, report impressively high C&DW recovery rates. Driven by a landfill ban the Netherlands has reported the high-recycling rate of 90%. However, in Dutch construction projects, secondary materials only make up around 8% of the total. This shows that the Dutch construction sector is focussing on downcycling instead of better CE strategies (Circle Economy, 2022). It is estimated that 85% of the total recycled C&DW is downcycled into road foundations and site elevations. Similarly, across the EU, recovery is largely based on backfilling operations and the use of mixed aggregates in low value applications like road sub bases (European Environment Agency, 2020).

This shows that current practices are completely different to the core principles of the CE. Downcycling results in lower value, quality and functionality which prevents them from being used in high-grade applications and failing in closing the material loop. Concrete crushed into aggregate for road fill cannot be used to create new structural concrete beams; high-quality timber mixed with other debris becomes low-grade biomass fuel rather than being remanufactured into new building components. This gap between the reported success of high "recycling" rates and the reality of low value downcycling represents a fundamental failure to achieve the qualitative goals of the Circular Economy.

2.2 Construction and Demolition Waste Management

Construction and demolition waste represents the substantial and heterogeneous materials stream generated from the construction, renovation, and demolition of buildings and infrastructure (Mercader-Moyano et al., 2021). This stream is complex as its composition varies significantly based on the activity from which it originates. Demolition activities typically yield a high proportion of inert mineral materials, such as concrete, bricks, tiles, and ceramics, which can constitute over 80% of the total mass (Kabirifar et al., 2020). In contrast, waste from new construction and renovation projects often contains a higher percentage of non-mineral materials, including wood, plastics, metals, insulation, and gypsum-based products, as well as significant amounts of packaging waste (Iqbal et al., 2023). This inherent heterogeneity presents a major challenge for effective waste management and material recovery.

The built environment is a principal contributor to global resource consumption and waste generation. Within the European Union alone, C&DW accounts for over 850 million tonnes annually, representing more than a third of the total waste generated (Eurostat, 2024). While many developed nations report high recycling rates for this stream, these figures often obscure the true nature of the material recovery. In many European contexts, a substantial portion of mineral-based C&DW is downcycled into lower-grade applications.

This practice of downcycling, where materials are reprocessed into products of lower quality and reduced functionality represents the least desirable form of recycling within a circular framework (Ginga et al., 2020). An example of downcycling is crushing C&DW and turning it into secondary aggregates (Zhang et al., 2020). Although this method can be seen as recycling by diverting waste from landfills, it results in the degradation of material properties and the permanent loss of the embodied energy and economic value inherent in the original building components. This highlights a critical inefficiency in current waste management systems: a vast stock of potentially valuable materials is systematically devalued, while the demand for virgin construction materials continues to grow.

This discrepancy between circular economy theory and current C&DWM practices highlights the challenges of transitioning to a circular model. To identify these challenges, Ferriz-Papi et al. (2024) performed a systematic literature review that identified 59 distinct challenges which can be categorized using a PESTLE (Political, Economic, Social, Technological, Legal and Environmental) framework. Table 2 lists the most significant and frequently cited barriers across the categories.

Table 2 Barriers to sustainable C&DW (Ferriz-Papi et al., 2024)

Category	Description	Impact on C&DW management	Supporting citations
Political /Legal	Regulation is non-existent or insufficient	Uncertainty and a lack of clear mandates for circular practices.	(Liu et al. 2021)
	Lack of specific standards and warranties for reused/recycled materials	Undermines stakeholder confidence in the quality and performance of secondary materials, leading to a preference for virgin materials with established certifications.	(European Environment Agency, 2020)
Economic	High extra costs for circular waste management	Creates a direct financial disincentive for project managers who often prioritize minimizing direct project costs	(Brusselaers et al., 2022)
	Price of virgin materials is often lower than recycled alt.	The market does not reflect the true environmental costs of virgin materials. Making recycled/reused materials uncompetitive	(European Environment Agency, 2020)
	Lack of viable business cases and financial incentives	Without a clear profitability or government support companies are hesitant to invest in the necessary technology	(Liu et al., 2021)
Social	Lack of awareness among stakeholders	Lack of knowledge across the industry to implement effective waste management strategies	(Liu et al., 2021)
	Conservative, change-resistance culture in construction industry	The sector is characterized by traditional practices and a reluctancy to change to new technologies and processes	Liu et al., 2021)
Technological	Lack of application of strong C&DWM practices	Inconsistent approaches to waste management on-site lead to inefficiencies and missed recycling opportunities.	(Guimaraes et al., 2021)
	Difficulties with on-site waste separation due to site constraints and material constraints	Traditional practices do not allow for deconstruction or proper material segregation. On-site constraints can hinder this further	(Guimaraes et al., 2021)
Environmental	Risk of contamination in recycled materials streams	The presence of hazardous substances can render a batch of waste unsuitable for high grade recycling	(European Environment Agency, 2020)

An analysis of the barriers mentioned in table 2 shows that they are not only independent obstacles but that they are also heavily intertwined. For example, the lack of a strict regulatory framework (political 1), results in the environmental costs of virgin materials to not be taxed to the buyer. This results in the prices of virgin materials often being lower than of recycled alternatives (economic 2). As the value of recycled materials is lower than virgin ones in this case this does not make circular waste management practices economically viable (economic 1) as it requires a higher upfront investment. Furthermore, because there is a lack of specific standards and warranties (political 1) most project managers will not use these materials, resulting in a lower market value. As there is no current financial incentive this results in there not being much technological advances (technological 1 and 2).

This entire sequence then validates the social barriers for the conservative stakeholders. They see no regulatory pressure, no clear economic benefit and a lack of supporting technology. This results in them being resistance to change. This results in a cycle of political inaction which results in no economic incentive which stalls technological progress and reconfirms social conservatism.

Previous sections show that the transition from a linear economy to a circular economy in the built environment is not a single action but a systematic shift. This shift requires changes across every stage of a construction project's lifecycle. Each phase has unique opportunities to close the material loop by

reducing waste and retaining value. Understanding the distinct and interconnected role of each phase is therefore critical for developing effective circular strategies (Akanbi et al., 2017).

The construction phase begins with the planning phase. During this strategic stage fundamental decisions with regards to project goals, feasibility and site selection form the foundation of a construction project (Ogunmakinde, 2024). In this phase it is important that circularity is established as a core objective, it should be on par with traditional metrics like cost and time. These objectives are translated into tangible specifications in the design phase. In this phase it is crucial that designers and architects use the principles for designing out waste and designing for disassembly (DfD). In addition, they can design buildings to only use sustainable materials and modular building components. These actors can use building information modelling (BIM) to create material passports that can later be used for material recovery (Ghaffarianhoseini et al., 2016).

The next phase of a construction project is the procurement phase. This phase focusses on turning the design plans into clear agreements. It includes planning to identify project needs, sourcing to select appropriate methods and suppliers, evaluating bids and quotes from different companies, and awarding contracts to finalize agreements (Naoum & Egbu, 2015). The scope of this research also entails this phase. This is the phase in which stakeholders will use the tool to determine which method of C&DWM is best for their project. In this phase the agreements for circular practices should be made if the circular economy is too be ensured. This phase is the followed by the construction phase itself. This also falls within the scope as it considers the phase that the tool predicts. In this phase the agreements and designs are executed, and the building is realised.

The last phase of the construction project is the post-construction phase. This phase encompasses the building's operational life and its eventual end-of-life, where the value created in earlier stages is ultimately realized. Proactive maintenance and repair during the use stage extends the service life of components, while at the end-of-life, a process of careful deconstruction or "urban mining" allows for the harvesting of components for reuse. The material passports developed during the design phase become invaluable at this stage, providing the necessary data to channel materials back into the economy, thereby closing the loop and completing the circular lifecycle (Abdelhamid, 2022).

A framework that currently tries to aid in the decisions making process that is needed in each construction phase is BREEAM (Building Research Establishment Environmental Assessment Method). BREEAM is a sustainable assessment framework that is used for infrastructure and buildings and looks at the decision making across all construction phases. Functioning as a multi-criteria rating tool that evaluates a project's performance across a range of environmental categories (figure 4). Its relevance to this study is particularly pronounced in its approach to C&DWM. In this "waste" category new construction can score points with regards to sustainable C&DWM practices, being the more points the more sustainable. The project has three different main criteria that it needs to achieve to score the maximum sustainability score. The first criteria is the efficient use of materials, this measure involves quantified waste reduction targets to ensure that the production of waste onsite is minimized. This is followed by the on-site separation of waste into seven different waste streams to prevent contamination (table 3). The last measure is performance-based criteria for material reuse and recycling which stipulates that at least 80% of non-hazardous waste must be diverted from landfill.

Figure 4 Aspects of BREEAM (Carel, 2025)

Table 3 Seven main waste streams of BREEAM (BREEAM, 2025)

Wood	board products such as plywood, particleboard, medium-density fibreboard (MDF).
Masonry materials	Bricks, patio tiles, concrete rubble etc.
Insulation materials	Mineral wool (rock wool, glass wool), foam plastic (PUR, PIR, EPS, XPS), insulating foils
Metals	Radiators, cables, wires, rods
Plastic	Hard plastics, PE foil
Paper and cardboard	Packaging material
Gypsum	Plasterboard, plaster, fibre cement boards

2.3 Inner-city Construction Projects

Separating waste into multiple streams is a process that is already being applied to construction projects throughout the Netherlands. For many projects, the disposal of waste streams is managed through separate waste management companies that arrange large containers of around 15m³, for all the main waste streams. Most construction projects have sufficient space for the seven different waste containers as defined through BREEAM. However, the problem with this practice is with projects in the inner-city. These projects often do not nearly have sufficient space for seven different large containers that facilitate waste separation, as shown in the case studies of Tivoli (4.1) and Renaissance (4.2). In these projects the common practice is to only use one large container for all mixed waste. This results in waste being sent in an unseparated state to the recycling centre.

The problem with this is that construction waste is only low-level recycled at these recycling centres. The valuable materials are extracted, and the rest of the construction waste is downcycled into road foundations and site elevations. The reason for this is because it is not economically viable to sort the materials at a higher level that would ensure a higher level of reuse (Wang et al., 2010). An example of this is gypsum, which is 100% recyclable into new sheets, not being separated from remaining concrete as new boards are cheaper to make than sorting this waste stream (Rivero et al., 2016). This in turn results in the concrete not being recyclable as the gypsum boards reduce the strength of the recycled

material (Abid et al., 2018). This example highlights why it is important to ensure onsite waste separation when having the goal to increase the recyclability of the construction sector.

2.4 The Critical Role of the Construction Finishing Stage

While C&DW is generated during each construction phase, the composition, nature and volume vary significantly. A traditional construction project starts with site preparations, foundation work, advancing with constructing the shell and ending with the finishing stage. The process begins with site preparation and excavation, activities that can yield substantial quantities of waste. These waste streams, however, are predominantly composed of homogenous materials such as soil, rock, and cleared vegetation. Therefore, there is not a need to separate this on-site and recycling is not relevant in this case (Poon et al., 2001).

Following this the foundation and shell construction marks the beginning in the rise of C&DW created. Despite this volumetric increase in C&DW, the resulting waste streams are still homogenous. In concrete-based construction, for instance, the principal waste components consist of surplus concrete, discarded timber or metal formwork, and steel reinforcement off-cuts (Sáez et al., 2013). Similarly, steel or timber frame construction projects generate predictable and homogenous streams of metallic or wooden scraps (Hossain et al., 2017). Therefore, while the structural phase may represent the largest volume of waste creation of the project, its management is simplified by the low complexity and high uniformity of the materials involved.

The last phase of construction, the finishing stage, is different to the other phases. It generates less waste than the shell construction However, while the total volume of a project might decline near the end of a project, the complexity of the waste streams increases significantly. Unlike the structural phase, which might produce large volumes of relatively homogenous waste like concrete, the finishing stage is characterized by the generation of a highly diverse and complex mix of materials. These waste streams typically include wood off-cuts, drywall, insulation, plastics from packaging, paper and cardboard, glass, tiles, and various metals. This heterogeneity complicates waste management, as separating a multitude of smaller, mixed waste streams is inherently more difficult than handling a few large, uniform ones (Villoria Sáez et al., 2012).

The causes of waste in the finishing phase are also distinct. A primary source is the generation of off-cuts from materials that need to be fitted to specific dimensions, such as tiles, drywall, flooring, and insulation. Packaging waste is another major contributor, as nearly every finished component arrives in some form of protective wrapping (Lamba et al., 2022). Furthermore, delays that occur near the end of the construction project have a larger impact on the overall time planning. This is because there is less time in the schedule to make up for these delays. In addition, due to this high number of subcontractors and the fact that this phase is susceptible to rework in design changes and specification errors, delays often occur during this phase.

These characteristics can create logistical challenges, especially in the inner-city construction projects that are the scope of this project. Inner-city construction projects often have limited space reserved for on-site waste storage (section 4.1 & 4.2). While in traditional projects there is often space for 7+ large containers which allow for easy waste separation and waste disposal, in these inner-city construction projects there is no such space available. In these projects project managers now often adopt the path of least resistance: emptying all different waste streams with high potential recyclable materials into one single container labelled as “mixed construction waste”.

In addition to the higher disposal costs of mixed construction waste, this act of mixing waste streams effectively contributes to the linear take, make, waste model. Once these materials are mixed it becomes significantly more difficult to later separate them at a recycling centre. This often results in it not being

financially viable to do so which results in the materials being downcycled or burned for their energy (Okonrecycling, 2025).

So, even though the finishing stage does not produce the highest volume of waste compared to demolition or structural stages, the high waste diversity and high lost potential in inner-city construction projects results in it being the focus of this research. The primary barrier to overcome is not the nature of the waste itself, but the logistical problems that occur through site constraints. Solving these problems and possibly enabling source separation can result in a higher level of reuse and recycling in these construction projects. This insight is used as the justification for the focus of this research being on the finishing stage of a construction project.

The complexity of the finishing stage, combined with the spatial complexities of inner-city construction projects transforms waste management into a difficult logistical puzzle. Solving this puzzle requires looking at alternatives to the traditional practices and exploring new logistical frameworks such as Construction Consolidation Centres (CCCs).

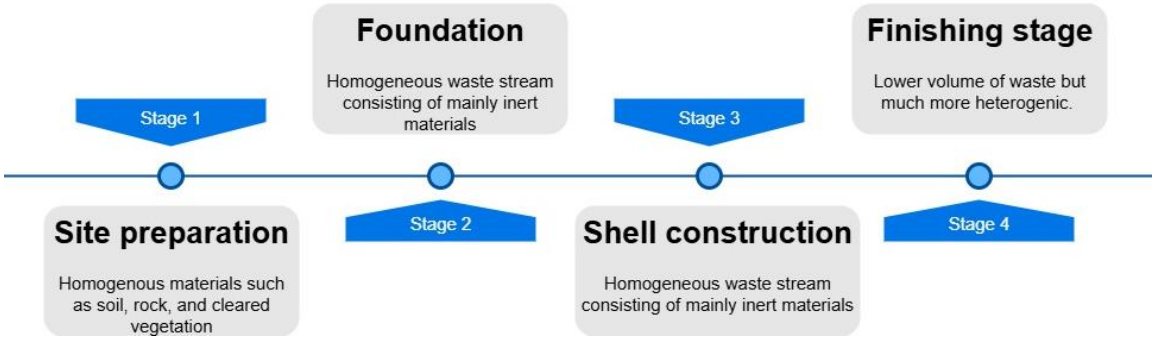


Figure 5 Construction phases

2.5 The Role of Logistics and Construction Consolidation Centres

This challenge of on-site waste separation is intrinsically linked to the broader logistical complexities that characterize inner-city projects. These construction sites have additional logistical challenges that stem from site constraints, which are often a limited storage space, limited accessibility hours, and vehicle constraints (e.g., length, weight, and height). Particularly in the finishing stage, where many different subcontractors are operating, a lot of different freights must be delivered and adhere to these constraints.

The advantages of using CCCs for the logistical problem are well documented and impact a project on multiple critical aspects. Economic savings can be achieved by reducing the number of trips needed, reducing the need for on-site space and reducing on-site labour costs through just-in-time deliveries (Guerlain et al., 2021. The main environmental impact is the reduction in the number of transportation trips needed for material delivery. Case studies have shown that CCCs can reduce this number by up to 70% (TKI Dinalog, 2024). This reduced number of trips directly leads to lower fuel consumption and reduced congestions, which both significantly reduce the greenhouse gas emissions (Guerlain et al., 2021). This reduction in the number of trips also has a social impact. It leads to less traffic related accidents, reduced noise pollution and less traffic congestion.

The integration of reverse logistics into the practices of a CCC would not merely be an efficiency gain, it also enables the on-site waste sorting of inner-city construction projects. With this integration it is therefore possible to improve the circular economy while also improving the logistical efficiency. As

established, the main barrier to on-site separation for construction projects in the inner-city (which is the scope of this thesis) is limited on-site storage space. The proposed solution is to use multiple smaller, waste specific, containers. However, this approach would traditionally be unviable as it requires frequent collection of many small, partly filled, waste containers. Scheduling transportation for this would be unviable. However, projects using CCC for their material delivery already involve frequent, planned, consolidated deliveries of materials in smaller batches to suit the limited on-site storage. By integrating reverse logistics, these frequent inbound material trips will possibly provide the necessary transport capacity for the frequent outbound collection of sorted waste. This is achieved without adding a significant number of new, dedicated waste vehicle journeys. The material delivery truck simply picks up the full small waste containers on its return trip to the CCC. Therefore, this model provides the essential mechanism that makes the frequent collection of source-separated waste both economically and environmentally viable.

While a CCC with integrated reverse logistics presents a powerful theoretical solution, its real-world value can only be determined through quantitative comparison against the current situation. Before any such comparison can be made, a reliable method for proactive waste quantification is required. This leads to the critical challenge of waste determination.

2.6 Integrated Decision Framework

The preceding review has established that C&DW management in inner-city construction projects is a complex challenge, driven by logistical constraints and the material diversity of the finishing stage. While innovative strategies like integrated CCC logistics offer a promising solution, the literature reveals a critical gap: stakeholders lack a practical, data-driven tool to holistically evaluate the trade-offs of these new circular approaches. To fill this gap, a new decision framework is needed, one that is both proactive in its analysis and holistic in its assessment.

Traditionally the approach to C&DW management has been mostly reactive, waste is generated as an inevitable byproduct that should be disposed of at the end of the process (Eze et al., 2024). However, the circular economy principle moves this to a more proactive stance. In this case the focus should shift from the disposal of waste at the end of a project, to the prevention of waste before the start of a project (Kirchherr et al., 2017). Literature agrees that the best moment to minimize waste is in the pre-construction phase (Llatas et al., 2022). According to the European Commissions (2008), decisions made during the design and planning phase have a large influence on the type and quantities of waste that will be generated. In addition, Othman & Elsawaf (2021) developed a model for the implementation of designing out waste in construction. The paper not only focusses on recycling or disposing after construction but also recognizes that a significant portion of on-site waste is a direct consequence of design choices. These papers and conclusions highlight the need for the proposed DST of this thesis to be used proactively in the pre-construction phase. Such a tool allows project stakeholders to model and evaluate the consequences of different waste management strategies during the planning phase, when the opportunity for cost-reducing and waste-minimizing changes is greatest.

To create a tool that is used in the pre-construction phase it is vital that reliable data regarding the waste determination is used. Without reliable data on the potential waste output of different design choices, decision-making remains subjective and inefficient (Lu et al., 2015). Numerous methodologies have been developed for the quantification of C&DW. As the tool will be used before the start of the construction phase it will only consider using proactive tools that predict the C&DW beforehand.

Numerous methodologies for C&DW quantification have been developed, with varying levels of complexity and accuracy. These range from simple methods based on gross floor area or project cost to more detailed approaches like material flow analysis (Lu et al., 2015). However, a common criticism of many existing models is that they are either too high in complexity for practical use by project

managers or too low in accuracy to provide reliable data for decision-making, thereby limiting their real-world benefit (Lu et al., 2015). Most research papers have looked at identifying the volume of total waste that is generated in a project. A study from Solís-Guzmán et al. (2009), developed a model for the quantification of C&DW. This model was developed through an extensive empirical study of 100 dwelling projects and their associated C&DW. Its key strength lies in its detailed, activity-based approach, which uses specific coefficients to estimate waste volumes from different sources. As the model determines the WGR of all different activities it becomes possible to only select the construction activities that occur in the finishing stage.

However, simply predicting waste is not enough. The second requirement for an effective framework is that it must be holistic, as the selection of an optimal C&DW management is an inherent complex, multi-criteria problem (Yazdani et al., 2021). Project stakeholders need to look at the different factors influencing the project, these objectives are far more complex than a simple cost minimization. Decision-makers must find a balance between direct economic costs, long-term environmental impacts and social impacts on the surrounding community.

However, currently, a tool that provides a robust impact analysis of the economic, environmental and social impact are limited (Brusselaers et al., 2022). Traditional decision-making processes have often been criticized of being too focused on minimizing initial direct costs (Yazdani et al., 2021). This results in the environmental aspects being lost in these tools as it fails to account for external costs such as resource depletion and pollution problems (Yazdani et al., 2021). This complexity and the shortcoming of current methods highlight the need for data driven decision support tools that can provide a framework for evaluating C&DW management alternatives.

A core approach is Multi-Criteratie Decision Analysis (MCDA), which is a term used for methods that are designed to compare multiple, often conflicting, criteria (Yazdani et al., 2021). To provide the data for MCDA frameworks, life cycle thinking approaches are becoming more common. As mentioned, it is important that the MCDA uses economic, environmental and social aspects (Yazdani et al., 2021). Life cycle thinking looks beyond the immediate project boundaries and considers the impact across the entire value chain.

2.6.1 Life Cycle Analysis

Life cycle assessment (LCA) is a standardized method for quantifying the total environmental impact of certain decisions/scenarios. In the C&DW context, LCA is used to assess impacts such as greenhouse gas emissions, energy consumption and resource depletion. It determines this throughout the entire supply chain. In the context of C&DWM, the application of LCA in literature consistently identifies two primary sources of environmental impact: transport emissions and emission related to waste processing. Studies such as Brusselaers et al. (2022) highlight that construction related transportation is a major contributor to urban traffic and associated CO_2 emissions. The second critical component identified in the literature is the emissions from the recycling process itself. A LCA performed by Llatas et al. (2022) has quantified that effective recycling can yield energy savings up to 85 times greater than disposal scenarios, which directly translates to a significant reduction in greenhouse gas emissions. This demonstrates that the C&DWM approach used in a construction project has a significant impact on the environmental impact. Blengini and Garbarino (2010) performed a study that reinforces this. The study presents an LCA that breaks down the C&DW management system into subsystems including collection, recycling, and avoided products, with greenhouse gas emissions and non-renewable energy used as key indicators.

2.6.2 Life Cycle Costs

Life cycle costing (LCC) is the economic counterpart of LCA. IT evaluates all the costs of a certain decision/scenario across the entire supply chain. In evaluating different C&DW management methods, economic performance is an important factor in determining the feasibility of proposed solutions. While

sustainability is often the goal, cost efficiency remains an important driver for decision makers. A study from Gálvez-Martos et al. (2018) synthesized core principles and best practices for C&DW management across the construction value chain. Among the identified strategies, they emphasized that improving resource efficiency and minimizing transport and treatment costs could significantly reduce environmental impact. However, this would only be feasible if such practices were economically viable. The study linked economic performance to various factors, including the cost of waste collection, sorting, recycling, transportation, and revenues from recycled materials.

As shown by Wang et al. (2010), on-site sorting increases the potential for reuse and recycling but also adds to project costs through labour, space, and equipment needs. Therefore, when assessing the economic performance, these sorting-related costs must be accounted for alongside transport and disposal.

These insights have been combined by a study from Yuan (2012) that looked at how this economic performance has been determined in previous studies. They performed a comprehensive literature review and combination with interviewing 3 researchers, 2 project managers and 2 supervisory engineers. In their study it was found that the economic performance is often determined through a costs analysis. The study identified key cost components, including:

1. Costs of waste collection, sorting, and separation
2. Costs of reuse and recycling
3. Waste transportation costs
4. Revenues from selling recyclable materials
5. Cost of disposing waste at landfills
6. Penalty paid due to illegal dumping of waste

This framework provides a foundation for selecting the most relevant cost categories in this research. Beyond the direct, project-specific costs, the literature also recognizes the importance of including overarching costs associated with the implementation of more advanced waste management systems. For example, a benefit-cost analysis by Begum et al. (2006) on construction waste minimization in Malaysia took a broad economic view. Their research evaluated the feasibility of waste minimization programs by weighing the long-term benefits (such as reduced disposal fees and revenue from salvaged materials) against the comprehensive costs, which included initial investments in on-site sorting equipment and worker training.

