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An Integrated Model for Sustainable Construction Logistics: Synthesising Eco-hauling with a Big Room-Based Collaborative Approach

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Copyright Statement

Abstract

The construction industry faces mounting pressure to decarbonise its logistics operations, particularly during the hauling phase, which remains a significant yet under-explored source of carbon emissions in practice and policy. While several assessment frameworks exist, few integrate real-time site constraints, collaborative decision-making, and dynamic optimisation.

This thesis responds to these challenges by developing the BASE model — an integrated, multi-layered approach combining Eco-hauling principles, the Big Room-based collaborative strategy, Discrete Event Simulation (DES) via AnyLogic, and optimisation using Stat-Ease's Response Surface Methodology (RSM).

The BASE model novelly synthesises these elements to identify and eliminate operational bottlenecks, reduce idle time and fuel consumption, and foster coordinated, low-carbon decision-making. The study applies the model to three real-world construction case studies, where various hauling scenarios are tested and validated using empirical data and simulation outcomes. These case studies demonstrate how the model reduces CO_2 emissions, mitigates delays, and enhances decision-making quality across stakeholders.

Collaboration within the Big Room environment emerges as a catalyst for aligning fragmented goals, streamlining communication, and co-creating feasible low-carbon logistics strategies.

This study makes three key contributions: (1) It introduces a novel and validated decarbonisation model specifically targeting construction transportation bottlenecks; (2) It bridges critical gaps between high-level sustainability aims and operational research tools using a data-driven collaborative lens; and (3) It offers practical, evidence-based recommendations for contractors, researchers, and policymakers to implement sustainable, optimised logistics strategies.

The findings contribute to advancing net-zero construction ambitions and inform future research on collaborative, simulation-based emissions modelling.

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1. My paper, titled *"Developing a Model for Reducing Carbon Emissions of Construction Heavy Machinery through ECO-hauling and Collaboration,"* co-authored with my supervisors, Dr. Ehsan Asnaashari and Dr. Amrit Sagoo, was accepted and presented at the SASBE Conference at AUT University, New Zealand, and is now set to be published in the Special Issue of the Q1 journal *Smart and Sustainable Built Environment (SASBE).*

2. The same paper was also accepted and presented at the ARCOM Doctoral Workshop 2024 held at London South Bank University and University College London.

Certificates and the manuscript related to this work can be found at the end of this thesis.

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Glossary of Abbreviations

Abbreviation	Meaning	Abbreviation	Meaning
ABM	Agent-Based Modelling	**LPDS**	Lean Project Delivery System
ABS	Agent-Based Simulation	**LPM**	Lean Project Management
AR	Augmented Reality	**LPS**	Last Planner System
BASE	Big Room, AnyLogic, Stat-Ease, Eco-Hauling	**MIT**	Massachusetts Institute of Technology
BIM	Building Information Modelling	**NO**	Nitric Oxide
BREI	Big Room Effectiveness Index	**NO2**	Nitrogen Dioxide
CO2	Carbon Dioxide	**OPEC**	Organization of the Petroleum Exporting Countries
CPM	Critical Path Method	**PALM**	People and Landscape Model
DES	Discrete Event Simulation	**PERT**	Program Evaluation and Review Technique
ECM	Electric Construction Machinery	**PM**	Particulate Matter
GHG	Greenhouse Gas	**SCI**	Supply Chain Integration
GPS	Global Positioning System	**SD**	System Dynamics
HC	Hydrocarbon	**SDG 13**	Sustainable Development Goal 13 (Climate Action)
IBR	Integrated Big Room	**STA**	Swedish Transport Administration
IPD	Integrated Project Delivery	**TPS**	Toyota Production System
IT	Information Technology	**UK**	United Kingdom
JIT	Just-In-Time	**UNFCCC**	United Nations Framework Convention on Climate Change
LCA	Life Cycle Assessment	**VM**	Visual Management

Chapter 1:

Research Background and Problem Statement

1-1 Introduction

The construction industry faces increasing pressure to reduce carbon emissions and improve sustainability performance, particularly during the logistics phase of projects. Material and waste hauling contributes significantly to greenhouse gas (GHG) emissions, yet this aspect of construction remains under-addressed in both research and practice. Logistics inefficiencies, such as excessive idling, fragmented decision-making, and poor route planning, are common on-site and result in elevated fuel use and emissions.

In response to this challenge, Lean Management and Eco-hauling principles have emerged as promising approaches. Lean focuses on reducing waste and enhancing efficiency through collaboration, while Eco-hauling seeks to optimise transportation by minimising unnecessary trips and improving resource use. However, these strategies are often applied in isolation and lack integration with simulation or collaborative tools that could enhance their impact.

This research addresses that gap by proposing an integrated BASE model that combines Eco-hauling principles, Big Room collaboration, simulation (AnyLogic), and optimisation (Stat-Ease). The model is designed to reduce emissions from hauling activities while improving stakeholder coordination and operational predictability.

This chapter introduces the research context and outlines the problem being addressed, the rationale behind the study, its aims and objectives, and the methodology employed. It concludes by outlining the structure of the thesis.

1-2 Problem Statement

Climate change, driven primarily by greenhouse gas (GHG)[1] emissions from human activities, continues to threaten ecosystems, economies, and communities across the globe (Jogdand, 2020). International efforts such as the Paris Agreement call for urgent actions to limit global temperature rise to well below 2°C above pre-industrial levels (Rogelj *et al.*, 2016).While these ambitions require collective action across all sectors, the built environment remains one of the most significant contributors to global carbon dioxide (CO_2) emissions.

The construction industry accounts for approximately 39% of global CO_2 emissions, with a substantial proportion generated during the construction phase (Müller *et al.*, 2013; UKGBC, 2023). Within this phase, logistics operations—particularly material and waste hauling—are major sources of fuel consumption and emissions. Despite this, hauling operations remain underexplored in emissions-reduction efforts. Heavy reliance on diesel-powered vehicles,

1- ‘’A **greenhouse gas** (or GHG for short) is any gas in the atmosphere which absorbs and re-emits heat, and thereby keeps the planet's atmosphere warmer than it otherwise would be. The main GHGs in the Earth's atmosphere are water vapour, carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O) and ozone.’’(Brander, 2012) inefficient routing, overlapping transport tasks, and poor coordination all contribute to high carbon outputs during project execution (Falakeh *et al.*, 2023; Kowalski *et al.*, 2023).

In response to climate targets, many countries have developed sustainability frameworks and emissions monitoring tools. Life Cycle Assessment (LCA), carbon calculators, and project-level GHG inventories are commonly used to evaluate environmental impacts (Bahramian and Yetilmezsoy, 2020; Pamukçu *et al.*, 2023; Rüdisüli *et al.*, 2022). However, these tools typically suffer from three major limitations. First, they are retrospective in nature, providing insights only after construction has begun or been completed, which limits their ability to inform timely interventions (Lu *et al.*, 2014; Xue *et al.*, 2022). Second, they often rely on generic datasets or industry-average emission factors, failing to account for the specific conditions of individual construction sites (Lasvaux *et al.*, 2015; Reap *et al.*, 2008). Third, they operate as isolated assessments with limited integration into project logistics planning or emissions-reduction strategies.

The fragmented nature of construction logistics further compounds these issues. Projects are typically delivered by multiple stakeholders—including contractors, suppliers, hauliers, and logistics coordinators—working under temporary, decentralised organisational structures (Ortiz *et al.*, 2009). This results in a lack of real-time collaboration and limited opportunities for strategic alignment on logistics or sustainability goals (Sagoo *et al.*, 2020). Hauling schedules are often determined independently by different actors, without coordination or shared access to site-level data. This leads to duplicated trips, under-utilised vehicle capacity, excessive idle times, and scheduling conflicts.

Lean Construction principles offer a pathway to address some of these inefficiencies. By promoting process efficiency, waste reduction, and stakeholder engagement, Lean methods can help streamline logistics operations (Ebbs *et al.*, 2018; Pasquire, 2012). Similarly, Eco-hauling techniques focus on route optimisation, load balancing, and reducing unnecessary vehicle movement to lower emissions and improve fuel efficiency (Krantz *et al.*, 2019a). However, in both research and practice, these approaches are often implemented independently and lack integration with advanced modelling tools or collaborative decision-making environments.

Meanwhile, simulation-based approaches—particularly Discrete Event Simulation (DES)—have gained recognition for their ability to model and optimise complex logistics systems (Banks *et al.*, 2010). DES allows planners to test different hauling scenarios, evaluate performance metrics such as idle time and emissions, and predict system-wide outcomes. Yet, in the context of construction logistics, simulation tools are rarely coupled with emissions optimisation frameworks or embedded within collaborative planning structures.

Their potential to inform real-time, carbon-aware decision-making remains largely unrealised.

Collaborative models such as the Big Room approach, widely used in Lean environments, have shown effectiveness in aligning multidisciplinary teams, enhancing communication, and enabling faster decision-making (Iacovidou *et al.*, 2020; Reja *et al.*, 2024). However, their application in emissions-sensitive logistics planning is underexplored. Few studies have investigated how such environments could be harnessed to integrate carbon optimisation into the daily planning and coordination of hauling activities.

Furthermore, construction projects typically experience a misalignment between the timing of key decisions and the availability of data for evaluating their impact. As project planning progresses, the opportunity to influence key logistics decisions diminishes rapidly, while the ability to measure emissions improves with greater information availability (Austern *et al.*, 2018; Boyd C. and Paulson Jr., 1976). This timing gap severely limits the potential of post hoc assessments to support emissions mitigation.

Collectively, these limitations reveal a critical gap in both academic research and construction practice. There is currently no validated, operational model that brings together: (1) emissions-focused logistics strategies, (2) predictive simulation, (3) optimisation, and (4) collaborative stakeholder engagement. This absence prevents construction teams from proactively designing and managing logistics plans that align with sustainability targets.

This research responds to this gap by developing the BASE model—an integrated approach that combines four key elements: Eco-hauling strategies, the Big Room collaborative framework, AnyLogic-based Discrete Event Simulation (DES), and Response Surface Methodology (RSM) using Stat-Ease software. The model is applied and evaluated through three real-world construction case studies involving transportation-intensive projects. Its purpose is to offer a scalable, data-driven solution for reducing logistics-related CO_2 emissions, improving workflow coordination, and enabling carbon-aware decision-making in construction.

By integrating technical, managerial, and collaborative components, the BASE model seeks to provide a practical method for advancing net-zero construction goals. The model addresses both the operational inefficiencies that drive logistics emissions and the methodological void in current emissions-reduction strategies. In doing so, this study contributes to the growing demand for tools that can bridge the gap between sustainability theory and construction practice.

1-3 Rationale

1-3-1 The importance of curbing CO_2 in the Construction Phase

Construction emissions are generally classified into two types: the amount of carbon emitted during the making of a building includes extraction of raw materials, manufacture and refinement of materials, transport, the construction phase, and the deconstruction and disposal of materials at the end of life, which is known as Embodied carbon (Figure 1.3), and Operational carbon that is the amount of carbon emitted during the operational or in-use phase of a building. However, embodied carbon has largely been overlooked historically but contributes around 11% of all global carbon emissions (WorldGBC, 2019).

Construction phase emissions as an element of embodied carbon possess various resources mainly caused by energy consumption in two aspects: transportation of material and construction equipment (Chen *et al.*, 2022). Meggers et al. (2012) argued that carbon emissions are the foremost reason for transforming the construction sector into a more sustainable one. Hence, the construction phase is very notable environmentally (Pacheco-Torres *et al.*, 2014).

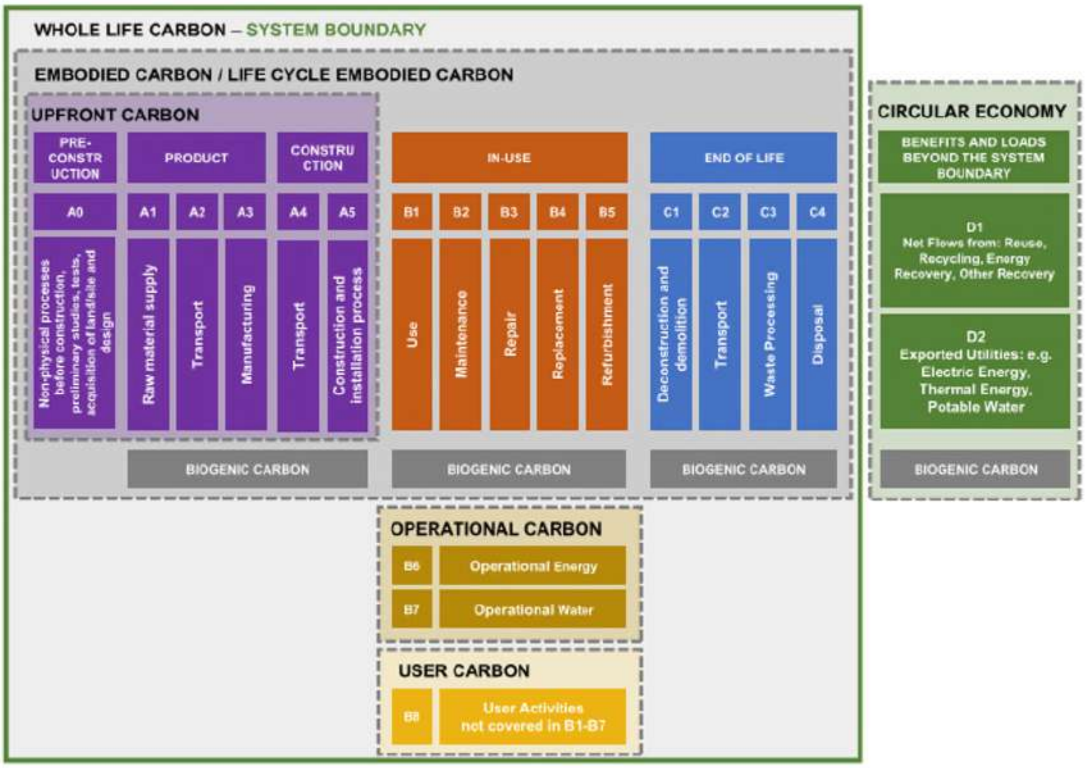


Fig. 1.1: Whole Life-Cycle Carbon (WLC) emissions in the Construction industry
Source: (RICS, 2024)

1-3-2 The Role of Hauling and Earth-Moving in Construction's CO_2

Hauling activities during the construction phase significantly contribute to a project's carbon footprint, primarily by transporting materials and waste. The energy consumption and emissions associated with these logistics are substantial. A study by Bhandari et al. (2011) emphasises that the carbon footprint of road construction is notably impacted by the transportation of materials like sand, gravel, and asphalt, which are essential for flexible pavements. Similarly, research by Karlsson (2024) highlights that the construction sector's emissions arise not only from material production but also significantly from transporting these materials to construction sites.

Furthermore, a review by Sizirici et al. (2021) identifies transportation as a critical phase in the construction process, contributing to the industry's overall carbon footprint.

Addressing the carbon emissions from hauling requires a multifaceted approach. These include optimising logistics to reduce travel distances, adopting fuel-efficient or electric vehicles, and selecting locally sourced materials to minimize transportation needs. Implementing these strategies can significantly reduce the carbon footprint associated with construction activities.

Also, earthwork activities are a major part of many construction projects (Lewis and Hajji, 2012a). These operations are one of the main contributors to GHG emissions, which is an inevitable stage in most construction projects (Barati and Shen, 2016). Earthmoving generally consists of excavation (cutting) at spots where there is an excess of earth, dumping (filling) of that material at spots with an earth deficit, and the materials haulage between those locations (Jassim *et al.*, 2020). Planners' primary goal in projects is to balance the cut and fills as far as possible so that dumping or sourcing materials outside the project is minimised or avoided altogether (Mawdesley *et al.*, 2002). Besides, reducing emissions and increased efficiency can be achieved by selecting an appropriate haul grade, truck payload, and the most suitable type of truck for the site conditions (Kaboli and Carmichael, 2016). As a result, earthmoving is an all-encompassing construction activity in which, by optimising its process, efficiency increases and the carbon footprint decreases.

1-3-3 Heavy-duty construction machinery impact on carbon emissions

Earthmoving, hauling, digging, and finishing processes require heavy-duty construction equipment (Jose, 2001). Diesel fuel has been described as "the lifeblood" of heavy-duty equipment (Hajji and Larasati, 2016), representing 88% of the energy consumption in earthmoving operations (Dipotet L, 2010). Dumper trucks are integral to construction operations, particularly during the materials transportation phase. Their fuel consumption significantly contributes to construction projects' carbon footprint (Wei *et al.*, 2022). A study analysing Environmental Product Declarations (EPDs) for asphalt mixes found that heavy-duty dump trucks transporting aggregates and asphalt added notable emissions (Gettu and Buttlar, 2024). Additionally, Wang et al. (2024) indicated that reductions in carbon emissions can be achieved by optimising transport logistics and improving energy efficiency. This finding suggests that immediate actions can be taken to reduce the carbon footprint of construction activities, including those associated with dumper truck operations. Moreover, Danielsen and Kuznetsova (2015) stated that focusing on a comprehensive approach that encompasses planning minimises the carbon footprint associated with transportation activities involving dumper trucks.

Other Heavy-duty construction equipment like loaders consumes large amounts of diesel fuel and results in large quantities of carbon dioxide (CO_2) emissions (Lewis and Hajji, 2012b). Heavy machinery is designed to offer superior performance and productivity, but the machinery mainly involved in large-scale earthmoving operations emits pollution far greater than other vehicles. For example, the pollution of a 130 kW-power loader is nearly 500 times more than that of a private car(EPA, 2005). Thus, the main environmental concern surrounding the use of this equipment is emissions of air pollutants that impact climate change and air quality (Heidari and Marr, 2015), and it is considered to be one of the primary contributors to carbon emissions in the construction phase (Guggemos and Horvath, 2005; Hong *et al.*, 2013; Junnila *et al.*, 2006).

1-3-4 Challenges of Adopting Electric Construction Machinery (ECM)

Electric construction machinery (ECM) holds significant potential for reducing greenhouse gas emissions and contributing to sustainable practices in the construction industry. However, several critical challenges hinder its widespread adoption, especially in handling heavy-duty tasks efficiently.

One of the primary issues is the reliance on diesel generators for on-site charging. While ECM eliminates direct emissions during operation, the environmental benefits are negated when these machines depend on diesel-powered generators in remote locations. This reliance perpetuates carbon emissions and undermines the sustainability narrative surrounding ECM. As highlighted by Tong et al. (2021), integrating cleaner energy sources into charging infrastructures is essential for realising the actual environmental benefits of ECM.

Additionally, inadequate infrastructure, particularly in developing countries, creates logistical hurdles. Many regions lack reliable access to electricity, let alone specialised charging stations, which significantly hampers the feasibility of ECM adoption (Huang et al., 2024).

Technical challenges further complicate ECM deployment. Current energy storage systems, including lithium-ion batteries, struggle to meet the energy demands of heavy construction tasks, particularly under fluctuating and high-load conditions. Battery life, charging times, and energy density remained insufficient for the intensive requirements of construction machinery (Tong et al., 2021). Furthermore, the mechanical design and energy management systems for ECM are still in their infancy, and operational efficiency often falls short compared to diesel-powered counterparts (Lin et al., 2020).

Given these limitations, it is clear that ECM technology has a long journey ahead before it can fully replace diesel-powered machinery. The continued use of diesel equipment, optimised for efficiency and emissions reduction, remains necessary. Innovations such as hybrid systems and regenerative technologies can serve as interim solutions while research and development efforts address the existing restrictions in battery performance, charging infrastructure, and motor design.

In conclusion, while electrifying construction machinery offers promising environmental benefits, technological and logistical constraints make it unsuitable for full-scale diesel machinery replacement at this stage. Continued reliance on optimised diesel solutions, alongside investments in ECM advancements, is crucial for a phased and practical transition.

1-3-5 Iran's CO2 Mitigation and its Global Impact

Iran ranks among the top 10 global contributors to carbon emissions (UN Iran, 2021). As a signatory to the Paris Agreement (UNFCCC), Iran has committed to cutting its greenhouse gas (GHG) emissions by 12% by 2030. However, this commitment would decrease to only 4% if international sanctions remain in place. Delbridge et al. (2022) remarked that developing countries like Iran, experiencing rapid urbanisation and infrastructure growth, are critical in reducing global CO_2 emissions. As their economies expand, adopting sustainable practices in this sector is essential to meeting international climate goals.

Seyedabadi et al. (2023) stated that construction transportation, accounting for part of the 30% CO_2 emissions from Iran's construction industry, relies heavily on fossil fuels. Besides, in Iran, the transportation involved in delivering materials, machinery, and waste accounts for a substantial portion of emissions due to reliance on fossil fuel-powered vehicles and inefficient logistics systems (Pakdel *et al.*, 2021; Saghafi and Hosseini Teshnizi, 2011). Thus, optimising logistics, reducing distances, and adopting sustainable practices are crucial for emission reduction and meeting Iran's commitments based on the Paris Agreement within the United Nations Framework Convention on Climate Change to reduce CO2 emissions (Seyedabadi *et al.*, 2023).

Developing countries face unique challenges, such as outdated infrastructure and limited access to green technologies (Pigato *et al.*, 2020). However, they can bypass carbon-intensive development pathways by adopting innovative solutions early. International collaborations, investments, and research initiatives also play a pivotal role in supporting these transitions (Mutuku, 2017).

In light of the above, global warming is a worldwide challenge, and every nation's commitment to reducing CO_2 emissions plays a vital role in collective action against climate change. Additionally, the construction industry, responsible for approximately 38% of global CO_2 emissions, has a key role in this effort (GlobalABC, 2020). Therefore, developing countries like Iran, which dramatically impacts global warming, can significantly reduce the construction sector's carbon footprint by integrating sustainable practices, contributing meaningfully to international efforts to combat climate change.

1-3-6 Contribution to knowledge

This study contributes significantly by introducing the novel integration of Eco-hauling principles with collaborative strategies to reduce carbon emissions in construction projects. This innovative approach combines environmentally conscious logistics with enhanced stakeholder collaboration, creating a framework that optimises operational efficiency and minimises environmental impacts. By addressing a critical gap in the knowledge, the research highlights the potential of merging sustainable hauling practices with collective decision-making to streamline construction processes and support net-zero goals. This synthesis offers a new pathway for achieving sustainability in construction, providing a foundation for broader applications across diverse construction projects.

1-4 Research Questions

Previous methods for assessing carbon emissions in the construction of transportation infrastructure largely overlook the constraints imposed by conventional project environments, where the ability to influence carbon emissions gradually decreases while the ability to assess emissions increases. Furthermore, while the significance of transportation has been extensively acknowledged within the Life Cycle Assessment (LCA) community, the scope of this focus is often too broad. Relatively few studies have specifically addressed the environmental impacts associated with onsite machinery. These shortcomings limit the scope of identifying effective emission reduction measures before the window of opportunity for planning and implementing them closes in a project.

The role of collaboration as a potential managerial solution has also not been fully explored in this context. Collaborative approaches could provide significant opportunities for integrating project-specific data, aligning stakeholders' goals, and addressing the limitations imposed by traditional project environments. Collaboration enables contractors, suppliers, fleet managers, drivers, and other key stakeholders to share critical knowledge and perspectives, paving the way for identifying innovative strategies for carbon reduction. However, despite these promising opportunities, the potential of collaboration as a transformative approach remains insufficiently explored in current research and practice.

Therefore, this thesis aims to investigate carbon reduction strategies for construction transportation through the integration of Eco-Hauling and collaborative approaches. These strategies reduce operating time and cost and encourage contractors to adopt more sustainable practices. The primary objective is to develop practical methods for assessing and mitigating carbon emissions, focusing on their application during the planning phase and before executing transportation operations.

Four research questions were posed to achieve this aim. Identifying the sources of carbon emissions in the hauling process requires project-specific data and an assessment method tailored to analyse this information effectively. This would require more individualised and project-focused carbon assessment methods.

This issue defines the focus of the first research question:

Q1- What are the significant sources of CO_2 emissions in the hauling process, and how can project-specific data improve the accuracy of their assessment in hauling operations?

Moreover, conditions such as concurrent operations, incomplete data, limited stakeholder engagement, or uncoordinated efforts can significantly influence the feasibility of carbon reduction strategies. Addressing these challenges requires a combination of collaborative approaches—such as stakeholder engagement, transparent communication, and shared decision-making—and operational practices, including route optimisation, payload planning, and equipment readiness, to implement carbon reduction strategies successfully.

The second and third questions address these issues:

Q2- How does stakeholder collaboration enhance workflows and minimise environmental impact during the construction phase?

Q3- What are the combined effects of integrating Eco-hauling principles with collaboration on carbon emissions and project efficiency in construction logistics?

Modelling offers a structured framework for simulating, analysing, and predicting outcomes; however, integrating two distinct concepts necessitates addressing specific requirements and complexities.

Lastly, the fourth question explores these challenges:

Q4- How can AnyLogic (simulation tools) and Stat-Ease (analytical tools) synthesise to model and identify the optimal hauling scenarios?

1-5 Aim and Objectives

1-5-1 Aim:

To develop and evaluate an integrated approach combining Eco-hauling principles and collaborative strategies to optimise construction logistics, reduce carbon emissions, and promote sustainability in construction projects.

1-5-2 Objectives:

1) **Investigate the environmental impact of construction heavy machinery** by analysing carbon emissions during hauling operations and identifying key contributing factors such as fuel consumption, total time, idle time, and vehicle efficiency.
2) **Examine Eco-hauling principles** as a method to optimise operational efficiency and reduce emissions through strategic, tactical, and operational measures.
3) **Explore the Big Room approach**, rooted in Lean Management, as a collaborative strategy to enhance stakeholder communication, eliminate blockages, and ensure seamless project workflows.

4) **Develop a simulation model** using Discrete Event Simulation (DES) and AnyLogic software to analyse and predict the effects of different hauling scenarios on carbon emissions.
5) **Evaluate and compare hauling scenarios** using optimisation techniques to identify the most effective combinations of operational parameters for minimising carbon emissions and improving project efficiency.
6) **Provide practical solutions** for implementing integrated Eco-hauling and collaborative strategies in construction projects, contributing to sustainable development goals and decarbonisation efforts.

1-6 Research Methodology

Research methodology encompasses the specific techniques and approaches used to gain knowledge about a subject or problem (Mukherjee, 2019). Fellows and Liu (2022) stated that selecting a research method depends on the nature of the research problem. Research methods are influenced by the underlying research philosophy, approach, and strategies that align with the study's objectives (Harrison *et al.*, 2017). Alharahsheh and Pius (2020) declared that Ontology, epistemology, positivism, and interpretivism are fundamental philosophical concepts that play a central role in discussions about research methodologies. Research philosophy determines the development and nature of knowledge, while epistemology focuses on how knowledge is acquired and understood within the research context (Partington, 2002).

This study adopts a pragmatic research philosophy shaped by its ontological and epistemological foundations. It follows a subjective or idealistic ontological stance and a social-constructivist epistemological perspective. Pragmatism, often described as the "Philosophy of Common Sense," values concepts that are useful for practical application, and its epistemology emphasises forming hypotheses based on observations and generalisations from real-world scenarios, promoting a practical, action-oriented approach to research (Shields et al., 1998).

Eventually, this research adopts a mixed-method approach to develop a comprehensive model focused on advancing sustainable construction logistics. The mixed-method approach is widely used to explore complex problems, combining diverse perspectives to develop effective solutions and foster the creation of innovative frameworks that advance knowledge and practice (Creswell, 1999). Therefore, this approach was selected to identify and address challenges in achieving sustainable construction transportation through integrating innovative sustainability concepts, collaborative strategies, and advanced simulation techniques aiming at reducing carbon emissions, improving logistics, fostering collaboration, and providing actionable insights for efficient hauling operations.

This study adopts a pragmatic research philosophy and employs a mixed-method approach to develop an integrated model for sustainable construction logistics. The research combines simulation modelling, optimisation, and collaborative strategies to address the challenges of carbon-intensive hauling operations. Discrete Event Simulation (AnyLogic) and Response Surface Methodology (Stat-Ease) are used to evaluate and optimise logistics scenarios, while principles of Eco-hauling and the Big Room collaborative approach are integrated to reflect real-world practice. The methodology is underpinned by constructivist and practical reasoning and is applied across three real-world case studies. A detailed explanation of the research philosophy, strategy, case study selection, data collection methods, and modelling process is provided in Chapter 3.

1-7 Research Process

1) *Literature Review:*

An extensive literature review was conducted to examine existing research on sustainable construction logistics. Foundational theories, including Lean Management, Discrete Event Simulation (DES), and optimisation techniques such as AnyLogic and Stat-Ease, were explored to understand their application in reducing CO_2 emissions and improving operational efficiency. Existing gaps indicated that while Eco-hauling principles looked promising for addressing current CO_2 challenges, their effectiveness was limited by certain operational complexities. These principles were found to require a complementary contributor, such as a collaborative approach, to identify deeper challenges and address critical hot points that Eco-hauling alone could not resolve. This highlighted the potential for combining these frameworks to enhance their practical impact on construction logistics.

2) *Open-Ended Interviews:*

In parallel with the literature review, open-ended interviews were conducted with construction practitioners, including project managers, logistics planners, and fleet managers. The interviews aimed to uncover practical challenges and opportunities associated with sustainable hauling practices. During these discussions, a significant finding was that operational constraints faced by contractors, such as concurrent operations, often led to traffic congestion and bottlenecks. These blockages substantially increased operational time and diesel consumption, as dumper trucks were frequently forced into idling or low-speed travel or wasting time in queues and bottlenecks. A specific concern highlighted was the increased number of times drivers needed to use the brake pedal due to stop-and-go conditions at congested sites. These frequent braking events disrupted the smooth flow of operations and added to fuel inefficiencies. Additionally, the prolonged idle times caused by these bottlenecks not only amplified CO_2 emissions from dumper trucks but also accelerated wear and tear on engines and other truck components. For example, interviewees reported that in some instances, dumper trucks experienced up to a 30–40% increase in idle time compared to planned operations, primarily due to poor coordination and overlapping tasks on-site. These findings emphasised the critical need for a more integrated approach to streamline operations and reduce emissions effectively.

3) *Identification of Knowledge Gaps:*

After completing the literature review and interviews, the collected data were analysed to identify key gaps in existing knowledge. It became evident that while Eco-hauling principles provided a strong foundation for improving sustainability, their effectiveness was limited without a collaborative framework to address real-world challenges. Specifically, issues like operational bottlenecks caused by overlapping tasks and poor coordination highlighted the need for more integrated approaches. Additionally, the use of simulation tools for optimising hauling processes was found to lack sufficient focus on incorporating stakeholder input and addressing site-specific constraints. These gaps emphasised the importance of combining Eco-hauling with collaborative strategies to create practical solutions that can be effectively implemented in construction logistics.

4) *Carbon Reduction Model Development (BASE Model)*

Following identifying knowledge gaps, the research progressed to developing a comprehensive theoretical foundation for addressing these challenges. This stage focused on defining and justifying the roles of key concepts, simulation methods, and analytical techniques. The Eco-hauling principles and the Big Room-Based Collaborative Approach were identified as central strategies for reducing CO_2 emissions in construction logistics. Their respective contributions to sustainability—Eco-hauling for optimising transportation processes and the Big Room approach for fostering collaboration among stakeholders—were thoroughly analysed and justified.

Furthermore, the integrative capabilities of AnyLogic and Stat-Ease software were established as essential tools for modelling and optimising logistics operations. These tools provided the necessary computational power and flexibility to simulate various hauling scenarios and identify optimal solutions. This stage ensured that all methods and frameworks were grounded in both theoretical and practical considerations, forming the basis for the subsequent development of the hauling model.

5) Developing the Basic Hauling Model in AnyLogic Software

After the theoretical foundation was established, the next stage involved developing a comprehensive hauling model using AnyLogic software. This model was designed to simulate various hauling operations and optimise key parameters to reduce CO_2 emissions and improve efficiency. The development process utilised three complementary simulation methodologies:

- Process Simulation (DES): This technique was used to model discrete events within the hauling process, such as loading, transportation, and unloading. It allowed the identification of inefficiencies in task sequences and resource allocation, providing insights into areas for improvement.
- Agent-Based Modelling (ABM): ABM was employed to simulate the actions and interactions of individual agents, such as drivers, vehicles, and site workers. This approach helped explore how individual behaviours influenced the overall efficiency of the hauling operations.

6) Selecting Case Studies

The integration of these simulation techniques allowed the creation of a versatile and detailed model capable of analysing both micro-level and macro-level dynamics in construction logistics. This stage provided the foundation for testing the model in real-world scenarios.

Following the development of the basic hauling model, the research progressed to testing its applicability and effectiveness through real-world case studies. Three specific scenarios were selected to evaluate the model under varying conditions:

- Case 1: Hauling 900 tonnes of soil.
- Case 2: Hauling 416 tonnes of asphalt.
- Case 3: Hauling 480 tonnes of soil.

Each case study involved specific operational parameters, including hauling distances, truck payloads, and site-specific constraints. The hauling model was applied to simulate these scenarios, allowing the identification of bottlenecks and inefficiencies. The results were used to optimise operational strategies, such as route planning, vehicle allocation, and task scheduling.

7) Big Room Establishing

In this stage, a virtual Big Room was established for each case to integrate diverse stakeholder opinions and foster collaboration. The Big Room focused on fostering collaboration and gathering input from diverse stakeholders to identify operational bottlenecks, coordination issues, and overlapping tasks.

8) Empirical Data Collection

The Big Room approach provided valuable insights into each case's conditions and limitations and facilitated a deeper understanding of the operational context. Building on this foundation, the research progressed to the empirical data collection stage.This stage aimed to gather baseline data for modelling and information on each case's existing hauling plan. Case-specific data were collected, including daily hauling targets, the availability of trucks and loaders, diesel consumption, speed, and payload ranges.

Structured observations were conducted to measure key operational metrics such as total operation time, idle time, number of brakes used, and the overall evaluation of the hauling process. These observations provided critical insights into the current state of hauling operations, enabling a detailed understanding of existing inefficiencies.

This stage's outputs included a comprehensive dataset capturing the baseline conditions and performance of the hauling operations. This dataset served as the foundation for subsequent scenario design and analysis.

9) Scenario Design

Building upon the empirical data, the next stage involved the design of structured scenarios for analysis. Using Stat-Ease software, 15–17 initial scenarios were generated based on combinations of input parameters, including the number of trucks, deliveries, speed, and payloads.

These structured scenarios allowed the research to systematically explore how changes in key variables influenced operational performance. By varying these parameters, the research aimed to uncover relationships between inputs and outputs, such as total operation time, idle time, diesel consumption, and CO_2 emissions.

The outputs of this stage included a structured matrix of input combinations, providing a clear framework for simulating and evaluating each scenario.

10) Outcome Simulation

After designing the scenarios, the research proceeded to the outcome simulation stage. Each of the 15–17 scenarios were simulated in AnyLogic software to calculate critical outcomes, including:

- Total operation time
- Idle time
- Number of brakes used
- Diesel consumption
- CO_2 emissions
- Costs

The simulations provided a dataset of calculated outcomes for each scenario, enabling a detailed evaluation of their operational and environmental performance. This stage was crucial for identifying the impact of various input configurations on key sustainability metrics.

11) Scenario Expansion and Visualization

Using Stat-Ease software, the initial 15–17 scenarios were expanded into over 300 scenarios for each case, allowing for a broader exploration of possible configurations. This expanded dataset facilitated a more comprehensive analysis of trends and relationships between inputs and outputs.

To aid in data analysis, visualisation tools such as 3D surface plots and Response Surface Methodology (RSM) were used to depict relationships between input variables (e.g., number of trucks, speed, payloads, and deliveries) and output metrics (e.g., total operation time, idle time, diesel consumption, CO_2 emissions, and costs).The outputs of this stage included a rich dataset of 300-1300 scenarios and visual insights into trends and relationships, providing a clearer understanding of how different configurations influenced performance.

12) Optimisation

The final stage focused on optimisation, identifying the best configurations for achieving operational goals. Trends in the expanded dataset were analysed to determine the most efficient and sustainable input configurations. The optimisation process sought to:

1-Minimise CO_2 emissions 2-Reduce costs 3-Improve operational efficiency

The outputs of this stage were optimised recommendations for sustainable and efficient operations. These recommendations provided actionable insights for stakeholders to implement more effective and environmentally friendly hauling practices in construction logistics. By combining empirical data collection, scenario design, simulation, expansion, and optimisation, the research developed a robust framework for improving construction hauling operations while addressing key sustainability challenges.

13) Validation

Once the optimisation process was completed, the research proceeded to the validation stage to ensure the reliability and practicality of the proposed solutions. The optimised recommendations were evaluated against real-world conditions and feedback from industry practitioners.

Validation involved comparing the outputs of the optimised configurations with actual field data to assess their accuracy and predictive capabilities. Discrepancies, if any, were analysed, and necessary adjustments were made to refine the model. The validation process also included testing the applicability of the recommendations in real-world settings to confirm their feasibility for reducing CO_2 emissions, improving operational efficiency, and lowering costs.

This stage provided final assurance that the research outcomes were robust and actionable, ensuring that the developed model and recommendations could be implemented effectively in construction logistics practices.

14) Final Stage: Results Interpretation and Conclusions

The final stage of the research centred on interpreting results and drawing conclusions. It brought together findings from earlier stages—data collection, scenario design, simulations, and optimisation—to align outcomes with the research objectives. Key insights assessed the hauling model's impact on CO_2 reduction, efficiency, and cost savings, while emphasising the value of collaboration and simulation tools in construction logistics. Broader implications for sustainable practices were explored, with practical recommendations for real-world application. Limitations were acknowledged, and directions for future research were outlined, ensuring the study offered meaningful insights into sustainable construction logistics.

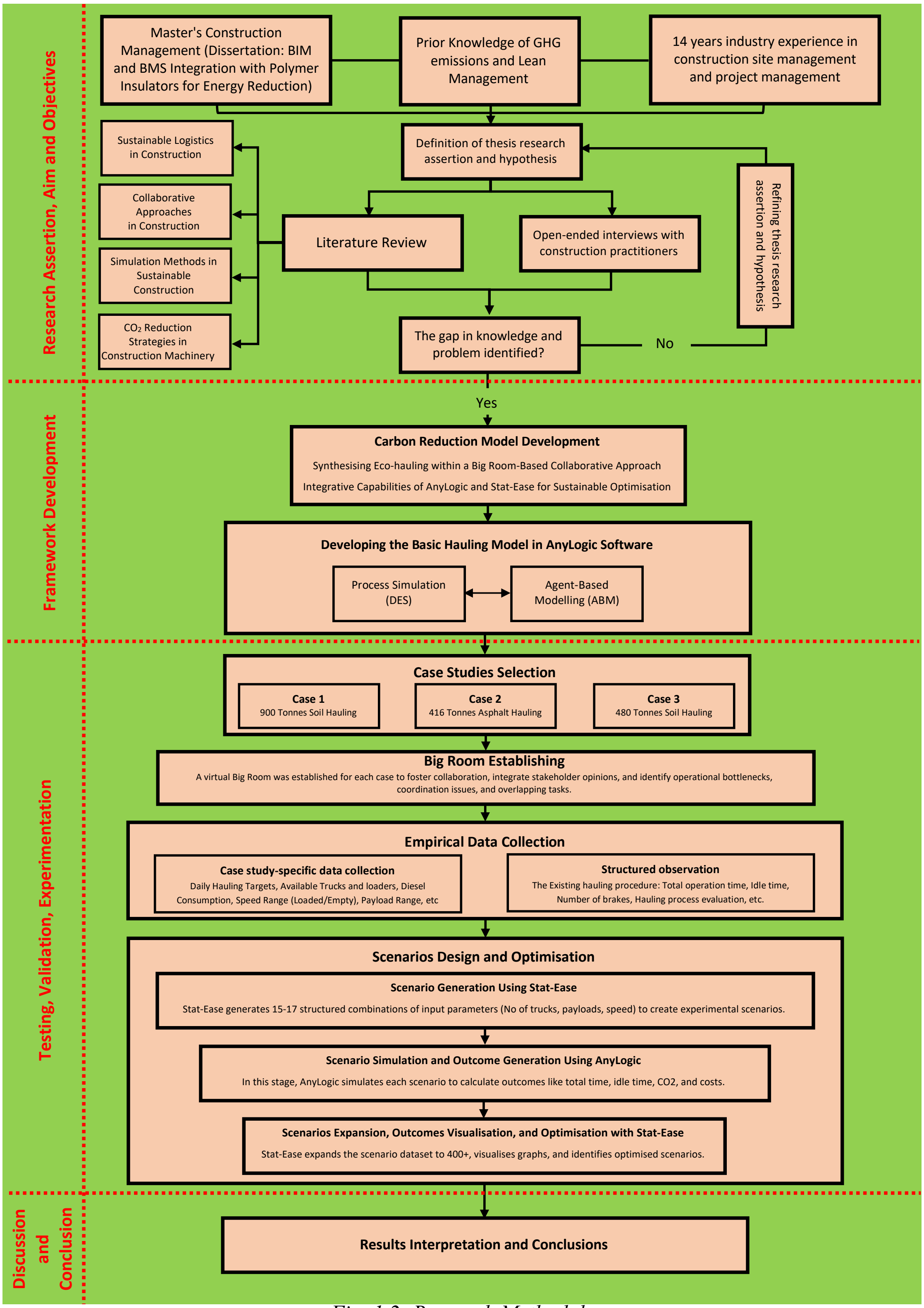


Fig. 1.2: Research Methodology

1-8 The research scope

This research focuses on the conditions and environments that construction practitioners encountered during various planning and implementation stages in order to improve their ability to identify practical strategies for reducing carbon emissions in the hauling process in the construction phase.

From a life cycle perspective, the study explored the upstream phase of transport infrastructure, focusing on on-site construction processes. This focus was selected due to the limitations of traditional Life Cycle Assessment (LCA) methodologies, which often fail to model this critical phase comprehensively.The developed methods primarily focus on on-site construction processes, specifically targeting the restrictions and constraints faced by project contractors whose duties fully or partially involve construction transportation.

Vegetation removal has minimal impact on carbon emissions and was therefore excluded from this study.

Activities related to externally manufactured materials and components under factory conditions, such as asphalt and concrete production, road marking, and installations, were also excluded due to their limited impact during construction.

This dissertation did not employ traditional functional units used in LCA-based studies, such as CO2 emissions per meter or square meters of transport infrastructure. While these units allow sufficient comparison between projects of similar scope, such comparisons have specific limitations in decision-making because each infrastructure construction project has unique characteristics and conditions.

Instead, to provide robust decision-making support, CO2 emissions were considered based on the full assessment scope for each option. This ensures that all possible options or scenarios within a project or activity can be compared regardless of their characteristics.

1-9 Thesis Structure

Chapter One

Research Background and Problem Statement- This section introduces the research topic and highlights its significance. It outlines the environmental challenges the construction industry poses, emphasising the urgency of sustainable practices. The section presents research objectives, questions, and an overview of theoretical and practical contexts.

Chapter Two

Literature Review—This detailed review of relevant literature explores key concepts like Eco-hauling, Lean Management, collaborative strategies, and simulation tools. It evaluates their strengths, weaknesses, and applicability to sustainable construction practices and identifies gaps to guide the research.

Chapter Three

Research Methodology- Presents the research methodology, employing case studies to investigate the integration of Eco-hauling and collaboration. It details the research design, data collection from stakeholders and operations, and simulation and analytical tools such as AnyLogic and Stat-Ease. This comprehensive approach establishes a robust framework for evaluating sustainable construction logistics practices while providing the analyses necessary to address the research questions effectively.

Chapter Four

Results Analysis- Delves into a comprehensive analysis and interpretation of the research findings. It examines the data, identifies patterns, and highlights key outcomes directly addressing the research questions. The chapter evaluates the integration of Eco-hauling and collaborative strategies and discusses their effectiveness in achieving sustainable construction transportation. Through detailed analysis, the results demonstrate the potential of innovative techniques to optimise operations, reduce carbon emissions, and enhance project efficiency.

Chapter Five - Conclusion and Summary - This chapter summarises the study's findings, highlighting integrating Eco-hauling principles and collaborative strategies as a novel approach to reducing carbon emissions in construction projects. It discusses the practical and theoretical implications of the results, emphasising the role of sustainable logistics and collaboration in achieving environmental goals. The chapter concludes with recommendations for future research to expand on these strategies and address remaining challenges in sustainable construction practices.

The present study is organised into five main sections:

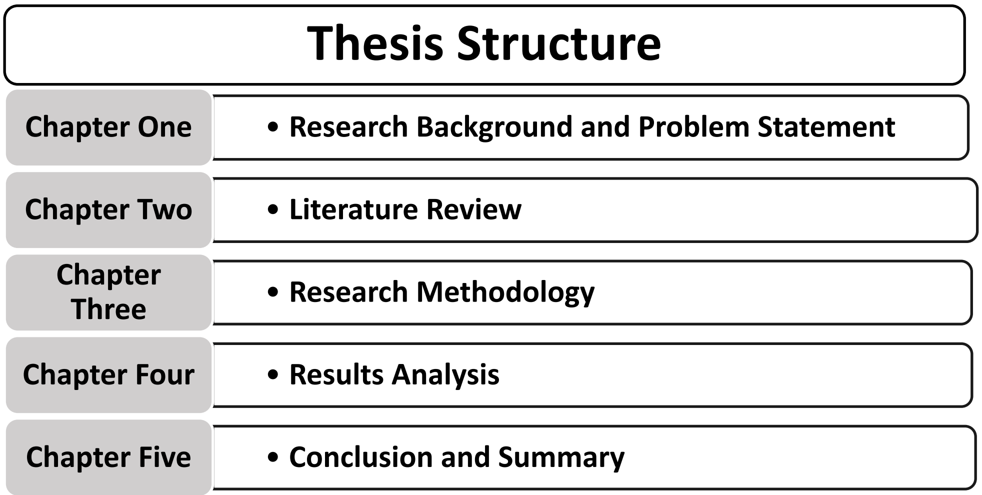


Fig. 1.3: Thesis Structure

Chapter 2:

Review of construction logistics, eco-hauling and lean construction

2-1 Introduction

This chapter critically reviews the existing literature related to construction logistics and sustainability, with a particular focus on carbon emissions during the hauling phase of construction projects. It aims to identify the strengths and limitations of current tools, methods, and strategies used to assess and optimise logistics operations in the construction sector. The review evaluates traditional and emerging approaches, including environmental assessment techniques, Lean Construction principles, Eco-hauling strategies, simulation-based models, collaborative frameworks, and digital technologies.

In response to the research gap identified in Chapter 1, this chapter also examines related advancements in logistics management such as inventory control, site space optimisation, material storage/retrieval systems, and last mile delivery methods, assessing their relevance and applicability to sustainable construction operations.

The objectives of this chapter are to:

- Explore the state of the art in construction logistics and emissions reduction;
- Identify key gaps in tools and models currently used to manage hauling activities;
- Highlight underdeveloped areas such as integrated simulation-collaboration approaches;
- Establish a conceptual foundation for the development of the BASE model.

The chapter is structured thematically, beginning with a review of general logistics challenges in construction, followed by a discussion on emissions evaluation tools, Lean and Eco-hauling approaches, simulation and optimisation techniques, collaborative methods, and finally, emerging logistics innovations. The chapter concludes by summarising the key findings and identifying critical knowledge gaps addressed by this research.

2-2 Global Warming

Climate change has become a significant concern for human beings. Specialists believe that the rate of global warming and climate change is related directly to the increase in the concentration of greenhouse gases, especially carbon dioxide (Farmer and Cook, 2013). United Nations in 2015 established '17 SDGs' talk about this aim. SDG13' is about climate action that considers reducing the carbon footprint as one of the principal aspects of moving towards sustainability(UN, 2015). Approximately 40% of the world's energy is consumed in the construction sector, and throughout its life cycle, including design, materials manufacturing, transportation, construction, operation, refurbishment, and demolishing, this industry emissions almost 35% of Global Greenhouse Gas (Khozema *et al.*, 2020). Given this context, addressing global warming in the construction sector requires greater attention to logistics-related emissions, particularly during the material transportation and on-site execution phases. Construction logistics, including hauling operations, contribute significantly to project-related carbon emissions, yet remain under-represented in sustainability planning. As such, the transition to low-carbon construction must include targeted strategies for optimising transport activities, reducing fuel consumption, and integrating sustainable logistics practices within overall project delivery systems.

2-3 Greenhouse Gases and the Significance of Carbon Dioxide

Greenhouse gases (GHGs) are atmospheric gases that absorb and emit infrared radiation, creating the greenhouse effect, which is essential for maintaining Earth's habitable climate. However, human activities have drastically increased the concentrations of key GHGs, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), causing global temperatures to rise. Among these, CO_2 is the most significant due to its abundance and its role in disrupting the natural balance of the carbon cycle (Van Wijngaarden *et al.*, 2020).

CO_2 accounts for approximately 76% of all GHG emissions globally (Figure 2.1) (Quéré *et al.*, 2018). The rapid increase in atmospheric CO_2 levels, from pre-industrial levels of approximately 280 parts per million (ppm) to over 424 ppm as of November 2024, underscores its significant role in global warming(NASA, 2024).

This increase has disrupted the carbon cycle, creating a positive feedback loop that exacerbates climate change impacts, such as rising temperatures, sea-level rise, and extreme weather events (Friedlingstein *et al.*, 2020).

The radiative forcing effect of CO_2, which measures its capacity to trap heat, is higher than any other GHG except for water vapour (Myhre and Shindell, 2013). Moreover, CO_2's impact extends beyond warming, as it also contributes to ocean acidification, harming marine ecosystems (Doney *et al.*, 2008). Addressing CO_2 emissions is critical for achieving global climate goals, such as limiting warming to 1.5°C above pre-industrial levels, as outlined in the Paris Agreement (UNFCCC, 2016).

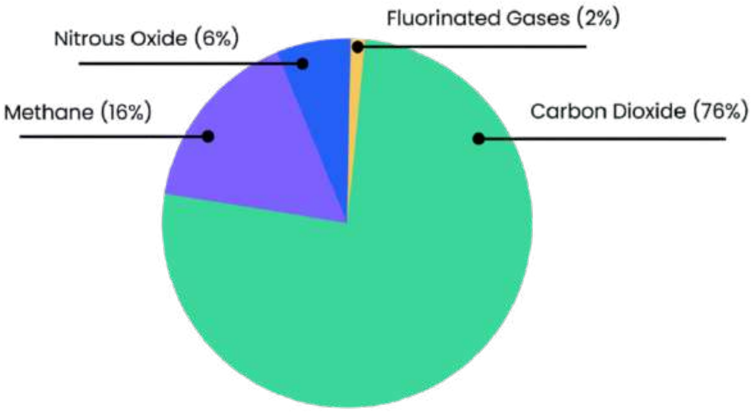


Fig. 2.1: Global Greenhouse Gas emissions
Source: (Net 0, 2024)

2-3-1 Carbon Footprint

A "carbon footprint" represents the total greenhouse gas emissions, mainly carbon dioxide (CO_2), generated directly and indirectly by an individual, organisation, event, or product over its entire lifecycle, usually quantified in tonnes of CO_2 equivalents (Wiedmann Thomas and Minx Jan, 2008). This measure comprehensively assesses environmental impact by tracking emissions from energy use, transportation, industrial processes, agriculture, and waste management (Hertwich and Peters, 2009; Prell and Sun, 2015). Carbon footprint analysis is a crucial tool for addressing climate change, guiding policies, and promoting sustainable practices at individual, corporate, and governmental levels. It emphasises reducing emissions to mitigate global warming's adverse effects (Steffen *et al.*, 2015).

2-3-1-1 Understanding Carbon Footprint Scopes

The Greenhouse Gas (GHG) Protocol defines three distinct scopes for the carbon footprint, which facilitates comprehensive and standardised emission accounting. These scopes help organisations identify and address emissions from various activities and sources.

- *Scope 1: Direct Emissions*

  Scope 1 includes all direct emissions from sources that are owned or controlled by an organisation. This encompasses emissions from burning fossil fuels for heating or vehicle operations and fugitive emissions from leaks in industrial processes. For instance, emissions from on-site natural gas boilers or a company's vehicle fleet fall under Scope 1. These emissions are directly attributable to the organisation and are critical to manage due to their proximity to operational activities(Huang *et al.*, 2009).

- *Scope 2: Indirect Emissions from Purchased Energy*

  Scope 2 covers indirect emissions associated with the generation of purchased electricity, steam, heating, or cooling consumed by the organisation. These emissions occur at the facility producing the energy but are attributed to the end user. Reducing Scope 2 emissions often involves energy efficiency improvements and transitioning to renewable energy sources like solar and wind (Sotos, 2015). For example, switching from coal-based electricity to solar power significantly lowers Scope 2 emissions.

- *Scope 3: Other Indirect Emissions*

  Scope 3 includes all other indirect emissions occurring across the value chain, both upstream and downstream. Examples include emissions from raw material extraction, product distribution, employee commuting, and waste disposal. For many organizations, Scope 3 emissions constitute the majority of their carbon footprint, making their measurement and reduction challenging but vital for comprehensive climate action (Hertwich and Wood, 2018; Pandey *et al.*, 2011).

Understanding and managing emissions across these scopes enables organisations to set effective sustainability goals, identify key reduction areas, and contribute to global climate mitigation efforts. In the context of construction logistics, carbon dioxide emissions are particularly significant due to the heavy reliance on diesel-powered transport for material delivery, waste removal, and on-site equipment movement. These logistics activities are often poorly coordinated, leading to inefficiencies such as idling, empty return trips, and duplicated tasks—all of which increase the carbon footprint of construction projects. Therefore, reducing carbon emissions from logistics operations must be a key focus of any strategy aimed at achieving sustainability in the construction sector.

2-4 Built Environment's Role in Global CO2 Emissions

The built environment plays a critical role in contributing to global CO_2 emissions, representing a substantial challenge in achieving net-zero goals. Globally, buildings and construction are responsible for approximately 39% of energy-related CO_2 emissions. Of this, operational carbon emissions, tied to the energy used during building operation, account for 28%, while embodied carbon, which includes emissions from material production and construction processes, contributes 11% (Figure 2.2) (WorldGBC, 2019). This dual impact highlights the necessity of addressing emissions across the entire lifecycle of buildings, especially as urbanisation accelerates and global building stock is expected to double by 2060 (Giesekam et al., 2014).

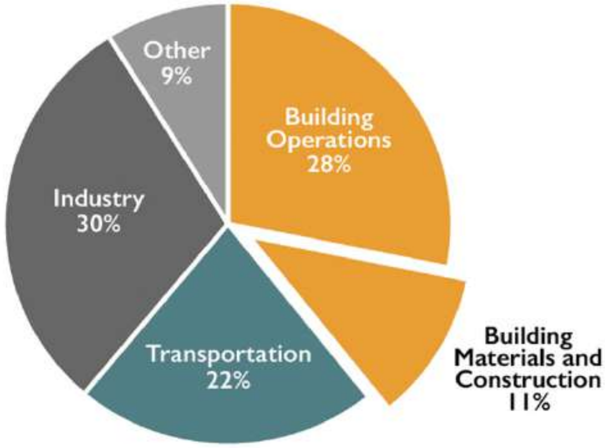


Fig. 2.2: Global CO2 Emissions by Sector
Source:(Bonnet-Masimbert et al.*, 2020)*

Operational carbon, the emissions associated with energy use during a building's operation, remains a dominant focus of mitigation strategies. Measures such as energy-efficient technologies, renewable energy integration, and retrofitting older buildings have shown substantial promise. Berardi (2017) noted that energy retrofitting in temperate regions can reduce heating and cooling demands by up to 60%, making it a vital strategy for cutting emissions in existing structures. Furthermore, advances in innovative technologies have significantly enhanced energy efficiency. Reyna and Chester (2015) demonstrated that automation systems, including intelligent thermostats and energy management platforms, can lower operational emissions by 10–20% when implemented alongside structural improvements.

In contrast, embodied carbon, though less visible, is a growing area of concern as operational emissions decline with improved energy performance (Esau *et al.*, 2021). Chastas et al. (2017)declared that embodied emissions are largely fixed once materials are produced and installed, with materials like concrete, steel, and glass among the most significant contributors. Cement production alone is responsible for 7% of global CO_2 emissions due to its energy-intensive manufacturing process (Belaïd, 2022). Innovations like geopolymer concrete and low-carbon steel are being developed to address this challenge. A study by Younes et al. (2023) highlights the potential of recycled aggregates to reduce embodied emissions by up to 30% in specific contexts. Similarly, circular economy principles, which emphasise material reuse and lifecycle thinking, offer a pathway to reducing waste and emissions in construction (Giesekam *et al.*, 2014).

The built environment is responsible for a substantial share of CO_2 emissions, with embodied carbon playing a critical role due to emissions from material production and construction processes. Prioritising sustainable practices, such as material reuse, low-carbon alternatives, and innovative construction techniques, is essential for achieving net-zero goals and fostering sustainable development.

While the built environment contributes significantly to global CO_2 emissions across its life cycle, logistics activities during the construction phase represent a critical yet often overlooked component. Material handling, waste transport, and equipment movement generate substantial emissions due to fuel consumption and operational inefficiencies. As construction processes become more complex and urban sites more constrained, the role of efficient and sustainable logistics becomes increasingly central to reducing the carbon intensity of the built environment. Therefore, addressing logistics emissions is essential for aligning construction practices with global sustainability and decarbonisation goals.

2-5 Carbon Emissions in Construction Logistics

The construction phase, specifically on-site operations, significantly contributes to CO_2 emissions within the built environment. This phase involves activities such as site preparation, material transportation, equipment operation, and various construction processes (Figure 2.3) (Wang *et al.*, 2024b). The majority of greenhouse gas (GHG) emissions on-site in the construction phase are attributable to the transportation of building materials, accounting for 64.47% of the total emissions (Hong *et al.*, 2015).