Similarly, a study by D'Onza et al. (2016), which applied a full-cost accounting method to separated waste collection, argued that a true assessment of economic efficiency must include all operational expenditures. Their framework incorporated fixed costs such as the maintenance of machinery and depreciation of equipment, which are often overlooked in analyses that focus solely on variable, per-tonne costs. These studies demonstrate that a complete LCC can be expanded to include the capital and operational expenditures required to establish and run a waste management infrastructure, providing a systems-level economic perspective.

2.6.3 Social Impact Assessment

Social impact assessment (SIA) is a less often used method of sustainability assessment. It aims to quantify the social consequences of a decision. In previous studies the social indicators are less used compared to the environmental and economic indicators. This is partly because they are deemed to be less important and more difficult to quantify (Sobotka and Sagan, 2021). The study from Sobotka and Sagan (2021) quantified the social impact by looking at the noise levels of the machinery that crushed concrete. In this study the only heavy machinery that is used is located on waste disposal plants where

noise is not a real issue. However, the noise impact can still be quantified through the amount of urban freight transport. Research by Brusselaers et al. (2022) analysed the role of construction logistics in urban areas, finding that construction-related freight accounts for 20–35% of total urban freight traffic in Europe. The authors highlight that vehicle congestion near construction sites exacerbates the problem, as idling trucks waiting to unload materials or collect waste generate additional noise emissions.

Furthermore, other studies have focussed on highlighting other social impacts of urban freight transport. Multiple papers have stated the fact that an inefficient last-mile delivery system and an increase in urban freight transportation results in an increase in traffic congestion (Amrani et al., 2024) (Musolino and Rindone 2023). The effect of this increased traffic congestion should not be understated. Samal et al. (2021) performed a study that looked at the congestion indices and the operational efficiency of the urban road network. The effect of traffic congestion on the economy, the environment and health were also analysed under mixed traffic conditions. To study the effects of congestion on health-related issues they performed a questionnaire at different workplaces. The study found that 85% of individuals reported their health being affected by traffic congestion, while 14% stated that their health was not impacted. Additionally, 1% of respondents provided an inconclusive answer. The symptoms experienced have been classified into various categories, including breathing difficulties, headaches, mental stress, hearing issues, unexpected sweating, fatigue, suffocation, dust allergies, eye problems, digestive issues, and dehydration. In addition to this they found that not only people experiencing traffic congestion, but also people in the surrounding area are disturbed by this. They found that 86% of inhabitants of Bangladesh are affected by noise pollution through traffic congestion.

Furthermore, a paper from Pokorny et al. (2017) looked at the accidents between bicycles and freight vehicles with a focus on urban areas. It investigated the accidents between trucks and bicycles in Norway, with a specific focus on urban areas. Descriptive statistics and binary logistic modelling were performed, on a Norwegian database regarding traffic accidents, in order to explore the data and relationships between variables. For the descriptive statistics, the data set containing all reviewed freight and bicycle accidents were used to find the count and percentage of each relevant characteristic for each accident. They found that freight and bicycle accidents (TCA) make up almost 20% of all cycle fatalities. Furthermore, they found that the majority of TCA were recorded in urban areas, mostly during working days when more trucks and commuting cyclists are expected on the roads. This paper shows relevance as according to the Ministry of infrastructure and water management (2018) 27% of all trips made by Dutch residents are travelled by bicycle. Furthermore, this number is expected to be higher in large cities as there is better cycling infrastructure and more traffic congestion for cars.

2.7 Conclusion

This chapter has provided a comprehensive review of the current C&DW practices and more sustainable changes that should be made. The circular economy offers a necessary framework, as current C&DW management practices are dominated by low-value downcycling rather than high-value material reuse.

While the concepts of BREEAM and the 10 Rs aid in this transition from a linear to a circular economy, they become difficult to integrate when the construction project becomes more complex. In inner-city construction projects, where spatial constraints make traditional on-site separation during the finishing stage difficult, project managers often revert to the traditional linear model.

A theoretical solution to this is integrating the reverse logistics with materials deliveries using CCCs. This creates the logistical viability for frequent collections of smaller, source-separated waste containers, directly addressing the inner-city space constraint.

However, the critical gap identified by this review is the lack of a practical, data-driven tool for stakeholders to evaluate this strategy. Decision-makers are currently forced to rely on fragmented information, often defaulting to the lowest initial cost, which ignores significant environmental and social externalities.

While the literature provides established methodologies for assessment of individual indicators like LCA, LCC, and SIA, it lacks a unified framework that integrates these conflicting criteria into a single, actionable tool for proactive, pre-construction decision-making.

Therefore, this review establishes the clear need for a Decision Support Tool that can aid stakeholders to make informed decisions based on the economical, environmental and social impact of the different C&DW management approaches.

3. Methodology

From the literature review, focussing on the circular built environment and C&DWM practices, it can be concluded that there are still opportunities in incorporating more sustainable C&DWM approaches. The main struggles are difficulties with choosing sustainable options, when the site limitations provide additional difficulties. To aid in this decision making, this thesis proposes a DST tool that can be used by decision makers in the construction sector. The tool allows users to compare different C&DWM approaches and see how they score on certain KPIs. The literature review has answered the first sub question of this thesis, the second and third will be answered in this chapter.

The first part of this chapter looks at quantifying the economic, environmental and social impacts of different C&DW management strategies as defined in the literature review. The second part focusses on the simulation models used to estimate the waste streams and trips generated during the project. The last part focusses on developing a decision support tool that can help stakeholders navigate trade-offs between the economic, environmental and social impact.

3.1 KPI Assessment

The literature introduced how the economic, environmental and social impact of different C&DWM approaches can be tested. This subchapter will go further into what indicators will be used and how they are quantified in this research. As mentioned, it starts with the KPIs for the economic, environmental and social impact. The last subchapter will explain how these costs will be combined though the use of carbon pricing.

3.1.1 Economic Performance Indicators (LCC)

The economic performance indicators used in this study are based on the indicators used in the life cycle costs analyses discussed in chapter 2.6.1.

$$EC = TRC + RC + REC + SC \quad (1)$$

Where:

- EC represents the economic costs
- TRC represents transportation costs
- RC represents recycling operation costs
- REC represents the rental costs of the containers
- SC represents sorting and separation costs

3.1.1.1 Transportation Costs (TRC)

To accurately determine transportation costs, all logistical components must be considered. This research conceptualizes transportation into two distinct phases: loading/unloading and in-transit. For the in-transit phase, travel time is determined through a Google Maps API. This method is in line with a study from Liu et al. (2023) that looked at including a time penalty for traffic delay and loading/unloading times.

The Dutch ministry of infrastructure published a paper determining the in-transit costs (€57.32/hour) and the loading/unloading costs (€40.54/hour) (Jonkeren, 2023). The total in-transit costs include the fixed costs, variable costs, employee costs and general transit costs. This is in line with the approach of Nolz (2020) which highlighted the importance of determining both fixed and variable costs. However, this paper is four years old. Due to high inflation over this period this is kept in mind when determining

the total final costs. The central bureau of statistics (2025) has determined that the freight transport using trucks in the Netherlands has risen 20,9% over the baseline in 2021. This results in the loading/unloading costs being €49.01 per hour and the in-transit costs being €69.30 per hour.

This results in the following formula for the total transportation costs:

$$\text{TRC} = (\text{time spend loading in hours X } 49.01) + (\text{time intransit in hours X } 69.30) \quad (2)$$

As mentioned, the in-transit time will be calculated using the number of trips and the travel time from the Google Maps API. The loading and unloading time has been determined through observation. A forklift was used to handle each container. Since the containers are all roughly the same size, the time to load or unload each one is expected to be consistent. Therefore, the total handling time is simply the time it takes per container multiplied by the number of containers. Observation occurred at three different case studies. For two case studies the loading time was around 1 minute per containers (Renaissance 4.2 and Beneluxlaan 4.3). The other case study (Tivoli 4.1) it was around two minutes. The reason for this difference is because the truck could not park close to the waste containers, this resulted in additional loading times. This is a site constraint that is specific to this project as it considers a renovation project of a building with a monumental status. Therefore, this is left out of consideration and a loading time of 1 minute per container is used.

3.1.1.2 Recycling Costs (RC)

The recycling costs in the model are calculated based on the quantity of waste generated per material type and the corresponding cubic meter recycling costs. The recycling costs for every waste stream are determined through a direct quotation from large recycling centre, which is kept anonymous for privacy reasons. This approach of using direct market-based pricing is consistent with methodologies in other detailed LCC studies. For instance, a study from Iodice et al. (2021) on C&DW management in Italy describes its data collection method for their Environmental Life Cycle Costing (ELCC) as follows: "Economic data regarding gate fees of landfill, recovery plants and incinerators, transport costs and revenues from selling secondary raw materials were collected by consulting official price lists of the Lombardy Region Chamber of Commerce and through direct contacts with a representative transport company."

The recycling costs of construction and demolition waste (C&DW) are influenced by several interrelated factors, including waste composition, processing requirements, and the quality of separation Bayram and Greif (2023). To build on this, Di Maria et al. (2018) developed a hybrid approach combining Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) to determine the true cost of recycling in various C&DW scenarios. Their findings highlight that different waste streams incur substantially different processing costs, up to 60% variation, depending on the technical complexity of the recycling process and the purity of the input material. The study further emphasizes that high-quality source separation, such as that achieved through well-managed on-site sorting, significantly improves material recovery rates and reduces downstream processing complexity. Therefore, in this research, it is assumed that the separated waste is of high quality, based on proper training and adherence to waste separation protocols by on-site workers. This results in minimal contamination between waste types and maximizes the potential for true recycling rather than downcycling.

$$\text{RC} = \sum_{w \in W} \sum_{c \in C} \left(RCU_c \times WR_{w,c} \right) \quad (3)$$

Where:

RCU_c represents the unit recycling cost for waste category c –To determine this a direct quotation is used from a large recycling centre that has provided pricing for the disposal of construction waste. The quotation from the recycling centre determines the price per weight of a waste type. However, the

model determines the amount of waste generated by cubic meters. Therefore, the density is added to make sure that the same unit is used. The density stems from a research paper from Lu et al. (2021) that looked at determining the bulk density for construction waste. If given a value range the average value has been chosen. Except for with wood, for this it assumes the density of plywood, which is the most used in buildings (Engineeringtoolbox, 2025).

In addition to this there is one waste type that has a negative value, meaning that it has a residual value when being disposed of separately. Metal still has a monetary value when disposing, in this case it is assumed that ferrous metals are used in the construction project. This is because most construction materials contain iron making it ferrous. According to the London metal exchange the current price as of July 2025 for ferrous scrap metals is €292 per ton.

Table 4 Disposal costs per waste stream

Waste type	Price	Density kg/m³	€/m³
Unseparated waste	€ 185/ton	1061	€ 196.29
Insulation material	€ 45/m³	Not relevant	€ 45.00
Wood type B	€ 38.5/ton	600	€ 23.10
Wood type C	€ 95/ton	600	€ 57.00
Gypsum	€ 95/ton	620	€ 58.90
Paper and Cardboard	€ 8/ton	925	€ 7.40
Glass	€ 3.65/ton	2600	€ 9.49
Tiles	€ 75/ton	1900	€ 142.50
Plastic	€ 20/ton	1536	€ 30.72
Metal	-€ 292/ton	7900	-€ 2306.00

$WR_{w,c}$ represents the quantity of waste in category c recycled in period w. To quantify the total recycling costs the system needs to include the total waste that needs to be recycled. The model will predict the waste created on the weekly delivery schedule of the materials. Therefore, it is an expected value and cannot give exact recycling costs. This is expected as the DST will be used before the start of a project when little is known about the final waste numbers. The waste generation will be determined for every waste stream and every discipline. Some disciplines have little waste generation as sizes are exact (glass waste is only produced when mistakes occur) while other disciplines have a significantly higher waste generation rates (WGR) (tiles need be cut to size and smaller pieces will be left after this process).

3.1.1.3 Rental Costs (REC)

The rental costs are the costs incurred when renting the needed material- and waste containers. These rental costs can be seen as an indicator of inefficiency as the extended presence of equipment and containers on-site is a form of waste that does not add value to the final product (Garcés & Peña, 2023). A high cumulative holding cost can indicate poor coordination, inefficient material flow, or suboptimal space management. It is determined by multiplying the weekly cost of a specific unit by the time that unit is rented to the construction site, so located on-site.

$$\mathrm{REC} = \sum_{i \in I} (n_i \cdot c_i) \qquad (4)$$

where:

- I is the set of all container and equipment types.
- n_i is the number of units of type i on-site during the week.
- c_i is the specified weekly cost for one unit of type i.

These costs are calculated through the CCC and are based on the time that a given container is rented to a construction site. The value of the rental cost per week is based on agreements made in the procurement phase. For this research the standard values of the collaborating company have been used. These are values that are currently used in project in which the CCC handles just the material delivery. However, as it uses the same containers the price is the same. If the type of containers is not named in the data upload it is assumed to be a tile container as this is the most occurring and standard container type.

- Blank (week/unit): €3.74
- Gypsum board cart (week/unit): €6.15
- Large waste container (week/unit): €15.00
- Pallet (week/unit): €2.50
- Roll container (week/unit): €2.16
- Tile container (week/unit): €3.74
- Small waste container (week/unit): €4.50

3.1.1.4 Sorting Costs (SC)

This thesis distinguishes between two types of sorting costs: those incurred on the construction site and those at the waste disposal facility. The costs for sorting at the disposal facility are already accounted for within the material-specific recycling fees. Therefore, this model exclusively calculates the on-site sorting cost. This cost is defined as the incremental labour time a worker needs to separate waste into multiple streams, a task that only occurs in the integrated scenario.

The on-site sorting costs are guided by a paper from D'Onza et al. (2016), this paper states that while separate collection incurs higher upfront sorting costs, it often leads to long-term economic benefits through reduced disposal fees and increased material value. While detailed frameworks exist for calculating these costs based on multiple granular inputs like material handling, equipment use, and site space constraints (Zhang et al., 2021), this thesis adopts a more pragmatic approach suitable for pre-project estimation.

The primary driver for this on-site cost is identified as the time and effort needed to transport the various waste containers to the active construction floors. The time it takes a worker to walk to the waste containers is assumed to be the same for both models as the containers are strategically placed on each floor where work is occurring (e.g., near the elevator). This makes the horizontal travel distance for workers consistent across all scenarios.

The significant difference, therefore, lies in the vertical logistics. In the baseline scenario, only one or two general waste containers need to be transported and placed. In contrast, the integrated scenario can require as many as seven distinct containers for different material types, which substantially increases the logistical task of deploying and managing the waste system.

The total on-site sorting cost is therefore determined by multiplying the additional time required for container logistics by the standard hourly wage for a construction worker. Through on-site observation, the additional time required is determined to be 5 minutes per waste container. In this observation it is determined how much time it takes a worker to transport a waste container to the right location. For the hourly worker rate a value of €26,- an hour is assumed. Based on the Collective Labour Agreement (CLA) a price of €20,- per hour is assumed (CAO bouw & infra, 2025). On top of this it is assumed that the employer has an additional cost of 30% (Tentoo, 2025). This results in a total hourly cost of €26. This cost may vary significantly per user based on their employee contracts. Therefore, the user can change this value in the front-end to match the costs he/she incurs for a worker.

3.1.2 Environmental Performance Indicators (LCA)

Carbon emissions are quantified for both transportation activities and waste processing operations, following the methodology established by Yang et al. (2018):

$$CO_2 = TE + RE \quad (5)$$

Where:

- TE = Emissions produced during transportation
- RE = Recycling emissions

3.1.2.1 Transportation Emissions (TE)

This thesis bases the transportation emissions on a paper from the International Council on Clean Transportation (Musa et al., 2024). This section outlines the framework for determining transportation emissions. The methodology uses the data from the European Union's heavy-duty vehicle (HDV) CO_2 standards.

To ensure a standardized and verifiable approach, the calculation of CO_2 emissions for freight transport will be based on the official reference values established by EU regulations (Ragon et al., 2021). The process uses data generated by the VECTO simulation tool, which determines emissions based on certified vehicle components and specific mission profiles. This ensures that the emissions calculated are directly comparable to the legal standards set for vehicle manufacturers. As this study focuses on inner-city material delivery, it will use the baseline value for the 4-UD vehicle subgroup. This subgroup represents a rigid, 4x2 axle truck with a Gross Vehicle Weight (GVW) of over 16 tonnes, used for urban delivery missions. The official baseline emission value for such a diesel truck is 307.2 gCO_2/t-km. A standard diesel truck used in regional transport is around 5 tons (Evofenedex, n.d.). This brings the total emissions to 1,536 gCO_2/km

However, since an electric truck may be required for city-centre access, an alternative calculation is provided. While electric trucks produce no direct CO_2, CO_2 is often generated to produce the electricity they consume. To determine this indirect emission, the electricity consumption of 1.48 kWh/km (Wang et al., 2021) is multiplied by the grid emission factor. For the Dutch electricity grid, this factor is 413 g/kWh (Bergsma et al., 2018). Multiplying these values gives a CO_2 production of 611.24 g CO_2/km.

To translate these per-kilometre rates into a total project impact, the model calculates the total transportation emissions by applying the appropriate rate to the logistics plan generated by the simulation. The final calculation multiplies the total number of round trips by the round-trip distance and the corresponding emission rate. For a diesel truck, the formula incorporates the weight and emission factor directly:

Transportation emissions = ((Total trips x distance x 2) x (truck weight x emissions factor))/1,000,000

In this formula; the total trips is an output from the simulation, distance is the one-way travel distance retrieved from the Google Maps API, and the factor of 2 accounts for the round trip. The denominator of 1,000,000 is used to convert the final result from grams to tonnes of. The same formula is used for the electric truck, substituting the relevant per-kilometre emission rate derived previously.

3.1.2.2 Recycling Emissions (RE)

The recycling emissions are a very complex indicator for the impact of different recycling methods. To simplify the process with the goal of determining the CO_2 production of both scenarios this thesis will focus on the sorting emissions at a recycling plant. It is assumed that when the mixed waste is separated at the recycling centre that it can be high quality recycled. It is also assumed that the materials that are separated on-site and at the recycling centre follow the same process after this point (Zhang et al. 2022). Therefore, CO_2 savings and costs are the same for both scenarios and can therefore be seen as not relevant.

So, for this section it is important to determine the emissions that are produced during the sorting of mixed construction waste at a recycling centre. To quantify these emissions, this study adopts an emission factor of 140 kg CO_2 per megagram (Mg) of waste. This value is derived from a study by Mamiya et al. (2005), who investigated environmental assessments for demolition and waste treatment processes. The methodology involved evaluating the actual input and output data from these plants to calculate the carbon dioxide emissions resulting from specific treatment pathways. The 140 kg-CO_2/Mg factor corresponds specifically to the emissions from the sorting of mixed construction waste. Important limitations regarding the adoption of this value, is that the study is based in Japan which can have different recycling approaches than plants in the Netherlands. Furthermore, different recycling machines and methods can have different CO_2 productions. This means that different recycling centres might have different CO_2 production levels for the sorting of waste.

3.1.3 Social Performance Indicator (SIA)

The SIA mentioned in the literature review has highlighted the need for a social KPI that can be used to quantify the social impact of both scenarios. The social impact has been established as traffic congestion, noise pollution and additional safety risk. Both the environmental and economical impacts will be quantified as a monetary cost. This will not be done for the social impact as it is too complex and intertwined between the different aspects influencing the social impact. Therefore, this study uses the number of trips as a proxy for the social impact. A higher number of trips negatively effects al aspects of the social impact. Therefore, a lower number of trips has a more positive effect on the social impact compared to a higher number of trips.

3.1.4 Monetized CO_2 Cost

Not all of these KPIs currently have the same unit. To allow the KPIs to be determined though the optimization model they will need to have the same unit. In this research this is done by transforming the CO_2 production into a monetary value. Previous research by Martinex-Sanchez et al. (2014) proved that this is possible. In their research a life cycle assessment was used to quantify environmental impacts and then applied monetization factors to convert these impacts into economic terms. The study found that different carbon price levels significantly impacted the economically optimal waste management strategy. It was found that at lower carbon prices (<25€/tonne), conventional practices remained economically favourable. However, at higher prices (>50€/tonne) more advanced recycling systems became the optimal choice.

Furthermore, a study from Marzouk and Azab (2013) developed a system dynamics model that was used to quantify economic and environmental impacts over a 20-year lifespan. The study assigned monetary values to carbon emissions and other environmental aspects. The study highlighted the importance of recycling over landfilling by turning the environmental costs into a monetary value. This study understates the relevance of turning environmental impacts into monetary values to evaluate the costs.

The total cost for each model is formulated as a sum of economic costs and environmental costs (monetized through carbon pricing), expressed as:

$$TC = EC + (CO_2 \times CP) \quad (6)$$

Where:

- TC represents the total cost in monetary units
- EC represents the economic costs in monetary units
- CO_2 represents the carbon dioxide emissions in tonnes
- CP represents the carbon price in monetary units per tonne of CO_2

The thesis uses a value of €71.2 per tonne CO_2 to determine the carbon costs of a project as this is the current value of the EU carbon price. However, some municipalities have already started using higher carbon price value in construction project tenders to ensure more sustainable construction practices. This research looks at two construction projects in Utrecht and one in Amsterdam. Both already use a significantly higher carbon price. Respectively being €875 per tonne CO_2 and €418 per tonne CO_2. Therefore, both the current price and the price used in municipal tenders will be used in evaluating both scenarios.

3.2 Simulation Models

The central method used in this thesis is the creation of a DST that compares the simulations of two different C&DW management scenarios. This approach is used to quantify the KPI trade-offs between the current and proposed practice for inner-city construction projects. The goal of this subchapter is to model both scenarios so that their corresponding KPI scores can be determined. The two scenarios are defined as a current situation, baseline model, and a proposed alternative, integrated scenario.

Starting with the current scenario, the material delivery is in this case assumed to be done by a CCC. This is because with limited on-site storage space traditional material delivery is often not feasible. Currently, the material delivery and waste disposal consider two different companies with no interplay. Meaning separate trucks for delivery and separate trucks for waste returns. In this scenario, all generated waste streams are collected in a single, large container of 15000 litre for mixed disposal, reflecting the common practice in projects with limited on-site storage space

The integrated scenario assumes that a CCC will handle material deliveries and waste returns. A CCC delivers less material at a the time compared to traditional delivery methods. This scenario will use smaller waste containers of 660 litre. It is assumed that the projects in the integrated model all use on-site sorting resulting a more recycling potential.

This subchapter starts by detailing the material deliveries expected in a construction project. The next step explains how the simulations will predict the amount of waste generated in a project. The material deliveries and the amount of waste generated is the same for both scenarios. Therefore, the method of determining the delivery schedule and amount of waste is the same for both scenarios. Following this start the subchapter will explain for both scenarios how they will be modelled so that they can be used to predict the KPIs.

3.2.1 Material Delivery Schedule

The first process is the same for both the baseline simulation and the integrated simulation. This process is concerned with determining the material delivery schedule and the amount of waste that is expected. Starting with the material delivery schedule, the user must upload an Excel file that contains the material

delivery on a weekly basis. This file should have a column that mentions in which week the materials will be delivered (in a YYYY-WW format) and how much of these materials. The YYYY-WW format is converted into a sequential week number, where "Week 1" signifies the start of the project. This adjustment is performed to make the overall project overview clearer and to simplify scheduling throughout the simulation model.

The Excel file must also contain the number of containers needed to transport the materials each week. To ensure data accuracy, the model looks for recognized container types (such as 'pallet' or 'gipskar') defined within an internal dictionary. For each valid entry found, the model extracts the type of container and the quantity being delivered for that week. This results in a clear overview of how many material containers need to be delivered to the construction site for each week of the project. These two aspects combined produce an overview of the materials that must be delivered each week, which is then stored in a dictionary that can later be used for both simulations

3.2.2 Waste Generation

In addition to the material delivery schedule, the weekly waste generation should be determined. This study uses proactive estimations rather than reactive measurements, as this allows for strategic planning of container requirements, transport schedules, and cost calculations. To achieve this, the model applies the methodology presented by Solís-Guzmán et al. (2009) which is explained in 2.6. The model takes two user-provided inputs: a project schedule that describes the detailed materials deliveries each week. And the total surface area of the construction project. The first step in determining the waste generation is the reading of the Excel file. For each week, it scans the columns that list materials being delivered, such as “Gyproc finesse” and “U75 metalstud profiel”. These product names are then interpreted through a configuration file that maps these products to certain construction activities. The construction activities are linked to the products through certain keywords.