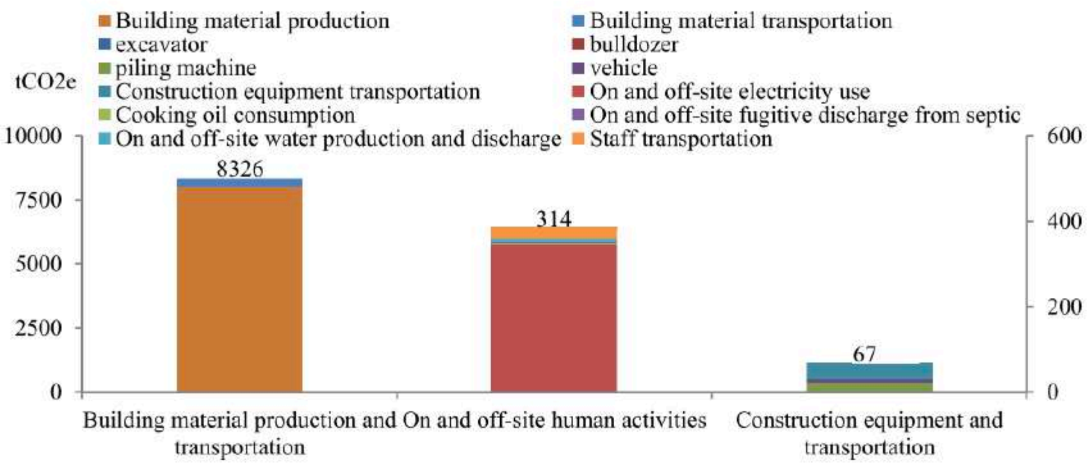


Fig. 2.3: The main sources of carbon emissions in the construction phase
Source:(Hong et al.*, 2015)*

In general, the contributions of the construction phase are 0.4–12% due to the enormous impacts of the lengthy operation phase of 40+ years (Guggemos and Horvath, 2006). In this regard, Hajdukiewicz et al. (2015) declared that researchers have predominantly focused on carbon emissions during building operations. However, the construction phase generates a significant share of emissions within a relatively short period, contrasting with the more gradual emissions accumulated over the building's operational lifespan (Sandanayake *et al.*, 2016). Evidently, the operational phase of buildings tends to dominate lifecycle emissions, and on-site construction activities remain a considerable source of embodied carbon. Addressing this phase is essential for reducing the environmental footprint of the construction industry.

A substantial share of emissions during the construction phase originates from the use of heavy machinery and equipment. These activities heavily rely on diesel-powered equipment such as excavators, cranes, and loaders, which are primary sources of greenhouse gas emissions (Hajji *et al.*, 2017). Diesel combustion produces not only CO_2 but also hydrocarbon (HC), particulate matter (PM), nitrogen monoxide (NO) and nitrogen dioxide (NO2) (together abbreviated NOx), which have detrimental environmental and health effects (Åberg *et al.*, 2015).

Transportation of materials to and within construction sites is another significant source of emissions. Studies suggest that the logistics of material transportation contribute a considerable share of on-site carbon emissions, with variations depending on the project's location and size (Greer and Horvath, 2024).

Delivering materials such as cement, steel, and aggregates involves substantial energy consumption, particularly when these materials are transported over long distances. Optimising supply chains, adopting on-demand delivery practices, and prioritising local sourcing have been shown to reduce transportation-related emissions (Akbarnezhad and Xiao, 2017).

Energy-intensive construction processes, such as concrete pouring, welding, and cutting, add significantly to emissions during the construction phase. Cabeza et al. (2022) found that on-site energy use can contribute substantially to large-scale infrastructure projects’ total greenhouse gas (GHG) emissions. For instance, direct on-site CO_2 emissions account for approximately 24% of total GHG emissions in the building sector, while indirect emissions from off-site electricity and heat generation contribute about 57%. Additionally, the production of construction materials like cement and steel adds another 18% to the sector's emissions.

Liu et al. (2023) noted that on-site waste sorting is critical in reducing carbon emissions by minimising transportation requirements and enhancing resource recovery efficiency. Although the initial costs of implementing advanced on-site technologies may be substantial, these systems yield long-term financial benefits by reducing disposal expenses and improving material reuse. This dual impact supports sustainable construction practices and contributes to achieving carbon neutrality goals, making it a cost-effective and environmentally responsible solution for the construction industry.

Prefabrication and modular construction methods have emerged as effective strategies for reducing emissions during on-site operations. These approaches allow components to be manufactured in controlled environments, reducing on-site construction time and waste (Jeong *et al.*, 2017). Du et al. (2019) found that prefabricated buildings produced approximately 18% lower cradle-to-site CO_2 emissions than conventional buildings. Prefabrication reduces CO_2 emissions during the construction phase by minimising transportation needs. Components are produced off-site and delivered efficiently, reducing vehicle trips, fuel consumption, and associated greenhouse gas emissions. The construction phase significantly contributes to CO_2 emissions due to machinery, transportation, and energy use. Implementing sustainable strategies, such as on-demand delivery, prefabrication, modular construction, and waste optimisation, can reduce emissions and enhance resource efficiency, ultimately promoting sustainable and carbon-neutral construction practices.

2-5-1 Construction Machinery: Key Driver of Carbon Emissions

Fossil fuel-powered construction machinery represents a substantial source of carbon emissions during the construction phase, underscoring its critical role in the sector's overall environmental impact (EPA, 2009). A study by Shahnavaz and Akhavian (2021) highlighted the importance of accurately estimating these emissions to develop effective mitigation strategies.

Case in point, Marrero et al. (Marrero *et al.*, 2017) evaluated the carbon footprint of five construction projects, including two industrial and three residential developments. Their findings demonstrated that, on average, construction machinery had the highest impact on carbon emissions, contributing 52% of the total emissions (Figure 2.4). Similarly, Li and Zheng (2020) conducted an analysis of six residential and industrial projects, confirming the significant effect of machinery, which accounted for an even higher share of 73% of total carbon emissions (Figure 2.5). These findings highlight the pivotal role of machinery in determining the environmental impact of construction activities. Additionally, Solís-Guzmán et al. (2013) examined the onsite activities that most heavily contribute to carbon emissions. Among these, site preparation and earthmoving were identified as the most carbon-intensive tasks, further emphasising the need for targeted mitigation strategies in these areas. Collectively, these studies underscore the critical importance of addressing emissions from construction machinery and high-impact activities to reduce the carbon footprint of the construction industry.

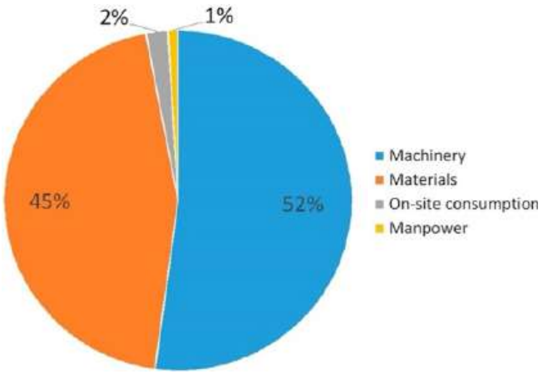


Fig. 2.4: Average Percentages of each Resource Footprint
Source: (Marrero et al., 2017)

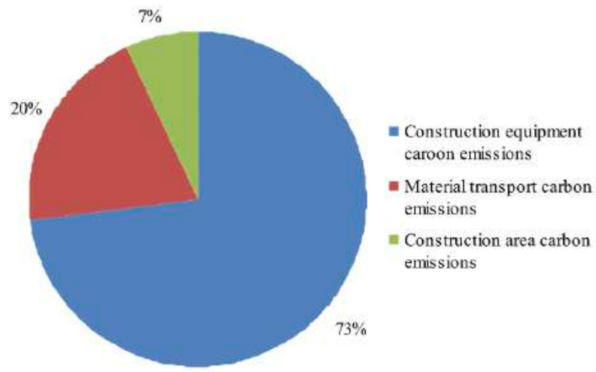


Fig. 2.5: Average Percentages of each Resource Footprint
Source: (Li & Zheng, 2020)

2-5-1-1 Energy Use by Construction Machinery: Impact on Carbon Emissions

The construction phase of large-scale projects necessitates the use of standard equipment to ensure effective and efficient operations, particularly within the realm of infrastructure development (Jaijith, 2020). Construction projects rely heavily on machinery for tasks such as excavation, transportation of materials, and on-site assembly, making their operation central to project execution. Historically, diesel fuel has been the predominant energy source for powering most construction machinery, a trend that persists in contemporary construction practices (Lewis and Rasdorf, 2017). Diesel, like other fossil fuels, is primarily composed of carbon and hydrogen. When burned, it undergoes a chemical reaction with oxygen, resulting in the formation of carbon dioxide (CO_2) and water (H_2O) (EIA, 2020). While this process generates the energy required to power construction equipment, it also releases a variety of tailpipe pollutants into the atmosphere, the most significant being CO_2 (Bruce et al., 2001).

The environmental impact of diesel-powered machinery has been a topic of increasing concern. Studies such as those conducted by the European Rental Association (2019) have highlighted that the energy consumption associated with fossil fuel-based machinery represents the largest share of its carbon footprint throughout its lifecycle. This finding aligns with earlier research demonstrating a direct correlation between energy consumption and carbon emissions in construction activities (Athanassiadis *et al.*, 2002; Kwak *et al.*, 2012a; Lee *et al.*, 2000). The principle is straightforward: the more energy consumed during the operation of construction equipment, the greater the volume of CO2 emissions released into the atmosphere (Lu et al., 2020). This interrelationship underscores the importance of addressing energy consumption in construction machinery as a critical step in reducing the sector's carbon footprint.

Energy consumption and carbon emissions are closely intertwined across the various phases of construction projects, from material production to the final operation of built infrastructure. The construction phase, in particular, stands out as a period of intense energy use due to the continuous operation of heavy machinery. Yan et al. (2010) illustrated this dynamic (Figure 2.6), showing how energy consumption and carbon emissions influence each other throughout the construction lifecycle. Therefore, managing construction machinery during this phase is pivotal to mitigating environmental impacts. Inefficient operation or poor management can significantly increase energy usage and, consequently, carbon emissions.

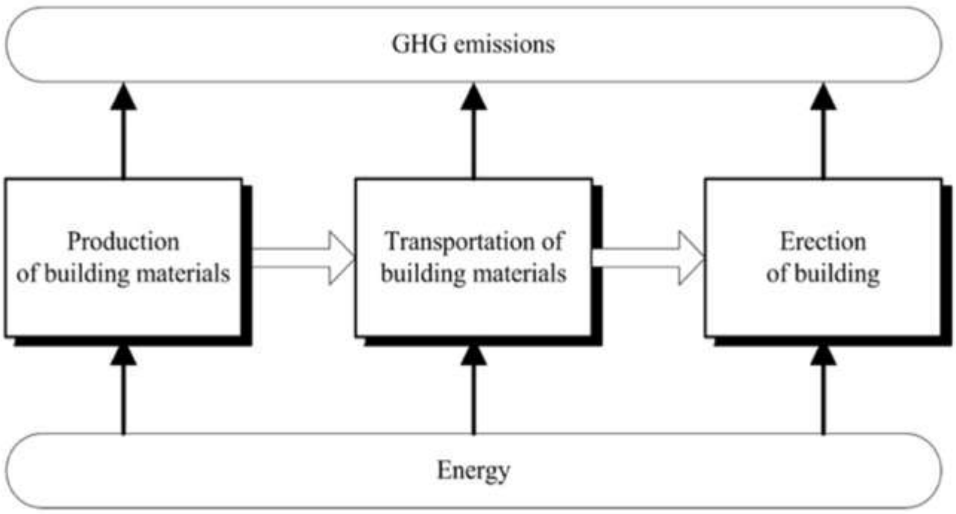


Fig. 2.6: Energy and GHG Emissions Relation in Construction
Source: (Yan et al.*, 2010)*

The economic implications of energy efficiency in construction machinery are significant, as fuel expenses constitute a substantial portion of operational costs in construction projects. Construction machinery is significant, as are fuel expenses (Ahn *et al.*, 2015). Implementing energy-efficient machinery and practices can lead to considerable cost savings by reducing fuel consumption (Ghisellini *et al.*, 2018). Hence, investing in energy-efficient technologies and sustainable practices offers the dual benefits of environmental stewardship and economic resilience.

2-5-1-2 The Carbon Footprint of Construction Machinery in the Lifecycle Perspective

Construction machinery is indispensable in modern construction projects, but its lifecycle is associated with substantial environmental impacts (Cao *et al.*, 2016). The lifecycle of construction machinery includes stages such as manufacturing, operation, maintenance, and end-of-life. Each stage contributes to varying degrees of emissions and environmental harm, making lifecycle assessment (LCA) essential for understanding and mitigating these impacts. The manufacturing phase involves energy-intensive processes, including material extraction, production, and assembly. Materials like iron-based products, tyres, and batteries account for substantial environmental burdens during manufacturing. Adopting sustainable materials and improving energy efficiency in manufacturing processes can reduce these impacts (Ercan *et al.*, 2015; Kwak *et al.*, 2012b)

The operational phase emerges as the most environmentally impactful stage. Tailpipe emissions, heavily influenced by diesel combustion, dominate the lifecycle emissions of construction machinery (Figure 2.7) (Komatsu Report, 2018; Lindgren, 2005). The weight of machinery directly correlates with emissions, as heavier equipment consumes more fuel during operation. For example, machinery in colder climates demonstrates increased emissions due to additional energy demands to maintain functionality under challenging conditions. Studies employing meso-level emission accounting highlight that operational efficiency, fuel efficiency, and the deterioration of engine performance over time are critical factors influencing emissions during this phase (Ahn *et al.*, 2013; Winther and Dore, 2017).

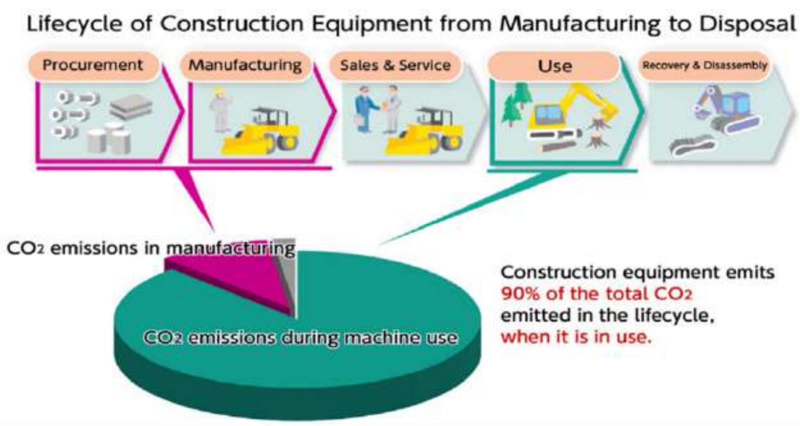


Fig. 2.7: Percentage of CO2 Emissions During Machinery Life Cycle
Source: (Komatsu Report, 2018)

Maintenance activities, though less impactful compared to manufacturing and operation, also contribute to lifecycle emissions. Periodic replacements of components such as tyres, lubricants, and mechanical parts incur environmental costs. End-of-life processes,

particularly tyre recycling, significantly impact categories like freshwater aquatic ecotoxicity. The incineration of used tyres, commonly employed in industries like cement production, introduces heavy metal pollutants into water bodies. This highlights the importance of efficient recycling methods and waste management strategies to minimize environmental damage during the machinery's disposal phase (Ebrahimi *et al.*, 2020).
Mitigation strategies for construction machinery's environmental impacts require adopting advanced technologies and alternative fuels. Measures such as restricting idle time, utilising machinery with higher emission standards, and shifting to electric powertrains are essential for reducing emissions (Barati and Shen, 2017). Transitioning to renewable or low-carbon fuels, such as biodiesel, significantly provides opportunities to lower carbon footprints during the operational phase. Incorporating energy-efficient technologies and improving operational practices are vital for achieving sustainability in the construction industry. Additionally, integrating real-time monitoring systems for emissions can offer insights into optimising performance and minimising unnecessary fuel consumption (Lewis and Rasdorf, 2017).

A comprehensive lifecycle approach is necessary to address construction machinery's environmental challenges. While the operational phase remains the primary contributor to emissions, strategies addressing impacts from manufacturing, maintenance, and end-of-life stages are equally critical (Kwak *et al.*, 2012b).

2-6 Carbon Reduction Strategies in Construction Logistics

Carbon reduction strategies in the construction phase focus on using sustainable materials, energy-efficient machinery, renewable energy, optimised logistics, waste recycling, and digital tools to minimise emissions and promote sustainability.

Various processes drive the construction industry’s emissions, including on-site activities, transportation logistics, and energy-intensive machinery operations. The emissions generated by construction equipment operations are a key factor contributing to construction phase carbon and embodied carbon (Moussavi Nadoushani and Akbarnezhad, 2017). Optimisation strategies are pivotal in supporting construction practitioners in balancing sustainability with operational efficiency, enabling them to reduce carbon emissions while maintaining both productivity and economic viability (Akbarnezhad and Xiao, 2017).

2-6-1 Construction Machinery and Equipment Optimisation

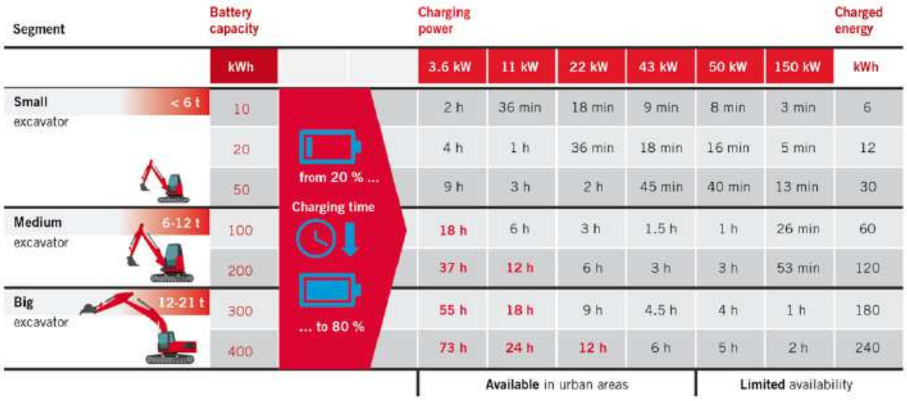
1) *Switch to Electric or Hybrid Machinery*

Switching to electric or hybrid machinery is a significant step in reducing carbon emissions during the construction phase (Wang *et al.*, 2016). Diesel-powered machinery is a major contributor to greenhouse gas emissions, particularly carbon dioxide and nitrogen oxides. Electric and hybrid alternatives produce fewer emissions, offer enhanced energy efficiency, and reduce operating costs over time. These machines operate more quietly, improving on-site conditions for workers and nearby communities. While the upfront cost of electric or hybrid equipment may be higher, the long-term savings in fuel and maintenance can offset this investment (Zhang *et al.*, 2019). However, (Truong *et al.*, 2018) argued that despite the introduction of various technologies for hybrid electric vehicles (HEVs) in the construction sector, significant technological challenges remain in implementing micro/mild hybridisation in construction machinery. Key challenges include:

1. *Machine Architectures*: Developing suitable configurations that integrate hybrid components effectively while maintaining functionality and efficiency.
2. *Energy Storage Devices:* Addressing limitations in storage capacity, durability, and cost to ensure reliable performance in demanding construction environments.
3. *Energy Management Strategies:* Designing advanced systems to optimise energy use, enhance efficiency, and balance the trade-offs between performance and fuel economy.

Construction machinery also faces significant challenges with recharging electric machinery due to limited power infrastructure and increasing energy demands. Figure 2.8 demonstrates this using an electrified hydraulic excavator, where a full battery charge can exceed 12 hours, making overnight charging inefficient and impractical. Larger excavators require additional measures to operate efficiently, while medium-sized excavators can only be fully charged overnight, not during break times (Halfen *et al.*, 2023).

Adopting this technology aligns construction projects with sustainability goals and prepares companies for future stricter environmental regulations. Still, these and other challenges require innovative solutions to realise the full potential of hybridisation in construction machinery.



Segment	Battery capacity (kWh)	Charging time from 20 % ... to 80 %	3.6 kW	11 kW	22 kW	43 kW	50 kW	150 kW	Charged energy (kWh)
Small excavator < 6 t	10		2 h	36 min	18 min	9 min	8 min	3 min	6
	20		4 h	1 h	36 min	18 min	16 min	5 min	12
	50		9 h	3 h	2 h	45 min	40 min	13 min	30
Medium excavator 6-12 t	100		18 h	6 h	3 h	1.5 h	1 h	26 min	60
	200		37 h	12 h	6 h	3 h	3 h	53 min	120
Big excavator 12-21 t	300		55 h	18 h	9 h	4.5 h	4 h	1 h	180
	400		73 h	24 h	12 h	6 h	5 h	2 h	240

Fig. 2.8: Charging time in hours (h) for typical on-site charging power
Source: (Halfen et al.*, 2023)*

2) *Implement Efficient Equipment Use*

Efficient use of machinery is essential to minimise unnecessary energy consumption and reduce fuel emissions on-site (Lewis *et al.*, 2011). One simple yet effective strategy is to minimise idling times, as idling engines waste fuel and produce emissions without contributing to productivity (Frey *et al.*, 2010). Construction managers can implement real-time monitoring systems to track and optimise equipment usage, ensuring machines operate only when necessary(Rao *et al.*, 2022). Scheduling equipment usage more effectively, such as avoiding simultaneous operation of high-energy machines, can also reduce peak energy demands. Training operators to handle machinery efficiently further contributes to energy savings. Additionally, maintaining machinery in good working order ensures optimal performance and prevents energy losses caused by inefficiencies (Waris *et al.*, 2014). These practices collectively improve fuel efficiency, lower emissions, and reduce overall project costs.

3) *Use Renewable Energy for On-Site Operations*

Harnessing renewable energy sources such as solar panels, wind turbines, and portable biomass generators offers a sustainable solution for charging construction electric vehicles and powering construction sites (El Afifi and Abdelrazik, 2023; Trinh *et al.*, 2022). By integrating mobile solar-powered generators, construction sites can efficiently provide clean and reliable energy to charge electric construction equipment, even in remote locations (Gharibeh *et al.*, 2021). Wind turbines can serve as a complementary energy source in regions with steady wind conditions, enhancing the overall energy supply (Ibrahim *et al.*, 2011).

Transitioning to renewable energy for construction machinery reduces fossil fuel dependency, significantly lowering construction activities' carbon footprint (Trinh et al., 2022). Moreover, it aligns with global decarbonisation objectives and strengthens projects' environmental credentials. These innovative energy solutions demonstrate a commitment to sustainability and appeal to environmentally conscious clients and stakeholders. They ensure regulatory compliance while setting a benchmark for green construction practices.

2-6-2 Waste Management

Understanding the distribution of CO2 emissions across different construction activities is crucial for identifying key areas for improvement. This analysis highlights the relative contributions of waste management, material transportation, and building construction phases. As illustrated in Figure 2.9, emissions from construction waste represent a significant share, accounting for 14% of the total CO2 emissions. However, the transportation of building materials remains the dominant contributor, accounting for 83% of the total emissions.

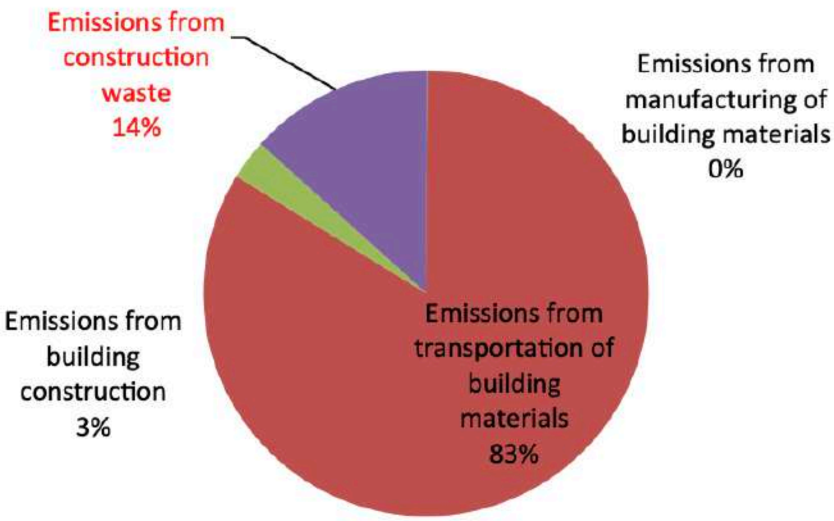


Fig. 2.9: Comparing the emissions from various steps of building construction
Source: (Jafary Nasab et al.*, 2020)*

1) *Implement On-Site Recycling*

Implementing on-site recycling involves processing construction waste directly at the construction site to recover reusable materials. This practice reduces the need to transport waste to external facilities, lowering transportation-related carbon emissions (Bao and Lu, 2020). On-site recycling also minimizes the demand for virgin materials, decreasing the embodied carbon associated with material production. Liu and Li,

(2023) analysed the carbon potential of construction waste resource management and found that recycling construction waste can significantly reduce carbon emissions, especially when combined with policies like carbon trading. By adopting on-site recycling, construction projects can enhance their sustainability and contribute to broader environmental goals (Peng *et al.*, 2022).

2) *Use Modular or Prefabricated Components*

Utilising modular or prefabricated components involves assembling parts of a building off-site in a controlled environment and then transporting them to the construction site for installation. This method reduces on-site waste generation and improves construction efficiency (Loizou *et al.*, 2021). Prefabrication allows for precise material usage, minimising off-cuts and excess materials that would otherwise contribute to waste (Wang et al., 2014). Research indicates that modular construction can significantly reduce material waste and associated carbon emissions. Additionally, the controlled manufacturing environment facilitates better waste management practices, further contributing to carbon reduction efforts (Jaques, 2000).

3) *Adopt Circular Economy Practices*

Adopting circular economy practices in construction involves designing buildings and processes that prioritise the reuse and recycling of materials, thereby extending their lifecycle and reducing waste (Spišáková *et al.*, 2022). This approach contrasts with the traditional linear economy of 'take, make, dispose' and aims to create a closed-loop system minimizing resource input and waste output. A review of waste management strategies highlights the importance of circularity in achieving net-zero goals, emphasizing that current waste management hierarchies should evolve to optimise resource use and minimise environmental impacts (Joensuu *et al.*, 2020). Implementing circular economy principles can substantially reduce carbon emissions by decreasing the need for new material production and reducing waste disposal (Haris *et al.*, 2024).

2-6-3 Construction Operations Simulation

Construction operations simulation is a methodological approach that leverages computational tools to replicate and analyse construction processes virtually. This technique enables project managers, engineers, and stakeholders to evaluate workflows, allocate resources efficiently, and optimise project timelines in a risk-free virtual environment. By providing a dynamic representation of construction activities, simulations empower decision-makers to predict outcomes, identify bottlenecks, and improve overall project performance (Khodabandelu and Park, 2021). Moreover, simulations enhance risk management by identifying potential issues, testing solutions, and improving decision-making through predictive and data-driven analysis (Tak *et al.*, 2021). For instance, figure 2.10 depicts how simulation reduces risks and predicts dangers by visualising mobile cranes as cylindrical safety zones. These zones help identify potential conflicts or interferences, such as overlapping spaces between multiple cranes, ensuring safe operations by highlighting hazardous overlaps and enabling better planning.

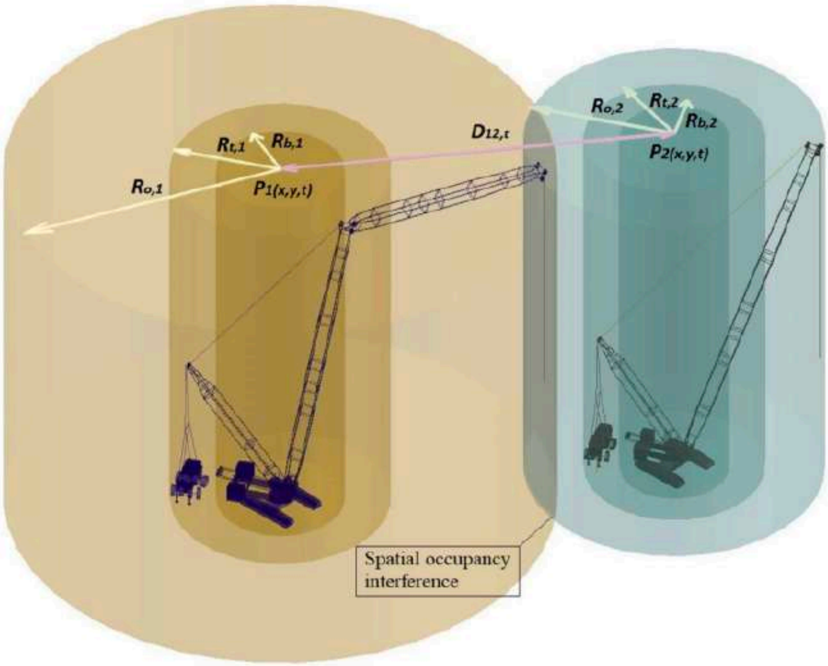


Fig. 2.10: Approximate mobile crane deployment interference checking
Source:(Tak et al.*, 2021)*

Crucially, simulation-based methodologies can significantly reduce carbon emissions in the construction industry. By analysing various operational scenarios, simulations enable the optimisation of material transportation, equipment usage, and resource allocation, leading to reduced fuel consumption and minimised greenhouse gas emissions (Li *et al.*, 2021). Additionally, they facilitate the integration of construction methods into workflows, enhancing sustainability outcomes (Liu, Li, Teng, *et al.*, 2022). Construction operations simulation involves the creation of models that mimic the behaviour and interactions of various elements within a construction project. These elements can include workers, machinery, materials, and environmental factors. The simulation process uses input data from project designs, schedules, and historical records to generate realistic scenarios for analysis. Tools such as Discrete Event Simulation (DES), Agent-Based Modeling (ABM), and System Dynamics (SD) are commonly used to facilitate this analysis (Mazzetto, 2024; Nili *et al.*, 2021; Sahlol *et al.*, 2021).

2-6-3-1 Adopting Simulation in Construction Scheduling

Effective scheduling is essential to reducing inefficiencies that lead to excessive energy use and emissions in construction. Jianhua et al. (2018) emphasised the role of simulation in reducing carbon emissions in transportation construction projects. It also supports collaborative decision-making by allowing real-time adjustments to schedules and materials, ensuring sustainable practices are prioritised throughout project lifecycles (Jianhua *et al.*, 2018).

Traditional methods prioritise cost and time over environmental impacts. However, technologies like Building Information Modelling (BIM) and Discrete Event Simulation (DES) now integrate sustainability metrics into scheduling, enabling data-driven decisions. These tools optimise resource use, reduce idle time, and minimise emissions, aligning project goals with sustainability. Such advancements support the industry's shift toward environmentally responsible practices while maintaining economic and operational efficiency.

2-6-3-1-1 BIM's Role in Optimising Construction Schedules to Reduce Emissions

Building Information Modelling (BIM) has become a cornerstone of innovation in the construction industry, offering robust tools to optimise construction schedules and reduce emissions (Liu, Li, Wang, *et al.*, 2022). BIM integrates complex project data into a unified digital model, enabling construction professionals to plan, visualise, and execute projects more precisely. This capability is particularly critical for addressing environmental challenges, as scheduling plays a pivotal role in minimising energy consumption and emissions throughout the construction process (Bouhmoud *et al.*, 2022).

Traditional construction scheduling has often prioritised cost and time efficiency at the expense of environmental considerations. BIM addresses this limitation by incorporating sustainability metrics into scheduling practices (Zhang *et al.*, 2022). For instance, BIM enables real-time simulations of project workflows, allowing stakeholders to identify the most energy-efficient construction sequences. This minimises equipment idle time and reduces unnecessary energy use, directly contributing to lower emissions (Xu et al., 2023).

Moreover, BIM integrates lifecycle data, facilitating the evaluation of a project's environmental impact across all phases. This capability ensures scheduling decisions align with broader sustainability goals, making BIM an essential tool for modern construction practices. By optimising resource allocation and minimising waste, BIM supports more efficient and environmentally responsible construction (Cavalliere *et al.*, 2019; van Eldik *et al.*, 2020).

BIM's contribution to emission reduction is multifaceted. It fosters collaboration among project stakeholders, aligning sustainability objectives from the project's inception. By integrating data and enhancing communication, BIM ensures environmental considerations are embedded in planning and decision-making processes, paving the way for efficient, sustainable construction practices that reduce waste and emissions (Ferdosi *et al.*, 2023; Santos *et al.*, 2019). Furthermore, BIM's ability to simulate resource utilisation and optimise schedule efficiency enables precise identification of energy-saving opportunities. This advanced capability reduces material waste, minimises unnecessary energy consumption, and lowers emissions, ensuring that construction processes are both efficient and environmentally sustainable throughout the project lifecycle (Jalaei *et al.*, 2021; Shi and Xu, 2021).

Additionally, scholarly research highlights BIM's pivotal role in facilitating comprehensive lifecycle assessments, allowing project teams to evaluate the environmental implications of scheduling decisions across the entire project duration. According to the Forth et al. (2023) and Shibata et al. (2023), this holistic approach ensures that emission reduction strategies are not confined solely to the construction phase. Instead, these strategies extend into the building's operational and maintenance phases, fostering long-term sustainability. By incorporating lifecycle considerations, BIM enables the identification and implementation of environmentally conscious decisions, supporting the reduction of carbon emissions and enhancing the overall sustainability of construction projects.

2-6-3-1-2 Discrete Event Simulation (DES)

Discrete Event Simulation (DES) is a modelling technique used to replicate the behaviour of complex systems where events occur at distinct points in time and affect the system's state (Cassandras and Lafortune, 1999). DES has been used as an effective approach to better absorb complex interactions and uncertainties in construction operations (Abbasi *et al.*, 2020). DES models the sequence of discrete events and the changes in the system state that occur due to these events(Abourizk and Asce, 2010). This approach is a way to understand how things work by pretending to let time pass and seeing how events happen step by step.

It's like a virtual lab where we can study processes, how things interact, and how resources are used. This helps us figure out how to make things work better in real life. (Kaudel, 1987). As one of the largest contributors to global carbon emissions, the construction industry faces increasing pressure to adopt innovative approaches that balance efficiency with sustainability. Among these approaches, Discrete Event Simulation (DES) has emerged as a powerful tool for optimising construction scheduling and minimising environmental impact (Zamani *et al.*, 2024). DES offers a dynamic, data-driven methodology for modelling, analysing, and improving complex construction operations, thereby playing a pivotal role in reducing waste, improving resource allocation, and ultimately mitigating carbon emissions (Fakhimi et al., 2015).

2-6-3-1-2-1 The Role of DES in Construction Scheduling

Construction scheduling is a vital element of project management, which is fundamental in ensuring resources, tasks, and timelines are effectively coordinated to achieve project objectives. Traditional scheduling techniques, such as the Critical Path Method (CPM) and the Program Evaluation and Review Technique (PERT), have long been used to plan and manage construction activities. However, these methods often fall short when addressing the dynamic and stochastic nature of construction projects, which are influenced by factors such as weather, resource availability, and unforeseen delays (Li and Lei, 2010). Discrete Event Simulation (DES) provides a more robust and flexible alternative by allowing detailed scenario analyses that account for variability and uncertainty. This advanced approach facilitates dynamic adjustments to schedules, offering construction managers better insights into potential risks and opportunities for optimisation (Fathi *et al.*, 2023). By integrating DES, construction projects can achieve greater efficiency and resilience. The following sections outline how DES can drive sustainability in construction (Araya, 2022; Limsawasd and Athigakunagorn, 2017).

I. Optimising Resource Use

Discrete Event Simulation (DES) models play a crucial role in enhancing sustainability within construction by identifying inefficiencies in the use of resources such as machinery, fuel, and materials (González and Echaveguren, 2012). Inefficient resource utilisation often results in increased emissions and higher costs. Through simulation, DES provides detailed insights into construction processes, enabling stakeholders to identify bottlenecks and areas where resources are being wasted. By optimising the allocation and utilisation of these resources, DES not only reduces waste but also significantly cuts greenhouse gas emissions. This approach allows the construction industry to achieve more sustainable operations without compromising productivity or quality.

II. Reducing Idle Time of Machinery

Idle time for construction machinery, such as dumper trucks, excavators, cranes, and loaders, is a major contributor to unnecessary fuel consumption and emissions (Agalianos *et al.*, 2020; Que *et al.*, 2016). DES simulations provide an innovative solution by modelling construction schedules and identifying periods of inactivity. These insights enable project managers to make adjustments that minimise idle time, such as reorganising tasks or rescheduling machinery operations. Reducing idle time not only improves fuel efficiency but also lowers operational costs and mitigates the environmental impact of construction activities. Additionally, DES enhances overall project productivity by ensuring machinery is utilised effectively and sustainably.

III. Optimising Transportation

Transportation in construction, including the movement of materials, equipment, and waste, is a significant source of carbon emissions. DES serves as a powerful tool to simulate and analyse logistics operations, facilitating the optimisation of routes and schedules (Agalianos *et al.*, 2020). By reducing travel distances and fuel consumption, DES significantly lowers the environmental footprint associated with construction transportation. Furthermore, DES models can assess various transportation scenarios, helping project managers to select the most sustainable options. This optimisation extends to the use of eco-friendly vehicles and the efficient scheduling of trips, ensuring transportation aligns with broader sustainability objectives in construction (Golzarpoor *et al.*, 2013).

IV. Lifecycle Emission Analysis

Lifecycle emission analysis is vital for achieving sustainability in construction, as it considers emissions across all project stages—from material sourcing and manufacturing to construction, operation, and eventual decommissioning (Golzarpoor *et al.*, 2013). DES enables a comprehensive emissions analysis, providing a holistic view of a project's environmental impact (Zhang, 2015). This capability empowers decision-makers to identify and implement low-carbon alternatives at each stage, such as selecting sustainable materials, adopting energy-efficient construction techniques, or optimising building operations. By employing DES for lifecycle analysis, the construction industry can make well-informed decisions that support sustainability goals and significantly reduce the carbon footprint of projects.

2-6-3-1-3 Agent-Based Modelling (ABM)

Agent-Based Simulation (ABS) has emerged as a critical tool for addressing the challenges of greenhouse gas (GHG) emissions and CO2 reduction in the transportation and construction sectors (Mazzetto, 2024)(Figure 2.11). By simulating the behaviours and interactions of individual agents—vehicles, construction equipment, decision-makers, or stakeholders—ABS offers a nuanced approach to understanding and optimising systems, integrating socio-economic and biophysical dynamics to achieve sustainability goals (Matthews and Macaulay, 2007).

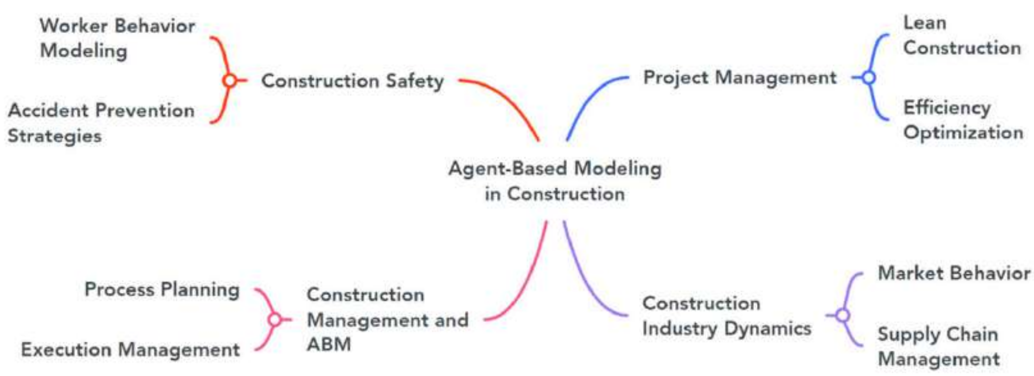


Fig. 2.11: ABM applications in the construction industry
Source: (Mazzetto, 2024)

2-6-3-1-3-1 Modelling Complex and Dynamic Systems

ABS is particularly suited to capturing the complexity of transportation and construction systems, where diverse agents with distinct objectives interact dynamically. These sectors face challenges such as managing emissions-intensive logistics, energy consumption, and material waste. ABS allows detailed representation of these interactions, uncovering system-level outcomes and emergent behaviours (Batty, 2012). In construction logistics, for instance, ABS models can optimise the use of heavy machinery, capturing variations in fuel consumption, equipment scheduling, and material delivery routes (Jabri and Zayed, 2017).

2-6-3-1-3-2 Combining Socio-Economic and Environmental Systems

One of the strengths of ABS is its ability to integrate socio-economic behaviours with biophysical models. This integration is exemplified by the People and Landscape Model (PALM), which simulates the decisions of household agents alongside the carbon and nitrogen dynamics of landscapes (Heppenstall *et al.*, 2012). By linking these dimensions, ABS helps evaluate the impact of different policies and practices on emissions reduction, such as low-carbon construction methods or optimised transportation routes (Akhatova *et al.*, 2022).
ABS can simulate interactions between building materials, energy sources, and emissions outputs in the construction sector. For example, simulations can reveal how adopting prefabricated components reduces CO2 emissions during both material transportation and on-site construction (Groenewolt *et al.*, 2018).

2-6-3-1-3-3 Improved Accuracy in Equipment Utilisation

Traditional Discrete-Event Simulation (DES) models often rely on fixed durations for activities, which do not account for variations in equipment specifications or unique operational constraints. For instance, in earthmoving operations, equipment units such as trucks with different capacities are treated as uniform in DES models, leading to inaccuracies in productivity and emissions calculations. ABM overcomes this limitation by modelling equipment as agents with distinct attributes, such as loading capacities and dynamic properties like carried earth. This approach ensures accurate representation of resource utilisation and emissions, even when diverse equipment is deployed (Jabri & Zayed, 2017).

2-6-3-1-3-4 Optimising Logistics and Operations

In logistics, ABM's strength lies in its ability to mimic intricate supply chain dynamics, enabling the analysis of resource allocation, transportation, and material delivery systems (Arvitrida, 2018). This approach enhances efficiency by identifying bottlenecks and optimising resource usage, often outperforming traditional methods like Discrete Event Simulation (DES) or System Dynamics (SD), which aggregate system variables or focus on discrete events. For example, ABM has been instrumental in simulating the interactions of various stakeholders—such as contractors and suppliers—providing granular insights into material flow and coordination challenges (Fang *et al.*, 2023).

Moreover, Mazzeto (2024) stated that ABM supports lean construction principles by minimising waste and optimising workflows. Simulating the behaviours and interactions of agents enables project managers to test different scenarios, analyse potential improvements, and refine processes without disrupting real-world operations. This ability is particularly useful for managing the complexities of construction sites, such as the coordination of machinery, material deliveries, and labour (Ding *et al.*, 2018).

Integrating ABM with emerging digital technologies like Building Information Modelling (BIM) and Digital Twins further amplifies its utility. This synergy allows for real-time monitoring and decision-making, enhancing operational adaptability and resource efficiency. For instance, integrating ABM with real-time data from sensor networks or IoT devices enables dynamic updates to agent behaviours, improving the responsiveness of logistics systems to unforeseen changes (Fang *et al.*, 2023).

In safety operations, ABM simulates worker behaviour under different conditions, identifying potential hazards and improving risk management strategies. By modelling individual responses to environmental stimuli, ABM helps create safer, more efficient operational environments (Awwad *et al.*, 2017). By addressing agents' heterogeneity and interactions, ABM offers a comprehensive framework for optimising logistics and operations (Nilsson and Darley, 2006).

2-6-3-1-3 System Dynamics (SD)

System Dynamics (SD), developed by Professor Jay W. Forrester at MIT in 1956, became an independent discipline in the late 1950s. It studies information feedback systems to address complex problems across social, economic, ecological, and biological domains. SD emphasises that a system's behaviour is primarily shaped by its internal dynamics and feedback mechanisms (Forrester, 1994).

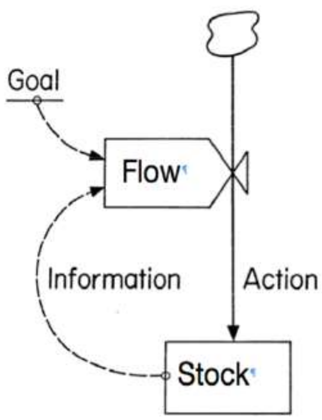
System Dynamics (SD) is a methodological framework for understanding the behaviour of complex systems over time, utilising stocks, flows, feedback loops, and time delays to model intricate interactions within a system (Sterman, 2003). SD has been instrumental in enhancing project planning and control in the construction industry by addressing complexities inherent in construction projects (Yu-Jing, 2012).

The construction sector significantly contributes to global carbon emissions, necessitating effective strategies for carbon reduction. SD offers a robust approach to model and analyse the dynamic interactions among various factors influencing carbon emissions in construction projects. By simulating different scenarios, SD enables stakeholders to assess the potential impact of multiple strategies on carbon reduction, facilitating informed decision-making. For instance, (Wei *et al.*, 2023) developed an SD model to explore the impact of carbon sources, carbon flows, and carbon sinks on carbon emissions under different scenarios in China's low-carbon development. Their findings indicate that energy restructuring is more effective in reducing carbon emissions than industrial restructuring, highlighting the importance of strategic planning in energy consumption for carbon reduction.

In the construction context, SD can be used to model a project's lifecycle carbon emissions, considering factors such as material selection, construction processes, and operational energy use (Liu *et al.*, 2020). By incorporating feedback loops and time delays, SD models can capture the long-term effects of early design decisions on carbon emissions, promoting sustainable construction practices. Moreover, (Du et al. (2019) declared thatSD facilitates the identification of leverage points within the construction process where interventions can lead to significant carbon reductions. This systemic approach ensures that efforts to reduce carbon emissions are efficient and effective, aligning with broader sustainability goals.

Foster, the founder of SD in 2009, simplified systems to these components and provided a clear and universal approach to modelling and understanding dynamic processes in fields like engineering, economics, and environmental management.

Forrester 2.12 illustrations demonstrate this concept. A stock represents an accumulation or level, while a flow changes a stock's quantity based on a rule that compares the stock's value to a goal. The first illustration shows the water level in a glass (stock) being adjusted by regulating water flow via a tap based on visual feedback. The second abstractly represents how a flow responds to a stock's current level relative to a goal. These two elements—stocks and flows—form the foundation of all systems, simplifying their structure and enhancing understanding.



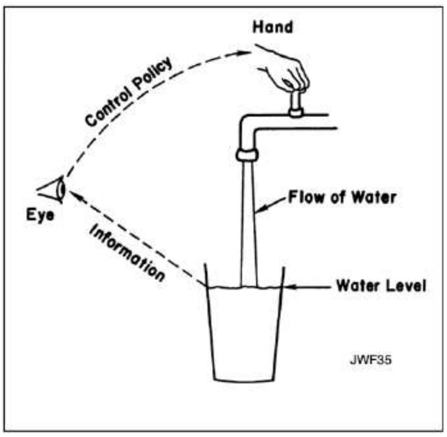


Fig. 2.12: Abstract representation of a feedback (Base of simulation)
Source: (Forrester, 2009)

2-7-3 Collaboration in Construction: Aiming for Decarbonisation

Collaboration is critical in reducing carbon emissions during the construction phase as it fosters shared accountability and innovative problem-solving. Effective collaboration between construction practitioners, from project managers to contractors and suppliers, ensures streamlined processes, minimising waste and inefficiencies (Bui *et al.*, 2023). Research in construction highlights that systemic optimisation, achieved through collaboration among disciplines and integration of components, provides the greatest carbon savings compared to focusing solely on individual techniques in construction (Azari and Kim, 2014). Rahman et al. (2014) highlighted key factors that encourage collaboration among stakeholders in construction projects (Figure 2.13).

Factors that lead to willingness for collaboration	Mean	Rank
Encourage teamwork.	3.911	1
Collaboration with same race will complement each other	3.900	2
Sharing information	3.811	3
A completed project within the time stipulated and quality	3.800	4
Improve quality of service	3.789	5
Facilitate communication among project members	3.744	6
Project completes in a short time	3.689	7
Open opportunities in the future	3.656	8
Collaborated with other parties	3.633	9
Profitable to company organization	3.544	10
Reduce bureaucracy	3.478	11
Commitment from all parties can avoid project failure	3.456	12
Collaboration with different races gives more benefits	3.444	13
The foreign company will give big threat to the local market	3.400	14
Friendship will sustain trust in each other	3.267	15
Encourage different area of business	3.144	16
Suitable for large project, not for small project.	3.122	17
Multilevel collaboration is essential to construction projects.	3.067	18
Suitable for large company, not for small company.	2.956	19
Nobody can be trusted to collaborate	2.578	20
Collaboration is more crucial	2.578	21

Fig. 2.13: key factors that encourage collaboration among stakeholders in construction projects
Source:(Rahman et al.*, 2014)*

Shelbourn et al. (2007) opined that effective collaboration in the construction industry involves the integration of three key strategies: business, technology, and people (Figure 2.14). Success relies on building trust, ensuring clear communication, establishing a shared vision, engaging stakeholders, defining clear processes, and utilising appropriate technologies. Also, in order to achieve optimal outcomes, it is essential to balance organisational, cultural, and technological factors.

Fig. 2.14: Effective collaboration elements
Source:(Shelbourn et al.*, 2007)*

Subsequently, MacLeamy (2004) posited that construction projects prioritising full collaboration and early information sharing are more likely to achieve desired outcomes, including speed, efficiency, effectiveness, and cost control. This collaborative approach redistributes the focus of analysis, design, and decision-making to earlier stages in the project, offering collaborators the greatest opportunity to make informed and optimal decisions. The following diagram illustrates this concept (Figure 2.15).

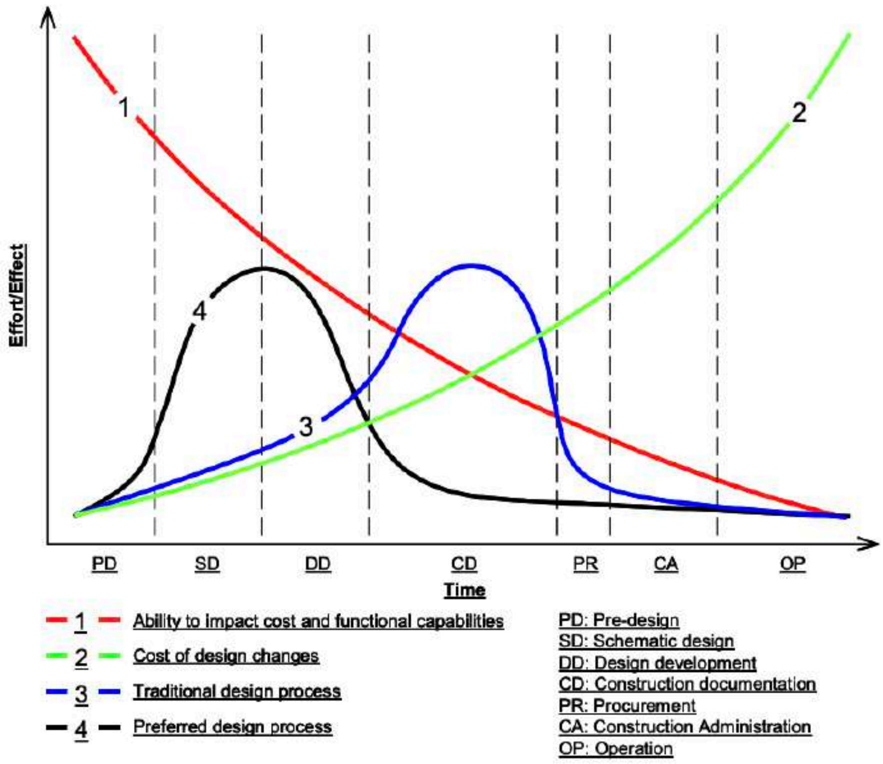


Fig. 2.15: The Impact of Early Collaboration on Design Efficiency and Cost Control
Source: (MacLeamy, 2004)

The construction sector has traditionally been characterised by fragmentation, adversarial relationships, and a lack of integration (Briscoe *et al.*, 2004), which create barriers to delivering low-carbon buildings. Supply chain integration (SCI) involves aligning processes, disciplines, and organisations to improve project performance and sustainability outcomes (Kesidou and Sovacool, 2019). Fragmentation in the construction industry is observed across horizontal (disciplines and trades), vertical (design, construction, and operation stages), and longitudinal (teams varying between projects) dimensions, leading to inefficiencies and missed sustainability opportunities (Vrijhoef *et al.*, 2005). Collaborative approaches, such as integrated procurement and project partnering, promote trust, shared goals, and mutual accountability among stakeholders, enabling better coordination and the delivery of sustainable outcomes (Cox and Townsend, 1997).

Benjaafar et al. (2013) emphasised that construction projects can effectively lower their carbon footprint without substantial cost increases by implementing operational adjustments and fostering collaboration among project members. Hamdan et al. (2021) stated that collaboration among stakeholders is indispensable for overcoming barriers to reducing construction carbon emissions. This highlights the necessity for a comprehensive and coordinated approach to address the carbon emissions associated with construction activities.

Effective collaboration requires shared goals, open communication, and mutual trust. Jackson and Ascui (2019) identified three essential factors that underpin successful collaboration: sharing information and data, strong leadership, and incentive mechanisms that encourage stakeholders to consider their carbon footprint throughout an asset's lifecycle. Sharing information and data ensures transparency and enables all parties to make informed decisions (Bui *et al.*, 2023). Subsequently, Siddiquei et al. (2022) stated strong leadership provides direction and fosters a culture of accountability. Incentive mechanisms motivate stakeholders to adopt sustainable practices by aligning environmental goals with financial benefits. These factors collectively drive the development of collaborative strategies to reduce carbon emissions cost-effectively.

Despite the potential benefits, a silo mentality poses a significant obstacle to collaboration. Nanayakkara et al. (2021) defined silo mentality as an attitude where individuals or teams are reluctant to share information with employees of different divisions. This mindset hinders organisational efficiency, limits innovation, and undermines the culture of cooperation. In the context of construction, a silo mentality can result in fragmented efforts and missed opportunities to achieve carbon reductions. Overcoming this barrier requires deliberate efforts to cultivate a collaborative culture (Guna *et al.*, 2024).

Collaboration techniques play a key role in addressing the challenges posed by the silo mentality and fostering effective interactions among project members. De Waal et al. (2019) argued that collaboration techniques, such as cross-functional teams, joint problem-solving sessions, and integrated digital platforms, can bridge the gaps between different divisions. Cross-functional teams bring diverse perspectives together to tackle complex issues, while joint problem-solving sessions encourage open dialogue and collective decision-making. Integrated digital platforms, such as Building Information Modelling (BIM), facilitate real-time data sharing and enhance stakeholder coordination (Okwandu *et al.*, 2024).

Simulation tools also play a vital role in this collaborative process by predicting the carbon impact of different scenarios and construction methods (Wang *et al.*, 2022). These tools allow stakeholders to model workflows, identify inefficiencies, and test sustainable strategies in a virtual environment before implementation. By integrating predictive simulations with collaborative efforts, teams can make informed decisions to maximise sustainability and align each phase of construction with carbon reduction goals (Ullah *et al.*, 2024). This unified and data-driven approach significantly enhances environmentally responsible construction practices.

2-8 Lean Management

A research team member studying the international automobile industry coined the phrase ‘lean production’. The team's report was published in The Machine That Changed the World (Womack *et al.*, 2007). Lean management is a methodology that focuses on maximising value while minimising waste. Developed from the Toyota Production System (TPS) in the mid-20th century, Lean management has evolved into a globally recognised approach to efficiency and quality improvement (Liker, 2003). This framework is not confined to manufacturing but has found applications in industries as diverse as healthcare, construction, IT, and education.

At its core, Lean management emphasises the delivery of value to customers by identifying and eliminating activities that do not add value. These non-value-adding activities are often referred to as "waste." By fostering a culture of continuous improvement and engaging employees at all levels, Lean management enables organisations to adapt to changing demands and maintain a competitive edge (Nicholas, 2018). The principles of Lean management trace back to Japan's post-World War II era, particularly to Toyota's manufacturing practices under the guidance of Taiichi Ohno and Shigeo Shingo. This system, known as the Toyota Production System, revolutionised traditional manufacturing by focusing on efficiency, quality, and customer satisfaction.

2-8-1 Toyota Production System (TPS)

The Toyota Production System is a Japanese manufacturing philosophy that aims to improve organisational efficiency and achieve the highest possible quality at the lowest cost. Its principles emphasize eliminating all forms of waste from processes to enhance the final value of outputs.

TPS was designed to meet the needs of manufacturing industries, particularly the automotive sector. Its development was driven by the need for transformation in Japanese industry after political changes following World War II. Japan had to reinvent its approach entirely to compete with U.S. and European industrial giants. This transformation began with an attempt to adapt Henry Ford's mass production system. However, this effort failed, prompting Toyota's chief engineer, Taiichi Ohno, to recognise the necessity of implementing fundamental reforms to mass production practices (Ohno, 1988)

Ohno and his colleagues realised Ford's mass production mindset, which focused on producing large volumes of identical products, was unsuitable for Japan. The challenge was to make smaller quantities of diverse models while reducing costs. This approach concluded that reducing system waste was key to cost reduction. The scarcity of resources like raw materials, productive labour, and capital further shaped the development of TPS (Womack *et al.*, 1991).

The system proved even more effective during the 1980s oil crisis when oil prices surged due to embargoes by OPEC members. Toyota responded by reducing production and viewing excess inventory as waste. This approach restored their productivity and established TPS as a catalyst for transforming Toyota into a global manufacturing powerhouse. While many competitors struggled to recover from the crisis, Toyota emerged largely unscathed, securing its position as a leading global manufacturer (Liker, 2003).