- The activity "Plaster spraying (ceiling/walls)" is associated with keywords like "gyproc", "gips", "spuitgips", "finesse", and "plaster".
- The activity "Metalstud walls (MS100)" is linked to keywords such as "profiel", "metalstud", and "staal".

For each product name read from the Excel schedule, the model performs a case-insensitive search to see if it contains any of the keywords from the configuration file.

Example: If a delivery for a specific week is listed as "Gyproc plaster", the model scans this text. It would find the keywords "gyproc" and "plaster", which are linked to the "Plaster spraying (ceiling/walls)" activity in the configuration file. As a result, the model logs "Plaster spraying (ceiling/walls)" as an active task for that week.

The model now uses this standardized activity name ("Plaster spraying (ceiling/walls)") to look up its specific WGR section of the configuration file. For "Plaster," the WGR is 0.001. This coefficient, based on the Solís-Guzmán methodology, represents the cubic meters (m^3) of waste generated for every square meter (m^2) of the project's total surface area. These rates comprehensively cover both waste from leftover materials (wreckage) and packaging waste.

The core calculation is then performed by multiplying this WGR by the total project area, which is provided by the user. Example: If the user specifies a total project area of 12,000 m^2, the total waste volume generated by the "Plaster" activity would be:

0.001 (WGR) * 12,000 m^2 (Area) = 12 m^3

It is crucial to note that this 12 m^3 represents the total waste produced by the "Plaster" activity over its entire duration in the project. The model then divides this total volume equally among the number of weeks that the activity is scheduled, resulting in a precise forecast of waste volume for each specific

week. This result is then stored in a dictionary listing the week and the amount of waste generated for each waste type.

Once the weekly waste volume for a construction activity has been calculated, it must be assigned to a specific waste category. This final classification step is crucial for planning which types of containers are required on-site. This process is governed by the container mapping section of the configuration file, which provides the definitive link between a standardized activity and its resulting waste stream. The model takes the standardized activity (e.g., "Plaster," "Steel frames") and uses it as a key to find the corresponding waste category in the container mapping dictionary. For example:

- The standardized activity "Plaster" is mapped to the final category "Gypsum".
- Similarly, the activity "Steel frames" is linked to the "Metal" category, and "Tiling" is linked to "Ceramic".

This ensures that the calculated volume of waste from plastering activities is correctly designated as gypsum waste, requiring a gypsum container. If a standardized activity does not have a specific entry in the mapping, its waste is assigned to a default category of "Remaining rubble" to ensure all generated waste is accounted for. The result is that every calculated waste volume is precisely categorized, completing the weekly forecast. The reason this method is chosen is because it fits best with the data input. During the pre-construction phase of the building the project managers have the list of materials that they need for construction. This list can be effectively transformed into a list of construction phases. The decision to divide them into seven different waste stream is based on the requirements mentioned in the BREEAM assessment method. This is a sustainability assessment method that evaluates the environmental performance of a building. It is chosen as a guideline for the number of waste streams as it is often used in new construction to ensure sustainably construction practices.

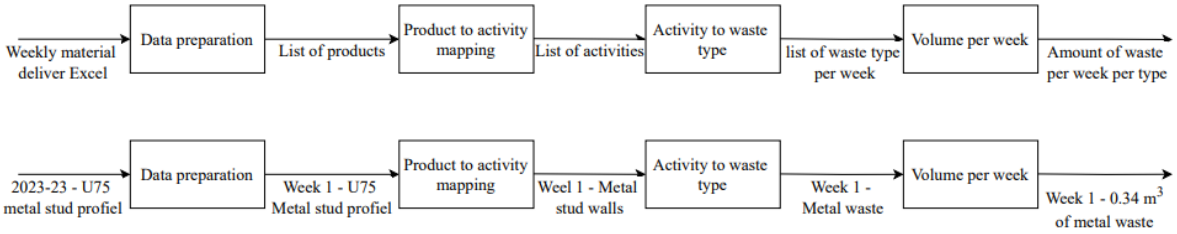


Figure 6 Weekly waste determination

3.2.3 Baseline Model

The baseline simulation was methodologically designed to serve as a quantitative benchmark of a traditional, uncoordinated approach to construction logistic. The purpose is to model the current scenario, thereby creating a control case against the proposed alternative. Figure 7 shows this scenario, where material deliveries and waste collections are treated as separate processes, and all generated waste streams are collected in a single, large container for mixed disposal. The model is divided into several key parts that define its parameters, data handling, and operational logic.

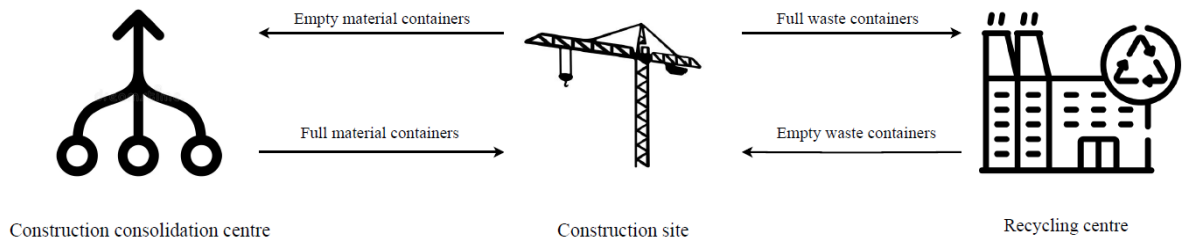


Figure 7 Baseline scenario

To ensure the model is representative of the real-world scenarios, the model requires an initialization phase that sets parameters, loads scenario specific data and sets state variables. The system parameters are used in the process of assigning quantitative values to the static properties of the model.

- *Mixed_Waste_Container_Volume_m3*: This parameter is set to a value of 15.0 m3, representing the high-capacity, open-top containers typically used for collecting mixed construction and demolition waste.
- *Truck_dimensions*, this parameter defines the internal floor dimensions (length and width) of a truck. It is used to determine how many containers can be transported on each trip. The user can choose between two different vehicles in the front end. A standard large diesel truck (2.5 x 12m) or a smaller electric truck (4.2 x 2.1 m)
- *Container_dimensions*, this is a dictionary that contains the dimensions of all the different types of containers used in the model. By using varying container dimensions, the model ensures that the correct sizes for each delivery are used. These sizes are used to determine how many containers can fit in a single truck

3.2.3.1 Main Simulation Loop

The main simulation loop iterates through every week of the project handling the material deliveries and waste returns as two separate events. (shown in the flowchart in figure 8). For the material deliveries the model identifies all scheduled deliveries through the dictionary defined in the data preparation. Based on these deliveries the model performs a 2D bin packing optimization. The goal of this is to pack as many containers into a truck as possible. It does this for each week and does not consider delays. For example, if there are 22 containers and a truck has a capacity of 20, the model assumes two trips in that week instead of moving the 2 containers to next week. This is done because construction is dependant on these materials as defined in the initial planning. The model tracks the number of trips made to deliver these materials by storing them in the dictionary. It is assumed that the returning empty material containers fit inside the truck that have delivered the materials. Therefore, no additional trips are needed.

To handle the waste that is created, the model calls a trip when the waste container is full. The process is governed by two state variables, *container_on_site* and *on_site_mixed_container_fill*, and follows a clear set of rules:

1. The simulation begins with no waste container on-site. A dedicated trip is dispatched to deliver a single, large empty container only in the first week that any waste is generated (if *waste_this_week* > 0 and not *container_on_site*). This initial trip represents the setup of the waste management system.

2. In each subsequent week, the generated volume of mixed waste is added to the *on_site_mixed_container_fill* state variable. This models the continuous accumulation of waste on-site.

3. A waste collection is only triggered when a specific threshold is met: if *on_site_mixed_container_fill* >= *mixed_waste_container_volume_m3*. This condition-based trigger is the essence of a reactive policy; no action is taken until the system reaches a critical state.

Once triggered, the model calculates the number of full containers to be removed using a floor function (math.floor), as only completely full containers are dispatched. The remaining fractional volume is left on-site for the next cycle. The *calculate_required_trucks* heuristic is then called again to determine the number of trips required to collect this specific number of full containers. It is assumed that the recycling company delivers a new empty container in the same trip as picking up the full one.

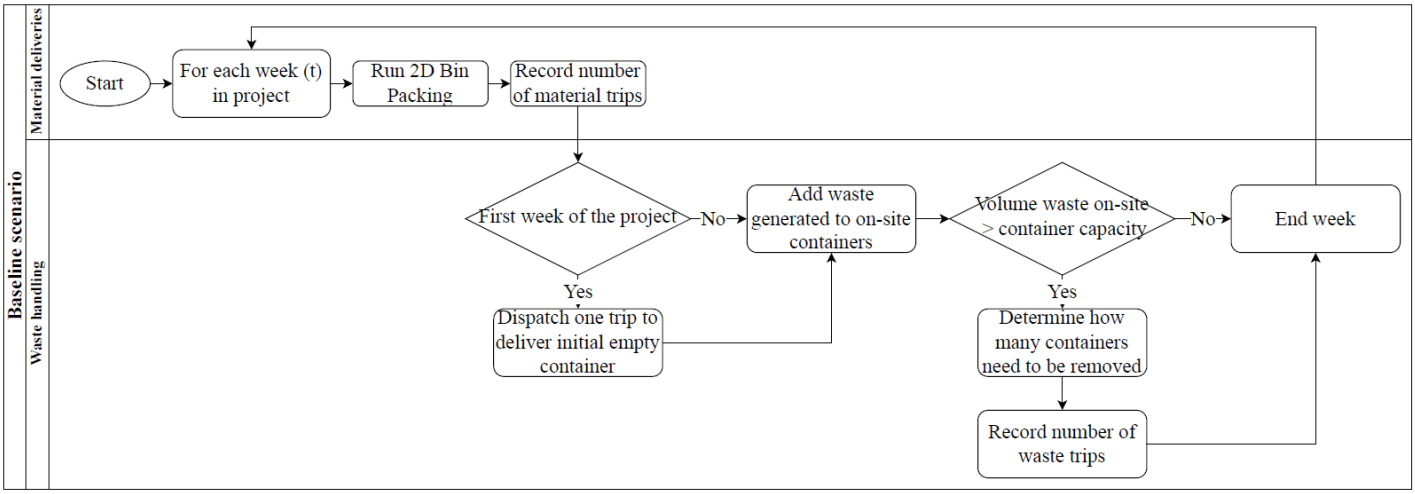


Figure 8 Flowchart baseline scenario

3.2.4 Integrated Model Overview and Purpose

The integrated model simulates the coordinated logistics strategy where inbound materials deliveries and empty waste containers are combined with outbound full waste containers and empty material containers (figure 9). These trips are combined into round trips starting at the CCC travelling to the construction site and back to the CCC. The model's architecture is built around a sequential weekly simulation loop. Within each week of this loop, a two-stage optimization process is executed:

(1) A heuristic pre-calculation using a bin-packing algorithm establishes a baseline for outbound logistics. This stage efficiently calculates the absolute minimum number of trucks required to deliver all scheduled materials and new, empty waste containers to the site.

(2) A linear programming (LP) optimization then refines this plan by optimizing the use of truck capacity for all inbound items (full waste containers and empty material containers), considering a variety of operational and physical constraints.

This hybrid approach of combining a heuristic with mathematical optimization is intentionally chosen to reduce computational complexity. It separates the deterministic problem of outbound packing from the more dynamic and constrained problem of inbound returns, allowing the model to find robust solutions efficiently.

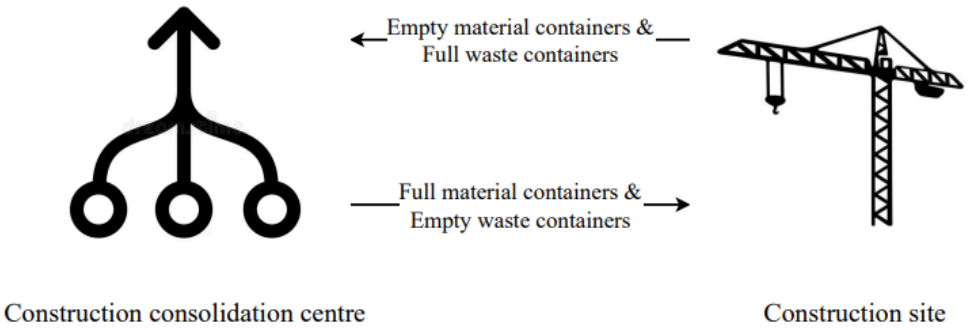


Figure 9 Integrated scenario

3.2.4.1 Model Architecture and Workflow

The core of the model is a simulation loop that advances the system state through a sequence of discrete one-week time steps. This one-week cycle is designed to mirror the real-world sequence of planning of a construction project. Figure 10 shows the flowchart of this weekly cycle.

Previous week

At the beginning of each week t, the state of the system is updated based on the decisions made in the previous week (t−1):

1. The results from the previous week's optimization *(logistics_plan[t-1])* are executed. The *scheduled_trips* are added to the project's total, and the number of *new_containers_to_send* are added to the on-site pool of available empty waste containers. This models the arrival of trucks and resources that were dispatched in the prior planning cycle.
2. The model iterates through every empty material container tracked in the *on_site_empty_material_containers* state variable. The age of each container is increased by one. This simple process models the passing of time in the relevant areas.
3. Material containers scheduled for delivery in week t−1 are assumed to have been used by the start of week t. They are therefore added to the *on_site_empty_material_containers* pool with an age of zero, transitioning them from "in-transit" or "in-use" to "available for return."

Current week

The model processes the forecasted waste generation for the current week t. To use container space efficiently, the model prioritizes filling partially full containers before deploying new ones. For each waste type in the weekly forecast, the model first attempts to fill any existing, partially filled containers associated with that stream. It iterates through the list in *on_site_filling_containers*, adding the generated waste volume until a container reaches its capacity *(waste_container_volume_m3)*. Only when all existing partial containers for that stream are full and waste volume remains does the model draw a new, empty container from the *on_site_empty_containers_count* pool. This ensures that the number of containers in active use is minimized.

Next Week

A crucial step in the model is its forward-looking approach to waste container management. To prevent a shortage of containers in the *next* week (t+1), the model forecasts the waste that will be generated in that future week. It then calculates the number of *new* empty waste containers that must be delivered in the *current* week (t) to satisfy that future demand, after accounting for any space remaining in currently active containers. This forecasted demand for new containers *(required_new_containers)* becomes a key input for the outbound logistics calculation.

The model calculates the absolute minimum number of trucks required for all outbound items scheduled for week t. These items include:

1. All new material deliveries for week t.
2. The *required_new_containers* calculated in the previous step.

This calculation is performed using a bin-packing algorithm, which efficiently arranges the footprints of all outbound containers to find the minimum number of trucks needed. The result, *MinOutboundTrip*, serves as a hard lower bound for the optimization model

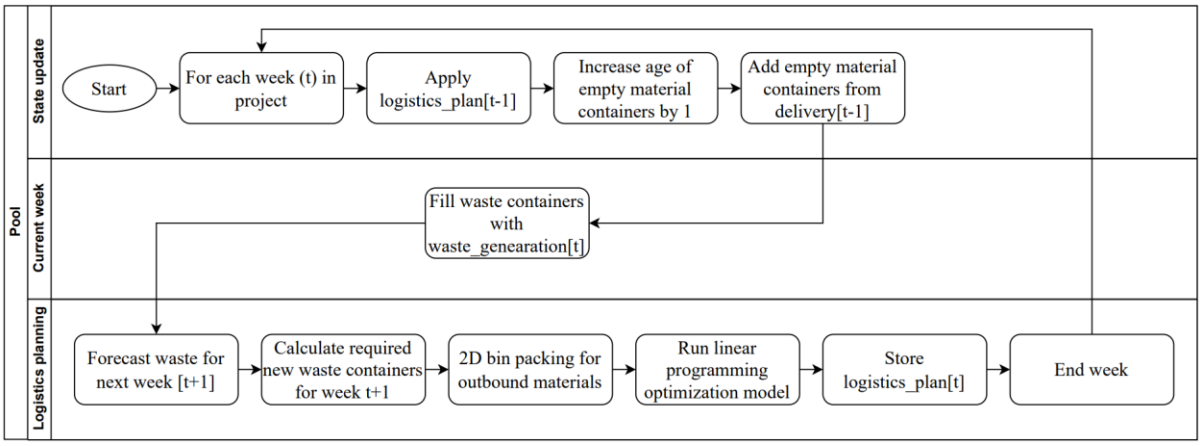


Figure 10 Flowchart integrated scenario

3.2.4.2 Model Components

Before the simulation loop starts, the model requires an initialization phase that sets parameters, loads scenario specific data and sets state variables. The system parameters are used in the process of assigning quantitative values to the model's static properties.

To accurately represent the real world constraints of the logistics system, the model is build around several key components.

- *Truck_dimensions*, this parameter defines the internal floor dimensions (length and width) of a truck. It is used to determine how many containers can be transported on each trip. The size of these trucks is dependant on the user choice between a traditional diesel truck and a smaller electric truck.
- *Container_dimensions*, this is a dictionary that contains the sizes of all the different types of containers that are used in the model. By using varying container sizes, the model ensures that the correct sizes for each delivery are used. These sizes are used to determine how many containers can fit in a single truck
- *Waste_container_volume*, this parameter defines the volumetric capacity of a waste container. It is used to track the current state of a waste container during the project when waste is created. Once the amount of created waste exceeds the volume of that specific waste container it is deemed as full and should be returned.
- *Material_return_window_weeks*, is an integer that represents a constraint that is used to ensure that material boxes are not left on site for too long. It imposes a cap on the total on-site inventory of empty material containers, forcing the model to balance the cost of returns against the risk of exceeding site capacity.

State Variables

State variables are dynamic state structures that are used to track the system's status as it runs over time. These variables are needed to capture the system dynamics while not losing information

- *on_site_filling_containers,* this is a dictionary that maps each waste type to a list of floats. Each float represents the current volume within a specific container, allowing the model to accurately track partially filled containers. This is then used to determine when waste containers are filled and must be picked up.
- *on_site_empty_material_containers,* this is again a dictionary that this time maps each material type to a list of integers. Each integer represents the age of an individual empty material container in weeks. This is used to ensure that empty waste containers do not spend too long at the construction site.

- *on_site_empty_containers_count,* this is an integer counter for the on-site pool of empty waste containers. This variable decouples the supply of empty containers from those already in use, simplifying the logic for deploying new containers. This can be modelled without the use of a dictionary as there is only one type of waste container.

3.2.4.3 Optimization Process

While a heuristic is sufficient for the deterministic outbound problem, the inbound problem involves more complex trade-offs between capacity and resource allocation. To solve this, linear programming (LP) is used, as it is designed to find a provably optimal solution for the allocation of scarce resources (truck space) under a set of linear constraints.

Sets:

t: index for the current week

m: index for material container types

Parameters:

$MinOutboundTrips_t$: the integer of the number of outbound trips as determined in the outbound bin packing section in week t

$NumFullWasteContainers_t$: The total count of full waste containers that are on-site and waiting to be returned in week t

$NumOnsiteEmptyContainers_m$: The total count of empty material containers of each specific type m that are placed onsite in week t

$NumUrgentReturn_m$: The total count of empty containers of type m that have met or exceeded the M*aterial_Return_Window_Weeks* and must therefore be returned in this week t

$Area_m$: floor area of a material container of type m (m^2)

$Area_c$: floor area footprint of a waste container of type c (m^2)

$Waste_{c,t}$: volume of waste of category c that must be removed in week t

$Capacity_v$: floor area capacity of vehicle type v (m^2)

$Maxstorage_c$: maximum number of full waste containers allowed on-site

Decision variable:

$TotalTrips_t$: The primary integer decision variable representing the total number of round trips to schedule in week *t*. Its domain is constrained such that $TotalTrips_t \geq MinOutboundTrips_t$

$ReturnMaterial_m$: An integer decision variable representing the number of empty material containers of type *m* to schedule for return in week *t*

Objective function:

$$Minimize \quad (TotalTrips_t - 0.001\, x \sum_m ReturnMaterial_m \tag{7}$$

The objective function is formulated to pursue two distinct goals; the first main goal is to minimize the total of number of trips as lower trips benefit each KPI. The second goal is to maximize the return of empty material containers and full waste containers into these trips. By adding a very low coefficient of 0.001 it is ensured that the model never adds a trip to return these containers if not needed. However,

it does ensure that the model also minimizes the empty space of the trucks travelling from the construction site to the CCC.

Constraints:

1. The total area required for full waste containers and returned empty containers must not exceed the total capacity of the trucks

$$(NumFullWasteContainers_t \times Area_c) + \sum_m (ReturnMaterial_m \times Area_m) \leq TotalTrips_t \times TruckArea \quad (8)$$

2. The logistics plan must ensure the return of any empty material container that has been on-site for a specified duration (e.g., 3 weeks or more).

$$\forall m,\ ReturnMaterial_m \geq NumUrgentReturn_m \quad (9)$$

3. The total number of full waste containers left on-site after the trip must not exceed the maximum storage limit.

$$\sum_m (NumOnSiteFullWaste_m - ReturnWaste_c) \leq MaxStorage_c \quad (10)$$

Simulation update

After running the simulation, the final step is to update the system. The state variables are updated based on the optimal solution found by the LP solver. Specifically, the model iterates through the solved values for *ReturnMaterial_m* and removes the corresponding items from the *on_site_empty_material_containers* inventory. The logic for this removal implements a first-in, first-out policy; by sorting the containers by age before removal, the model ensures that the oldest assets are always the first to be returned, which is the most logical implementation of the aging mechanism. Similarly, returned full waste containers are removed from the *on_site_filling_containers* state. This step cleanly concludes the weekly cycle and prepares the system's state for the next weeks

3.3 Decision Support Tool

The Decisions Support Tool was conceptually designed as an integrative framework that translate the KPI assessment, as defined in section 3.1, and the simulation results, as defined in section 3.2, into a user-oriented decision environment. The tool is architected as a client-server application using Python and the Flask framework. This approach is chosen to methodologically separate the user-facing interface from the data processing and simulation logic, ensuring both usability and robustness.

The resulting DST provides a final summary comparing how both scenarios score on the KPIs, as well as a detailed weekly logistics plan. The section will cover these elements in the same flow as mentioned in figure 11.

3.3.1 Target User

The methodological design of the DST is tailored for project managers and logistical planners, for who the tool is intended to aid in decisions making during the procurement and planning phases. This user-centric design principle is critical; it ensures that the data required is readily available to these stakeholders and that the resulting analysis is presented in a format that is intuitive and directly applicable to their decision-making context.

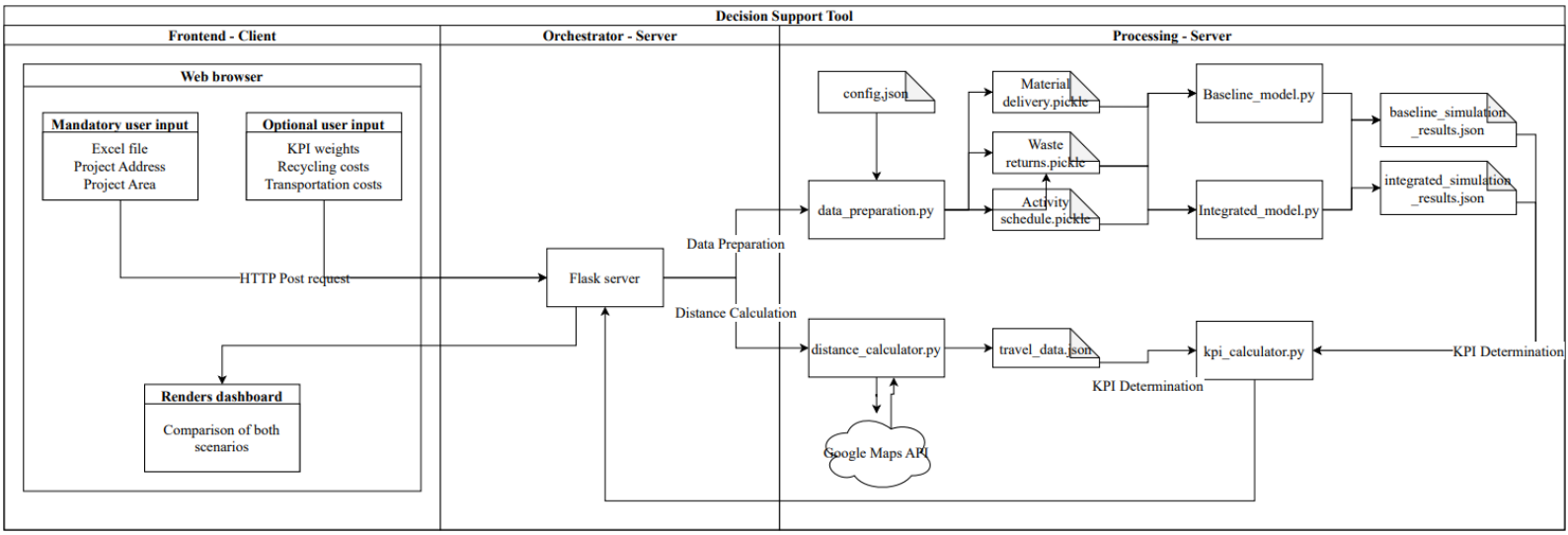


Figure 11 Decision support tool

3.3.2 Frontend

The frontend serves as the primary data ingestion layer of the methodology. A web-based interface was chosen to ensure accessibility without requiring specialized software installation. Through this interface, the user provides the necessary inputs to initialize the simulation models: an Excel file that includes the weekly material planning (this planning should list each specific materials stream to be delivered so that the volumes that are transported can be determined), the project address and location of the recycling centre (to determine the travel data), the size of the storage area designated for waste storage, and the project area (to determine the volumes of generated waste). Once submitted, the frontend sends this data as an HTTP POST request to the Flask server.

The Flask server functions as the central backend controller that orchestrates the data flow. Its specific role is to host an API endpoint that listens for the user's file submission. Upon receiving the data, the Flask application directs the project address to the distance calculation module and the Excel file to the data preparation script. It does this by calling the Google Maps API to determine the distance between the project location and the three different CCC locations. The tool then compares them and lists the travel distance and time for the shortest route. This information is stored in a JSON file to be later used in determining the KPIs. The specific function of the JSON file is to cache the output from the Google Maps API call. This prevents the need to make repeated, time-consuming API requests during the session, as the KPI determination script can simply read the static distance and time values directly from this file.

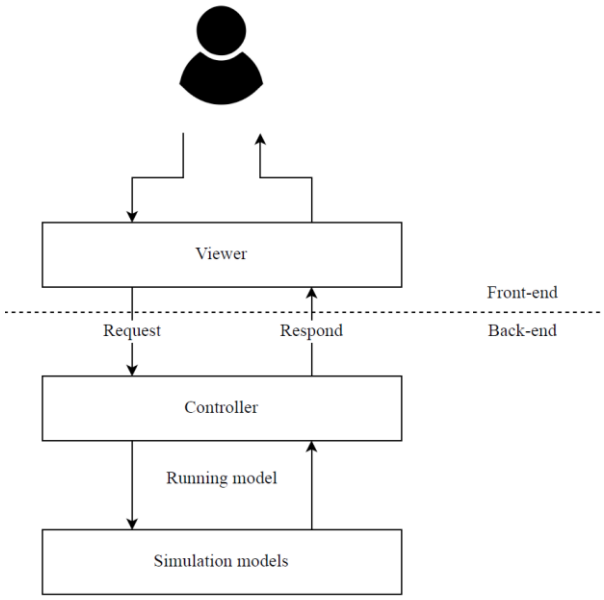


Figure 12 User and tool interaction

3.3.3 Data Preparation

This module serves as the critical data transformation step in the methodology. Its purpose is to convert the raw, user-provided project schedule into a standardized, structured format that the simulation models can process (this process is explained in chapter 3.2.2). The output of this module, dictionaries detailing the material deliveries and waste generation, is saved as pickle files to be used in the simulation.

3.3.4 Baseline Model

This model functions as the control case. It uses the standardized data from the preparation module and simulates the current, uncoordinated industry practice for inner-city construction projects. The purpose of this simulation, of which the method has been explained in section 3.2.3, is to establish a quantitative benchmark against which the proposed alternative can be measured. The results are then exported as a JSON file which will be used in the KPI determination

3.3.5 Integrated Model

This model will be used as the tested alternative, using the same input data as the baseline model, the integrated model simulates the coordinated logistics strategy where inbound materials deliveries and empty waste containers are combined with outbound full waste containers and empty material containers. The method applied here is a more advanced simulation logic from section 3.2.4. This utilizes a hybrid heuristic and linear programming optimization. This approach was chosen to effectively model the complexities of a coordinated system of forward and reverse logistics. The output provides a dataset that represents the performance of this alternative. This output is exported as a JSON file so that it can be used to determine the KPIs.

3.3.6 KPI Determination

This final module represents the synthesis and quantification stage of the methodology. Its function is to translate the raw output from the two simulation models (e.g., number of trips and waste volumes) into the performance indicators defined in section 3.1. It reads the simulation results from the JSON files and systematically calculates the economic, environmental, and social scores for both scenarios.

To enhance the usability of the tool, this KPI determination screen is designed to be interactive. Users can adjust key parameters (e.g., hourly labour rates, recycling costs) to reflect their specific project context. This allows the tool to function not just as a static model but as a flexible decision support environment. The results from this KPI determination section are send to the flask server where they are translated back to the frontend.

3.4 Validation

The credibility of a decision support tool is determined through the quality of the models that are used to determine the end results, and the validation of the DST itself. To ensure the decision support tool is both functionally robust and practically useful, a two-part validation strategy will be executed, focusing on the tool's usability and the predictive accuracy of its underlying models.

3.4.1 Model Validation

The first part of the validation will focus on the accuracy of the simulation's material deliveries. This will be evaluated using a retrospective case study. The validation will use the project's original pre-construction weekly planning as input to generate a logistics plan. The outcome of this plan will be compared against the actual transport logs from the completed project. This comparison is limited to the material deliveries of both scenarios. As the CCC has never handled waste returns there is no data to validate the waste returns of both models. Furthermore, the accuracy of the underlying waste generation forecast, while critical to the simulation, will not be re-validated in this study. Its reliability is instead accepted based on the 95% accuracy achieved in the foundational research by Solís-Guzmán et al. (2009). This additional validation is again not made due to missing data regarding waste volumes.

3.4.2 Tool Validation

The second part of the validation focusses on the user usability of the tool. The practical utility of the decision support tool will be evaluated through usability testing. A representative user will be asked to participate in a test session. In the test session they will be asked to upload the input required to run the model. After this they are asked to use the model without help. They are then asked to give feedback regarding the usability of the tool. Are all aspects clear and does it provide insight into the decision making.

The validation is structured as a test for a representative user that can show if the user benefits from the decision support tool. This study is structured as usability test that sees the user interacting with the DST to provide additional information regarding relevant KPIs. The participants in this test are all potential users of the tool. This means that they should be responsible for the logistical plan of a construction project. The study needs at least five different participants to validate the tool. This number is based on an article that argued that five different users will uncover 85% of usability problems. (Nielsen, 2000). As the collaborating company deals with a lot of different stakeholders in the project management and logistic sector, their network will be used to reach out to five different participants.

In the test the users are supplied with a case study that can be used as an example. This means the user gets provided a laptop that can access the tool via a private web browser connection and project details regarding the project area, location, and onsite storage space. The participants are then asked to use

these project details in combination with the tool to gain insight into the different KPIs. When the participants are using the tool, they are asked to think aloud, this means that they verbalize their thoughts during the test, which includes:

- Entering the project parameters into the tool's input fields.
- Uploading the provided Excel file to run the simulation.
- Navigating to the results summary to compare the two scenarios.
- Interpreting the detailed Key Performance Indicator (KPI) comparison for economic, environmental, and social metrics.
- Exploring the interactive KPI calculation page to understand how certain parameters influence the outcome.

After performing these tasks, they are asked to fill in two different small questionnaires. The first being a System Usability Scale (SUS) test. This is standardized industry recognized test which has the purpose of giving in a general score of the overall usability of the tool. The test consists of a 10-item questionnaire with alternating positive and negative statements, which participants rate on a 5-point scale. The advantage of this is test is that it allows for comparisons as it considers a standardized test. The downside is that it is not specifically tailored to this tool. Therefore, the second questionary focusses on directly on the tool. It asks about the clarity of the KPI breakdowns, the usefulness of the monetized cost feature, and the confidence of the user in the results. The specific questions can be found in appendix 1.

The scoring for the SUS is calculated based on a specific formula that accounts for the alternating positive and negative phrasing of the statements. For odd-numbered items (1, 3, 5, 7, 9), the score contribution is the user's response (1-5) minus 1. For the negatively phrased even-numbered items (2, 4, 6, 8, 10), the contribution is calculated as 5 minus the user's response. The sum of these ten adjusted scores is then multiplied by 2.5 to convert the result to a 0-100 scale, where 100 represents the highest possible usability score. This results in the following formula:

Score = 2,5 * ((score uneven numbers – 1) + (5 – score even numbers))

Interpretating the score a score above 70 is seen as a good score and above 85 is seen as excellent (Soegaard, 2025). A high SUS score is a strong predictor of user acceptance and adoption, indicates a high level of user satisfaction and indicates a positive attitude towards the tool (Bangor et al., 2008) (Lewis & Sauro, 2009).

The tool specific questionnaire moves away from the alternating formula of the SUS and employs a more direct scoring method. For this test, the final score is calculated by adding all the individual scores from each question together. This total sum is then multiplied by 2 to determine the final score.

The two questionnaires are designed to be complementary to each other. The SUS test provides a global, benchmark score of overall usability, while the tool-specific test offers feedback that helps explain the score. For instance, a high overall SUS score paired with low scores on questions regarding confidence in the results would indicate that while the tool is easy to use, its credibility or transparency needs improvement.

3.5 Sensitivity Analysis

Following the validation of the model and the DST, a sensitivity analysis will be conducted to assess the robustness of the decision support tool's recommendations. The primary goal of this analysis is to understand how uncertainty and variability in key input parameters affect the relative performance of the baseline and integrated scenario. Many economic and environmental parameters are subject to market fluctuations, policy changes, and project-specific negotiations. Therefore, this analysis is critical for determining the conditions under which one model becomes more favourable than the other, thereby providing the end-user with a deeper understanding of the risks and opportunities associated with their decision.

3.5.1 Sensitivity Analysis of Economic Parameters

The first part of this sensitivity analysis focused on quantifying the impact of the key economic parameters on the total cost outcome. These parameters are susceptible to regional differences, project specific negotiations and market volatility. Therefore, this analysis seeks to identify which parameters exert the most influence on the financial viability in each scenario. This analysis is performed on the Renaissance project as it is the archetype of inner-city construction projects with site constraints.

To identify this influence, a one-at-a-time sensitivity analysis is used. In this analysis, a single input parameter is varied across a 15% increase and decrease while all other parameters are held constant. This method allows for the clear isolation and direct measurement of each parameter's individual impact on the model's primary economic output. This analysis is performed on all the economic parameters to understand which of them has the largest input on the total economic costs. These results will be shown using tornado plots. This graph type provides immediate visual ranking of the tested parameters by plotting the impact on the total economic costs against each parameter.

The parameter that has the largest impact on the economic performance is then investigated future. The break-even point of this parameter is determined to investigate the robustness to changes in the main parameter. This analysis is performed on every case study. This is done to determine the robustness across different case studies.

3.5.2 Scenario Analysis of Project Constraints

This second part of the sensitivity analysis investigates the model’s response to changes in the physical and logistical project characteristics. Its purpose is to define the specific operational context and boundary conditions under which a certain model is advantageous over the other model. This analysis will evaluate the model's performance by systematically varying four primary inputs and contexts:

On-site storage area, this variable is an important reason that most project managers are interested in working with a CCC in the first place. It is a central problem challenge for inner-city construction projects. This scenario will explore how increasing and decreasing the available on-site storage area impacts the number of trips and how this in turn influences the KPIs. This is only interesting for the integrated scenario as the baseline scenario does not benefit from more storage space as it only considers one container on-site.

The amount of waste that is generated in a project, this variable tests the scalability of each model. To test this the project size is used as this is a direct proxy for waste generated in a construction project. The analysis will determine if there is a tipping point for which one scenario is more viable than the other.

Transportation is a key differentiator in both cost and emissions. As the integrated scenario often necessitates more frequent trips, this scenario will assess how increasing travel distance between the construction site, and the consolidation hub affects the relative performance of the two models.

Carbon pricing scenarios, this analysis evaluates the economic impact of varying carbon prices, reflecting different current and future regulatory environments. The analysis will compare the total monetized cost under the standard baseline price set by the EU emissions trading rate against higher "shadow prices" adopted by progressive municipalities. These shadow prices are adopted in tenders to ensure that construction projects are more sustainable. In addition, the carbon costs will be plotted for both models for different carbon prices. The goal is that this section shows the current effect of the carbon cost as well as the anticipated increases in carbon pricing for both scenarios.

For each scenario, these analyses will seek to identify the economic and environmental tipping points. There are thresholds at which the net the outcome of both scenarios are the same. This allows the stakeholder insight into at which moment a certain scenario becomes more effective.

3.6 Conclusion

This chapter discussed the methodology used to construct a quantitative DST designed to answer the main research question. The methodology uses a three-part structure.

First it defines and quantifies the KPIs using literature with regards to the economic, environmental and social impacts. In addition, it describes how carbon pricing can be used to allow for a semi-integrated total costs calculation.

Secondly, it outlined the architecture of two comparative simulation models. With one simulating the current scenario and the other a scenario where waste returns are integrated with material deliveries.

The third main section details the assembly of the complete DST using information retrieved from running both simulations. The DST is explained from the user-facing frontend to the backend processing that integrates data preparation, running both simulation models, and the KPI calculations. To ensure the tool's credibility, the methodology also established a two-part validation strategy. This strategy focussed on the predictive accuracy of the models and the tool's usability with end-users. Furthermore, a series of sensitivity analyses were designed to test the robustness of the tool's recommendations against variations in key economic parameters and project constraints. This chapter has thus laid the necessary groundwork for applying the DST to real world case studies.

4. Case studies

To test and validate the Decision Support Tool (DST) developed in the preceding methodology chapter, a case study approach has been employed. The method was chosen to asses the tool's practical applicability and robustness by testing it on real-world construction projects. The case study approach serves to bridge the gap between the theoretical framework of the simulation models and the operational realities of construction project. By applying the DST to real-world projects, this chapter aims to evaluate the tool's ability to generate meaningful, data-driven insights that are relevant and actionable for project stakeholders.

The case studies used in this chapter have been chosen to ensure diversity across project types and constraints. Three distinct projects have been chosen; the renovation of the former Tivoli music venue in Utrecht, the renovation of the Renaissance Hotel in Amsterdam, and the new construction of the Beneluxlaan residential tower in Utrecht. This chapter will present each case study in detail. For each project, it will outline the specific context, the logistical and spatial constraints observed during site visits, and the data gathered to be used as inputs for the simulation. This detailed exposition provides the necessary foundation for the comparative analysis presented in Chapter 5, where the DST is applied to these cases to quantify and evaluate the performance of the baseline and integrated C&DWM strategies.

4.1 Tivoli

This considers a renovation of the old music venue Tivoli. It concerns a full renovation project in the middle of Utrecht (figure 14). The old music venue is being transformed into a multifunctional building that includes a wine bar, restaurant, podium and hotel. During the site-visit the project was in different phases. Parts of the building were in the finishing stage while other parts were still in the demolishing phase.

The unique aspect of the building is that different construction phases were occurring at the same time in the project. In addition, the project is a complex renovation project within a dense, historic urban environment. The project is subject to numerous site constraints that impact material delivery, waste management, and overall operational efficiency.

4.1.1 Data and Observations

Logistical and access constraints:

- The site's central location in Utrecht is difficult to reach for large trucks.
- Roads next to the canals, which are necessary for access, have a maximum axle load of 2000kg, restricting vehicle size.
- All materials and waste must be moved through a narrow corridor approximately two meters wide, making it impossible to use large containers.
- The existing building has multiple levels, with only partial elevator access. Some areas can only be reached via stairs.

Space and storage constraints:

- There is an extremely limited storage area of only 30m² for waste collection.

Waste management practices and consequences:

- Due to space limitations, waste is collected in small containers that are picked up one to three times per day by a car with a double-axle trailer.
- There is no room on-site to store separate containers for different types of waste. Consequently, all waste is collected together and labelled as general "construction waste."

- In areas accessible only by stairs, waste is collected in large bags and then manually carried down to the containers, increasing labour time and physical strain.

In conclusion, this renovation project serves as an example of a how severe physical site constraint in urban city construction projects can dictate operational methods and increase inefficiency. The result of restricted access, minimal storage and challenging on-site logistics impacts the project's budget and timeline but also significantly curtails sustainability efforts like waste separation and recycling.

Figure 14 Project overview. (de Bonth van Hulten, n.d.)

Figure 13 Largest container that fits

Figure 16 On-site waste container

Figure 15 Storage area for waste containers

4.2 Renaissance

The Renaissance project considers the renovation of a hotel that is situated in the centre of Amsterdam (figure 17). It concerns a full renovation that is done in different phases so that parts can still be rented out to tourists. This means that during the site visit the construction project was in different phases. Parts of the building were in the finishing phase while other parts were still being demolished.

The key challenge is managing a large-scale renovation within a live, operational hotel in a high-traffic urban centre. The need to minimize disruption to guests, combined with severe spatial and logistical constraints, creates a disorganized environment for material and waste management.

4.2.1 Data and Observations

Logistical and access constraints:

- Its location in the centre of Amsterdam makes access for delivery and waste-removal trucks difficult.
- There is only enough space for a single truck to load or unload at one time, creating potential bottlenecks.

Space and storage constraints

- A very limited space of approximately 40m² is available for all material and waste storage. This area contained one large container designated for mixed construction waste.
- The shared storage areas were visibly disorganized, a condition exacerbated by the simultaneous operation of different construction phases.

Waste management practices and consequences

- Waste is primarily stored in smaller on-site containers with minimal separation; most of it is treated as unseparated waste and picked up almost daily.
- A notable unexpected practice was observed: workers were using material delivery boxes as makeshift waste bins within the active construction zones (figure 19).
- This unseparated waste disposal is not the intended purpose of the containers, and some are beginning to break from the pressure and weight.
- While problematic, this behaviour highlights a clear demand from workers for more numerous and conveniently located waste containers.

In conclusion, this renovation project demonstrates the conflict between construction logistics and the demand of an operational business. The space limitations and disorganization from overlapping construction phases leads workers to adopt inefficient, informal waste disposal methods. This suggests that the current waste management, in addition to being not sustainable, is also inadequate for the practical needs of the on-site workers.

Figure 17 Project overview (Hospitality Management. 2023)

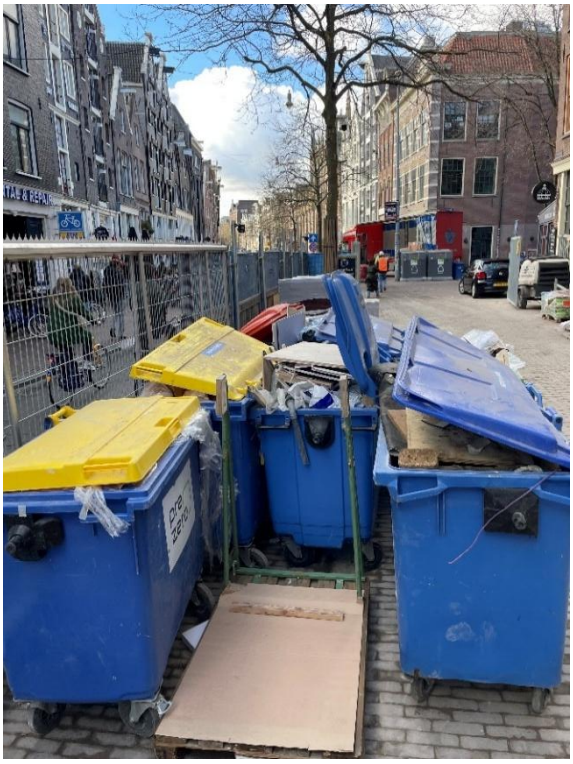


Figure 18 Storage area for waste containers

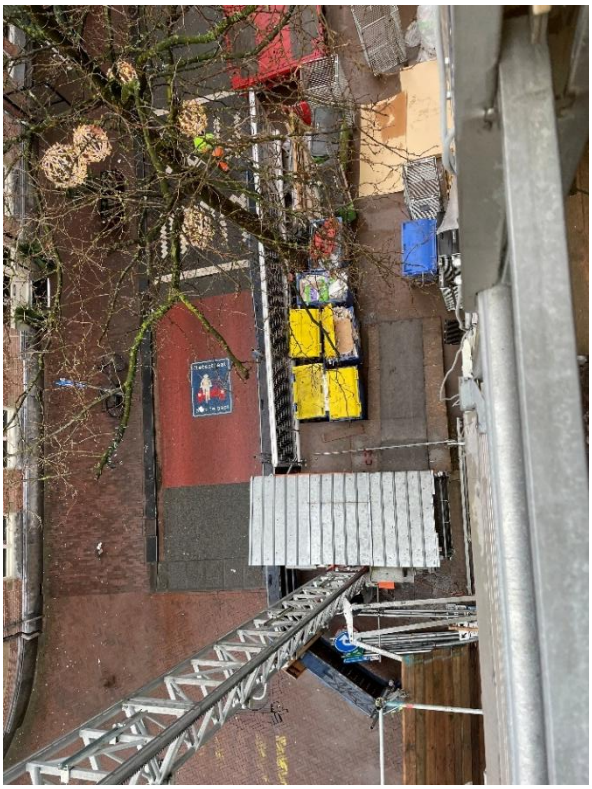


Figure 20 Top view of storage area

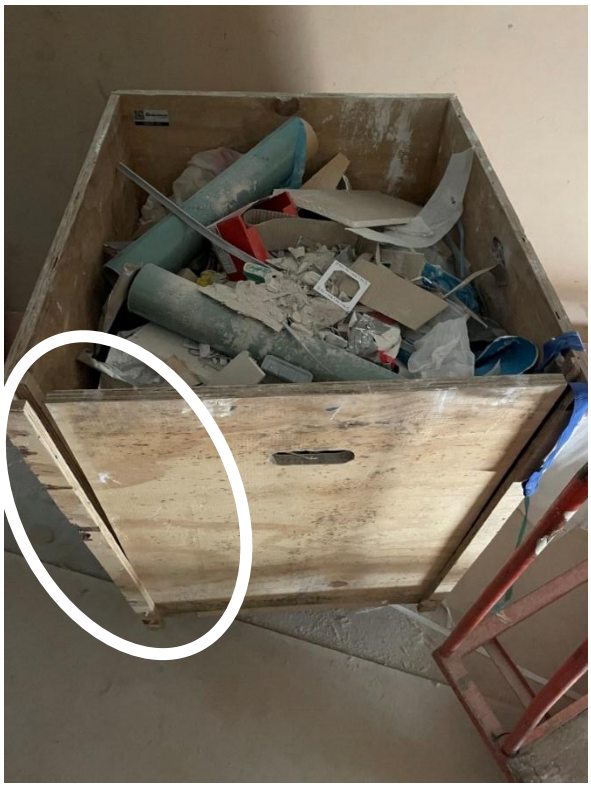


Figure 19 Misuse of material containers

4.3 Beneluxlaan

This considers the construction of a high-rise tower located in Utrecht (figure 21). This construction project is different from the other projects as it is a location with less site constraints. As it is not located in the city centre it allows the rent of nearby space that can be used for storage space during the construction phase. This allows for large waste containers in which waste can be separated on-site.

The primary challenge for this project is not the presence of severe physical constraints, but rather the economic trade-off associated with achieving efficient on-site logistics. The ability to rent adjacent space for storage and waste management is a key advantage, but it comes at a direct financial cost.

4.3.1 Data and Observations

The following conditions and practices were observed:

Logistical and access constraints:

- As the project is not in the city centre, it has better accessibility for large vehicles and equipment.

Space and storage constraints:

- The project has the option to rent nearby space, which is used for material storage and waste collection. This allows for a more organized and spacious logistics operation than is possible at the inner-city sites.

Waste management practices and consequences

- The additional space allows for the placement of large waste containers dedicated to different materials, enabling effective on-site waste separation.
- The primary consequence of this method is the cost of renting the additional land.
- There is a clear financial incentive to optimize the use of this space; if waste separation could be achieved in a smaller footprint, it would directly reduce project costs.

In conclusion, this project provides a valuable counterpoint to the inner-city cases. It demonstrates that when physical constraints are removed, effective waste separation is achievable. However, it also shifts the primary constraint from the physical to the financial, highlighting that even in less-constrained environments, there is a strong business case for developing more space-efficient logistics and waste management solutions.

Figure 21 Project overview (Wessels Rijssen n.d.)