2-8-1-1 Lean Toyota Production System's key principles

The Toyota Production System focuses on optimising processes by reducing inefficiencies and aligning production closely with customer needs. It encourages streamlined workflows, minimising delays and maintaining flexibility to adapt to demand. Continuous evaluation and improvement are integral, ensuring consistent quality and efficiency. Employee involvement is prioritised, fostering a collaborative environment where innovations and refinements can emerge naturally from those engaged in the work (Figure 2.16). This approach balances productivity with resource conservation, creating a system that delivers high value while minimising waste (Ng *et al.*, 2010). TPS emphasises creating value for customers while fostering a culture of respect and continuous improvement (Wahab *et al.*, 2013).

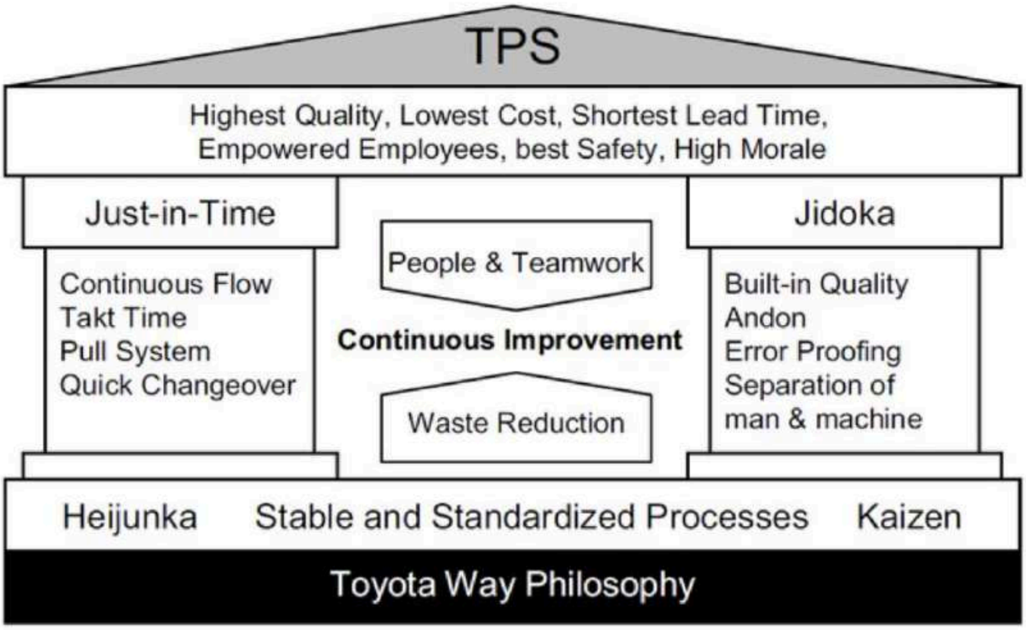


Fig. 2.16: Lean Toyota Production System's key principles
Source: (Romvall et al.*, 2010)*

1) *Continuous Improvement (*Kaizen*)*

A cornerstone of TPS is continuous improvement, known as *Kaizen*. This principle encourages a culture where employees at all levels are empowered to identify inefficiencies and propose solutions (Pinto *et al.*, 2018). Small, incremental changes over time lead to significant improvements in processes, products, and services. *Kaizen* ensures that innovation is an ongoing activity rather than a one-time event (Iwao, 2017).

2) *Respect for People*

This is another key tenet of TPS. The system recognises the value of employees, promoting teamwork, collaboration, and engagement (Liker and Morgan, 2006). Workers are considered vital contributors to the organisation's success, and their insights are actively sought to enhance processes. This principle improves operational outcomes and fosters loyalty and job satisfaction.

3) *Just-in-Time (JIT)*

This principle focuses on delivering the right product at the right time and in the exact quantity needed. This demand-driven approach minimises excess inventory and reduces waste (Golhar and Stamm, 1991). JIT requires precise planning and coordination, ensuring that materials and resources are available exactly when required. By avoiding overproduction and unnecessary storage, companies can enhance efficiency and reduce costs.

4) *Jidoka (Automation with a Human Touch)*

Jidoka is another critical principle of TPS. It empowers machines or employees to detect and address abnormalities immediately. This ensures that quality issues are resolved before they escalate, preventing defective products from continuing through the production line (Tekin *et al.*, 2019). Jidoka combines automation with human oversight, maintaining high standards of quality while safeguarding operational reliability.

5) *Elimination of Waste (*Muda*)*

The elimination of waste, or muda, is central to TPS. Waste is classified into eight types: overproduction, waiting, transportation, overprocessing, inventory, motion, defects, and unused employee creativity. By systematically identifying and eliminating these inefficiencies, TPS ensures that every step in the production process adds value to the end product. This focus on value creation is a hallmark of lean manufacturing (Werner-Lewandowska and Grzelczak, 2021).

6) *Standardised work*

This is another essential component of TPS. It involves establishing consistent and repeatable processes to ensure efficiency and quality. By documenting best practices, companies can maintain uniformity across operations, making it easier to train employees and identify deviations. Standardised work also serves as a foundation for continuous improvement by providing a baseline for assessing changes (Kasul and Motwani, 1997).

7) *Continuous flow*

Continuous flow aims to ensure a smooth and uninterrupted production process. Overboom et al. (2013) declared that by minimising delays and bottlenecks, Lean Management enhances overall productivity and reduces lead times. This principle requires a streamlined workflow where materials and tasks move seamlessly from one stage to the next, aligning with the principles of JIT and waste elimination.

8) *Pull System*

The pull system is another vital aspect of TPS. Sundar et al. (2014) argued that unlike traditional push systems that rely on forecasts, the pull system produces items based on actual customer demand. This approach reduces the risk of overproduction and ensures that resources are used efficiently.

9) *Visual Management*

Visual management is a tool used in TPS to monitor operations and highlight issues. Tools like Kanban[3] boards, colour-coded indicators, and charts provide real-time information, enabling quick decision-making and problem resolution. Visual cues ensure transparency and allow employees to identify and address inefficiencies effectively (Eaidgah *et al.*, 2016).

10) *Problem Solving and Root Cause Analysis*

Finally, TPS emphasises problem-solving and root-cause analysis**.** Using tools such as the *5 Whys*, employees are encouraged to identify the underlying causes of issues rather than merely addressing symptoms. This structured approach ensures that solutions are practical and sustainable, driving long-term improvements in quality and efficiency (Hassan, 2013).

TPS has revolutionised production methodologies through these principles and set the standard for operational excellence worldwide.

3- Kanban is a Japanese word which literally means signboard. A key Lean tool for managing workflows is the pull system, which is often represented with a Kanban board. In simple terms, Kanban is a process that limits the amount of work being done at one time (Work-In-Process or WIP) and uses the Kanban board to visually track tasks as they move through the workflow (Corona *et al.*, 2013).

2-8-2 Lean Thinking

Womack and Jones, (1996) described Lean Thinking as a systematic approach focused on maximising value for customers by eliminating waste, enhancing efficiency, and continuously improving processes through principles like value definition, value stream mapping, flow, pull systems, and perfection pursuit, they stated that these are the key characteristics of Lean management that organisations must adopt to ensure success (Figure 2.17).

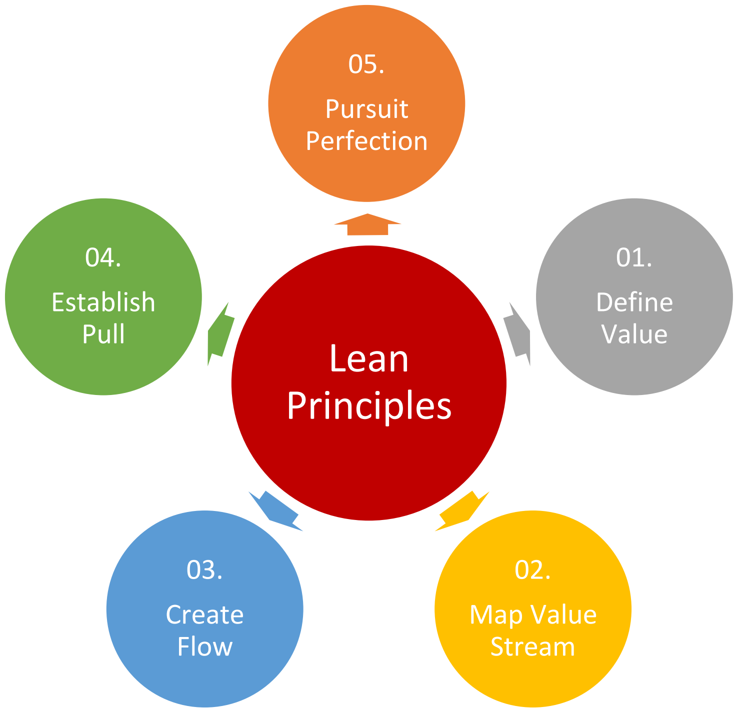


Fig. 2.17: Lean Management Principles

I. *Specify Value:*

The first step in Lean thinking is to define value solely from the customer's perspective. This approach ensures that organisations focus on delivering what the customer truly wants and needs, rather than what they assume is valuable. Frequently, businesses add unnecessary complexity to their products, services, or processes, which does not enhance customer satisfaction. By identifying and focusing exclusively on what the customer values, organisations can eliminate superfluous efforts and concentrate on activities that directly contribute to meeting customer expectations.

II. *Identify the Value Stream:*

Mapping the value stream involves examining all the steps required to deliver a product or service, from start to finish. These steps are then categorised into three types: value-adding activities, necessary but non-value-adding activities, and waste. Value-adding activities directly contribute to the customer's satisfaction or the functionality of the product. Necessary non-value-adding activities, such as compliance checks, may not enhance customer value but are unavoidable. The goal is to streamline the process by focusing on reducing or eliminating non-value-adding activities and waste, ensuring a more efficient and effective workflow.

III. *Create Flow:*

To ensure a smooth, uninterrupted delivery of value, organisations must focus on creating a seamless flow of activities. This involves eliminating bottlenecks, departmental silos, and delays that disrupt productivity and add unnecessary costs. For instance, traditional batch-and-queue systems, which group tasks or products in batches, often cause delays and inefficiencies. By shifting to continuous flow production, businesses can significantly enhance operational efficiency and responsiveness to customer demands.

IV. *Establish Pull:*

A pull system aligns production with customer demand, ensuring that goods or services are created only when required. This approach minimises overproduction, reduces inventory, and prevents waste. The principle can be summarised as a "sell one, make one" strategy, where production is driven by actual demand rather than forecasts or schedules, fostering a more adaptive and customer-focused operation.

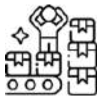
V. *Pursue Perfection:*

The pursuit of perfection is an ongoing journey in Lean thinking. Organisations must commit to continuous improvement by consistently identifying and eliminating waste, optimising processes, and aiming for error-free execution. This mindset fosters innovation, enhances customer satisfaction, and ensures long-term competitiveness in a dynamic marketplace.

2-8-3 Wastes of Lean

Womack and Jones (1996) defined waste as any human activity that consumes resources without creating value. The Japanese term *muda* refers to waste, and Ohno (1988) identified seven types of waste, commonly known as Ohno's Seven Muda: overproduction, waiting, transportation, unnecessary motion, inappropriate processing, inventory, and defects. Waste is intrinsically linked to lean principles. Later, an eighth type of waste, "underutilised people," was added to Ohno's original list by other scholars. Liker (2003) offers an alternative term for this category, referring to it as "unused employee creativity." Numerous scholars have widely described and endorsed the eight types of waste (Bertagnolli, 2022). Liker (2003), in *The Toyota Way*, highlights the importance of eliminating waste to achieve efficiency and value in lean systems. He identified eight types of waste that hinder productivity and classifies them as follows:

1. *Overproduction*



- Definition: Producing more than what is needed or producing too early.
- Impact: Leads to excessive inventory, wasted resources, and additional storage costs.
- Examples:
    - Manufacturing items before they are needed.
    - Printing unnecessary documents.
- Solution: Use Just-In-Time (JIT) production to align output with actual demand.

2. *Waiting*

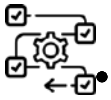
- Definition: Idle time when people, machines, or materials are waiting for the next process step.
- Impact: Reduces productivity and increases lead time.
- Examples:
    - Employees waiting for machine repairs.
    - Machines waiting for raw materials.
- Solution: Improve workflow scheduling and synchronise processes.

3. *Transportation*

- Definition: Unnecessary movement of materials or products.
- Impact: Adds time and cost without adding value to the product.
- Examples:
    - Moving items multiple times between locations.

  - Poor layout, causing excessive material handling.
- Solution: Optimise facility layout and streamline supply chains.

4. Overprocessing



- Definition: Performing more work or using higher-quality resources than required.
- Impact: Wastes time, effort, and materials.
- Examples:
  - Adding unnecessary features to a product.
  - Excessive polishing or inspections.
- Solution**:** Focus on delivering what the customer truly values and simplify processes.

5. Excess Inventory

- Definition: Holding more raw materials, work-in-progress, or finished goods than necessary.
- Impact: Ties up capital, increases storage costs, and risks obsolescence or damage.
- Examples:
  - Overstocking materials "just in case."
  - Producing goods without immediate demand.
- Solution: Implement inventory control systems and demand forecasting.

6. Motion

- Definition: Unnecessary movements of people or equipment.
- Impact: Reduces efficiency and increases fatigue or injury risk.
- Examples:
  - Employees walking long distances to access tools.
  - Reaching or bending unnecessarily during tasks.
- Solution: Ergonomic workspace design and proper tool placement.

7. *Defects*

- Definition: Errors in the product or service that require rework or result in customer dissatisfaction.
- Impact: Wastes time, materials, and can damage the company's reputation.
- Examples:
    - Misaligned parts in assembly.
    - Incorrect billing or shipping errors.
- Solution: Focus on quality control, error-proofing (Poka-Yoke), and continuous training.

8. *Unused Employee Creativity*

- Definition: Failure to utilise employees' full skills, ideas, and potential.
- Impact: Lost opportunities for innovation, reduced engagement, and slower problem-solving.
- Examples:
    - Overlooking a frontline worker's suggestion to simplify manufacturing could have saved time and resources.
- Solution: Establish a structured idea-sharing system and encourage participation in problem-solving discussions.

2-8-4 Lean Construction Waste

Lean construction waste refers to non-value-adding activities within construction processes that hinder efficiency and increase project time and cost (Figure 2.18). Common causes include poor site planning, inefficient workflows, ineffective communication, and lack of coordination among stakeholders. For example, defects and delays in material movement due to inadequate planning are critical issues that significantly impact project time, budget, and resource utilisation (Aravindh et al., 2022). Addressing these challenges through innovative tools like value stream mapping, digital twins, Big Room collaboration, or continuous improvement strategies can optimise resource use, minimise waste, and significantly enhance productivity, sustainability, and overall project delivery outcomes (Zsofia, 2024).

Key	Waste factors
Time waste	
TF1	Delay in start of successive activities due to additional construction of predecessor activity
TF2	Time spent in construction of excess facilities than Client requirement
TF3	Labor time spent in higher-quality construction than proposed in contract
TF4	Time spent to implement advance construction techniques than required
TF5	Time spent in storing materials on site that is not required
TF6	Time lost by labors due to misplacement of tools on site
TF7	Waiting time due to equipment failure
TF8	Waiting for drawings or planning from Engineers, document approval
TF9	Improper utilization of labor talent
TF10	Time lost due to allocation of labor with poor knowledge about the activity
TF11	Unnecessary motion of labors due to poor site facility planning
TF12	Unnecessary movement of material/tools in site
TF13	Time lost due to relocating site facilities
TF14	Time lost due to delayed material/tools delivery on site
TF15	Labor time spent in construction of faulty work
TF16	Labor time spent in correction of defect
TF17	Time lost due to inefficient Workmanship in executing an activity
TF18	Time lost in correcting a work executed by Labor with inadequate information
Cost waste	
CF1	Excessive use of raw materials than required
CF2	Additional Labor allocated to construct extra facilities
CF3	Using high-cost materials not required by Client
CF4	Using advanced construction practices that costs higher than proposed
CF5	Loss of materials/tools from site due to theft
CF6	Loss of capital due to excessive material inventory on site
CF7	Idle time of rented machinery due to poor planning
CF8	Labor salary when idle between two work activities
CF9	Paying Labor to execute a task that requires less talent
CF10	Excess Labor allocated for an activity
CF11	Cost spent in transporting Labors from welfare facility to the site
CF12	Cost spent in movement of material/equipment due to poor site planning
CF13	Delivery of wrong machinery due to poor planning
CF14	Payment to transport companies for delivery of unnecessary inventory due to poor Planning
CF15	Construction and Correction of defective/faulty work
CF16	Defective/faulty material delivered on site
CF17	Fault in construction due to poor workmanship
CF18	Fault in construction due to difference in planning and execution

Fig. 2.18: Construction Wastes' Factors
Source: (Aravindh et al.*, 2022)*

2-8-5 Lean Project Management (LPM)

Ballard and Howell (2003) opined that projects are temporary production systems. When those systems are designed to deliver the product while minimising waste and maximising value, they are called 'lean' projects. Lean project management differs from traditional project management because of its specific goals and unique organisation of phases. They also vary regarding the relationship between phases and how people are involved in each phase. Lean Project Management (LPM) is a transformative methodology that diverges from traditional project management by focusing on maximising value and minimising waste within project-based production systems. This approach redefines projects as temporary production systems integrated with enduring systems that provide materials, resources, and information. Derived from lean manufacturing principles, LPM originates from the Toyota Production System, recognised for its efficiency and systematic approach to waste reduction (Havn, 1994). The Lean Project Delivery System (LPDS) embodies this philosophy, offering a structured framework to achieve these objectives.

The LPDS is organised into distinct but interconnected phases: Project Definition, Lean Design, Lean Supply, and Lean Assembly. Each phase highlights collaboration, stakeholder alignment, and deferring decisions until the last responsible moment to minimise rework and disruption (Ballard *et al.*, 2001). This method contrasts sharply with traditional project management models, which rely on sequential decision-making and localised optimisation, frequently leading to inefficiencies.

Central to LPM are its tools and techniques, exemplified through four practical applications. The Last Planner System, a key production control tool, enhances project reliability through proactive planning, quality task assignments, and continuous feedback loops (Ballard, 1998). Addressing constraints and ensuring clear directives facilitates smooth task progression. Work Structuring through Pull Scheduling introduces backward planning from target milestones, streamlining workflows and eliminating unnecessary buffers. Whenever there is inventory, there are hidden problems, as stockpiles often cover them up. This can be explained using the analogy of a ship and sea level (Figure 2.19): the ship represents production, and the water level represents inventory. As the water level drops (inventory is reduced), hidden obstacles under the surface become visible – these are the unresolved problems. Solving these problems sustainably allows the ship to sail smoothly with less water (less inventory). Similarly, when more stock appears, it indicates some issues must be addressed (Bertagnolli, 2022).

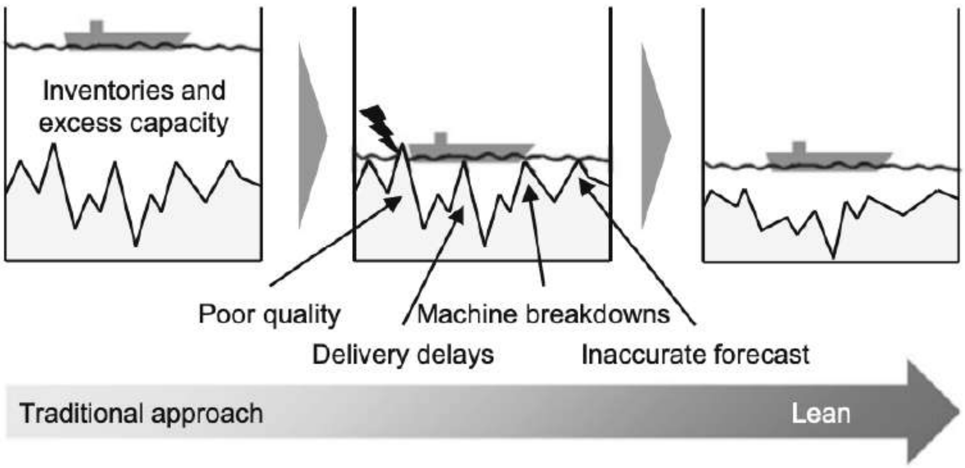


Fig. 2.19: Analogy for production with high and low inventory: Ship with different sea depth
Source: (Bertagnolli, 2022)

The design process within LPM aims to minimise wasteful iteration by distinguishing between necessary and unnecessary iterative loops. Collaborative tools such as cross-functional teams and shared design criteria enable efficient problem-solving and reduce design errors (Lottaz *et al.*, 2000). This restructuring transforms design activities from sequential to concurrent, optimising time and resource allocation.

LPM principles also apply in precast concrete fabrication, where techniques such as pull mechanisms and work structuring have increased productivity and reduced lead times. For example, Malling Precast Products significantly improved its throughput by implementing a one-piece flow, demonstrating the scalability and adaptability of LPM concepts to manufacturing processes (Ballard *et al.*, 2003).

In contrast to traditional methods, which often prioritise transactional efficiency and isolated optimisation, LPM fosters a holistic, system-wide perspective. It delivers superior outcomes by aligning stakeholder interests, enhancing learning, and integrating all lifecycle stages (Construction Task Force, 1998).

2-8-6 Lean Construction

Lean Construction is a philosophy that reimagines construction management by focusing on efficiency, value generation, and waste reduction. Originating from Lean Production in the automotive industry, particularly the Toyota Production System (Ohno, 1988), Lean Construction adapts these principles to the construction sector to address inefficiencies and improve project outcomes (Ballard and Howell, 2003). This approach represents a shift from traditional project management by integrating tools and systems that optimise processes and minimise waste.

At its core, Lean Construction is grounded in the Transformation-Flow-Value theory of production, which views construction as a combination of material transformation, resource flow, and value generation (Koskela, 1992). This model challenges conventional construction methods that focus solely on transformation while neglecting the flow and value aspects (Garcés and Peña, 2023). Lean Construction advocates for continuous improvement, process simplification, and the elimination of activities that do not add value in order to achieve optimal results (Ogunbiyi *et al.*, 2014a).

Lean Construction principles emphasise collaborative workflows, reliability, and proactive problem-solving. For instance, the Last Planner System, developed by Glenn Ballard and Greg Howell in 1992, facilitates improved planning and execution. It encourages stakeholder engagement and stabilises workflows through reliable planning mechanisms ((Aziz and

Hafez, 2013). By integrating intermediate and weekly planning within a master schedule, the Last Planner System significantly reduces uncertainty and improves project reliability.

The Lean Project Delivery System is another essential framework that structures construction projects as value generation processes. This system delineates five phases and introduces tools to create value and minimise waste throughout a project's lifecycle (Alarcón *et al.*, 2005). Unlike traditional project management approaches, which often fail to address interdependencies among project phases, the Lean Project Delivery System explicitly outlines these relationships to enhance efficiency (Garcés and Peña, 2023).

The application of Building Information Modelling (BIM) within Lean Construction further optimises project outcomes. BIM supports visualisation, enhances coordination, and reduces material waste in complex designs (Eadie *et al.*, 2013; Ghaffarianhoseini *et al.*, 2016; Huovila and Koskela, 1998). This integration is increasingly recognised as pivotal to aligning construction practices with contemporary demands for precision and sustainability.

Lean Construction's influence extends to sustainability. By focusing on waste reduction and value creation, it aligns closely with sustainable construction objectives. Huovila and Koskela (1998) first proposed the potential of Lean Construction to support environmental goals, emphasising its ability to reduce resource consumption and minimise environmental impact. Subsequent studies corroborate that Lean Construction can enhance sustainability through efficient resource utilisation and reduced emissions (Jamil and Fathi, 2016; Ogunbiyi *et al.*, 2014b).

Despite these benefits, significant challenges persist in Lean Construction adoption. Cultural resistance, insufficient training, and partial implementation of its tools hinder widespread uptake (Sarhan and Fox, 2013; Wandahl, 2014). Moreover, the misinterpretation of tools such as the Last Planner System often leads to suboptimal outcomes (Viana *et al.*, 2018). Addressing these barriers requires a tailored approach that accounts for organisational culture, leadership support, and comprehensive education initiatives (Huaman-Orosco *et al.*, 2022).

Lean Construction has also faced criticism for its limited application in certain regions and sectors. For instance, research indicates that many developing countries struggle with the implementation of Lean principles due to economic constraints and entrenched traditional practices (Panwar *et al.*, 2016). Furthermore, while the integration of Lean Construction with sustainability has made significant strides, gaps remain in creating cohesive frameworks that align both paradigms (Bolade-Oladepo *et al.*, 2023).

Bibliometric studies of Lean Construction research highlight its growing prominence, with increased publications exploring its principles, tools, and sustainability applications (Garcés and Peña, 2023). However, they also underscore the need for further research to address its practical challenges and improve its adaptability across diverse construction contexts.

2-8-6-1 Lean Construction Tools and Techniques

Lean and techniques tools are methods within the Lean Project Delivery System (LPDS) designed to minimise waste, enhance workflows, and maximise value. They integrate design and processes, optimise schedules, improve collaboration, and ensure efficient production control across construction projects (Ballard *et al.*, 2002). Borrowed from lean manufacturing principles, these tools and techniques streamline workflows, enhance collaboration, and improve project outcomes. Below are key examples of lean construction tools and techniques:

1) ***Last Planner System (LPS)/Pull Planning***

Last Planner System (LPS) is the most developed tool of Lean Construction that provides a predictable workflow that emphasises the relationship between scheduling, planning and production control (Adamu and Howell, 2012). The base of this system is to ensure that every contractor and subcontractor on a construction site can manage and control their workloads (Figure 2.20). At the same time, they are responsible for completing their promised work. In a nutshell, this system engages the people ultimately responsible for getting the work done (last planners) to plan and efficiently execute a project (Carr, 2018).

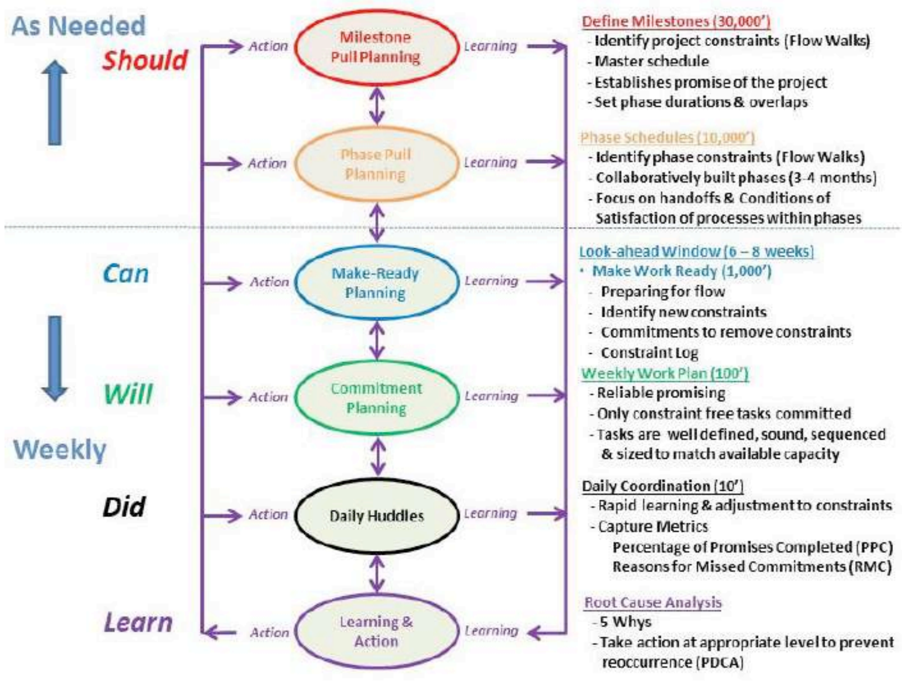


Fig 2.20: Six Levels of LPS
Source:(Ebbs and Pasquire, 2019)

2) Visual Management

Visual Management (VM) is an essential management strategy and a fundamental component of the Toyota Production System. It provides highly visual information to individuals, enabling them to gather the information needed for improved self-management and control (Greif, 1991). For instance, colour-coded boards, graphs, and signs help communicate progress, highlight issues, and ensure transparency. A typical example is the use of visual boards in daily meetings to update schedules, track constraints, and discuss deliverables. This approach improves decision-making and self-management among teams (Tezel *et al.*, 2008).

3) Big Room (Obeya)

The Big Room concept brings together all project stakeholders in a shared workspace, fostering collaboration and quick problem-solving (Alhava *et al.*, 2015a). For example, designers, contractors, and operators work side-by-side to resolve issues in real-time, promoting alignment and innovation. Metrics like the Big Room Effectiveness Index (BREI) measure success by evaluating collaboration, planning quality, and improvements achieved during the project (Joshi *et al.*, 2020a).

4) 5S Methodology

5S—Sort, set in order, Shine, Standardise, and Sustain—is a workplace organisation technique that eliminates clutter and ensures efficiency(Galsworth, 1997). For example, construction teams might use labelled storage areas to quickly locate tools and materials, reducing downtime and preventing waste. A clean, organised site also promotes safety and productivity.