Figure 23 Large containers for three different waste streams

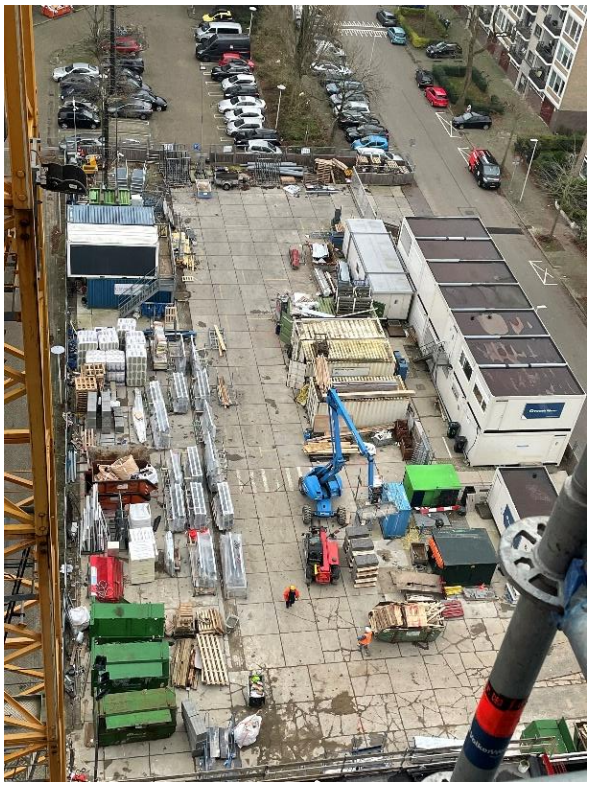


Figure 22 Top view of storage space

4.4 Conclusion

This chapter has presented three different case studies to have been selected to provide a robust empirical foundation for the validation and testing of the Decision Support Tool. The Tivoli and Renaissance projects are the archetypes of the constrained inner-city construction project which form the scope of this thesis. The Beneluxlaan provides a project that is less constrained. It is a larger-scale new construction project in a location where the physical constraints are less severe. In this project the more efficient integrated scenario can still be beneficial.

Collectively, these cases understate that severe spatial limitations area primary driver of current unsustainable C&DWM practices. These projects adopt mixed-waste practices to solve the site constraints that are present. Furthermore, the Beneluxlaan case demonstrates that even when space is available, its associated rental cost introduces a financial imperative to optimize its use, highlighting the universal need for more space-efficient logistics and waste management solutions.

These real-world projects and their specific operational parameters and constraints form the groundwork for the subsequent analysis. The following chapter will apply the DST to these three cases to quantitatively evaluate the performance of the baseline and integrated scenarios. Resulting in a data-driven assessment of the economic, environmental and social impacts.

5. Results

This chapter presents the primary findings of the research. Following the dual focus of the study, the results are organized into two main sections. The primary objective is to quantify the economic, environmental, and social impacts of both the baseline and integrated C&DWM strategies, providing an empirical basis for evaluating their respective impacts. The chapter begins by validating the predictive accuracy of the logistics simulation against historical project data. Following this, it provides an in-depth analysis of the Renaissance case study. Followed by a comparative analysis across all three projects to identify performance trends and sensitivities. The chapter concludes with a series of sensitivity analyses designed to test the robustness of the findings against variations in key economic and operational parameters.

5.1 Validating Material Deliveries

Before presenting the results, it is methodologically essential to first establish the credibility of the simulation's output. To test this a retrospective validation was conducted on the model's predicted number of material delivery trips against the actual transport logs from the completed case studies. This process serves as a validation of the underlaying bin-packing algorithm for both the baseline and integrated scenario. The results of this validation, as presented in table 5, show a high degree of correlation between the predicted values and the historical data.

Table 5 Baseline material delivery validation

Project	baseline result for delivery	Actual trips made for delivery
Beneluxlaan, Utrecht	51 trips	51 trips
Tivoli, Utrecht	72 trips	72 trips
Renaissance	72 trips	74 trips

As can be seen in table 5 the baseline results closely resemble the actual trips made for material delivery. For two projects the number is the exact same and for one project there is a difference of 2 trips (2.78%). This difference can be explained by some late deliveries demanded by the project manager. In these cases, the project manager forgot to order certain materials or made a last-minute schedule change resulting in an inefficient additional trip. This is not expected beforehand but can be seen in the final number of trips. This falls within the margin of error of 5% that has been established in the methodology section. As mentioned, this is only the delivery of materials that is being modelled. This is being modelled the same way for both the baseline- and integrated model. Therefore, it can be assumed that the delivery can be fully predicted by both models.

Testing the return of waste is not possible as there is no data that has tracked the number of trips needed for waste disposal in these case studies. This means that there is no absolute certainty in the return of the waste materials for both models. However, the waste return uses comparable methods to the material delivery determination so it can be assumed to be at least somewhat reliable.

5.2 Case Study Renaissance

As the material deliveries have been validated the next step in the result is to test the tool using the Renaissance case study. This case study has been chosen to investigate in depth as it is the case study that is most in line with the scope of this project. This case study will be explained in full detail showing all the results for each individual KPI. After this the percentual differences between the baseline model and integrated model will be shown for each case study. This allows for easy comparison between the

case study without providing redundant information. The full explained case studies for the Beneluxlaan and Tivoli are still presented in appendix 2.

This case study looks at the Renaissance project, involving the renovation of a hotel situated in the centre of Amsterdam. The renovation was a construction project of around 8500m^2. The project is distinct due to its phased approach, allowing parts of the hotel to remain operational while construction is underway. This means different construction phases, such as demolition and finishing, occur simultaneously, creating a complex logistical environment. The project faces several site constraints typical of a dense urban core: it is difficult for trucks to reach, there is only space for one truck to load or unload at a time, and the available on-site storage is limited to approximately 40 m². This case provides a valuable opportunity to assess the model's impact in a highly constrained and dynamic environment.

Table 6 Economic score Renaissance case study

Economic costs	**Baseline scenario**	**Integrated scenario**
Transportation costs	**€ 3,888.63**	**€ 4,508.57**
Rental costs	**€ 5,695.68**	**€ 7,487.46**
Blank	*€ 2,823.70*	*€ 2,909.72*
Gypsum board cart	*€ 1,881.90*	*€ 2,521.50*
Pallet	*€ 170.00*	*€ 220.00*
Roll container	*€ 25.92*	*€ 25.92*
Tile container	*€ 314.16*	*€ 347.82*
Large waste container	*€ 480.00*	-
Waste container	-	*€ 1,462.50*
Recycling costs	**€ 26,499.15**	**€ 16,005.33**
Mixed waste	€ 26,499.15	-
Ceramic		*€ 9,447.75*
Gypsum	-	*€ 1,051.37*
Remaining rubble	-	*€ 5,329.50*
Wood	-	*€ 176.72*
Sorting costs	**-**	**€ 2,808.00**
Revenue from metal	**€ 9,408.48**	**€ 9,408.48**
Carbon cost	**€ 1,597.73**	**€ 195.09**
Total economic costs	*€ 28,272.71*	*€ 21,595.97*

Table 6 shows the results from the simulation; it reveals a significant disparity in the economic outcomes of the two scenarios. The baseline scenario resulted in a total economic cost of €28,272.71. In contrast, the integrated scenario yielded a substantially lower total economic cost of €21,595.97, representing a cost reduction of €6,676.74, or 23.62%. This substantial financial advantage is not only caused by simple cost-cutting measures, but it also shows a strategic shift of how waste is managed, driven by one primary factor and several smaller trade-offs.

The primary factor of this economic difference is the significant reduction in recycling costs. The baseline model, using a mixed-waste approach, incurs a high disposal cost of €26,499.15. This high cost is caused by the recycling centre having to sort the waste at the recycling plant before it can be recycled. By enabling on-site source separation, the integrated model reduces recycling costs by 39.60% to €16,005.33. This finding confirms that the economic viability of a circular C&DWM strategy relies on the ability to produce clean, separated waste streams that result in lower recycling fees.

However, to achieve this saving, operational costs slightly increase. The integrated model incurred higher transportation costs and rental costs. The increase in transportation is caused by the inefficiency in transporting multiple smaller containers as opposed to one large container. The higher rental cost of the integrated model is incurred similarly. Using multiple smaller containers results in more inefficient use of containers. This means that containers spend more time on-site waiting to be transported to the CCC. The use of more containers that spend more time on-site result in higher rental costs.

In addition, the integrated model introduces a new sorting cost of €2,808.00. This cost represents the monetized value of shifting the sorting process from the recycling centre to construction site. The additional cost is an increase in the on-site labour as it takes workers additional time to sort the waste. To conclude, the stakeholders must determine if incurring an increase in operational costs for transport, rental, and on-site sorting is outweighed by the much larger reduction in waste disposal fees. The results for the Renaissance project show that in this case the integrated scenario is significantly advantageous to the baseline scenario.

Finally, the analysis incorporates the carbon costs, a metric that is used to link the project's environmental emissions to the economic costs. As shown in table 6, the baseline scenario's higher emission result in a carbon cost of € 1,597.73, compare this to the integrated model's lower CO_2 production resulting in a cost of just €195.09. This shows that the environmental benefits explained in the subsequent section are not merely abstract. The lower CO_2 production also translates into a tangible financial advantage. The inclusion of this cost provides a holistic economic overview, concluding that the integrated scenario is more resilient to regulatory changes which are expected to increasingly penalize carbon emissions.

Table 7 Environmental score Renaissance case study

Environmental impact (tonnes CO_2 produced)	**Baseline scenario**	**Integrated scenario**
Transportation emissions	2.39 t CO_2	2.74 t CO_2
Sorting emissions	20.05 t CO_2	-
Total CO_2 production	***22.44t CO_2***	***2.74 t CO_2***

The environmental impact, as shown in table 7, reveals a significantly lower CO_2 production for the integrated model. It achieved an 87.79% reduction in total CO_2 production. This outcome provides insight into the true drivers of carbon emissions in C&DW management. Table 7 shows that the main source of emissions is the mechanical sorting of mixed waste at the recycling centre which generated 20.05 tonnes of CO_2. This value is significantly higher than the slight increase in transport emissions for the integrated scenario that is caused by an increase in the number of trips.

This finding shows that the primary environmental benefit of the integrated model stems from the elimination of an entire energy consuming industrial process. By sorting waste on-site, the integrated model avoids the need for heavy machinery to sort mixed waste, thereby resulting in a significantly lower total CO_2 production. The modest increase in transportation emissions is insignificant when compared to the massive savings achieved by preventing waste from being mixed in the first place. To conclude, from an environmental perspective, the benefits of enabling on-site separation far outweigh the marginal impact of the increased logistical activity required to facilitate it.

Table 8 Social score Renaissance case study

Social impact	**Baseline scenario**	**Integrated scenario**
Total number of trips	82	94

The social impact analysis, represented by the total number of vehicle trips as detailed in table 8, quantifies the primary trade-off inherent in the integrated approach. The integrated scenario required 94 trips compared to the baseline's 82, an increase of 14.63%. This shows that the stakeholders should weigh the economic and environmental benefits against the increase in traffic congestion, noise pollution and decreased traffic safety.

5.3 Comparative Results Analysis

Going beyond the analysis of a single case, this section synthesizes the findings across al three case studies to identify overarching trends and links between them. This comparison is important for validating the generalizability of the DST's findings. The analysis focuses on the percentage difference for each Key Performance Indicator (KPI), which quantifies the relative increase or decrease when shifting from the baseline to the integrated model. For instance, a value of 15.94% for transportation costs signifies that this cost is 15.94% higher in the integrated model. While the detailed results and explanations for each case study follow a similar pattern, they are provided in full in Appendix 2 for completeness. To avoid repetition in the main body of this thesis, this section will therefore focus on the more insightful analysis: explaining the variations in these percentage changes between the different case studies.

Table 9 Difference between baseline and integrated scenario

	Renaissance	**Tivoli**	**Beneluxlaan**
Transportation costs	15.94%	11.93%	8.92%
Rental costs	31.46%	24.30%	64.74%
Recycling costs	-39.60%	-44.17%	-40.67%
Sorting costs	-	-	-
Revenue from metal	0.00%	0.00%	0.00%
Carbon costs	-69.07%	-85.96%	-81.86%
Total economic costs	**-23.62%**	**-20.29%**	**-37.15%**
Transportation emissions	14.78%	12.50%	-39.63%
Sorting emissions	-	-	-
Total CO_2 production	**-87.79%**	**-85.88%**	**-93.77%**
Total number of trips	**14.63%**	**13.70%**	**8.45%**

The most significant insight from the comparative analysis shown in table 9, is the universal decrease in recycling costs and sorting emissions in the integrated model. Across all three case studies this resulted in the integrated model consistently delivering substantial economic savings (ranging from 20.29% to 37.15%) and substantial CO_2 reductions (85% to 94%). This consistency demonstrates that the financial and environmental viability of a circular C&DWM strategy is less depended on optimizing transportation and more on avoiding high cost and emissions associated with mixed-waste processing.

While the net benefits are universal, the analysis showed that there is a difference between the operational costs and emissions. The rental costs and number of trips is shown to be sensitive to certain site-constraints. The Beneluxlaan project, with its large 100 m² on-site storage area, provides a clear example. It exhibited the highest increase in rental costs (+64.74%) but the lowest increase in total trips (+8.45%). Greater on-site storage provides the optimization model with logistical flexibility. It can hold containers on-site for longer periods to consolidate return trips more efficiently, thereby minimizing the social impact (fewer trips) at the expense of higher rental fees. In contrast, highly constrained sites like Tivoli and Renaissance have less flexibility, resulting in a different cost structure and a more

pronounced increase in vehicle movements. This demonstrates that the DST successfully captures how physical site characteristics mediate the trade-offs between economic efficiency and social impact.

The analysis also highlights the importance of geographical context, particularly concerning transportation emissions. While the Renaissance (+14.78%) and Tivoli (+12.50%) cases saw an increase due to more trips, the Beneluxlaan case saw a -39.63% reduction. This is because the distance from the construction site to the CCC was very short, while the distance to the recycling centre used in the baseline model was significantly farther. In this specific case, the CO_2 savings from the shorter waste journeys outweighed the emissions from the extra trips.

In conclusion, the comparative analysis confirms that the integrated scenario provides an economic and environmental superior alternative to traditional C&DWM practices. The findings support the research objective by demonstrating that the DST can effectively quantify these benefits while also capturing the nuanced influence of site-specific factors like storage space and geography on operational costs and social trade-offs.

5.4 Carbon Cost

While the preceding analysis established the general economic and environmental performance of each scenario, this section provides a more focused investigation into the monetized cost of carbon. This section tests financial robustness of each case study under different regulatory environments. By modelling the impact of different carbon prices, this analysis addresses a key aspect of the research: creating a decision framework that accounts for not only current costs, but also foreseeable future financial risks associated with environmental policy.

To achieve this, two different carbon pricing schemes have been used to determine the carbon costs for each case study. The first is the standard EU carbon price of €71.2 per tonne CO_2, representing the current market-based costs, and the significantly higher prices that are adopted in municipal tenders. This research has looked at two construction projects in Utrecht and one in Amsterdam. Both municipalities already use a significantly higher carbon price. Respectively being €875 per tonne CO_2 and €418 per tonne CO_2.

Table 10 Impact of different carbon prices on the carbon costs of the case studies

	Standard	**Municipal price**	**Difference**
Amsterdam – Renaissance			
Baseline	€ 1,597.73	€ 9,379.92	+€ 7,782.19
Integrated	€ 195.09	€ 1,145.32	+€ 950.23
Utrecht – Beneluxlaan			
Baseline	€ 3,360.84	€ 41,302.50	+€ 37,941.66
Integrated	€ 209.36	€ 2,499.37	+€ 2,290.01
Utrecht – Tivoli			
Baseline	€ 363.01	€ 4,333.71	+€ 3,970.70
Integrated	€ 50.97	€ 608.47	+€ 557.50

Table 10 shows the impact of the standard carbon price compared with the carbon price set by the municipality. It compares the impact of these different carbon prices on both scenarios. As seen in the previous subchapter the baseline scenario always has a higher total CO_2 production. This results in the increase in carbon price having a larger effect on the baseline scenario compared to the integrated scenario. The most significant change can be seen in the Beneluxlaan case study, where the stricter municipal price adds €37,941.66 in carbon costs to the baseline model, compared to just €2,290.01 for the integrated model. This shows that as project scale increases, the financial risk of the high-emission

baseline model escalates dramatically under stricter carbon pricing policies. Also, for the projects of smaller scales it can be seen that the integrated model becomes even more financially advantageous as the carbon price rises.

The graphs in figures 24, 25, and 26 provide a visual representation the carbon costs using different carbon prices. The widening gap between the cost lines for the baseline and integrated scenarios illustrates that as the carbon price rises, the financial advantage of the integrated model becomes increasingly pronounced. Therefore, this analysis concludes that the integrated scenario not only outperforms the baseline scenario economically but is also more future-proof as carbon prices are expected to rise.

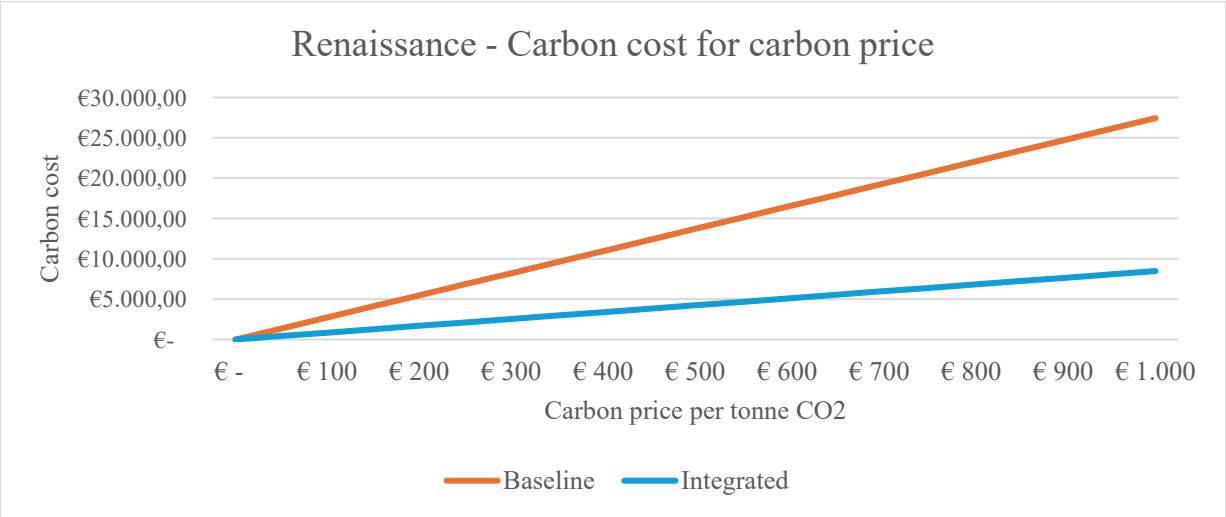


Figure 24 Carbon cost for different carbon prices Renaissance

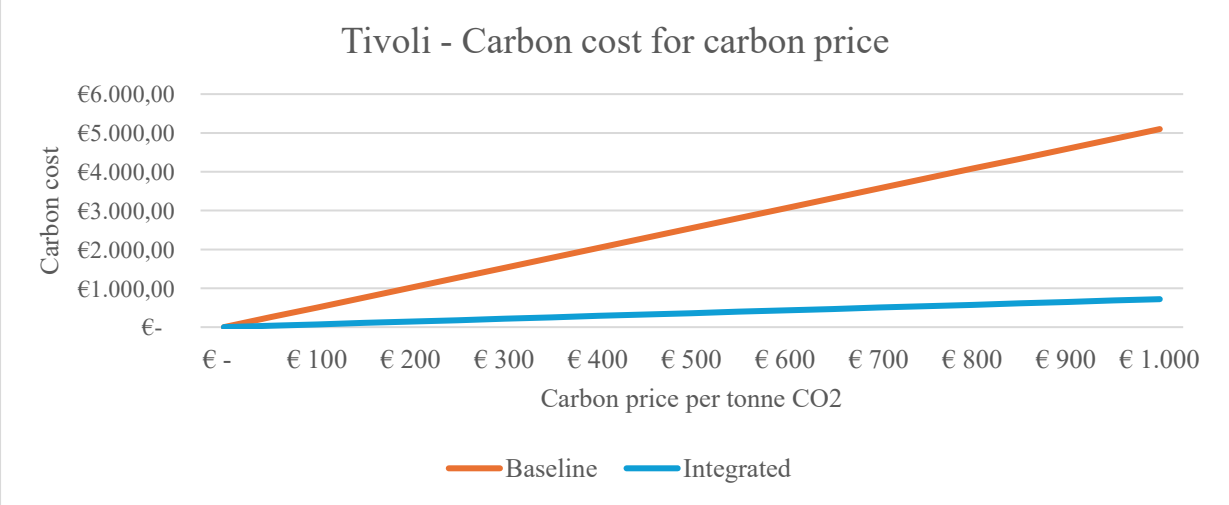


Figure 25 Carbon cost for different carbon prices Tivoli

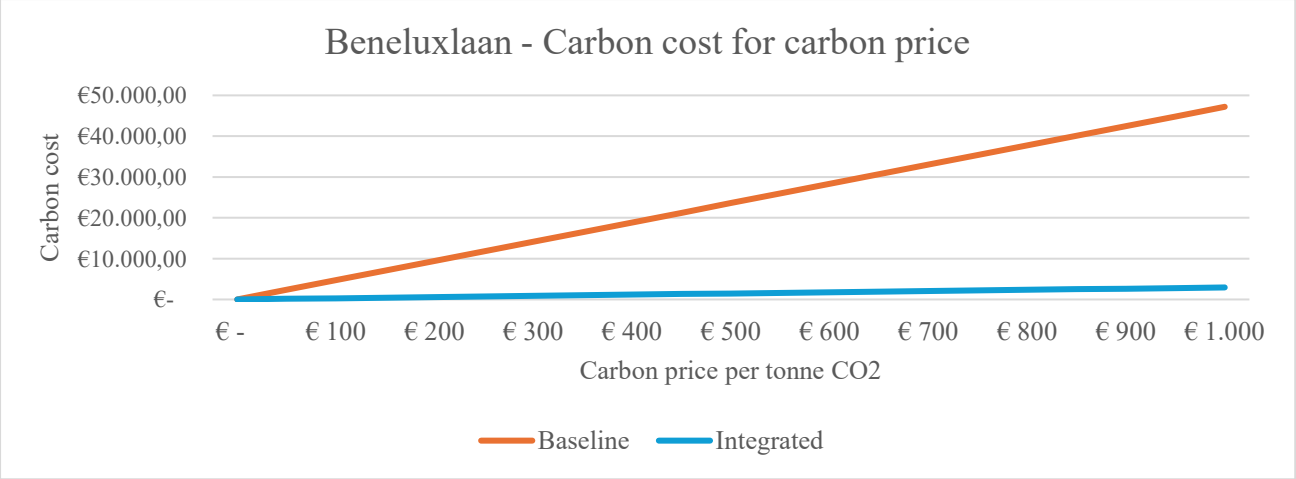


Figure 26 Carbon cost for different carbon prices Beneluxlaan

5.5 Sensitivity Analyses

To complement the case study results, this chapter conducts a series of sensitivity analyses to assess the robustness of the model's recommendations and to identify the key drivers of performance. As this model is used in the procurement phase many of the model's inputs must be predicted and can differ from the final real values. In addition, these inputs are impacted by market changes and project specific constraints. This analysis is therefore critical for understanding the conditions under which one model becomes more favourable than the other.

The chapter is divided into three parts: first, a parameter sensitivity analysis investigates the impact of key economic variables on the total cost. Second, a waste generation analysis examines how the models' performance scales with project size. Finally, a scenario analysis explores the tipping points related to physical and logistical constraints, such as on-site storage area and travel distance.

5.5.1 Cost Parameters Analyses

An initial analysis on the Renaissance case study, visualized in the tornado plots in figure 27 and 28, identified recycling costs as the dominant economic variable. In both the baseline and integrated scenarios, this parameter influences the total financial costs the most. This finding is critical as it confirms that any C&DWM strategy's economic success is primarily dictated by how effectively it manages waste disposal fees.

Given its high degree of influence, a break-even analysis was performed on the mixed-waste recycling cost to determine the threshold at which the traditional baseline scenario would become as economically viable as the integrated scenario.

Table 11 Recycling cost break-even point

Case study	Market value	Break-even point	Reduction %
Renaissance	€196.29	€147	25.1%
Tivoli	€196.29	€150	23.6%
Beneluxlaan	€196.29	€136	30.7%

Table 11 shows that the mixed-waste disposal costs would need to reduce significantly from the market rate of €196.29 per m³. before the baseline model would become more advantages. Especially as such a reduction would likely be paired with a reduction of the recycling costs of the other waste streams,

which is currently left out of this analysis. The recycling costs of mixed waste would need to drop by 23.6% to 30.7% across the different case studies for the baseline model to become more favourable.