5) Building Information Modelling (BIM)

Lean principles, such as waste reduction and process optimisation, align with BIM's capabilities for visualisation and data integration, fostering enhanced collaboration and efficient project execution (Sacks *et al.*, 2010). For example, BIM allows teams to detect potential clashes in structural designs before construction begins, saving time and costs. It also enhances information sharing, enabling better decision-making throughout the project lifecycle (Uusitalo *et al.*, 2017).

6) Mistake Proofing (Poka-yoke)

Poka-yoke techniques prevent errors and ensure quality in construction processes. For instance, using templates or jigs to ensure accurate measurements can eliminate rework. This approach helps teams deliver consistent results while minimising waste and delays (Singh *et al.*, 2018).

7) Collaborative Process Mapping

This technique visualises workflows to identify inefficiencies and improve processes. For example, mapping out the sequence of tasks in a construction phase can reveal bottlenecks and redundancies, allowing teams to streamline operations and enhance productivity (Patel *et al.*, 2018).

8) Heijunka

Heijunka focuses on leveling workloads to avoid overburdening workers or equipment. For example, project managers might balance resource allocation across tasks to ensure consistent progress and avoid delays caused by uneven work distribution (Barbosa *et al.*, 2013).

9) Augmented Field Visualization

Augmented reality tools project 3D models onto construction sites, helping teams visualise designs in real-world contexts. For instance, stakeholders can use AR devices to assess project progress, detect design discrepancies, and make real-time adjustments (Kamat *et al.*, 2011).

2-8-6-1-1 ***Big Room Approach***

The concept of the Big Room, originating from Toyota's Obeya practices, has emerged as a critical tool in lean construction for fostering collaboration, enhancing communication, and driving efficiency across project lifecycles. It serves as a co-located environment where stakeholders, including designers, builders, and sometimes facility operators, collaborate closely, aligning their goals and actions to enhance project outcomes (Figure 2.21) (Alhava *et al.*, 2015b; Joshi *et al.*, 2020b). Big Room can exist as either a physical space or a virtual environment (Dave *et al.*, 2015). This structured interaction helps mitigate fragmentation, a pervasive issue in the construction industry and supports the seamless integration of processes, people, and technology (Sacks, 2010).

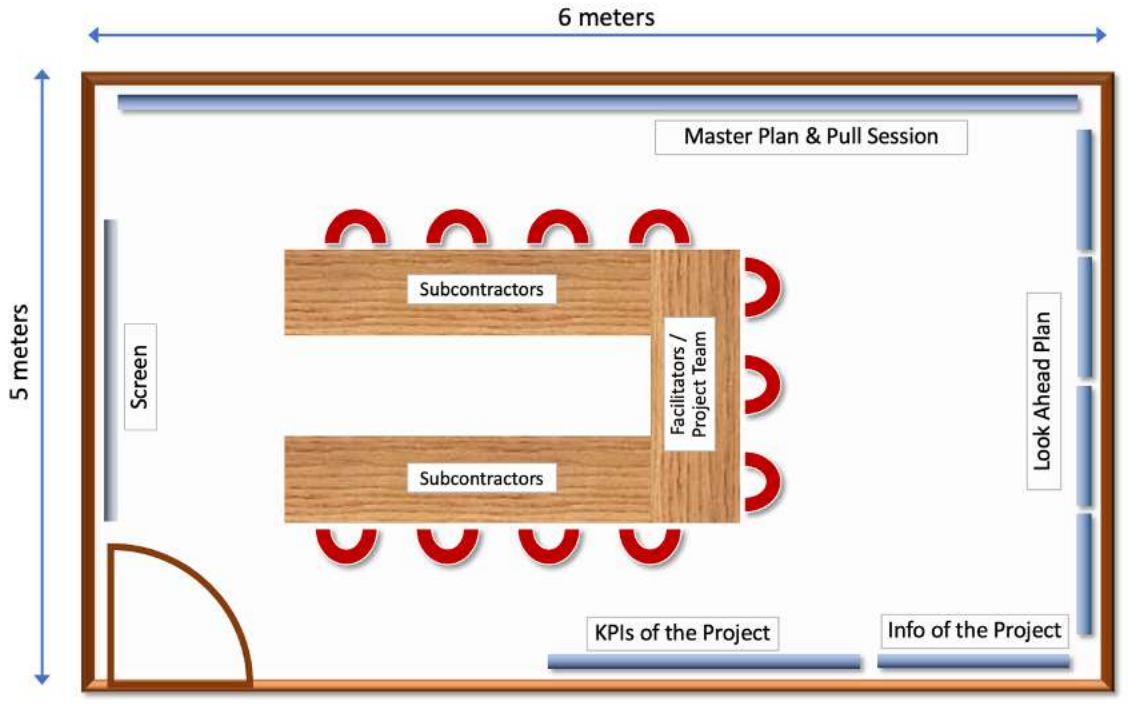


Fig. 2.21: Example of a Big Room
Source:(Pons, 2022)

In practice, the Big Room is more than a physical space—it symbolises a culture of transparency and co-creation. It promotes behaviours essential to teamwork, such as open communication, rapid feedback, and shared accountability (Gokberk Bayhan *et al.*, 2022). The Intensive Big Room (IBR) concept, developed by Fira Oy, exemplifies this philosophy by integrating Building Information Modelling (BIM) and lean principles like pull scheduling, facilitating collaborative problem-solving and accelerated decision-making during the design phase (Alhava *et al.*, 2015b). This approach is particularly beneficial in addressing changes in client requirements, which are often seen as disruptions in traditional project management methods (Juntunen *et al.*, 2015).

Visual management, a key component of the Big Room approach, enhances communication and decision-making by presenting critical information through easily interpretable visuals, such as graphs and boards. This practice fosters a high level of transparency and self-management among stakeholders, reducing the risks associated with miscommunication and delays (Patel *et al.*, 2018; Singh *et al.*, 2018). Additionally, emphasising tools like the Last Planner System (LPS) within Big Rooms aids in look-ahead planning and constraint analysis, ensuring project schedules are reliable and adaptable to changes (Seppänen *et al.*, 2015).

The effectiveness of the Big Room approach lies in its ability to embed continuous improvement (Kaizen) into project workflows. (Joshi *et al.*, 2020a) introduced the Big Room Effectiveness Index (BREI) to quantify this impact, emphasising metrics like collaboration quality, look-ahead planning, and knowledge building. Big Room enables alignment with client needs by fostering an environment where stakeholders can dynamically engage and adapt, reducing design revisions and streamlining workflows (Zsofia, 2024).
Moreover, Big Room supports integrated project delivery (IPD) by emphasising shared goals over individual stakeholder priorities, thus overcoming challenges like adversarial relationships and fragmented communication (Lahdenperä, 2012). This alignment is critical for optimising value, enabling the construction industry to prioritise outcomes such as cost. Ultimately, Big Room is not merely a collaborative tool but a strategic approach that aligns with modern demands for sustainability and innovation in construction. It has proven its versatility across various contexts, from legacy projects to real estate development, offering a scalable model for fostering collaboration and achieving excellence in project delivery (Alhava *et al.*, 2015b; Joshi *et al.*, 2020a). As the industry continues to evolve, the Big Room principles will remain integral to overcoming systemic inefficiencies and advancing lean construction practices (Zsofia, 2024).

2-9 Eco-Driving

Eco-driving, defined as a set of driving behaviours aimed at reducing fuel consumption and emissions, has emerged as a pivotal strategy to mitigate climate change and improve energy efficiency in the transport sector (Tu et al., 2022). It encompasses techniques such as maintaining optimal speeds, minimising idling, and reducing aggressive acceleration and braking. Figure 2.22 shows the ranges of percentages of fuel savings or CO2 reduction contributed by each eco-driving factor.

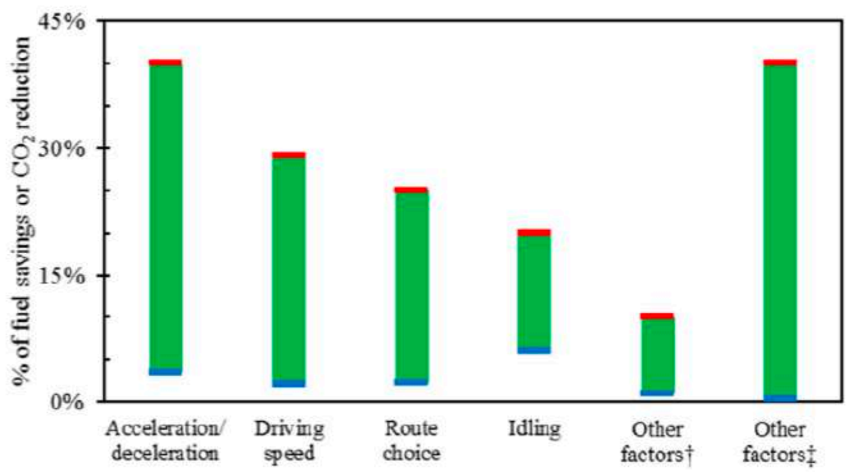


Fig. 2.22: Eco-Driving: Factors of Eco-driving
Source: (Huang et al.*, 2018)*

With growing global awareness of the environmental impact of fossil fuel usage, eco-driving offers a cost-effective and immediate solution to reduce greenhouse gas (GHG) emissions and conserve energy resources (Yang *et al.*, 2021).

Carbon emissions from transportation in some developing countries have been rising, driven by urbanisation and increased vehicle dependency. Conversely, emissions in developed countries have declined, supported by energy-efficient innovations. Transportation in developed countries emits 3.5 times more CO2 than developing ones (Demircan Çakar *et al.*, 2021). Eco-driving has been shown to reduce fuel consumption by 5–40%, depending on conditions such as traffic congestion and driving habits. These reductions mitigate climate change and provide economic benefits to drivers through lower fuel costs (Alam and McNabola, 2014a).

2-9-1 Techniques and Theoretical Underpinnings

Eco-driving behaviours can be broadly categorised into strategic, tactical, and operational decisions:

1. *Strategic Decisions:* These include vehicle maintenance and choice. Proper maintenance, such as ensuring optimal tyre pressure and keeping emission control systems in good condition, can significantly enhance fuel efficiency. Research suggests that up to 40% of excess emissions can be attributed to poorly maintained emission systems. Routine servicing and careful vehicle health management are essential components of eco-driving practices (Sivak and Schoettle, 2012).

2. *Tactical Decisions:* Tactical eco-driving involves effective trip planning to minimise energy consumption. For instance, selecting less congested routes or driving during off-peak hours can lead to measurable savings in fuel. A study's findings indicate that selecting routes optimised for energy efficiency can lead to energy savings between 25% and 51%, which often results in increased travel distances of 3% to 19% (Awardee *et al.*, 2012).

3. *Operational Decisions:* On-road driving behaviours represent the most direct and impactful area of eco-driving. Key techniques include smooth acceleration and deceleration, maintaining an even driving pace, and reducing excessive idling (Wang and Boggio-Marzet, 2018). Aggressive driving behaviours—speeding, rapid acceleration, and hard braking—can significantly reduce fuel economy. The U.S. Department of Energy indicates that these actions can lower gas mileage by approximately 15% to 30% at highway speeds and 10% to 40% in stop-and-go traffic.

Implementing sensible driving practices enhances fuel efficiency and promotes safer driving conditions (Huang *et al.*, 2018).

Figure 2.23 illustrates that driver factors should be prioritised among the primary factors affecting vehicle energy consumption, and eco-driving holds significant potential for energy savings.

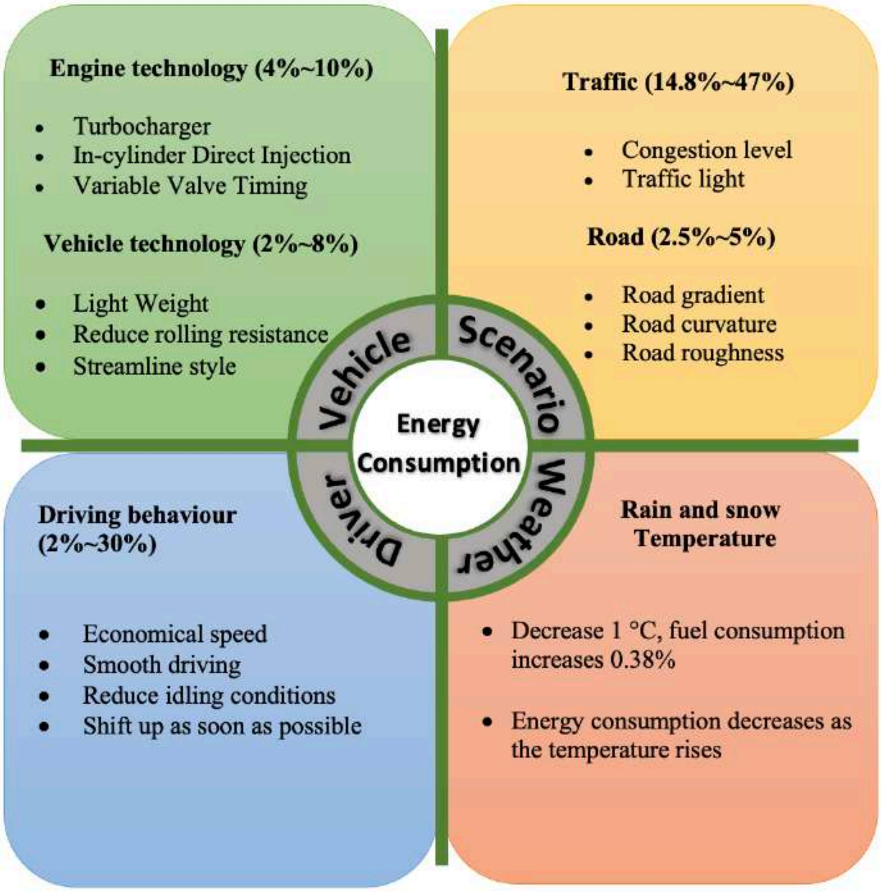


Fig. 2.23: The primary factors affecting vehicle energy consumption
Source: (Xu et al.*, 2021)*

Eco-driving training programmes and in-vehicle feedback systems are essential for embedding these behaviours into everyday driving practices. Training initiatives focus on educating drivers about the benefits of eco-driving and equipping them with practical techniques, such as shifting gears at optimal engine speeds and anticipating traffic flow to minimise unnecessary braking (Barkenbus, 2009). Such programmes have yielded fuel savings ranging from 5–25%, depending on the initial driving style and level of adherence (Hennig, 2008). In-vehicle feedback systems further support drivers by providing information on fuel consumption and emissions in real-time. These devices, which often incorporate GPS and engine data, encourage drivers to adjust their behaviours dynamically. For example, systems that suggest optimal acceleration rates or cruising speeds can help drivers align with eco-driving principles (Alam and McNabola, 2014b). However, the effectiveness of these systems depends on their accuracy and user-friendliness. Current feedback devices often rely on average emission factors, which may not account for individual driving styles or real-time traffic conditions.

2-9-2 Challenges and Limitations

Despite its benefits, eco-driving faces several challenges in achieving widespread adoption. Tu et al. (2022b) stated that Eco-driving faces significant challenges, including difficulties in translating knowledge into practice, as it is not a natural driving style and lacks focus in current training courses. Most guidance only reminds drivers of inappropriate behaviour without offering practical, adaptive suggestions (Allison and Stanton, 2019). Factors like socio-demographics, suitable guidance types, and tailoring to traffic conditions and habits remain unexplored. The long-term impact of eco-driving guidance is inconsistent, often fading over time. Drivers' trust in guidance is limited due to generalised, non-specific advice (Pampel *et al.*, 2018).

2-10 Eco Hauling

Krantz et al. (2019) offered the term Eco-hauling, which represents an eco-driving concept to reduce carbon emissions during earthmoving operations. The authors (Krantz *et al.*, 2019b) defined eco-hauling as strategies to be adopted in construction projects and equipment operator levels to minimise activities that could generate carbon emissions during earthmoving operations. Although authors highlighted the benefit of this principle in decreasing carbon footprint, they equally emphasised the requirement to balance productivity and cost when employing the eco-hauling concept. Moreover, Krantz et al. (2019) noted that having up-to-date information of a site and detailed planning is crucial when implementing the eco-hauling principle. Given these, the eco-hauling concept has some similarities with lean management principles. Therefore, it will be reasonable if contractors combine both principles to minimise carbon emissions during the construction phase (Arogundade *et al.*, 2021). Figure 2.24 shows the adaptation of Eco-Driving principles for individual vehicles into Eco-Hauling, a system designed for earthmoving contractors and equipment operators. Both aim to reduce costs, fuel consumption, and CO_2 emissions but differ in scale and application.

At the strategic level, Eco-Driving focuses on acquiring energy-optimal vehicles, regular maintenance, and navigation system optimisation for long-term benefits. Eco-Hauling translates these goals to a company-wide perspective, emphasising the acquisition of fuel- and productivity-optimal fleets and regular equipment maintenance to sustain operational efficiency. At the tactical level, Eco-Driving strategies include optimising route choices (eco-routing) and eliminating excess load to enhance vehicle efficiency during trips. In Eco-Hauling, these concepts are expanded to project and task-level decisions, such as optimising equipment assignments, planning earthmoving operations (mass-haul), determining optimal equipment speeds, and selecting appropriate fuel types for specific tasks.

At the operational level, Eco-Driving practices focus on maintaining fuel-efficient speeds, anticipating obstacles, using high gears, and minimising throttle for individual drivers. Similarly, Eco-Hauling emphasises operator behaviour, such as maintaining even speeds, anticipating obstacles, and adhering to predetermined optimal speeds for efficient fleet operation. This integration shows how Eco-Hauling applies Eco-Driving principles to construction logistics while addressing fleet-level productivity and sustainability (Krantz et al., 2019a).

levels in Eco-Driving and Eco-Hauling.

Eco-Driving	Eco-Hauling
General characteristics - For individual drivers. - Reduces costs, fuel use, and CO_2 emissions at vehicle level.	General characteristics - For earthmoving contractors and equipment operators. - Reduces costs, fuel use, and CO_2 emissions at fleet level. - Maintains or increases productivity.
Strategic (long-term decision level) - Acquire energy-optimal vehicle. - Regular vehicle maintenance. - Install energy-optimal navigation system.	*Strategic* (company level) - Acquire fuel/productivity-optimal equipment fleet. - Regular equipment maintenance.
Tactical (trip level) - Optimal route choice (eco-routing). - Eliminate excess load from the vehicle.	*Tactical* (project and task level) - Optimize equipment assignments. - Optimize earthmoving (mass-haul) plan. - Determine optimal speed for equipment in earthmoving task. - Select fuel types.
Operational (driver behavior level) - Use fuel-optimal speed. - Anticipate upcoming obstacles to maintain even speeds. - Use high gears while cruising. - Minimize throttle.	*Operational* (equipment operator behavior level) - Anticipate upcoming obstacles to maintain even speeds. - Use the determined optimal speed.

Fig. 2.24 Characteristics and possible decisions to be made at specific decision
Source: (Krantz et al.*, 2019b)*

2-11 Logistics Innovations for Sustainable Construction

Recent innovations in logistics management, originally developed in manufacturing and supply chain sectors, are increasingly being adopted and adapted in the construction industry. These innovations have become particularly relevant in addressing the challenges of carbon-intensive logistics operations and enabling sustainability in project delivery. Four areas in particular—inventory management systems, organisation and space management, storage and retrieval systems, and last-mile delivery—offer significant potential for improving efficiency and reducing emissions within construction logistics.

2-11-1 Inventory Management Systems

Construction projects often face challenges related to overstocking, late deliveries, or untracked material usage, which can result in waste and higher emissions. Inventory management systems aim to reduce these inefficiencies by improving the visibility, timing, and control of materials. Just-in-Time (JIT) delivery is one such method, designed to minimise the need for on-site storage and reduce material handling. By synchronising material arrival with construction schedules, JIT helps prevent idle stock, material degradation, and excessive vehicle movement (Sacks, 2010).

Technologies such as RFID (Radio Frequency Identification), GPS tracking, and digital inventory software offer real-time visibility into material flow. This allows for better planning, reduction in unnecessary deliveries, and proactive management of supply chain disruptions. Moreover, building strong supplier relationships enhances collaboration and reliability, allowing for more consistent, lower-carbon deliveries tailored to site requirements. Collectively, these systems reduce emissions by streamlining logistics, lowering the frequency of deliveries, and preventing over-ordering (Akintoye *et al.*, 2000; Vrijhoef and Koskela, 2000).

2-11-2 Organisation and Space Management

On congested construction sites—especially in urban areas—poor organisation and space constraints often lead to inefficient material movement, double handling, and increased idling of transport vehicles. Organisation and space management focuses on optimal site layout planning, creating designated access routes, clear material storage zones, and efficient delivery drop-off points.

Digital tools, such as Building Information Modelling (BIM) and construction site layout simulation, are increasingly being used to visualise and plan logistics space in advance. These tools help in identifying spatial clashes, reducing on-site confusion, and improving the flow of vehicles and equipment. When logistics activities are well-organised spatially, construction teams can minimise vehicle dwell times and reduce emissions related to site congestion. Structured space management also enhances health and safety performance by reducing risks related to obstruction and unplanned vehicle movements (Chavada et al., 2012; Detty et al., 2000).

2-11-3 Storage and Retrieval Systems

Storage and retrieval efficiency plays a critical role in ensuring materials are used in a timely and sustainable manner. Inadequate material handling can lead to damage, reordering, or increased waste, all of which carry embedded carbon costs. The First-In, First-Out (FIFO) approach is widely used in warehousing and has clear benefits for construction. It ensures that older materials are used first, minimising the likelihood of material degradation or obsolescence.

Smart storage systems can be enhanced with barcoding and tagging, allowing for tracking of batch dates, quantities, and usage timelines. These technologies support traceability and compliance while enabling project teams to better align delivery schedules with material demand. When integrated with inventory and scheduling systems, these storage strategies support efficient workflows and help avoid emissions-intensive emergency orders or on-site waste generation (Navon and Berkovich, 2006; Nikakhtar et al., 2015).

2-11-4 Last-Mile Delivery in Construction

The final segment of the supply chain—the last mile—is often the most complex and least efficient. In construction, last-mile delivery typically involves transporting materials from local depots or consolidation centres to the project site (Macioszek, 2018). Urban construction sites, in particular, face constraints such as restricted delivery times, limited laydown areas, and traffic congestion. Innovative strategies have emerged to improve the sustainability of last-mile delivery in construction. These include using off-site consolidation centres to pre-assemble deliveries, reducing the number of trips into city centres. Micro-distribution hubs and localised staging areas allow for smaller, more frequent deliveries that match on-site consumption rates. In some cases, electric or low-emission vehicles are being trialled to reduce the carbon intensity of this phase.

Time-windowed delivery systems and appointment-based scheduling help reduce vehicle queuing and idling. Furthermore, digital delivery tracking and coordination platforms allow for better synchronisation of materials with construction tasks, ensuring just-in-time arrival and minimising wasted trips (Boysen et al., 2020; Mangiaracina et al., 2019).

These innovations when implemented collectively can significantly improve the carbon performance of construction logistics. They complement Lean Construction principles, Eco-hauling strategies, and simulation-based planning by addressing operational inefficiencies and enabling smarter logistics decisions. Integrating these logistics innovations into the overall construction management process represents a key step towards decarbonising the sector and supporting the transition to net-zero construction.

2-12 Conclusion

This chapter has critically examined the current literature surrounding construction logistics and sustainability, with a focus on carbon emissions associated with hauling operations and site logistics. It reviewed the environmental implications of construction activities, particularly those linked to logistics inefficiencies, and evaluated a range of existing tools and strategies, including Life Cycle Assessment, Lean Construction principles, Eco-hauling, and simulation-based modelling.

The chapter also addressed key gaps identified by the examiners by introducing logistics-focused themes such as inventory management systems, space and organisation planning, storage and retrieval practices, and last-mile delivery strategies—each of which offers practical pathways for improving the carbon performance of construction logistics.

Despite the growing awareness of sustainable practices, the literature reveals that construction logistics remains a fragmented and under-optimised domain in both research and practice. There is a lack of integrated, operational models that link emissions data, collaborative planning, and real-time logistics decision-making.

These gaps establish a clear justification for the development of the BASE model, which aims to synthesise eco-hauling, stakeholder collaboration, simulation, and optimisation into a unified approach for decarbonising construction logistics. The next chapter outlines the research methodology adopted to develop, apply, and validate this model.

Chapter 3:

Research Methodology

3-1 Research Methodology

This chapter presents the research design, philosophical foundations, and tools employed to meet the study's objectives. At the centre of the investigation is the BASE model—an integrated, stakeholder-driven approach aimed at reducing carbon emissions in construction logistics through simulation, optimisation, and collaborative planning.

Adopting a pragmatic research philosophy, this study follows a mixed-methods approach that bridges theoretical understanding with practical application. The methodology is designed not only to assess but also to improve hauling operations by focusing on emissions reduction and enhanced collaboration. Three real-world case studies were selected to capture a range of logistics scenarios, each involving different service configurations, operational constraints, and multi-contractor settings.

The methodological structure is based on abductive reasoning, which blends deductive and inductive approaches in a cyclical manner. Deductive reasoning applies existing theories—such as Lean Management, Eco-hauling practices, and the Big Room approach—to the construction logistics context. Inductive reasoning uses empirical observations and stakeholder input to uncover inefficiencies, bottlenecks, and decision-making challenges. This iterative process supports the continuous development and validation of the BASE model.

The model integrates four key components: (1) Eco-hauling strategies targeting emission reductions from transport and heavy machinery; (2) Big Room collaboration to support joint decision-making among stakeholders; (3) Discrete Event Simulation (DES) with AnyLogic to model current and alternative logistics scenarios; and (4) Response Surface Methodology (RSM) via Stat-Ease to analyse variable interactions and optimise performance metrics. These components are designed to address specific limitations in the literature, particularly the need for a dynamic, stakeholder-informed logistics model.

The research progresses through three phases: data collection from case study projects, simulation modelling of logistics operations, and optimisation of outcomes through RSM. Stakeholder workshops are used to review findings, ensure practical relevance, and validate proposed improvements.

Overall, this chapter outlines a rigorous and integrated methodology that connects theory with practice. It offers a pathway for reducing emissions and improving the sustainability of construction logistics through data-driven modelling and collaborative planning.

3-2 Research Philosophy and Approach

3-2-1 Research Philosophy: Pragmatism

This research adopts a pragmatic philosophy, which prioritises practical solutions and real-world applicability over rigid adherence to any single theoretical framework(Suckiel, 1982). Pragmatism is particularly suited to addressing complex challenges (Light, 2004). Hence, this philosophy is applicable in sustainable construction logistics, where the integration of theory and practice is essential for meaningful outcomes. Rather than focusing solely on abstract models or purely empirical data, this approach allows for a flexible combination of methodologies to achieve the research objectives.

By aligning with pragmatism, this study bridges the gap between academic theory—such as Lean Management, Eco-hauling principles, and the Big Room approach—and the practical realities of construction logistics. Pragmatism ensures that the research is grounded in stakeholder needs and industry challenges, such as bottlenecks in hauling operations, blockages caused by concurrent workflows, and the lack of collaboration among contractors. This philosophy supports the iterative development and validation of a carbon reduction model that is both theoretically robust and practically viable.

3-2-2 Research Approach: Abductive

This research adopts an abductive reasoning framework, which combines deductive and inductive elements to iteratively test existing theories while incorporating new insights from empirical data. This approach is particularly suited to addressing the complexities of sustainable construction logistics, where theoretical principles must be tailored to real-world scenarios.

Deductive reasoning starts with general theories or principles and applies them to specific cases to validate or challenge their relevance (Gallaire *et al.*, 1984). Inductive reasoning, on the other hand, builds generalisations and theories from observed data or particular instances (Thomas, 2003). Abductive reasoning combines the two, using an iterative process to test existing theories while refining them based on real-world observations and data (Dubois and Gadde, 2002).

Abductive reasoning is a flexible and iterative approach that integrates the strengths of deduction and induction. It begins with established theories, such as Lean Management, the Big Room approach, and Eco-hauling principles, and tests their applicability in practice. Through this process, empirical observations—such as data from case studies and stakeholder feedback—are used to refine and adapt these theories to the specific context of construction logistics. For example, inefficiencies identified during simulations or Big Room sessions inform adjustments to the model, ensuring both theoretical validity and practical relevance.

This approach allows the research to bridge the gap between theory and practice. Deductive reasoning ensures that the study is grounded in established frameworks, while inductive reasoning enables the development of new insights based on real-world data. Together, these processes form the foundation of abductive reasoning, enabling iterative refinements to the integrated model. By doing so, the research achieves a balance between theoretical rigour and practical applicability, making abductive reasoning the most appropriate framework for this study.

3-2-3 Methodological Choice: Mixed-Methods Approach

This research adopts a mixed-methods approach, combining quantitative and qualitative methods to comprehensively address the research questions and objectives (Leech *et al.*, 2009). The mixed-methods approach is well-suited to the interdisciplinary and complex nature of sustainable construction logistics, where operational efficiency must be balanced with stakeholder collaboration and contextual challenges (Dubey *et al.*, 2015). By integrating both methods, this research ensures a comprehensive understanding of the problem, the development of robust theoretical models, and their validation in real-world settings.

The mixed-methods approach supports the primary objective of this study: to develop and validate a carbon reduction model for construction hauling logistics. Quantitative methods, such as simulation and optimisation using AnyLogic and Stat-Ease, provide measurable insights into operational performance, including route optimisation, reduced idle times, and CO_2 emissions. Qualitative methods, including open-ended interviews and the application of the Big Room approach, enable the identification of bottlenecks, inefficiencies, and collaboration challenges. Together, these methods ensure that theoretical insights are grounded in practical realities, making the research outcomes both rigorous and applicable.

A significant focus of this research is the evaluation of the Big Room approach as a tool for improving collaboration and resolving bottlenecks in multi-contractor environments. The mixed-methods approach supports this by using qualitative data from stakeholder sessions to inform and refine quantitative simulations and optimisation processes. For example, interviews revealed critical challenges, such as bottlenecks caused by concurrent contractor operations, which directly informed the selection of case studies and design simulation scenarios. By integrating these findings, the research captures the technical and human dimensions of construction logistics, offering a more holistic understanding of the problem. The mixed-methods approach also provides the flexibility to adapt the methodology as new insights emerge during the research. For example, qualitative feedback from stakeholders revealed specific bottlenecks and inefficiencies that were subsequently incorporated into quantitative models. This adaptability ensures that the proposed solutions align with construction logistics' dynamic and context-specific nature. Furthermore, by combining quantitative precision with qualitative depth, this approach overcomes the limitations of relying solely on one method, offering a balanced and comprehensive perspective.

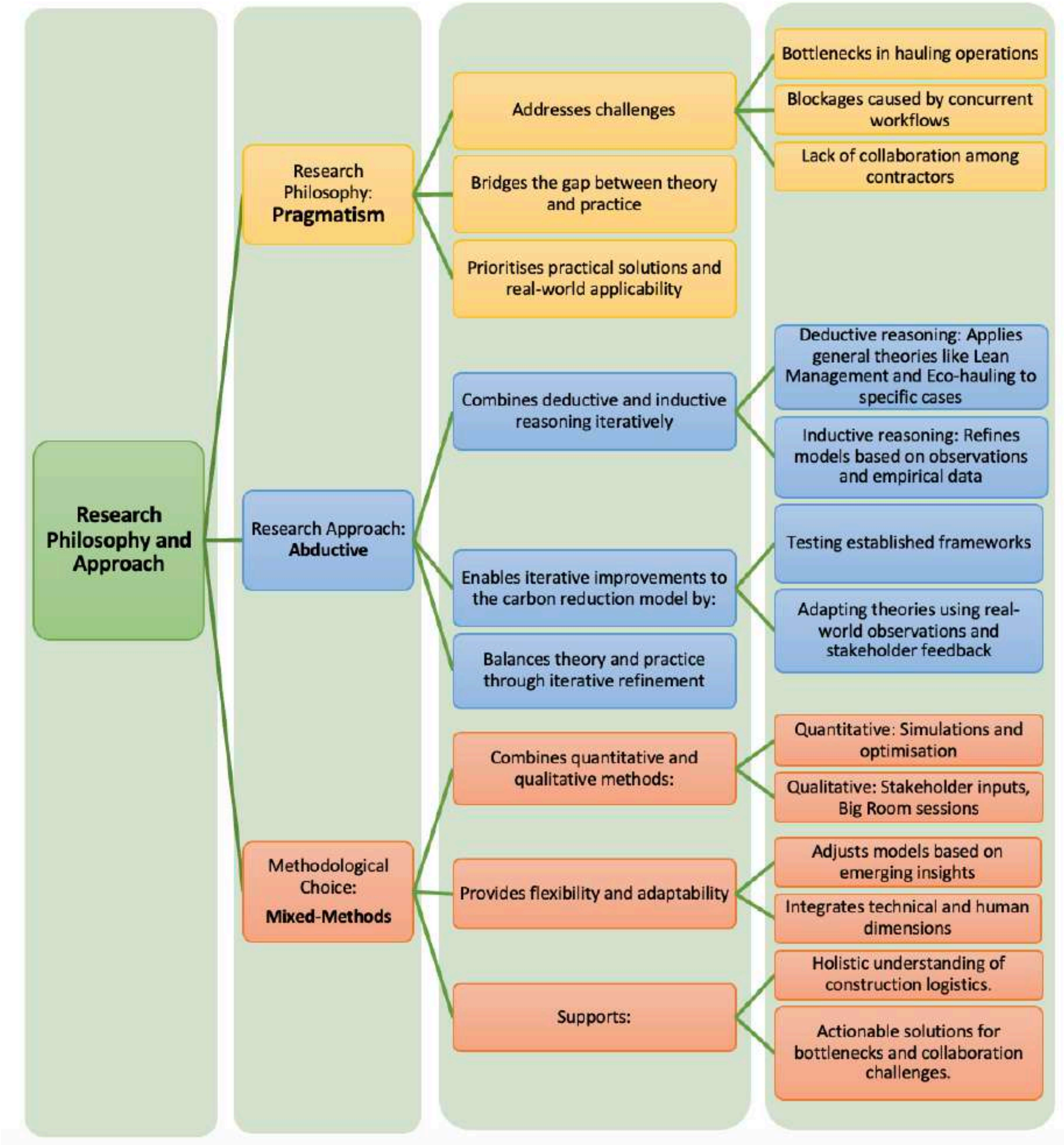


Fig. 3.1: Research Philosophy and Approach

In conclusion, the adoption of a mixed-methods approach aligns with the pragmatic philosophy underpinning this research. It bridges the gap between theory and practice, combining measurable outputs with contextual insights to ensure the carbon reduction model is both theoretically robust and practically applicable. This integrated approach not only addresses the research objectives but also contributes actionable solutions to enhance the sustainability of construction logistics (Figure 3.1).

3-3 Research Design and Implementation

The research followed a structured process aimed at addressing sustainability challenges in construction logistics, particularly through optimising hauling operations to reduce CO_2 emissions. It began with an extensive literature review to explore foundational theories, including Lean Management, Discrete Event Simulation (DES), and optimisation techniques such as AnyLogic and Stat-Ease. These frameworks were examined for their applicability in improving operational efficiency and reducing emissions. The review revealed that while Eco-hauling principles provided a promising foundation, their standalone application was insufficient due to operational complexities. It was identified that combining Eco-hauling with a collaborative framework could address deeper challenges, including site-specific inefficiencies and bottlenecks.

In parallel, open-ended interviews were conducted with construction practitioners, such as project managers, logistics planners, and fleet managers, to uncover real-world challenges and opportunities. The interviews highlighted significant operational constraints, such as traffic congestion and overlapping tasks, which frequently caused bottlenecks and prolonged idle times. These inefficiencies not only increased CO_2 emissions but also resulted in excessive diesel consumption and wear and tear on machinery. For instance, some sites reported up to a 40% increase in idle times compared to planned operations, primarily due to poor coordination. These findings underscored the need for a more integrated and collaborative approach to streamlining operations and achieving sustainability.

After consolidating the findings from the literature review and interviews, key knowledge gaps were identified. It became clear that existing methods for optimising hauling operations lacked sufficient integration of stakeholder input and site-specific constraints. Moreover, operational inefficiencies caused by poor coordination and overlapping tasks limited the effectiveness of Eco-hauling principles. This analysis highlighted the importance of combining simulation methods with collaborative strategies to develop practical solutions for sustainable construction logistics.

The research then progressed to developing a comprehensive theoretical foundation for addressing these challenges. Central to this framework were Eco-hauling principles and the Big Room-based collaborative approach, both of which were identified as critical strategies for reducing emissions. Eco-hauling optimised transportation processes, while the Big Room fostered collaboration among stakeholders to address coordination issues and operational bottlenecks. Advanced tools such as AnyLogic and Stat-Ease software were integrated into the framework to model and optimise hauling scenarios. These tools provided the computational power and flexibility needed to simulate various operational configurations and identify optimal solutions.

A basic hauling model was developed in AnyLogic using two complementary simulation methods: Discrete Event Simulation (DES) and Agent-Based Modelling (ABM). This model was tested using three case studies, representing different hauling scenarios, including 900 tonnes of soil and 416 tonnes of asphalt. Empirical data from these case studies, including diesel consumption, idle times, and payload ranges, informed scenario generation and analysis. Stat-Ease software was employed to design initial scenarios, which were then expanded to over 400 configurations. The results were simulated to evaluate metrics such as CO_2 emissions, costs, and operational efficiency.

Response Surface Methodology (RSM) was then employed to explore the interaction between key variables and their effects on sustainability metrics. RSM played a pivotal role in examining relationships between variables, such as payload size and the number of trucks, to determine their combined impact on CO_2 emissions. By modelling these interactions, RSM provided a detailed understanding of how operational adjustments influenced emissions and efficiency. This methodology also enabled the identification of optimal configurations for hauling operations, ensuring that emission reductions were balanced with other operational goals, such as cost savings and time efficiency.

The Big Room approach was implemented to gather stakeholder feedback and refine the model. This collaborative environment provided insights into site-specific constraints, enabling the design of actionable strategies. The research concluded with scenario optimisation, validation, and results interpretation. Key findings demonstrated the effectiveness of combining Eco-hauling and collaboration in achieving sustainable construction logistics while providing actionable insights for industry implementation. The following sections provide a detailed explanation of every stage within this structured process.

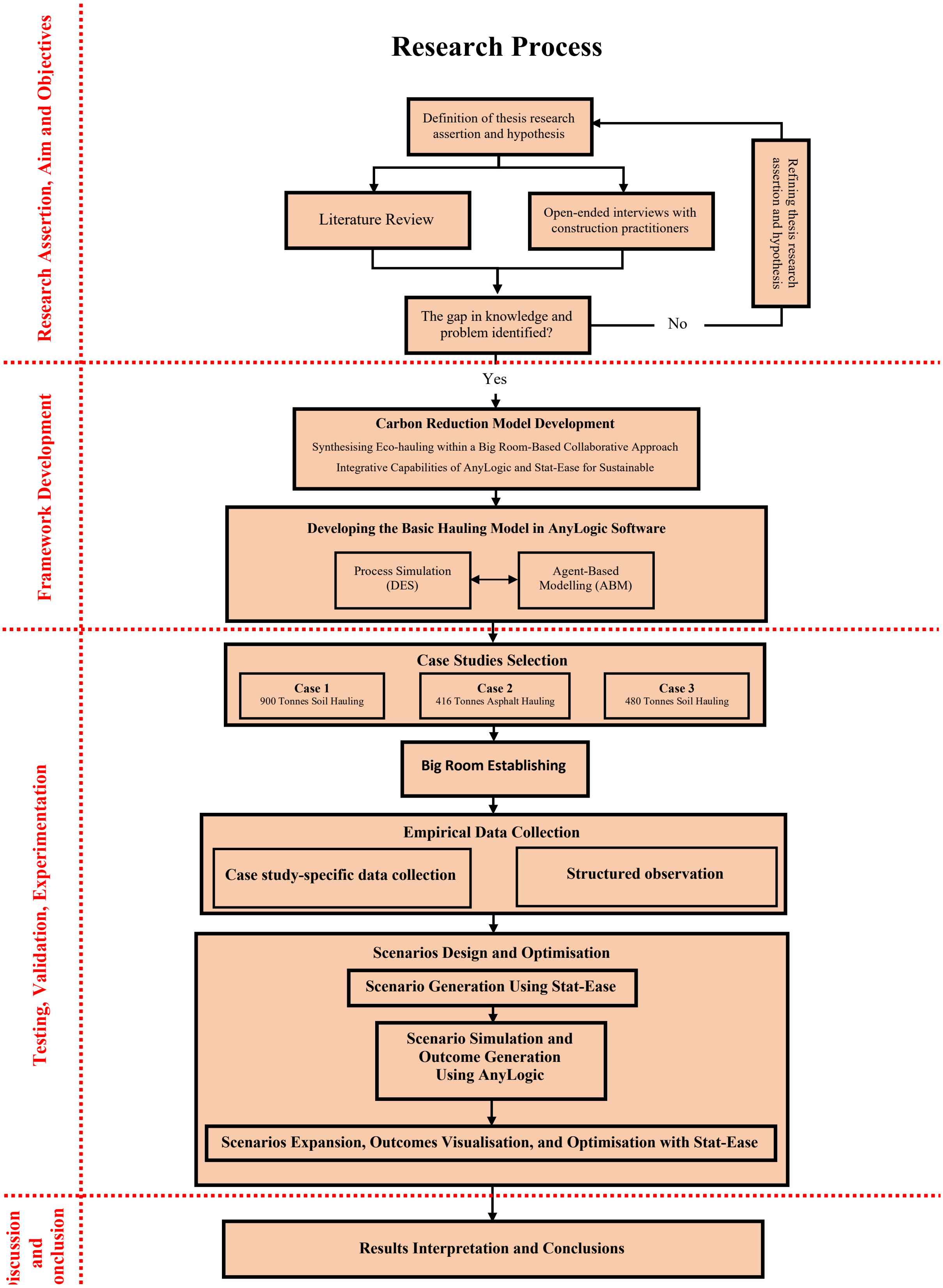


Fig. 3.2: Research Methodology

3-4 The BASE Model: Big Room, AnyLogic, Stat-Ease, and Eco-Hauling for Sustainable Logistics

Building on insights from the literature review and interviews, the Carbon Reduction Model Development stage focused on developing a practical carbon reduction model. This section comprehensively explains the research framework, illustrating how the components of the study—Eco-hauling principles, the Big Room approach, simulation tools, and stakeholder collaboration—are systematically integrated to develop a comprehensive and practical carbon reduction model for construction logistics. Designed to ensure cohesion and adaptability, the framework addresses the complexities of diverse hauling operations in various construction projects. The model is focused on solving immediate operational challenges and aims to provide long-term strategies for enhancing efficiency and sustainability in construction logistics. By combining theoretical principles with real-world practices, this framework serves as a replicable and adaptable tool for industry practitioners seeking scalable solutions for hauling operations.

Ultimately, the research framework is built on two intersecting components: the combination of Eco-hauling and the Big Room approach and the integration of AnyLogic and Stat-Ease for simulation and optimisation. Together, these components form the backbone of the research's contribution to advancing sustainable construction logistics, addressing operational inefficiencies and environmental sustainability (Figure 3.3).

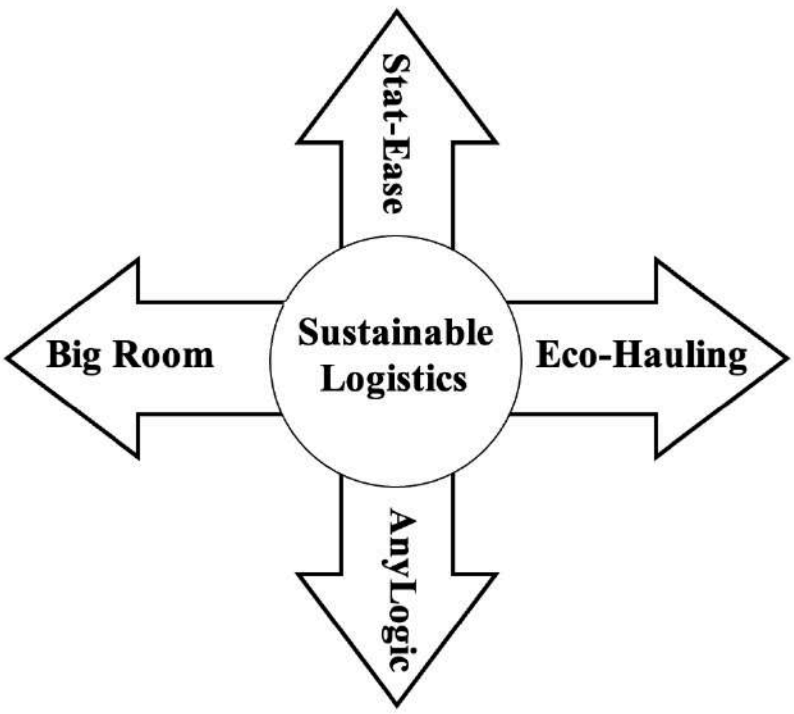


Fig. 3.3: The BASE Model: Big Room, AnyLogic, Stat-Ease, and Eco-Hauling for Sustainable Logistics

3-4-1 Integration of Eco-Hauling and Big Room Approach

The integration of Eco-hauling principles and the Big Room approach offers a comprehensive framework to address both operational inefficiencies and collaborative challenges in construction logistics. By combining the technical strengths of Eco-hauling with the collaborative focus of the Big Room approach, this synergy ensures that both tactical and operational levels are managed effectively (Figure 3.4).

At the tactical level, Eco-hauling focuses on optimising equipment assignments, determining the optimal speed for hauling operations, and implementing these strategies to enhance overall efficiency. However, a notable drawback of Eco-hauling is the fragmented nature of decision-making. Upstream decision-makers often overlook the insights of downstream contributors, leading to suboptimal equipment utilisation and speed. The Big Room approach resolves this limitation through collaborative alignment. By uniting upstream and downstream stakeholders in a shared environment, the Big Room fosters transparent communication, shared insights, and collective decision-making. This alignment ensures that equipment assignments and speed optimisations are not only technically sound but also practically viable, aligning with the realities of on-site operations.

At the operational level, Eco-hauling focuses on anticipating upcoming obstacles, such as delays, congestion, and inefficiencies in hauling operations. While this proactive approach identifies bottlenecks, it lacks a structured mechanism for resolving these challenges effectively. The Big Room approach addresses this gap through collaborative problem-solving. By bringing together all stakeholders—such as contractors, fleet managers, and project decision-makers—the Big Room creates a platform for real-time discussions and joint ownership of solutions. This collaborative effort eliminates blockages and operational inefficiencies, ensuring smoother workflows and enhanced project outcomes.

The integration of these two frameworks is further strengthened by specific features of the Big Room approach, which complement Eco-hauling principles. Multi-disciplinary collaboration and shared goals ensure that all stakeholders are aligned toward common objectives, reducing conflicts and improving coordination. Visual management tools provide real-time updates, enabling stakeholders to monitor operations and address issues promptly. Iterative and adaptive planning allows the model to remain flexible, accommodating feedback and evolving project requirements. Furthermore, concurrent decision-making expedites the resolution of bottlenecks, while a strong focus on value creation ensures sustainable and efficient outcomes.

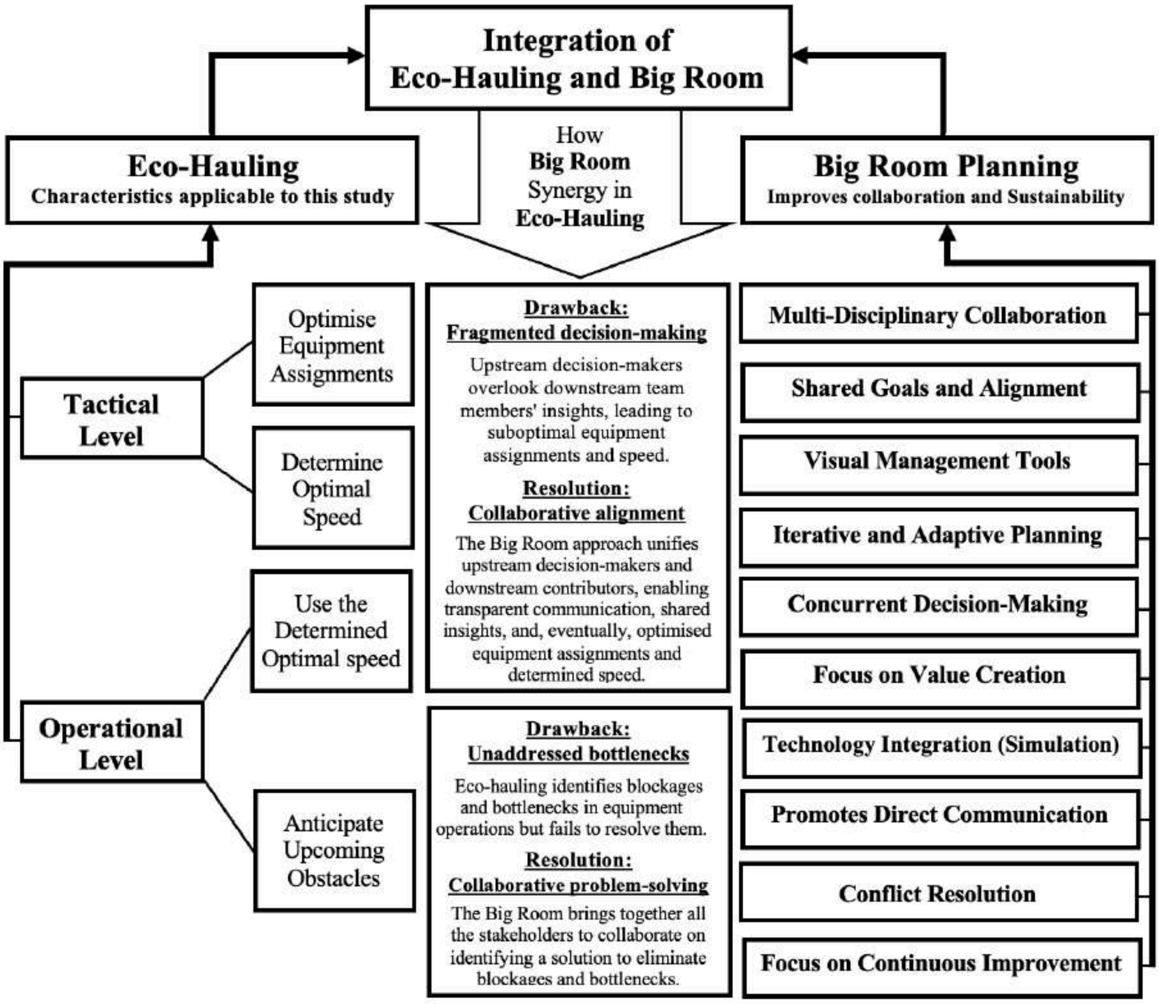


Fig. 3.4: Integration Framework for Eco-Hauling and Big Room Approach

Technology integration is a cornerstone of this synergy. Tools such as AnyLogic and Stat-Ease are used to simulate hauling operations and optimise configurations collaboratively, bridging the gap between theoretical planning and practical implementation. This integration not only enhances operational precision but also provides a shared platform for stakeholders to test and refine strategies in a virtual environment before applying them on-site.

In summary, the Eco-hauling and Big Room integration creates a robust framework that balances operational efficiency with collaborative decision-making. Eco-hauling's technical focus is amplified by the Big Room's ability to unify stakeholders, resolve conflicts, and adapt to dynamic project conditions. This synergy ensures that the developed model is both practically applicable and theoretically robust, making it a valuable tool for addressing the complexities of construction logistics.

3-4-2 AnyLogic and Stat-Ease: Merging Simulation and Optimisation

AnyLogic is a versatile simulation software that integrates Discrete Event and Agent-Based enabling the modelling of complex systems and processes. It is widely used for simulating logistics, supply chains, and operational workflows. Stat-Ease, on the other hand, is a powerful design of experiments (DOE) tool that systematically generates, analyses, and optimises experimental scenarios. By applying statistical techniques, it identifies relationships between variables and optimises configurations to enhance efficiency and performance. Together, they provide a comprehensive framework for simulation and optimisation.

A core challenge in construction hauling is managing multiple operational variables, such as the number of trucks, payload sizes, and travel speeds, which vary depending on project-specific constraints (Roy *et al.*, 2024) In this study, contractors provided minimum and maximum ranges for these parameters based on site requirements, creating opportunities for data-driven optimisation. To address this complexity, the research combines two powerful tools—Stat-Ease and AnyLogic—to develop a structured simulation, analysis, and optimisation framework.

Stat-Ease generates initial structured combinations of variables using contractor-provided ranges, while AnyLogic simulates these scenarios to evaluate key performance metrics, such as total operation time, idle time, diesel consumption, CO_2 emissions, and costs. By expanding initial scenarios into a comprehensive dataset and employing Response Surface Methodology (RSM) to uncover relationships between inputs and outputs, the research identifies optimal configurations for sustainable hauling operations.

The following steps outline the structured process adopted in this research to optimise sustainable hauling operations. Each step is detailed below, showcasing how Stat-Ease and AnyLogic were utilised to achieve operational efficiency and sustainability goals.

1) *Scenario Generation with Stat-Ease*

   The process begins with contractors providing minimum and maximum ranges for the key operational parameters, such as:

   - Number of Trucks (e.g., 1–5).
   - Payload (e.g., 4–16 tonnes).
   - Speed (e.g., 20–40 km/h).

With these inputs, Stat-Ease uses its powerful design of experiments (DOE) capabilities to generate a structured set of combinations. From this, a strategic selection of 15–17 scenarios is made to ensure that the most diverse and meaningful possibilities are represented. This initial set is designed to capture a broad spectrum of operational possibilities, setting the stage for deeper analysis.

2) *Outcome Simulation with AnyLogic*

The selected scenarios are then fed into AnyLogic, a versatile simulation tool known for its ability to model complex systems. Using its Discrete Event and Agent-Based, modelling techniques, AnyLogic simulates each scenario to calculate key performance metrics, including:

- Total operation time – How long it takes to complete the hauling process.
- Idle time – How much time is wasted when trucks are not actively transporting.
- Number of brakes used – A reflection of stop-and-go conditions that impact fuel efficiency and wear.
- Diesel consumption – The fuel used during operations.
- CO_2 emissions – The environmental impact of each scenario.
- Costs – The financial implications of operations.

This step generates a dataset filled with performance insights, helping identify inefficiencies and areas for improvement in hauling operations.

3) *Scenario Expansion and Response Surface Methodology with Stat-Ease*

Once the initial results are available, the focus shifts back to Stat-Ease for scenario expansion and deeper analysis. The original 15–17 scenarios are expanded into a much larger dataset, with the total number of scenarios depending on the ranges provided by contractors. For example, if the parameters range between 1–5 trucks, 4–16 payloads, and 20–40 speeds, 1,365 combinations might be generated.

Stat-Ease doesn't just stop at expansion; it also uses response surface graphs to visualise the data. These three-dimensional graphs make it easier to interpret complex relationships between inputs (like trucks, payloads, and speeds) and outputs (like CO_2 emissions, costs, and operation time). With the help of Response Surface Methodology (RSM), the tool uncovers patterns and interactions in the data, providing statistical insights that allow for better decision-making and fine-tuning of configurations.

4) *Optimisation with Stat-Ease*

The expanded dataset is now ready for optimisation. Stat-Ease analyses the trends and patterns revealed by the simulations and visualisations to identify the most efficient configurations. The focus is on:

- Minimising CO_2 emissions – Reducing the environmental impact.
- Cutting costs – Ensuring financial feasibility.
- Improving operational efficiency – Streamlining processes and reducing delays.

The final output is a set of practical recommendations tailored to real-world implementation. These optimised strategies help contractors adopt sustainable hauling practices that balance environmental sustainability with logistical and financial efficiency.

The following diagram (Figure 3.5) illustrates how the integration of Stat-Ease and AnyLogic facilitates scenario generation, simulation, and optimisation, ultimately delivering actionable insights for reducing emissions and enhancing operational efficiency.

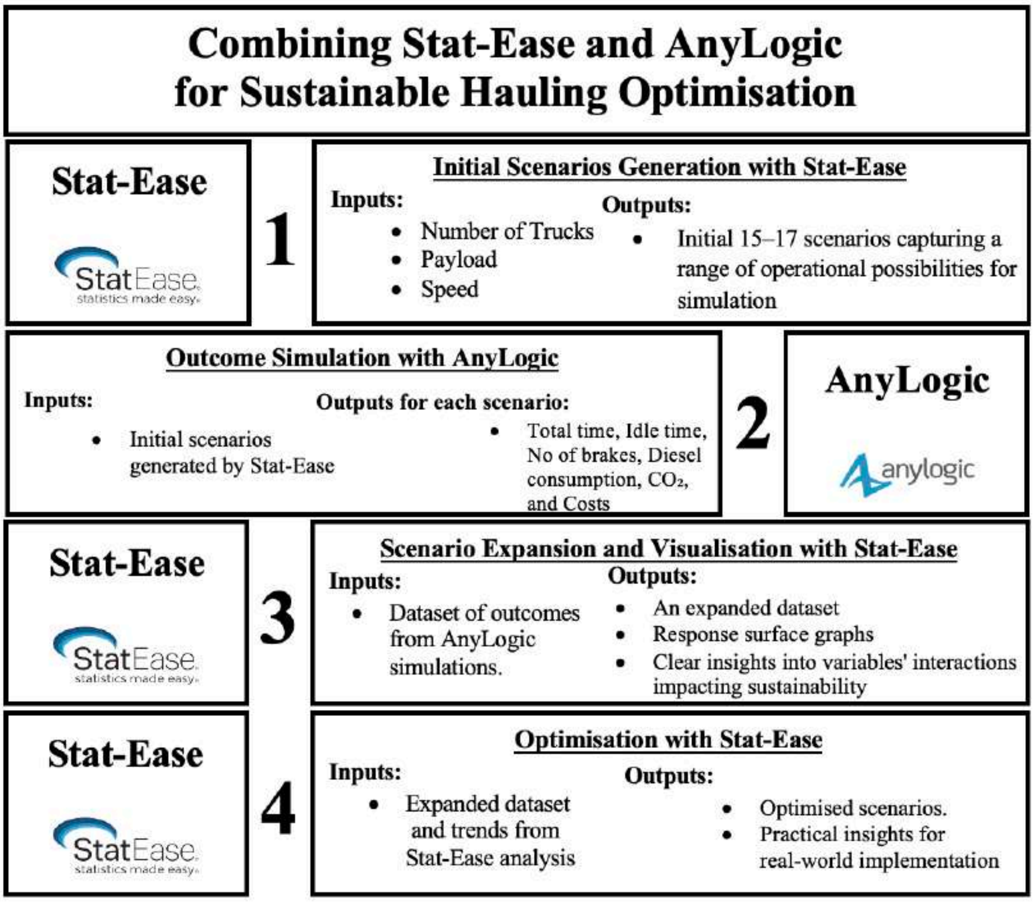


Fig. 3.5: Combining Stat-Ease and AnyLogic for Hauling Optimisation

3-4-3 Validation of the Research Framework

The validation of the developed framework will be integrated into the selected case studies, where its applicability and effectiveness will be tested under real-world conditions. Empirical data collected during these case studies, including metrics such as fuel consumption, CO_2 emissions, and operational delays, will serve as the basis for evaluating the model's performance. The validation process will ensure that the framework is both theoretically robust and practically applicable, aligning with the specific challenges and objectives of construction logistics.