In conclusion, this analysis shows that the financial advantage of the integrated model is resilient to price changes in the recycling cost. The findings provide evidence that the economic benefits from on-site waste separation are robust against foreseeable fluctuations in the price for the most influential cost parameter.

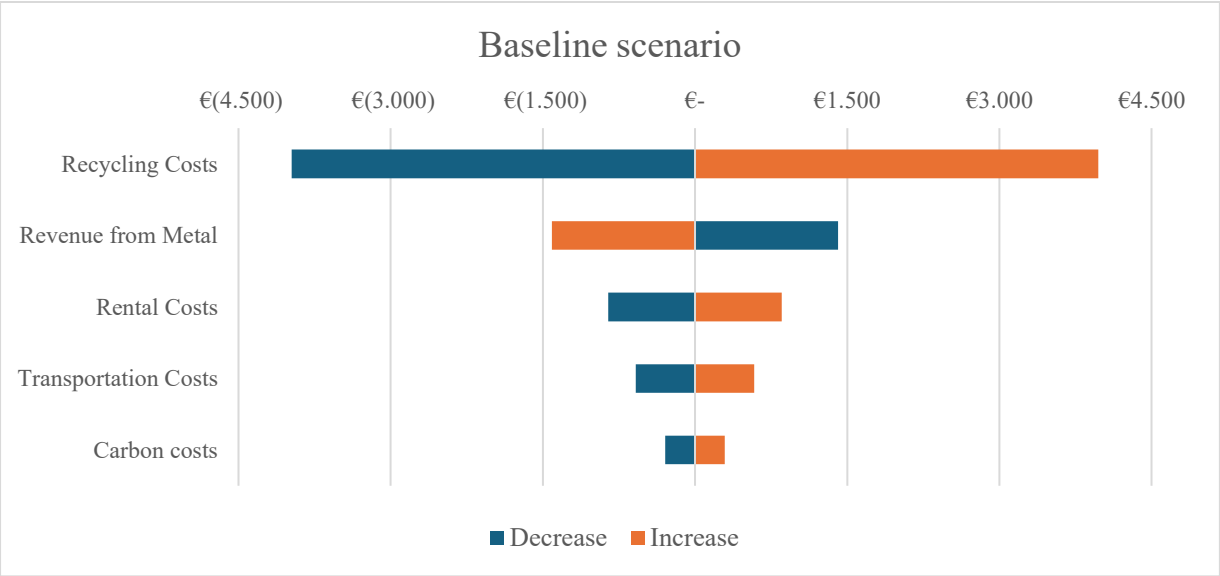


Figure 27 Sensitivity analysis baseline economic costs

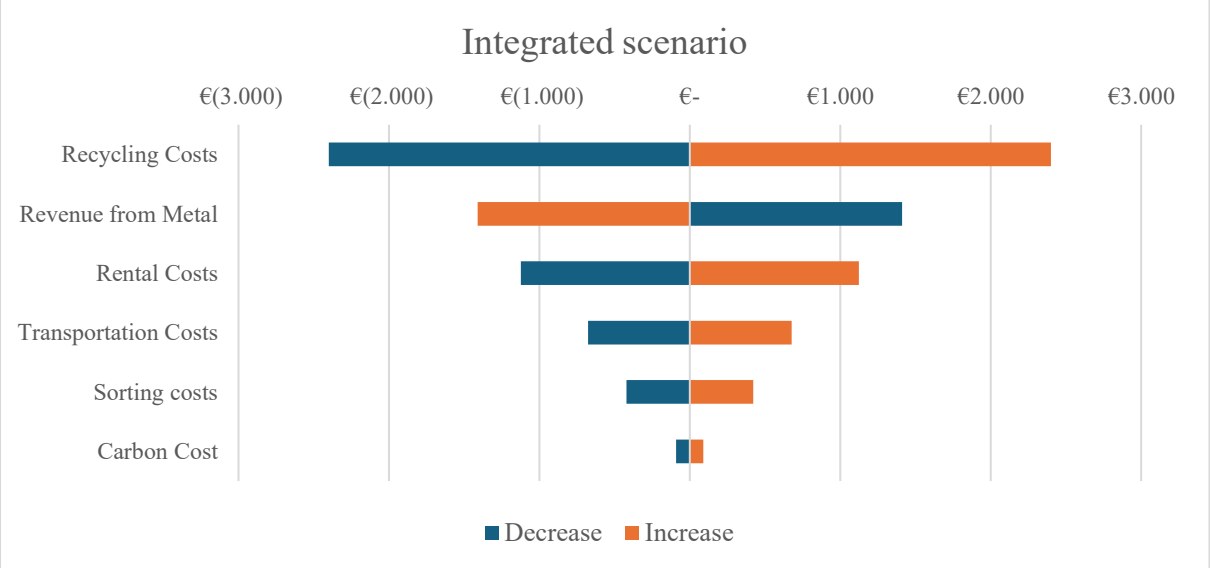


Figure 28 Sensitivity analysis integrated economic costs

5.5.2 Sensitivity to Waste Generation

Pre-construction forecasts of C&DW generation are inherently subject to uncertainty and often deviate from the actual volumes produced on-site. To account for this variability and assess its impact on the model's recommendations, a scenario analysis was conducted to assess the impact of this variability on the performance of each C&DWM strategy. This analysis quantifies how fluctuations in waste volume affect the absolute and relative performance of the baseline and integrated scenarios across economic, environmental, and social KPIs. The absolute performance metrics for all three waste volume scenarios are presented in table 12.

The economic performance results demonstrate that as waste generation increases, the financial advantage of the integrated model grows substantially. An analysis of table 12 shows that for a ±15% variation in waste volume, the total economic cost of the baseline scenario fluctuates by a significant ±€6,039.78. In contrast, the integrated model's cost changes by a much smaller ±€3,471.57.

The environmental performance also shows an increase in CO_2 emissions for both models as the WGR increases. This increase in the integrated scenario is however significantly smaller at ±0.11 t when compared to the ±7.13 t from the baseline scenario. The primary driver for this widening gap is the sorting emissions in the baseline model, which are directly proportional to the volume of mixed waste requiring energy-intensive mechanical separation. The emissions from the integrated model, dominated by transportation, experienced only marginal increases with volume.

The social impact, measured by the total number of round trips, reveals a small change between the different scenarios. While all scenarios saw an increase in trips corresponding to the increase in waste volume, the differential between the two models remained consistent. The integrated scenario required ±3 additional trips compared to the baseline scenario across the entire range. This finding suggests that while the integrated scenario is inherently more transport-intensive, this relative disadvantage does not escalate significantly with changes in project scale.

Table 12 Senstivity to waste generation

	Standard	**±15%**	**Difference integrated**
Total Economic Cost (€)			
Baseline	€ 43,142.92	± € 6,039.78	± € 2,568,21
Integrated	€ 29,020.58	± € 3,471.57	-
Net CO_2 Emissions (t)			
Baseline	47.20 t	± 7.13 t	± 7.02 t
Integrated	2.94 t	± 0.11 t	-
Total Round Trips			
Baseline	71	± 3	0
Integrated	77	± 3	-

5.5.3 Scenario Sensitivity

In addition to the sensitivity analysis of cost parameters and WGR, a scenario analysis was conducted to evaluate the model's response to variations in key physical and logistical inputs. This analysis is crucial for understanding the specific project conditions under which the integrated model provides the most significant advantages over the baseline. The investigation focused on three primary inputs: on-site storage area, project size (as a proxy for waste generation volume) and travel distance.

Table 13 Tipping point for project constraints

	Renaissance	Tivoli	Beneluxlaan
Economic tipping point project size	1880 m^2	1900 m^2	1800 m^2
Environmental tipping point project size	900 m^2	1850 m^2	900 m^2
On-site storage tipping point	100 m^2	20 m^2	25 m^2

Table 13 shows that the economic and environmental viability of the integrated scenario is highly dependent on the total volume of waste generated, which is directly correlated with the project's size. For smaller projects with low waste volumes, the additional overhead of the integrated scenario can outweigh the financial benefits gained from cheaper recycling rates. An analysis of the economic tipping points with regards to the project size shows consistent values ranging from 1800 m^2 and 1900m^2. This consistency shows that despite the substantial differences in project type, location and waste streams, the financial break-even point remains within a narrow range. This suggests that the point at which the economic benefits of on-site sorting outweigh the required logistical overhead is the same across projects.

In contrast, the environmental tipping point is context dependant. The Renaissance and Beneluxlaan project have the same value at 900 m^2, the Tivoli project however, has a value that is more than twice as high at 1850 m^2. This difference is explained by the use of electric vehicles for the Tivoli project. The lower carbon emissions from electric transport reduce the environmental cost of the integrated model's additional trips. Consequently, a much larger volume of waste (and thus a larger project size) is required before the CO_2 savings from avoiding mechanical sorting are sufficient to offset the transport emissions

The tipping point for on-site storage, which represents the point at which increasing the on-site storage space no longer has a positive effect on the logistical efficiency, differs between projects. At the Renaissance this was identified at 100 m^2, this large value is likely caused by a more complex mix of materials which requires a larger buffer of on-site waste containers. For the Tivoli and Beneluxlaan projects, this point was reached much earlier, at 20 m^2 and 25 m^2 respectively. This finding indicates that the optimal storage footprint is not simply a function of project size, but is highly dependent on the specific logistical profile of the construction process. In addition, it shows that the integrated approach can be optimal even at construction projects where the on-site space for containers is merely 20 m^2.

Transportation costs are a direct function of travel distance and the number of trips. As the integrated scenario inherently requires more trips, its economic advantage diminishes as the distance between the construction site and the consolidation centre or recycling facility increases. The analysis indicates that as travel distance grows, the cumulative cost penalty from the additional trips of the integrated scenario begins to erode the savings gained from efficient recycling. An important limitation of this tool is that it does not consider the additional trip from the CCC to the recycling centre.

A key principle supporting circularity in construction is the willingness of material producers to reclaim their products, a practice contingent upon the availability of clean, separated material streams. Manufacturers like Rockwool and Knauf have already established or expressed strong interest in such take-back systems for their respective insulation and gypsum products, which can be fully recycled into new materials (Rockwool, 2018) (Knauf Insulation, n.d.).

This industrial trend implies that separated materials retain a residual value. It is therefore assumed that this value is adequate for the original manufacturers to manage the logistics of collecting their materials from a central point, like a CCC, for recycling. Based on this assumption, the final transport journeys from the CCC to various specialized manufacturing plants are excluded from the scope of this analysis.

5.6 Conclusion

This chapter presented the findings from the application and testing of the DST as designed through the methodology. It began by validating the simulation's predictive accuracy for material deliveries. This analysis showed a high degree of correlation with actual project data. Therefore, contributing to the overall credibility of the tool.

The core of the chapter focussed on a detailed comparative analysis of both scenarios using different case studies. The results consistently demonstrated that the integrated scenario, despite incurring higher transportation and rental costs, delivered significant overall economic savings, ranging from 20%-37%. This saving was primarily driven by a significant reduction in the recycling costs of the integrated model caused by allowing for on-site waste separation. The environmental impact also saw large reductions in the integrated scenarios of 85-94%. Again, the main saving was a lower recycling emission in the integrated scenario. The total number of trips, which was used as a proxy for social impact, saw an increase in the integrated scenario. This means that the integrated model has a positive economical and environmental impact but does create more social problems.

Furthermore, the sensitivity analyses showed that the recycling costs were the most influential economic parameter for both models. The analyses also established tipping points, demonstrating that the integrated model's economic and environmental advantages grow non-linearly with project size and become even more pronounced under stricter carbon pricing policies.

6. Validation

This chapter will show the final tool that is created for the stakeholders. It starts with a storybook that describes all the steps the user will take when using the tool. After this the tool will be tested by five different users. The users are all relevant stakeholders for the project and will be described in detail. The storybook will help provide an overview of how these users see and use the tool.

To allow for validation of the models, and to ensure transparency, a complete repository containing all the source code is archived using Gitlab.

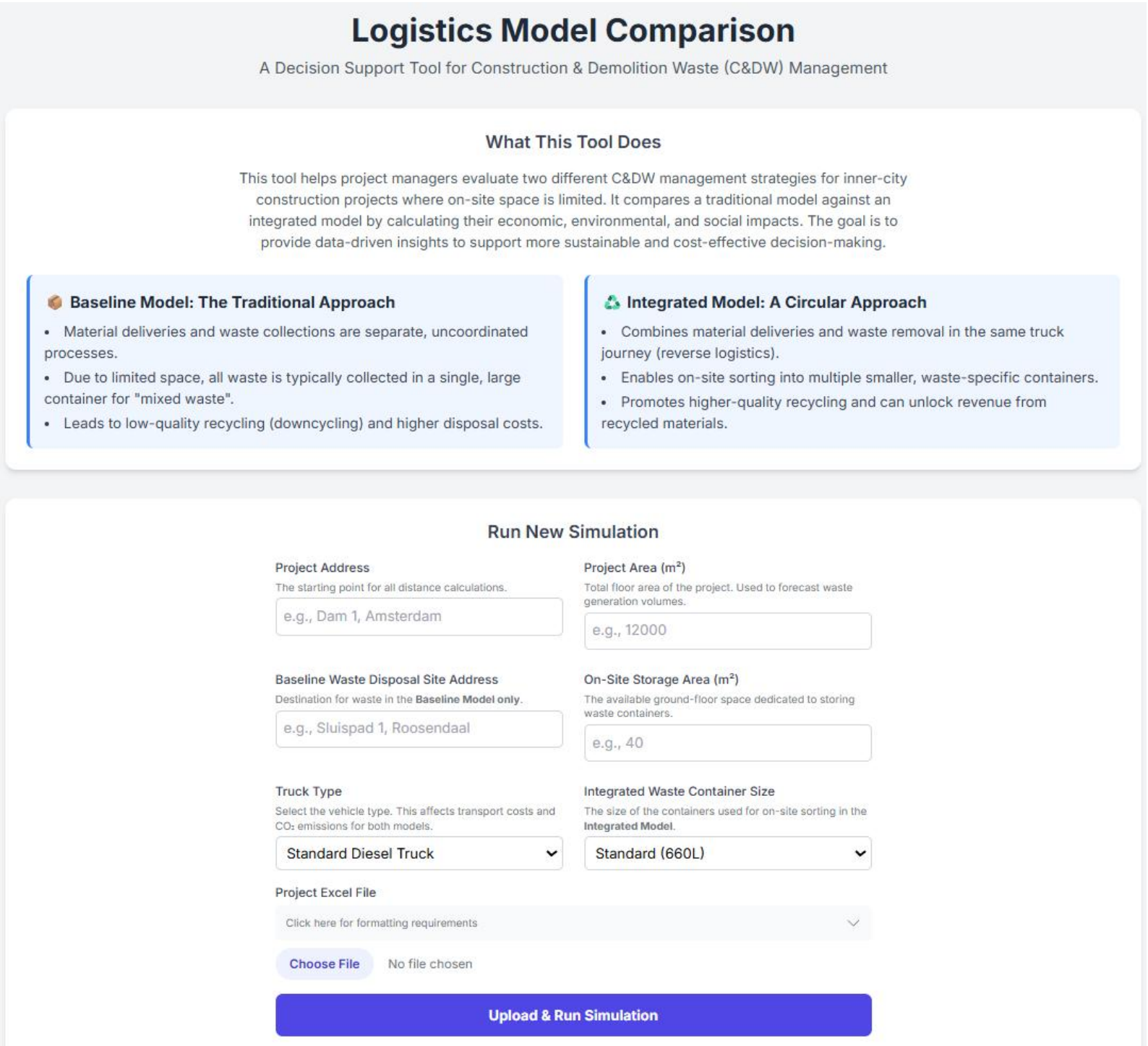
6.1 Storybook

To provide a clear understanding of the DST's practical application and user experience, this section presents a storybook walkthrough. The storybook guides the reader through the entire process of using the tool. Beginning with the opening screen where the user uploads project data. Followed by the various output dashboards; summary screen, overview of weekly trips, weekly delivery overview, and the detailed KPI overview. The storybook ends with showing how the user can adapt specific KPIs to better match their construction project.

1. Opening screen

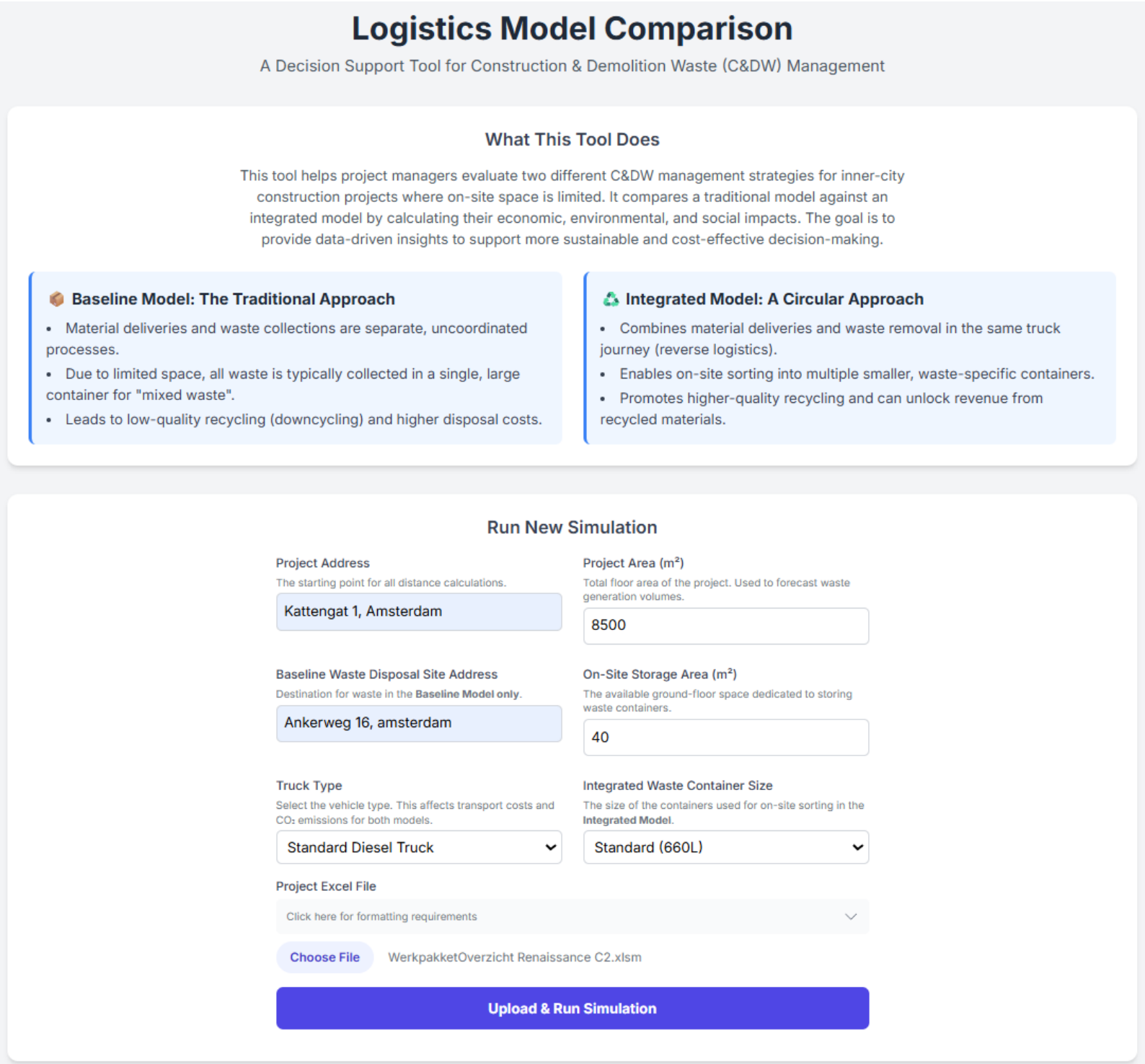
The DST is initiated through a frontend client designed to serve as the primary user interface. The opening screen is meant to provide the user with the information regarding the tool. It explains both scenarios and how the comparison aids the user.

The tool is intended for use during the procurement and planning phase of a construction project, providing stakeholders with a quantitative overview of the potential economic, environmental, and social impacts of different waste management strategies. To facilitate ease of use at this early stage, the required user inputs are designed to be straightforward and readily available to project managers. It is the location of the project site, location of the recycling centre, size of the project, size of on-site storage, type of truck and waste container size, and a weekly delivery schedule of the materials.



2. Opening screen Renaissance case study

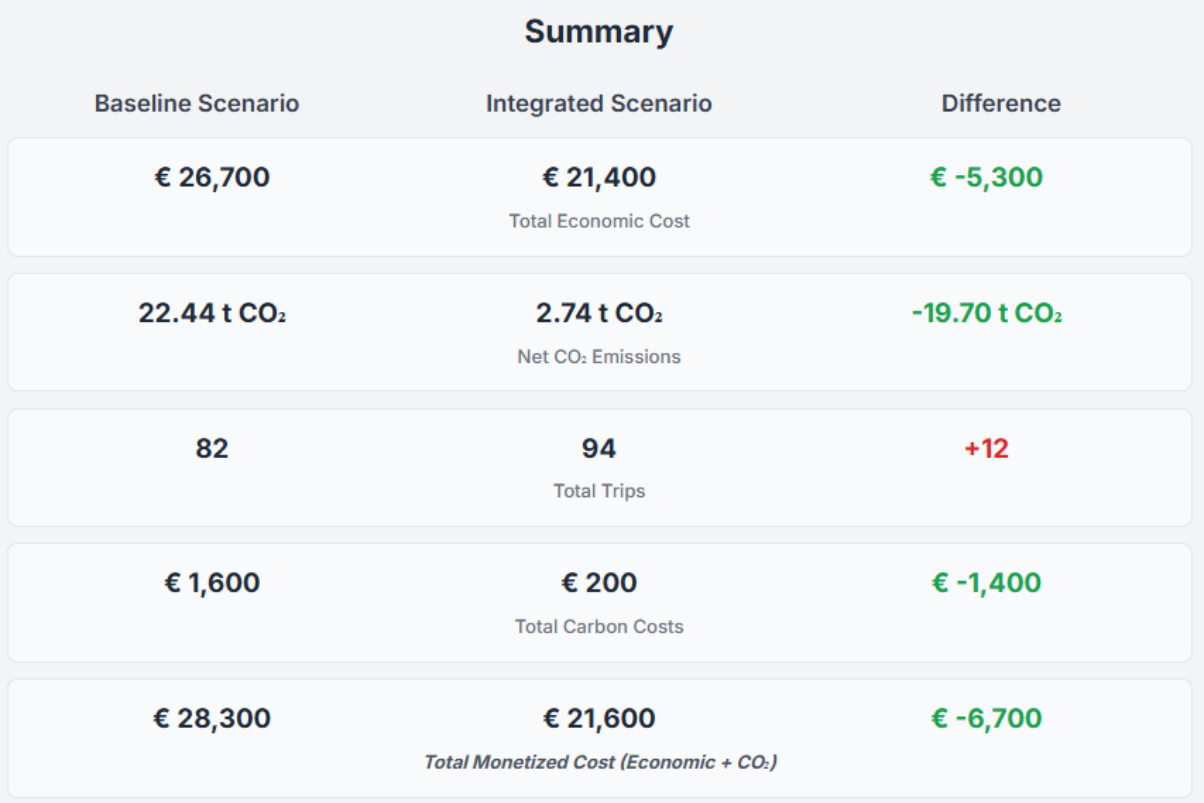
The second image shows how the frontend looks with all the necessary values filled in. In this case it uses the project data of the case study for the Renaissance construction project



3. Summary screen

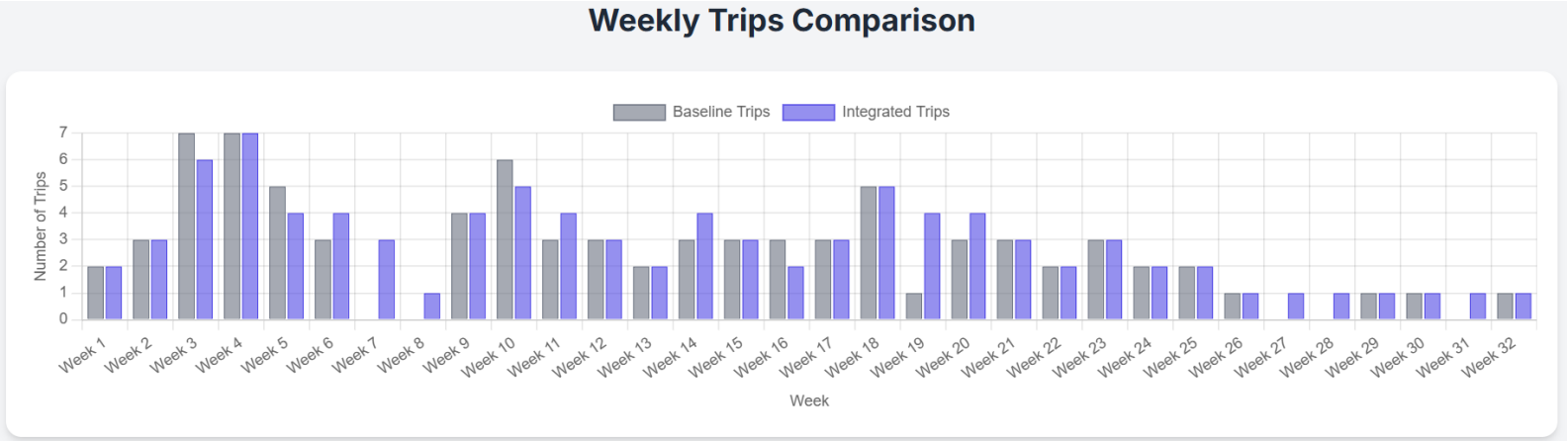
After running the model, the first information that is shown is the summary section. This summary provides a clear, comparative overview of the performance of both the baseline and integrated scenario against the established KPIs. In addition, it displays not only the absolute scores for each scenario but also the difference between them, allowing the user to immediately identify which strategy is more favourable for a given KPI and the scale of its advantage.

This summary section does not show in detail how the scores are calculated and presents financial values rounded to the nearest €100. The reason for this is that this summary should merely be used to create a quick overview, further in the page will more detail be provided.



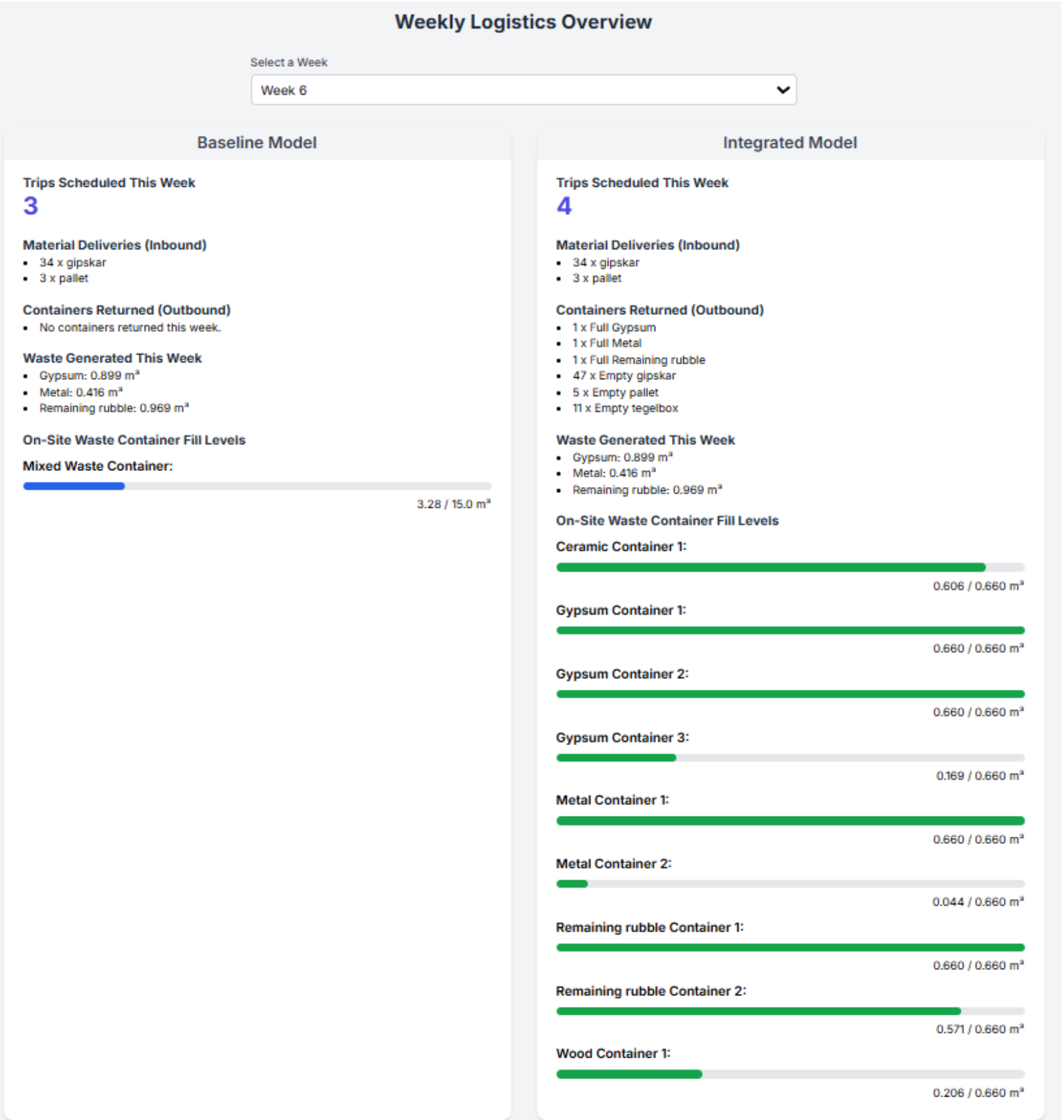
4. Overview of weekly trips

Below the summary the overview of the weekly trips is shown. This section provides insight into the difference between both models on a weekly operational level. Furthermore, this weekly visualization provides a secondary purpose, it demonstrates to the user that the tool's output is based on a detailed weekly simulation rather than a static top-down calculation. This transparency into the underlying model is intended to increase the perceived reliability and credibility of the tool.



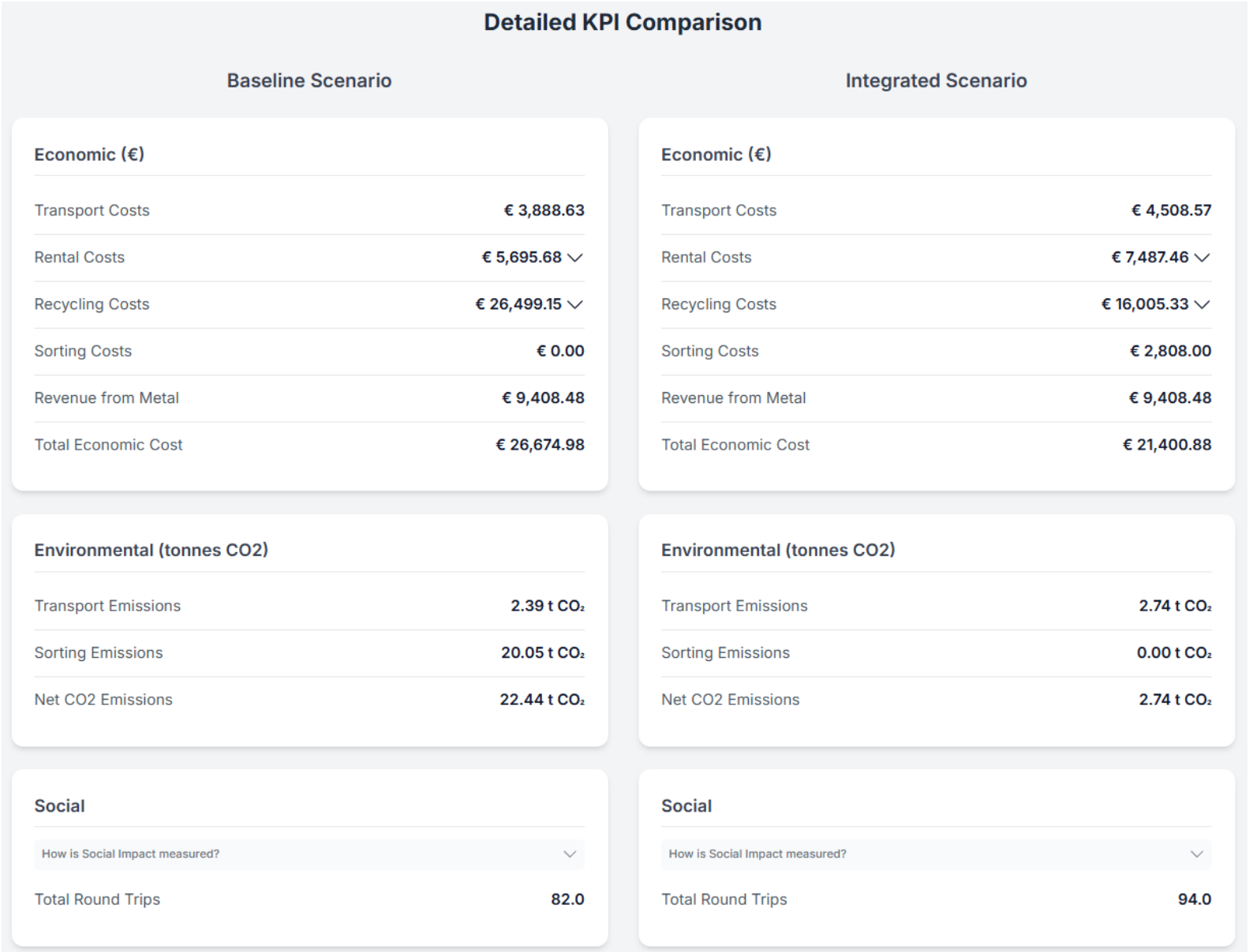
5. Weekly delivery overview

Following this overview of all weekly trips the user is provided with a drop-down menu. In this drop-down menu they can chose a certain week and the DST provides a detailed overview of the scheduled trips for both scenarios.



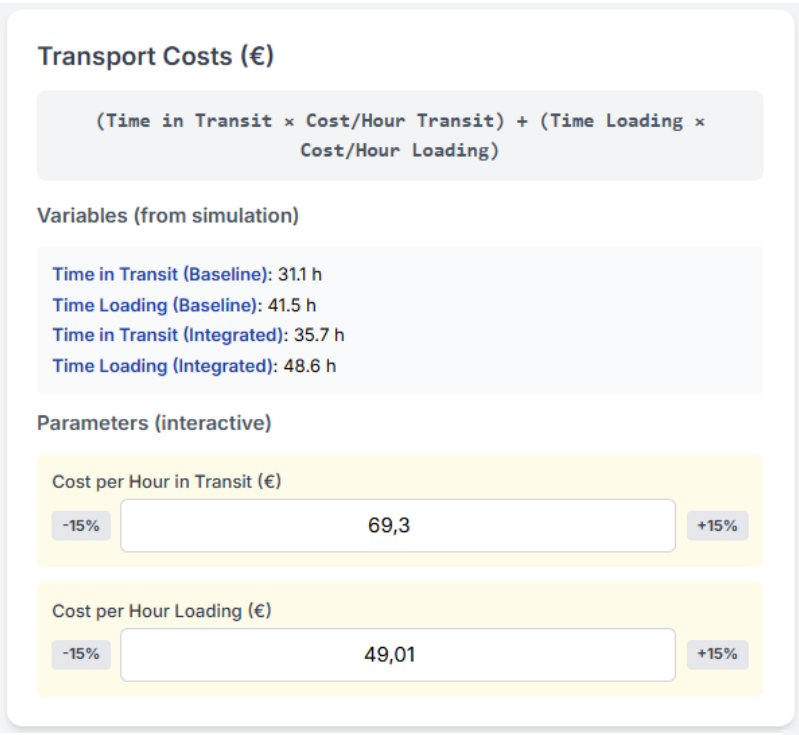
6. Detailed KPI overview

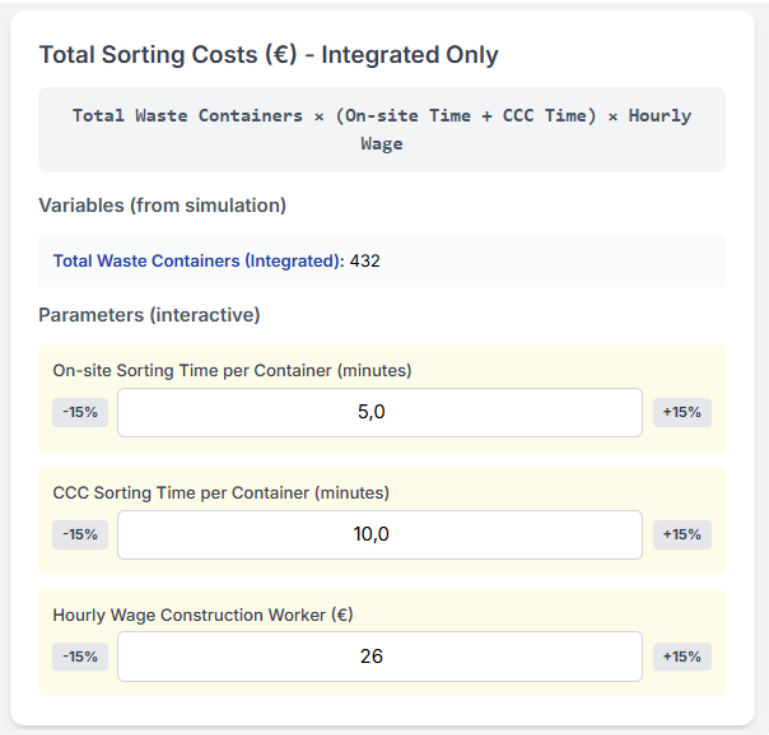
This section shows the same main information as the summary screen. In addition, it also provides insight into how these different KPIs are determined. It shows how the economic cost and environmental impact are constructed. In addition, it has the option of a dropdown page that shows the rental- and recycling costs in more detail.

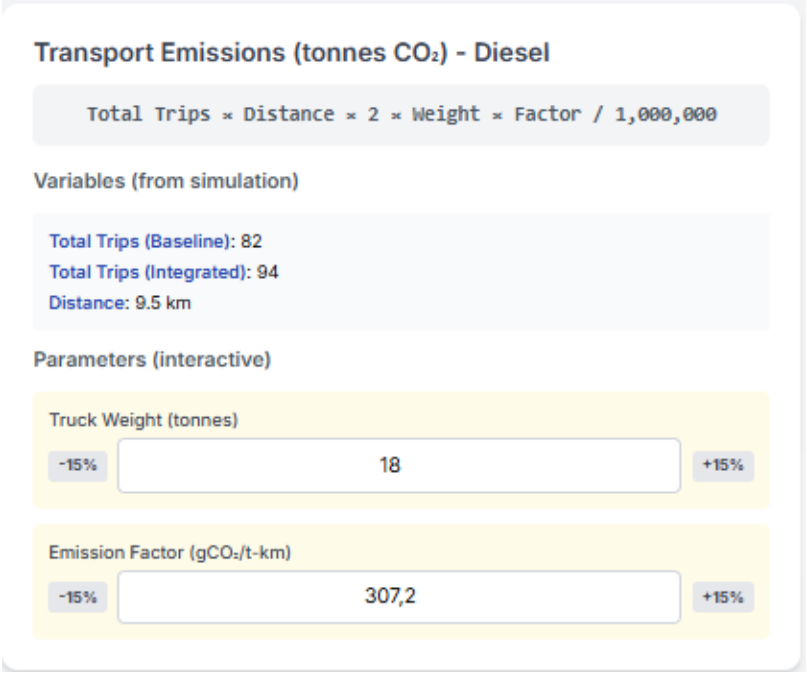


7. Detailed KPI determination

Lastly the tool shows a different page which the user can switch to via a button at the top. This section provides very detailed information for how all the different KPIs are determined. It shows the calculation behind the numbers. In this screen the user can make adaptations if some of the values do not correspond with their given project. These adaptations then directly change al the previous overviews. For example, if a project manager has a higher cost/hour for his employees he can adapt this in this view, and it will automatically update the summary and the detailed KPI overview







Total Recycling Costs (€)

`SUM(Volume × Cost/m³) + (Metal Tonnes × Price/Tonne)`

Variables (from simulation)

Volume Mixed Waste (Baseline): 135.0 m³
Volume Ceramic (Integrated): 66.3 m³
Volume Gypsum (Integrated): 17.9 m³
Volume Remaining rubble (Integrated): 37.4 m³
Volume Wood (Integrated): 7.6 m³
Tonnes of Metal (Integrated): 4.1 t

Parameters (interactive)

Cost/m³ Mixed Waste
-15% 196,29 +15%

Cost/m³ Ceramic
-15% 142,5 +15%

Cost/m³ Gypsum
-15% 58,9 +15%

Cost/m³ Remaining rubble
-15% 142,5 +15%

Cost/m³ Wood
-15% 23,1 +15%

Price /tonne Metal (Revenue is negative)
-15% -2306 +15%

Sorting Emissions (tonnes CO_2) - Baseline Only

`Total Mixed Waste × Factor / 1000`

Variables (from simulation)

Total Mixed Waste (tonnes): 143.24

Parameters (interactive)

Emission Factor ($kgCO_2$/tonne)
-15% 140 +15%

Total Monetized Cost (€)

`Total Economic Cost + (Net CO₂ × Carbon Price)`

Variables (from simulation)

Total Economic Cost (Baseline): € 26,974.34
Total Economic Cost (Integrated): € 21,731.49
Net CO_2 (Baseline): 28.64 t CO_2
Net CO_2 (Integrated): 9.86 t CO_2

Parameters (interactive)

Carbon Price (€ per tonne)
-15% 71,2 +15%

Container Rental Costs (€)

`SUM(Total Weeks × Cost/Week)`

Variables (from simulation)

Weeks blank (Baseline): 755
Weeks blank (Integrated): 779
Weeks gipskar (Baseline): 306
Weeks gipskar (Integrated): 408
Weeks large_waste (Baseline): 32
Weeks pallet (Baseline): 68
Weeks pallet (Integrated): 90
Weeks rolcontainer (Baseline): 12
Weeks rolcontainer (Integrated): 12
Weeks tegelbox (Baseline): 84
Weeks tegelbox (Integrated): 93
Weeks waste (Integrated): 323

Parameters (interactive)

Cost/Week Blank (€)
-15% 3,74 +15%

Cost/Week Gipskar (€)
-15% 6,15 +15%

Cost/Week Large_waste (€)
-15% 15 +15%

Cost/Week Pallet (€)
-15% 2,5 +15%

Cost/Week Rolcontainer (€)
-15% 2,16 +15%

Cost/Week Tegelbox (€)
-15% 3,74 +15%

Cost/Week Waste (€)
-15% 4,5 +15%

6.2 User Testing

This section presents the findings from the usability testing of the Decision Support Tool (DST). The validation was conducted with five participants, all of whom are potential end-users with professional expertise in project management or logistics. The results are systematically presented, beginning with the standardized System Usability Scale (SUS) scores, followed by an analysis of the tool-specific questionnaire, which provides targeted feedback on the DST's features and functionality.

The participants of this research need to be in line with the final users of the tool as determined in 3.5.1. As the tool is used in the procurement phase, the envisioned users are logistics planners- and project managers of inner-city construction projects. These functions are each represented by at least two participants, participants 1, 2, and 3 are logistics planners of a CCC and 4 and 5 are project managers at construction firms.

To evaluate the overall usability of a system, the standardized and empirically validated SUS test is used. Research has consistently demonstrated that despite its simplicity, the SUS provides a robust assessment that correlates strongly with more complex usability metrics (Bangor et al., 2008)

Table 14 shows the scores of the SUS test in detail. Using the formula as defined in the methodology, it can be determined that the tool has a score of 86 (with a range of 0-100). As mentioned, a score above 85 is seen as excellent (Soegaard, 2025). A high SUS score is a strong predictor of user acceptance and adoption, indicates a high level of user satisfaction and indicates a positive attitude towards the tool (Bangor et al., 2008) (Lewis & Sauro, 2009). Seeing as the score is 86 it can be said with confidence that the system scores excellent on the SUS test.

Table 14 SUS test

Code	***Questions***	***Participant 1***	***Participant 2***	***Participant 3***	***Participant 4***	***Participant 5***	**Average**
Q1	I think that I would like to use this system frequently	4	4	3	5	4	**4**
Q2	I found the system unnecessarily complex	1	1	1	2	2	**1,4**
Q3	I thought the system was easy to use	5	5	5	5	5	**5**
Q4	I think that I would need the support of a technical person to be able to use this system	4	1	1	1	2	**1,8**
Q5	I found the various functions in this system were well integrated	4	4	4	4	4	**4**
Q6	I thought there was too much inconsistency in this system	1	2	3	2	3	**2,2**
Q7	I would imagine that most people would learn to use this system very quickly	5	5	5	4	5	**4,8**
Q8	I found the system very cumbersome to use	1	1	1	1	1	**1**
Q9	I felt very confident using the system	3	5	3	4	5	**4**
Q10	I needed to learn a lot of things before I could get going with this system	1	1	1	1	1	**1**

While the SUS provides a reliable, high-level metric of overall usability, it is not designed to yield diagnostic feedback on specific features or content within a system (Brooke, 1994). To create more actionable tool specific insight an additional tool-specific questionnaire is used. The first three questions focus on the clarity of information, question 4,5 and 6 focus on the perceived usefulness, question 7 and 8 describe the interface and interaction and the last two questions focus on confidence and trust.

Table 15 Tool specific questionnaire

Code	*Questions*	*Participant 1*	*Participant 2*	*Participant 3*	*Participant 4*	*Participant 5*	Average
Q1	The summary comparison between the 'baseline' and 'integrated' scenarios was easy to understand.	3	4	4	5	5	**4,2**
Q2	The detailed breakdown of economic costs was clear and insightful	5	5	5	4	4	**4,6**
Q3	I understood the environmental metrics and how they were presented	3	4	4	5	5	**4,2**
Q4	This tool would be valuable for making strategic decisions during the planning phase of a real project.	4	4	3	4	4	**3,8**
Q5	The tool effectively demonstrates the financial and environmental trade-offs between different waste management strategies.	5	5	4	3	4	**4,2**
Q6	The 'total monetized cost' feature is a powerful and convincing metric for comparing the scenarios.	4	5	5	4	5	**4,6**
Q7	The process of inputting project data and running the simulation was straightforward.	5	4	4	4	5	**4,4**
Q8	Navigating between the input screen, the results summary, and the interactive calculations page was intuitive.	2	4	4	5	5	**4**
Q9	I feel confident in the results and recommendations generated by the tool.	4	4	2	4	4	**3,6**
Q10	The information presented is credible enough to support a real-world project decision.	3	4	3	4	4	**3,6**

The results of this questionnaire can be seen in table 15. The overall score of the tool is 82,4 which means that the tool is generally well perceived. However, there is some distinction between the different areas. The tool scores high on the clarity of information, which after questioning the participants is attributed to the clear summary table at the start. The lowest scores are attributed to the confidence and trust in the tool. The main reason for this is that the tool provides limited insight into how the KPI scores are determined and how the simulation works.

6.3 Conclusion

This section tested the effectiveness of the DST with the end-users. The storybook walkthrough demonstrated the practical workflow showing how project data is entered and how the DST presents the results. The tool was then tested using a SUS test. The DST achieved a score of 86 which indicates a high degree of usability and user satisfaction. To gain more specific feedback, a tool-specific questionnaire was also used, yielding a strong score of 82.4 out of 100. The results also showed that enhancing the transparency of the underlying calculations could further increase user confidence and trust in the results. In conclusion, these results provide evidence that the DST provides users with accurate, usable and valuable data that they can aid their decision making with regards to C&DWM practices.

7. Conclusion & Discussion

This final chapter provides on overview of the findings of the research. First, it presents the conclusion of this research, discussing both the main- and sub questions. Once these questions have been answered the theoretical and practical impact of this research will be discussed. This discussion is then followed by acknowledging the limitations of this study. Based on these limitations the recommendations for future research are constructed. Lastly it ends with final remarks to the contribution of this thesis to the field of sustainable construction waste management practices.

7.1 Conclusion

The aim of this study was to create a DST that could aid decision makers in choosing the most appropriate C&DWM approach to a specific project. This resulted in the following research question:

How can the economic, environmental and social impacts of different C&DW management strategies in urban construction projects in the finishing stage be quantified and integrated in a decision-making framework that is used to support the selection of the preferred option?

SQ1: What are the most critical key performance indicators (KPIs) required for a comprehensive assessment of economic, environmental and social C&DW management?

A comprehensive literature review was used to identify and quantify the KPIs that were found to be important in this research. It identified three main groups used to determine the effectiveness of both scenarios, economic costs, environmental impact and social impact. The economic performance was measured using a life cycle costing approach, encompassing transportation, containers rental, recycling and on-site sorting costs. The environmental performance was quantified by calculating the CO_2 emissions from transportation and waste sorting emissions. It transformed this CO_2 production into a monetary value using carbon prices. Social performance was assessed using the total number of vehicle trips into the city centre as a proxy for negative externalities such as traffic congestion, noise, and safety risks.

SQ2: How can a simulation be structured to quantify the specific waste streams produced during the construction finishing stage, utilizing project-specific data?

To answer this sub question this study used a predictive model that first quantified the different waste streams based on the methodology of Solís-Guzmán et al. (2009). This is combined with a weekly delivery schedule that details the number of materials that need to be transported to the construction site. These two forecasts are used as the main input for both the baseline and the integrated model. The baseline model simulates uncoordinated logistics reactively. It treats material deliveries and waste collection as separate processes and only triggers a waste trip when a single large container reaches capacity. In contrast, the integrated model simulates a coordinated system using a hybrid heuristic and linear programming approach. For each week, it calculates the minimum required outbound delivery trips and then uses a linear programming model to optimize the return capacity, deciding which full waste containers and empty material containers to send back to the CCC under constraints like on-site storage limits and container aging. The logistics component of the model was validated against historical data from three completed projects, demonstrating a high degree of accuracy and confirming the reliability of its underlying calculations.

SQ3: How can a decision support tool be structured to help stakeholders navigate the performance trade-offs between economic cost, environmental impact, and social impacts when selecting a C&DW management strategy

A decision support tool can be structured to help stakeholder to navigate performance trade-offs by methodologically integrating certain design components. The DST must be able to compare different C&DWM approaches using identical input data. This structure ensures that the different approaches can be compared on a direct and unbiased bases. The tool must then be structured to translate the raw outputs from these simulations into a unified, multi-criteria KPI framework. Finally, these trade-offs need to be presented through an interactive user-oriented framework. This allows user to quickly view the high-level summary while also being able to adapt individual parameters to fit their own data.

The practical effectiveness of the developed Decision Support Tool was confirmed through its application to three real-world case studies. The results from the case study analyses consistently showed that the integrated model performed better on both the economic and environmental performance. It delivered total economic savings ranging from 20% to 37% and a reduction in CO_2 emissions between 85% and 94%. These savings and reduction in CO_2 production were mainly caused by the on-site separation allowing for higher quality recycling. However, the social impact of the integrated model was higher than the baseline. The usability of the DST was validated through user testing, which yielded an excellent average SUS score of 86.25, confirming its practical utility and intuitive design for target users like project managers and logistics planners.

Now that these sub questions have been answered, the main research question can be answered: *How can the economic, environmental and social impacts of different C&DW management strategies in urban construction projects in the finishing stage be quantified and integrated in a decision-making framework that is used to support the selection of the preferred option?*

This research has demonstrated that the economic, environmental, and social impacts of C&DW management strategies can be effectively quantified and integrated within a comprehensive decision-making framework. The argumentation for this answer can be split into three main parts. First, the framework employs quantification through simulation, using weekly simulation models to transform user input into tangible outputs such as number of trips and the amount of time an activity takes. The second part facilitates a holistic framework for assessment using KPIs. The last part considers the quantification of these KPIs through the DST and by using carbon pricing. It transforms the CO_2 production into a monetary value so that an overview of the total costs can be determined. The result is a DST that aids user in their decision making, it allows them to make informed decisions based on information regarding economic, environmental, and social impacts.

7.2 Discussion and limitations

The main finding of this research is that the integrated scenario consistently outperforms the baseline scenario in economic and environmental terms, while the baseline outperforms the integrated model on social impact. The significance of this finding, however, is not static; as the sensitivity analyses demonstrate, the magnitude of these advantages and trade-offs is highly dependent on project scale and market conditions.

These results are in line with the expected results determined through the literature review. The economic savings are a direct consequence of overcoming high costs of processing mixed waste. As established by Wang et al. (2010) and Yuan (2012), mixing different waste streams renders high-value recycling economically unviable. As the integrated model separates this waste on-site this waste sorting cost does not occur which makes it the economically favourable scenario. This is the main reason why the integrated model has a 20-37% economic saving over the baseline model.

Similarly, the large reduction in CO_2 emissions align with the principles of the waste hierarchy (Zhang et al., 2021). The results show that the main factor for environmental impact is the energy-intensive sorting of mixed waste instead of the transportation emissions. For instance, in the Renaissance project, sorting emissions accounted for 20.05 tonnes of CO_2, over eight times the 2.39 tonnes generated by transportation. This massive emission source is entirely eliminated in the integrated scenario through on-site source separation. This approach to waste handling at the source is a clear move up the waste hierarchy as it allows for high quality recycling instead of downcycling to lower grade materials.

The social impact of the integrated scenario is slightly higher than the baseline. At an 8-15% increase across the different case studies this outcome highlights the logistical trade-off of this research. One large container can be transported more efficiently than multiple containers with the same waste volume.

Overall, the results have met and exceeded the initial expectations of this research. It was hypothesized that an integrated logistics model would be beneficial, but the sheer scale of the financial savings and CO_2 reductions provides a more powerful validation than anticipated. The findings confirm that for inner-city projects, the logistical barrier to on-site sorting is the central problem, and the integrated CCC model presents a financially and environmentally robust solution.

Despite the robust findings it is important to reflect on the limitations of this study. The first limitations stem from the scope of the project, which focusses on inner-city construction projects in the Netherlands in the finishing stage. The study uses current practices which apply in the Netherlands, interpretation should be careful outside the Netherlands. In addition, the focus of the finishing stage does not provide a complete overview. A whole-lifecycle analysis that also includes the demolition and shell construction phases would be required to provide a more comprehensive picture of a project's total C&DW impact and logistical needs.

Another limitation is the waste generation prediction. As mentioned, this predictor is critical to predict the impact both models will have on the KPIs. As there is no data available with regards to the waste production of construction projects in the finishing stage in the Netherlands, this thesis relies on coefficients derived through a Spanish study. This results in two main limitations; a lack of data prevented the validation of the waste forecast and the type, and amount of waste generated in Spanish projects may be different to Dutch projects. However, as concluded in the sensitivity analysis of the waste generation, the integrated model still is favourable at each case study if the WGR is to decrease by 15%. In addition, as the WGR rises the integrated model becomes even more favourable.

In addition, the CO_2 production of the sorting at the recycling centre is based on the results from a Japanese study. These results may differ from the sorting practices in the Netherlands. In addition, to determine the environmental impact, an assumption is made that has significant impact on this research. This assumption is that after waste separation at the recycling centre the waste can be seen as sorted and the resulting material stream is of equivalent quality and follows identical recycling pathways as the baseline scenario. On-site source separation likely yields cleaner, less contaminated materials with a higher potential for true high-value recycling compared to mechanically sorted mixed waste. This limitation means the model may underestimate the full environmental and economic advantages of the integrated scenario, as it does not account for potential differences in the final value and recyclability of the recovered materials.

The social impact also has some limitations. Using the number of trips as a proxy for the social impact of both scenarios was needed for simplicity of the research. However, it does not capture the full complexity of the social impact. A more detailed social impact analysis would need to include more detail such as time of day, vehicle size, transport route, noise levels and impact on traffic.

In addition, a more operational limitation is that the integrated scenario does not assume the trips from the CCC to the recycling centre. It does not consider the last trip from the CCC to the specialized

recycling centre. This is done because of reasoned simplification; it will however add marginal cost and emissions to the integrated scenario. Multiple material manufacturers have already established interest into these waste streams (Rockwool, 2018) (Knauf Insulation, n.d.). Therefore, it is assumed that the additional costs are marginal as these streams have a residual value.

The success of the integrated model is predicated on the assumption of perfect on-site sorting by construction workers. The simulation does not account for the "human factor," such as insufficient training, motivation, or human error, which can lead to cross-contamination of waste streams. Such contamination could downgrade the value of the materials and incur additional sorting costs, thereby reducing the realised benefits of the integrated scenario.

Finally, the usability testing was conducted with a limited sample of five participants. A larger and more diverse sample of users would be needed to more comprehensively validate the tool's usability and identify a wider range of potential improvements.

7.3 Recommendations

Based on the limitations of this study it is possible to determine several recommendations for future research. Future research should prioritize the development and validation of waste generation coefficients for every construction stage in the Netherlands. This would allow studies like this to have valuable data that can be used to determine waste generation in the planning phase. In addition, the research should be expanded so that it encompasses the entire lifecycle of the building. So, from construction to deconstruction. This would create a holistic C&DW management tool capable of providing a complete picture of a project's circularity potential.

Another new research potential is to investigate the environmental difference between source-separated construction waste and construction waste that is sorted mechanically at the recycling centre. This would involve an empirical analysis of the quality, contamination levels, and recycling potential of recovered materials from both streams. Such research will allow more detailed data with regards to the environmental impact of on-site separation.

To fully understand the social impact of both C&DWM approaches additional research is needed. Research could employ agent-based simulation to simulate traffic congestion and map potential noise pollution. In addition, noise pollution and traffic safety around the construction site could be monitored. This would result in a more detailed social impact that provides more insight than the proxy used in this research.

A final recommendation is to integrate the DST with Building Information Modelling (BIM) platforms. BIM models contain detailed data on the types and quantities of materials used in a project, which could be used to generate the waste forecasting process with a higher degree of precision. Such an integration would allow designers and project managers to run different C&DWM scenarios within the BIM environment, receiving immediate feedback on the logistical, economic, and environmental impact of all scenarios. Furthermore, this connection could be used to facilitate the creation of digital material passports directly from the BIM data, which would be invaluable for material recovery and reuse at the building's end-of-life, thereby more effectively closing the material loop

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Appendix 1

Score the tool from 1-5 on the following statements. (Scale: 1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree)

System usability scale

1. I think that I would like to use this system frequently.

2. I found the system unnecessarily complex.

3. I thought the system was easy to use.

4. I think that I would need the support of a technical person to be able to use this system.

5. I found the various functions in this system were well integrated.

6. I thought there was too much inconsistency in this system.

7. I would imagine that most people would learn to use this system very quickly.

8. I found the system very cumbersome to use.

9. I felt very confident using the system.

10. I needed to learn a lot of things before I could get going with this system.

Tool specific questionnaire

Clarity of information

1. The summary comparison between the 'baseline' and 'integrated' scenarios was easy to understand.

2. The detailed breakdown of economic costs (e.g., Transport, Recycling) was clear and insightful.

3. I understood the environmental metrics (e.g., Net CO_2 Emissions) and how they were presented.

Perceived Usefulness

4. This tool would be valuable for making strategic decisions during the planning phase of a real project.

5. The tool effectively demonstrates the financial and environmental trade-offs between different waste management strategies.

6. The 'Total Monetized Cost' feature is a powerful and convincing metric for comparing the scenarios.

Interface and Interaction

7. The process of inputting project data and running the simulation was straightforward.

8. Navigating between the input screen, the results summary, and the interactive calculations page was intuitive.

Confidence and Trust

9. I feel confident in the results and recommendations generated by the tool.

10. The information presented is credible enough to support a real-world project decision.

Appendix 2

Beneluxlaan

The simulation was configured using the project's pre-construction planning data. The finishing stage encompasses a constructed surface area of 17,500 m2. The available on-site storage area was observed to be approximately 100 m2, which is substantially larger than most inner-city projects. The specific waste disposal company used for the project was known and input into the DST. A standard diesel truck and standard waste containers were assumed.

KPI analysis

The economic performance of each scenario was evaluated by aggregating all relevant costs and revenues. The analysis includes a detailed breakdown of transportation, container rental, recycling, and sorting costs, offset by the revenue generated from recovered metals. A standard carbon price was also applied to internalize the cost of emissions. This carbon price is based on the stock price of the EU carbon permits.

Table 16 Economic results Beneluxlaan case study

Economic costs	**Baseline scenario**	**Integrated scenario**
Transportation costs	**€ 2,684.99**	**€ 2,924.50**
Rental costs	**€ 3,885.68**	**€ 6,401.32**
Blank	*€ 3,122.90*	*€ 3,351.04*
Gypsum board cart	*€ 123.00*	*€ 184.50*
Pallet	*€ 2.50*	*€ 2.50*
Tile containers	*€ 82.28*	*€ 82.28*
Large waste container	*€ 555.00*	-
Waste container	-	*€ 2,781.00*
Recycling costs	**€ 55,942.65**	**€ 33,188.40**
Mixed waste	€ 55,942.65	-
Ceramic	-	*€ 19,451.25*
Gypsum	-	*€ 2,164.57*
Insulation materials	-	*€ 236.25*
Remaining rubble	-	*€ 10,972.50*
Wood	-	*€ 363.83*
Sorting costs	**-**	**€ 5,876.00**
Revenue from metal	**€ 19,370.40**	**€ 19,370.40**
Carbon cost	**€ 3,360.84**	**€ 609.77**
Total economic costs	*€ 46,503.76*	*€ 29,229.18*

The simulation reveals a significant disparity in the economic outcomes of the two scenarios. The baseline scenario resulted in a total economic cost of €46,503.76. In contrast, the integrated scenario yielded a substantially lower total economic cost of €29,229.18, representing a cost reduction of €17.274,58, or 37,15%.

The transportation costs are significantly higher for the integrated scenario when compared to the baseline model. The baseline has a cost of €2,684.99 which is 8,19% lower than the integrated costs of €2,924.50. The reason for this is the higher number of trips needed to transport the waste in a separated way. The smaller containers result in an additional number of trips in the integrated model.

The integrated scenario incurred higher rental costs, driven by its use of numerous smaller containers for source separation in place of the single large container used in the baseline. In the baseline model the waste containers account for €555,- this value is more than four times higher in the integrated model

at €2,781.-. Additionally, the rental costs for certain material containers were elevated in the integrated scenario (€184.50 vs. €123.00) because the model's logistics resulted in these empty containers remaining on-site for a longer duration, thereby accumulating further charges.

By far the biggest cost contribution to both the baseline and integrated scenario is the recycling cost. The baseline model assumes that no waste is separated and that all waste is being sent to the recycling centre as mixed waste. For this case study that results in a recycling cost of €55,942.65. The cost per volume is higher than for the integrated scenario where waste is being delivered in a separated state to the recycling centre. The integrated scenario has a cost for all the different waste types present in the project: ceramic, gypsum, insulation material, remaining rubble and wood. These types all have different prices but combined result in a total of €33,188.40. In addition to being the biggest contributor for both scenarios it is also the biggest differentiator between both scenarios. The integrated scenario achieves a 40,7 % reduction in recycling costs by separating it on-site.

This on-site separation does come at an additional sorting cost of €2,781,-. This cost is mainly constructed by the time it takes to place the containers on-site and to empty them at the CCC. This cost does not occur at the baseline scenario as there is no separation happening.

Out of the materials that are separated steel and other metals have a significant residual value. It is assumed that this value is also accrued in the baseline model when it is separated at the recycling centre. Therefore, this value is subtracted from the total costs for both scenarios. The value, €19,370.40, is not really important as it is the same for both scenarios and therefore does not contribute to the differentiation between scenarios.

The final economic KPI, the monetized cost of carbon, serves not only as a current expense but also as a proxy for future policy risk. By testing both the standard EU carbon price and the significantly higher shadow price used by the municipality of Utrecht (€875 per tonne CO_2), the analysis effectively stress-tests each model's financial resilience against anticipated regulatory tightening. While the integrated model is more cost-effective under the standard price, the cost differential between the two scenarios expands dramatically under the stricter municipal price. This demonstrates that the integrated model is not only financially superior under current conditions but also serves as a strategic hedge, effectively "future-proofing" the project budget against the foreseeable financial impact of more stringent environmental policies. With the value of €71.2 per tonne CO_2 the carbon price only has a small impact on the total costs at €3,360.84 for the baseline model and €209.36 for the integrated model. When using the value of €875, - per tonne CO_2 this cost rises significantly. It results in a value of €41,302.50 for the baseline model and €2,499.37 for the baseline model. This increase shows that when this value becomes higher, which is expected to occur in the future as this a necessary step to achieve environmental goals in the future, that the integrated model becomes even more favourable than with the current price of €71.2 per tonne CO_2.

Table 17 Carbon cost with the standard carbon price of 71.2€ per tonne

Carbon cost standard	**€ 3,360.84**	**€ 209.36**
Total economic costs	*€ 46,503.76*	*€ 29,229.18*

Table 18 Carbon cost with a carbon price of 875€ per tonne

Carbon cost Utrecht	**€ 41,302.50**	**€ 2,499.37**
Total economic costs	*€ 84,445.42*	*€ 31,519.19*
Difference	*+ € 37,941.66*	*+ € 2,290.01*

Table 19 Environmental impact Beneluxlaan case study

Environmental impact (tonnes CO_2 produced)	**Baseline scenario**	**Integrated scenario**
Transportation emissions	4.87 t CO_2	2.94 t CO_2
Sorting emissions	42.33 t CO_2	-
Total CO_2 production	***47.20 t CO_2***	***2.94 t CO_2***

To quantify the environmental impact of both scenarios, the tool compares the amount of CO_2 produced in both scenarios. It is constructed by adding both the transportation emissions and the sorting emissions. The results show that the integrated scenario produces nearly halve as much CO_2 as the baseline scenario, namely 2.94 tonnes of CO_2 vs 4.87 tonnes of CO_2, which is a decrease of 39,63%. This is different from the cost of transport as the environmental impact looks at the distance and the economic cost is determined by the time. The baseline scenario 42.33 tonnes of CO_2 is produced during sorting. This is produced at the recycling centre by the heavy machinery needed to sort the mixed waste before it can be recycled. In the integrated scenario the waste is already sorted at construction site and can therefore be recycled without the need of sorting it first. Therefore, the recycling centre does not produce any CO_2 in the integrated scenario. After recycling it is assumed that the waste streams for both scenarios are identical. Therefore, the CO_2 cost of recycling and the CO_2 savings from using recycled material instead of virgin materials are left out of the scope. It is assumed that for both scenarios these costs and savings are the same and therefore not relevant to show in the comparison. The large amount of CO_2 produced when sorting the waste in the baseline model outweighs the increase of the transport emissions of the integrated scenario. The integrated scenario shows a reduction of CO_2 production of -93,8% when compared to the baseline model (2.94 tonnes of CO_2 vs the baseline of 47.2 tonnes of CO_2.

Table 20 Social score Beneluxlaan case study

Social impact	**Baseline scenario**	**Integrated scenario**
Total number of trips	71	77

The social impact metric reveals the central paradox of the integrated model. While proving to be the superior option from both an economic and environmental standpoint, it consistently generates a negative social externality in the form of increased vehicle traffic. For the Tivoli project, this manifested as a 13.7% increase in the total number of trips into a constrained city centre. This finding does not invalidate the model but rather quantifies the primary trade-off that stakeholders must navigate: the significant financial and ecological benefits of the integrated approach must be weighed against a measurable increase in its social footprint, specifically concerning local traffic congestion and disruption.

Case study Tivoli

The case study for the renovation of the old Tivoli music centre in the inner-city of Utrecht epitomizes the challenges of inner-city construction, with severe logistical constraints that increase difficulties. The case study is explained in more detail in the appendix. The main importance for the tool is that there is only an on-site storage space of 30 m^2. In addition, it is not possible to reach the location with a traditional large diesel truck. This is because the bridges cannot handle the weight, and the streets are too narrow. Therefore, a smaller electric truck is used for the deliveries. It is however a smaller project with it only being 5000 m^2 of construction area

Table 21 Economic results Tivoli case study

Economic costs	**Baseline scenario**	**Integrated scenario**
Transportation costs	**€ 2,193.18**	**€ 2,454.72**
Rental costs	**€ 2,178.04**	**€ 2,707.40**
Blank	*€ 1,668.04*	*€ 2,000.90*
Large waste container	*€ 510.00*	-
Waste container	-	*€ 706.50*
Recycling costs	**€ 5,888.70**	**€ 3,287.40**
Mixed waste	€ 5,888.70	-
Gypsum	-	*€ 618.45*
Remaining rubble	-	*€ 2,565.00*
Wood	-	*€ 103.95*
Sorting costs	**-**	**€ 767.00**
Revenue from metal	**€ 4,496.70**	**€ 4,496.70**
Carbon cost	**€ 363.01**	**€ 50.97**
Total economic costs	*€ 6,126.23*	*€ 4,882.99*

The simulation reveals a significant disparity in the economic outcomes of the two scenarios. The baseline scenario resulted in a total economic cost of €6,126.23. In contrast, the integrated scenario yielded a substantially lower total economic cost of €4,882.99, representing a cost reduction of €1,243.24, or 20.29%.

The transportation costs are higher for the integrated scenario when compared to the baseline model. The baseline has a cost of €2,193.18, which is 11.93% lower than the integrated costs of €2,454.72. The reason for this is the higher number of trips needed to transport the waste in a separated way. The use of multiple, smaller-volume containers for different materials results in more frequent vehicle movements in the integrated model.

The integrated scenario incurred higher rental costs, driven by its use of numerous smaller containers for source separation in place of the single large container used in the baseline. In the baseline model, the large waste container accounts for €510.00; this value is replaced by a higher cost of €706.50 for multiple smaller containers in the integrated model. Additionally, the rental costs for certain material containers were elevated because the model's just-in-time logistics resulted in these empty containers remaining on-site for a slightly longer duration, thereby accumulating further charges.

By far the biggest cost contribution to both the baseline and integrated scenario is the recycling cost. The baseline model assumes that no waste is separated and that all waste is being sent to the recycling centre as mixed waste. For this case study, that results in a recycling cost of €5,888.70. The cost per volume for mixed waste is higher than for the integrated scenario, where waste is delivered in a separated state. The integrated scenario has costs for all the different waste types present in the project: gypsum, remaining rubble, and wood. These types all have different prices but combined result in a

total of €3,287.40. In addition to being a major contributor for both scenarios, it is also the biggest differentiator between them. The integrated scenario achieves a 44.17% reduction in recycling costs by separating it on-site.

This on-site separation does come at an additional sorting cost of €767.00. This cost is mainly constructed by the time it takes for workers to correctly place waste into the appropriate containers. This cost does not occur in the baseline scenario as there is no separation happening on the construction site itself

Out of the materials that are separated, steel and other metals have a significant residual value. It is assumed that this value is also accrued in the baseline model when it is separated at the recycling centre. Therefore, this value is subtracted from the total costs for both scenarios. The value, €4,496.70, is not really important as it is the same for both scenarios and therefore does not contribute to the differentiation between them.

The last cost for the economic KPI is the carbon cost. As with the previous study, two different values have been tested. With the EU carbon permit value of €71.2 per tonne CO_2, the carbon price has a small impact on the total costs. However, when using the municipality of Utrecht's value of €875 per tonne CO_2, this cost rises significantly. This increase shows that as carbon pricing becomes more stringent—a necessary step to achieve future environmental goals—the integrated model becomes even more financially favourable.

Table 22 Carbon cost with a standard carbon price of 71.2€ per tonne

Carbon cost standard	**€ 363.01**	**€ 50.97**
Total economic costs	€ 6,126.23	€ 4,882.99

Table 23 Carbon cost with a carbon price of 875€ per tonne

Carbon cost Utrecht	**€ 4,333.71**	**€ 608.47**
Total economic costs	*€ 10,096.93*	*€ 5,440.49*
Difference	*+ € 3,970.70*	*+ € 557.50*

Table 24 Environmental score Tivoli case study

Environmental impact (tonnes CO_2 produced)	**Baseline scenario**	**Integrated scenario**
Transportation emissions	0.64 t CO_2	0.72 t CO_2
Sorting emissions	4.46 t CO_2	-
Total CO_2 production	***5.10 t CO_2***	***0.72 t CO_2***

To quantify the environmental impact of both scenarios, the tool compares the amount of CO_2 produced. It is constructed by adding both the transportation emissions and the sorting emissions. The results show that the integrated scenario's transportation emissions are slightly higher (0.72 tonnes vs 0.64 tonnes) due to the increased number of trips.

However, in the baseline scenario, 4.46 tonnes of CO_2 are produced during sorting. This is generated at the recycling centre by the heavy machinery needed to sort the mixed waste before it can be processed. In the integrated scenario, the waste is already sorted at the construction site and can therefore be recycled without this energy-intensive step. Therefore, the recycling centre does not produce any

sorting-related CO_2 in the integrated scenario. After recycling, it is assumed that the waste streams for both scenarios are identical. The large amount of CO_2 produced when sorting the waste in the baseline model far outweighs the slight increase in the transport emissions of the integrated scenario. The integrated scenario shows a total reduction of CO_2 production of -85.88% when compared to the baseline model (0.72 tonnes of CO_2 vs the baseline of 5.10 tonnes of CO_2).

Table 25 Social score Tivoli case study

Social impact	Baseline scenario	Integrated scenario
Total number of trips	73	83

As mentioned, the number of trips is used as an indicator for the social impact of both scenarios. The integrated model has a slightly higher number of trips compared to the baseline model. There is an increase of 13.7% as there are 10 more trips planned from the 73 of the baseline scenario.