3-5 Developing the Basic Hauling Model in AnyLogic Software

This section outlines the development of a base hauling model using AnyLogic software, which integrates two simulation approaches to capture the complexities of construction logistics. The model serves as the foundation for analysing operations, testing improvements, and validating strategies such as Eco-hauling principles and Big Room collaboration.

The model incorporates Discrete Event Simulation (DES) to map sequential operations like loading, hauling, delays, and unloading; Agent-Based Modelling (ABM) to simulate individual agent behaviours, such as Dumper trucks and loaders. Together, these approaches allow the creation of a flexible and scalable simulation environment capable of addressing bottlenecks, optimising logistics, and assessing CO_2 reduction strategies.

The subsequent sections describe the role of each simulation technique and its application in developing this foundational model.

3-5-1 Discrete Event Simulation (DES)

Discrete Event Simulation (DES) is a modelling method used to mimic the behaviour of complex systems where events occur at specific points in time, influencing the system's state (Goldsman and Goldsman, 2015). DES models the sequence of discrete events and the changes in the system state that occur due to these events. DES models the sequence of discrete events and the resulting changes in the system's state, simulating processes step by step over time, much like a virtual laboratory for studying interactions and resource utilisation. This enables better understanding and optimisation of real-world systems. In the context of the hauling project, DES is employed to model the sequence of events related to hauling operations, including loading, transportation, unloading, and other relevant activities. By simulating these events, researchers can assess the efficiency of different strategies, optimise resource allocation, and identify potential bottlenecks or areas for improvement within the hauling system.

3-5-2 Simulating Hauling Operations in AnyLogic Using DES and ABS

In AnyLogic, Discrete Event Simulation (DES) is the core method for modelling hauling processes, which plays a critical role in achieving sustainable construction logistics as emphasised in this study. DES is used to represent and analyse sequential activities, such as loading, transportation, and dumping, while integrating bottleneck delays and checkpoints. These operations are modelled using time distributions, such as for example Triangular (2, 3, 5) minutes, to reflect real-world variability. Additionally, stochastic delay modelling is applied to simulate delays introduced through bottlenecks (e.g., closed 40% of the time), capturing the unpredictability of real-world interruptions in the hauling process.

The DES, as the Backbone of the model (Figure 3.6), facilitates detailed process flow analysis:

- *Loading and Dumping Points:* Dumper trucks complete tasks like loading and unloading based on predefined time distributions. These operations are critical to evaluating efficiency in material handling.
- *Bottlenecks and Checkpoints:* Delays are introduced through bottlenecks where checkpoints determine whether routes are closed or open. For instance, bottlenecks are closed 40% of the time, requiring dumper trucks to adjust speed or queue, allowing the model to simulate real-world impacts of congestion.
- *Task Completion Criteria:* The system is designed to run until a predefined number of deliveries (e.g., 90 trips) is completed. This enables researchers to evaluate total operation time, queue lengths, and idle times at various stages.

The DES framework captures the sequence of events and tracks critical metrics such as delays, bottleneck impacts, and overall system efficiency, providing actionable insights for optimising construction logistics.

While DES governs the overall process flow, Agent-Based Simulation (ABS) is used to model specific entities, such as dumper trucks and loaders, for enhanced visualization and interaction (Figure 3.7). Each dumper truck operates within the DES framework, looping through tasks such as loading, dumping, and waiting at bottlenecks. Loader are modelled to interact with dumper trucks at loading stations, ensuring resource allocation aligns with the system's predefined logic. Although ABS does not include independent decision-making in this model, it enhances the simulation's interpretability by dynamically representing individual entities.

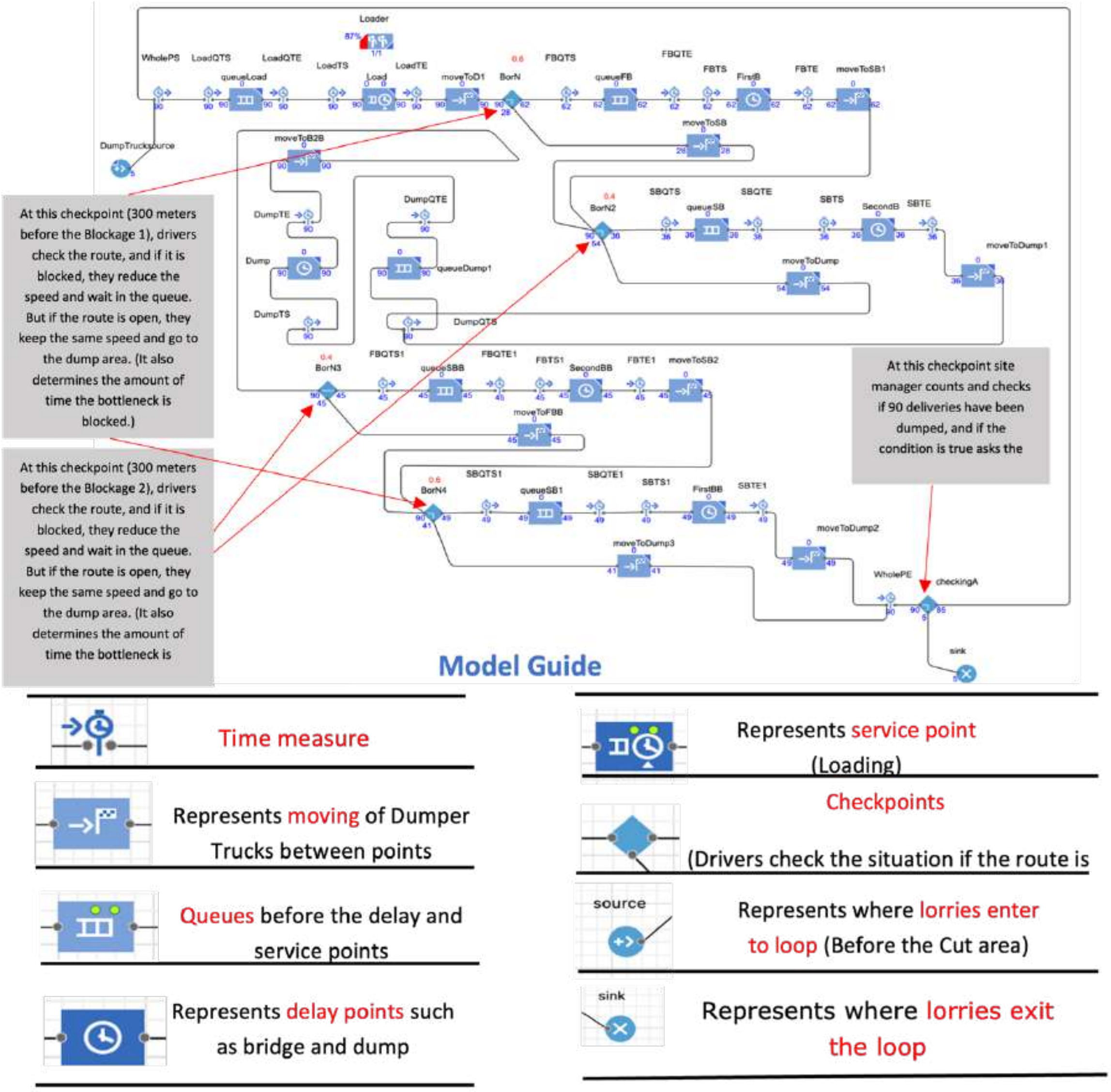


Fig. 3.6: Basic Hauling Model in AnyLogic Software

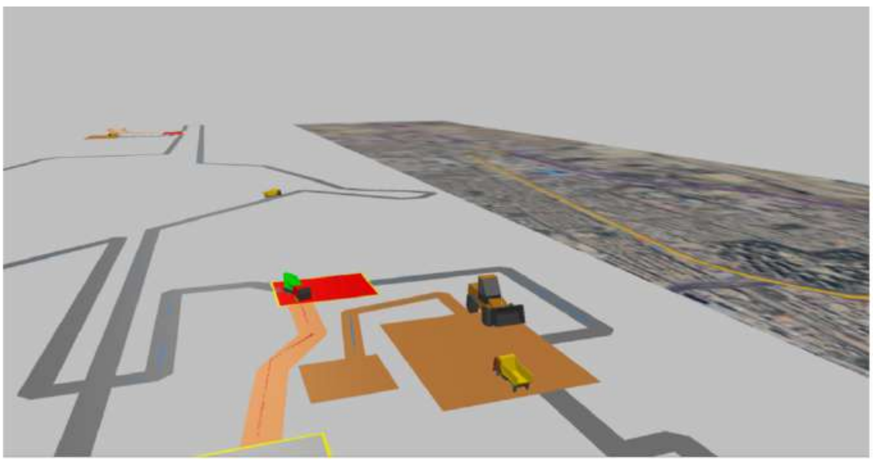


Fig. 3.7: 3D Simulated Model of Interaction between Loader and Dumper Trucks

Finally, by combining DES and ABS within AnyLogic, the model generates key outputs, including:

- Total operation time to complete all deliveries.
- Idle times and queue lengths at loading, dumping, and bottleneck points.
- Frequency of bottleneck encounters and associated delays.
- Number of braking events which directly impact diesel efficiency and emissions.

These outputs enable researchers to test and compare different scenarios by adjusting dumper truck speed, fleet size, and payload capacity. While factors such as the number of bottlenecks and their probabilities and time distributions reflect each case study's inherent conditions, adjusting operational parameters ensures actionable insights for practical improvements. Thus, optimised scenarios can be identified by generating various scenarios with different combinations of these parameters (dumper truck speed, fleet size, and payload capacity), then comparing and analysing the results to determine the most optimised scenario across multiple criteria, such as minimising total time and cost, improving diesel efficiency, and lowering CO_2 emissions.

This basic model was developed to test the ability to calculate factors that impact the CO2 emissions of each case study and contributes to the study's broader goal of advancing sustainable construction logistics and enhancing the efficiency of hauling operations.

3-5-3 Validation of the Hauling Model

The validation of the developed model will be conducted using real-world case studies. These case studies will serve as a practical platform to test the accuracy, applicability, and adaptability of the model under diverse operational conditions. Each case study will provide specific data, such as bottleneck probabilities, time distributions, and resource configurations, reflecting real-world hauling systems. By applying the model to these scenarios, researchers can evaluate its ability to calculate key metrics like CO_2 emissions, diesel consumption, and operational efficiency. The case studies will also allow for the identification of optimised scenarios by testing combinations of parameters such as dumper truck speed, fleet size, and payload capacity. This validation process ensures the model's relevance to sustainable construction logistics and strengthens its capacity to contribute actionable insights for real-world improvements.

3-6 Rationale for Case Study Selection

The case studies were selected based on insights gathered from open-ended interviews conducted with construction practitioners, including project managers, hauling contractors, and fleet managers. These interviews highlighted key challenges in construction hauling logistics, primarily arising from contractors' constraints and operational bottlenecks. The selection of case studies in Iran strategically aligns with this research's objectives to develop a carbon reduction model tailored for construction logistics. Iran's construction as a fragmented industry presents unique logistical challenges, offering rich and diverse contexts to address inefficiencies and validate practical solutions. The insights gathered from the interviews provide a detailed understanding of the recurring issues, inefficiencies, and their impact on CO_2 emissions in construction hauling logistics. These practitioner perspectives shaped the selection of case studies and highlighted critical areas of focus, such as bottlenecks, lack of collaboration, and operational constraints, all of which contribute to increased fuel consumption and emissions. The following analysis summarises the key themes and challenges identified during the interviews, serving as a foundation for designing and validating the carbon reduction model.

3-6-1 Interview Findings on Hauling Logistics Challenges

The analysis of open-ended interviews with construction practitioners, including project managers, hauling contractors, and fleet managers, revealed key themes and recurring challenges in construction hauling logistics. MAXQDA software was employed to ensure a rigorous and systematic analysis of the qualitative data. This tool facilitated identifying and categorising key themes based on word frequency and contextual relevance, allowing for a deeper understanding of practitioner priorities and challenges. Table 3.1 and Figure 3.8 presents the results of a frequency-based word count generated using MAXQDA, highlighting the most prominent concerns and concepts discussed during the interviews.

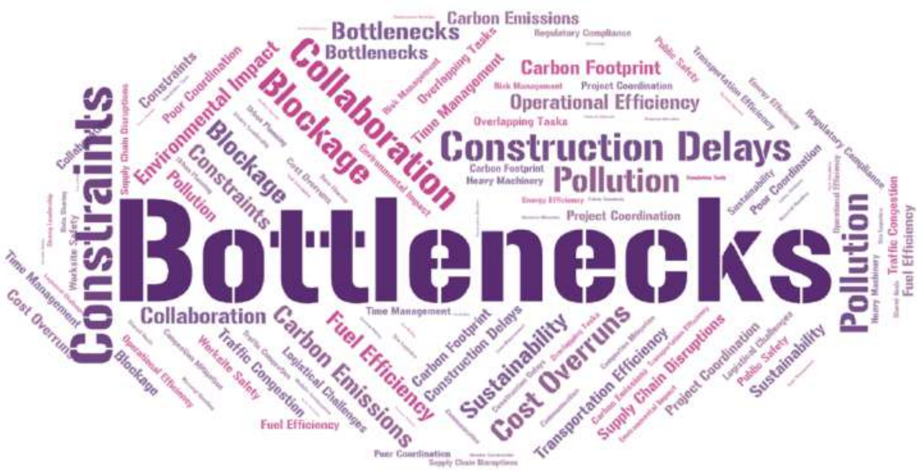


Fig 3.8: Key Themes in Construction Logistics Challenges

Table 3.1: Key Themes Identified in Construction Practitioner Interviews

Word	Count	Word	Count
Bottlenecks	567	Regulatory Compliance	232
Constraints	545	Heavy Machinery	221
Construction Delays	525	Energy Efficiency	209
Collaboration	510	Congestion Mitigation	197
Pollution	495	Risk Management	185
Blockage	478	Urban Planning	175
Cost Overruns	459	Communication	165
Carbon Emissions	448	Data Sharing	155
Sustainability	429	Strong Leadership	147
Fuel Efficiency	415	Shared Goals	139
Environmental Impact	399	Site Logistics	131
Operational Efficiency	385	Material Handling	124
Carbon Footprint	371	Simulation Tools	118
Transportation Efficiency	355	Safety Standards	101
Supply Chain Disruptions	341	Task Scheduling	97
Time Management	329	Resource Allocation	93
Traffic Congestion	317	Construction Workflow	89
Project Coordination	305	Decision-Making	85
Poor Coordination	292	Big Room Approach	81
Overlapping Tasks	281	Eco-Hauling	77
Logistical Challenges	269	Emissions Reduction	73
Worksite Safety	257	Urban Design	69
Public Safety	245	On-Site Collaboration	65

The results emphasise significant focus areas, such as bottlenecks, constraints, and construction delays, which align closely with the research objectives. Additionally, concepts such as collaboration, pollution, and cost overruns underscore the industry's need for enhanced communication and sustainability strategies.

3-6-2 Rationale for Selecting Iran as a Study Context

Iran is listed as one of the world's top 10 largest carbon emitters (UN Iran, 2021). Construction Sector Iran's construction logistics significantly contributes to CO_2 emissions due to outdated practices and inefficiencies (Danesh and Jalali, 2020). For instance, the frequent use of older machinery and fragmented workflows creates higher emissions. By addressing these issues in Iran, this research focuses on a region where sustainable practices can make a meaningful environmental impact.

Alignment with National Priorities Iran's Intended Nationally Determined Contributions (INDCs) prioritise emission reductions in key sectors (Figure 3.9), including transportation and construction. This research directly supports those goals by proposing practical solutions for construction hauling logistics, which align with international commitments like the Paris Agreement.

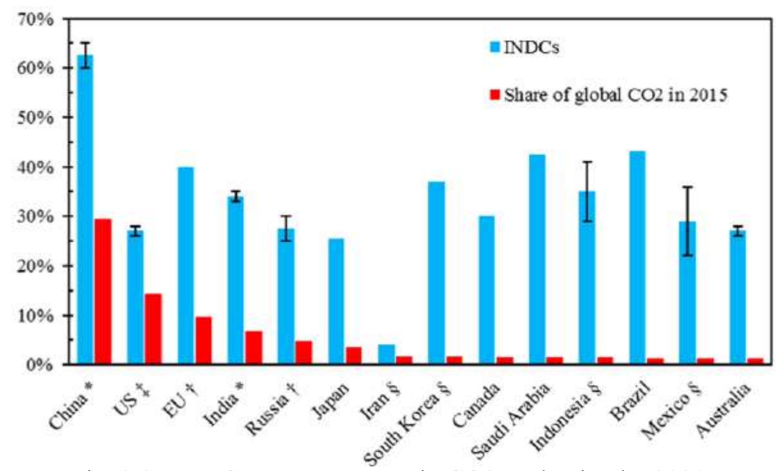


Fig. 3.9: INDCs as Percentages in CO2 Reduction by 2030
Source: (Huang *et al.*, 2018)

Relevance to Real-World Complexities Iran's construction sector reflects common challenges globally, such as contractor coordination failures, traffic bottlenecks, and poor logistical planning (Ahmadabadi and Heravi, 2019). These features ensure that findings are relevant locally and transferable to similar regions worldwide.

3-6-3 Case Studies

Three distinct case studies representing diverse construction logistics conditions were selected to validate the proposed model. Each case explores unique challenges, such as fleet size, payload capacity, and bottlenecks, to evaluate the effectiveness of Eco-hauling and Big Room approaches in improving performance and reducing diesel consumption and CO_2 emissions.

The minimum and maximum payloads (tonnes) and speeds (km/h) permitted for each case study were determined based on data collected from fleet managers and drivers of each project. These values were defined considering road conditions and safety requirements, ensuring operational feasibility and compliance with safety standards. Additionally, the minimum and maximum number of available dumper trucks represents the daily availability of vehicles for each project, reflecting the constraints of fleet operations. These inputs provide essential parameters for modelling and analysing the scenarios within each case study.

Case 1:

- Location: Iran
- Project Type: Road Construction
- Key Features

Table 3.2: Case 1 Characteristics

Case 1	Loop length Meters	Amount of Material Tonnes	Min and Max of Available Dumper Trucks	Min and Max of the Payloads (Tonnes)	Min and Max of the Accepted Speed (Km/h)	Allowed Work Hours
Soil Hauling	6620	900	1-5	8-12	14-26	24 hours a day

Case 2:

- Location: Iran
- Project Type: Road Construction
- Key Features

Table 3.3: Case 2 Characteristics

Case 2	Loop length Meters	Amount of Material Tonnes	Min and Max of Available Dumper Trucks	Min and Max of the Payloads (Tonnes)	Min and Max of the Accepted Speed (Km/h)	Allowed Work Hours
Asphalt Hauling	2660	416	1-5	4-16	20-40	24 hours a day

Case 3:

- Location: Iran
- Project Type: Road Construction
- Key Features

Table 3.4: Case 3 Characteristics

Case 3	Loop length Meters	Amount of Material Tonnes	Min and Max of Available Dumper Trucks	Min and Max of the Payloads (Tonnes)	Min and Max of the Accepted Speed (Km/h)	Allowed Work Hours
Soil Hauling	23000	480	3-7	8-16	30-50	Only from 23:00 to 07:00 in the morning

The selected case studies highlight the diverse and complex realities of construction logistics in Iran, focusing on key challenges such as concurrent operations, lack of collaboration, diverse service agent configurations, and real-world variability. Concurrent workflows, common across all cases, lead to bottlenecks and inefficiencies caused by conflicting priorities among contractors. These cases provide an ideal testbed for implementing the Big Room approach and Eco-hauling principles, which aim to align schedules, minimise delays, and enhance operational flow.

A recurring challenge in Iranian construction logistics is the lack of collaboration, characterised by poor communication and siloed decision-making. Overlapping hauling routes often result in congestion, operational delays, and resource wastage. By introducing collaborative frameworks, this research examines their potential to optimise resource allocation, improve coordination, and significantly reduce CO_2 emissions.

The case-specific conditions further demonstrate the diversity in construction operations. Cases 1 and 3 involve simple operational flows with loaders at loading points but no service agents at dumping points, where challenges include delays and queues at loading stations. In contrast, Case 2 features an asphalt plant at the loading point and an asphalt paver at the dumping point, requiring synchronisation of truck speed with the paver's gradual unloading process. These conditions reflect the variability of real-world projects, including earthmoving operations (Cases 1 and 3) and asphalt paving (Case 2).

The following section thoroughly explores these case studies, providing an in-depth analysis of their unique challenges, operational characteristics, and the application of the proposed strategies.

3-7 Big Room Establishment Using Miro

After selecting case studies, a Big Room approach was established for each case study to create a collaborative environment where key stakeholders could actively participate in identifying challenges, brainstorming solutions, and refining the BASE model for hauling logistics. Recognising the complexity of multi-contractor operations and the diversity of issues such as bottlenecks, delays, and resource allocation, the Big Room provided a structured platform to align objectives and ensure operational efficiency. Miro was used as a virtual collaboration tool to enhance this process, allowing stakeholders to interact in real time, visually map out issues, and document ideas (Figure 3.10). This digital approach not only streamlined communication but also fostered an inclusive and transparent environment where all voices—from drivers to project managers—could be heard and integrated into the decision-making process. By leveraging Miro's versatile features, the Big Room became a hub for problem-solving, data sharing, and customisation of the BASE model to meet the unique needs of each case study. This setup ensured that solutions were practically feasible and strategically aligned with project goals, particularly reducing inefficiencies, CO_2 emissions, and operational delays.

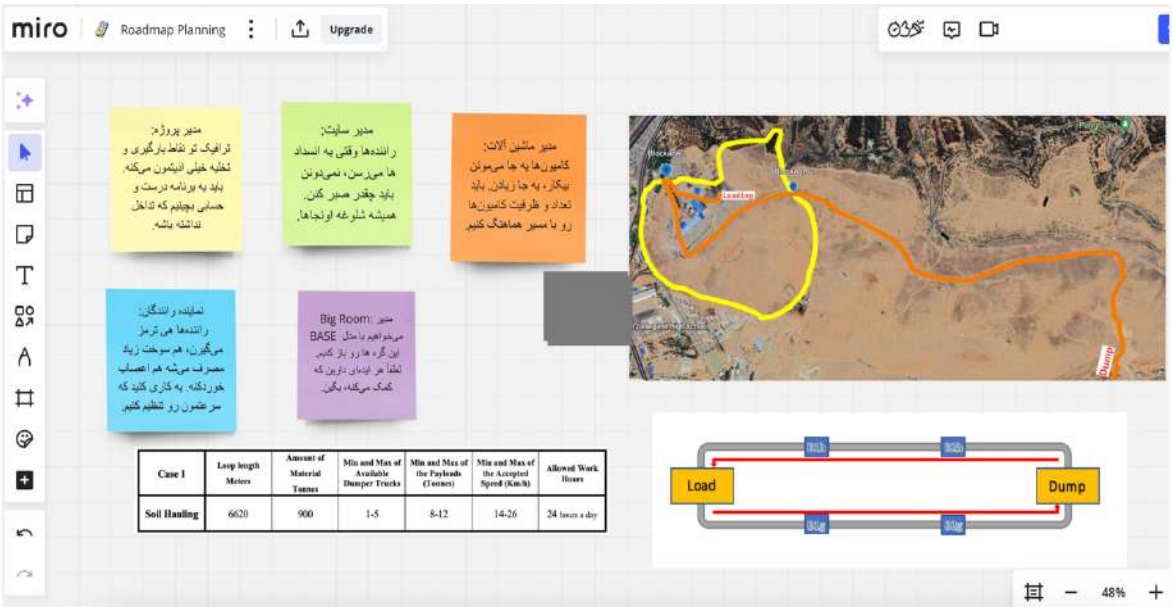


Fig. 3.10: Virtual Big Room for Case Studies on Miro

3-7-1 Big Room Purpose

The Big Room aimed to:

The Big Room was designed to serve as a centralised and collaborative space where all stakeholders could converge to address the operational challenges faced during the hauling operations. Its primary objectives were:

1. *Identify Bottle necks and Inefficiencies:*
   By utilising tools such as route diagrams, operational flowcharts, and visual markers on Miro, stakeholders were able to pinpoint specific delays, traffic congestion points, and coordination gaps in real time. This visualisation made it easier to analyse the root causes of bottlenecks and collaboratively propose targeted solutions.

2. *Foster Collaborative Problem-Solving:*
   Miro's sticky notes, comment features, and voting tools provided an open and inclusive platform where stakeholders could share diverse perspectives and experiences. This encouraged constructive dialogue and helped generate actionable solutions that addressed the practical needs of all parties.

3. *Customise the BASE Model:*
   The Big Room discussions facilitated the customisation of the BASE model by refining key components such as truck speeds, checkpoint placements, and route schedules. Stakeholders worked together to tailor the model to the specific requirements and constraints of each case study.

4. *Simulate Scenarios:*
   Visual representations of hauling routes and operational constraints uploaded to Miro allowed stakeholders to simulate and evaluate various scenarios. This iterative process enabled them to refine assumptions and validate the feasibility of proposed strategies, ensuring that solutions were both practical and data-driven.

3-7-2 Big Room Members

To ensure the success of the Big Room approach, representatives from all critical stakeholder groups were included. This diversity in participation allowed for a comprehensive understanding of the challenges and opportunities in each case study:

1. *Project Manager:*
   The project manager provided strategic oversight, ensuring that the proposed adjustments to operations aligned with overall project timelines and goals. Their perspective helped bridge the gap between operational and strategic priorities.

2. *Site Manager:*
   The site manager brought in-depth knowledge of on-site workflows, such as loading and dumping processes, and highlighted critical resource constraints. Their role was vital in identifying operational bottlenecks and offering practical solutions for resource management.

3. *Fleet Manager:*
   The fleet manager contributed valuable insights into truck deployment, fuel consumption patterns, and vehicle performance metrics. This data was essential for evaluating logistical efficiency and optimising fleet operations.

4. *Drivers' Representative:*
   The drivers' representative played a crucial role in conveying the real-time challenges faced by drivers, such as delays, braking patterns, and traffic congestion. Their feedback ensured that the solutions developed in the Big Room were grounded in practical realities.

5. *BASE Model Facilitator (Researcher):*
   Acting as the facilitator, the researcher guided the discussions, ensured that all voices were heard, and integrated the insights gathered into the simulation models. They also ensured that the solutions were systematically evaluated and incorporated into the BASE model for validation.

The combination of the Big Room approach and Miro's collaborative tools ensured a systematic, stakeholder-driven process for tackling operational challenges. This integration streamlined discussions and enhanced the BASE model's applicability and practicality in diverse hauling scenarios.

3-8 Case Study Selection to Address Operational Challenges

The selection of case studies was guided by a comprehensive set of variables that allowed for an in-depth evaluation of hauling logistics under different operational scenarios. These variables were carefully chosen to capture the diverse challenges and complexities faced in real-world projects (Table 3.5).

Table 3.5: Key Variables in Case Study Selection

	Case Specifications	Case 1 Soil Hauling	Case 2 Asphalt Hauling	Case 3 Soil Hauling
1	Loop length Meters	6620	2660	23000
2	Amount of Material Tonnes	900	416	480
3	Average Time of Loading	Between 2-10 mins depends on the amount of the Payload	Between 6-12 mins depends on the amount of the Payload	Between 2-10 mins depends on the amount of the Payload
4	Average Time of Dumping	Between 2-6 mins depends on the amount of the Payload	Between 5-28 mins depends on the amount of the Payload	Between 2-6 mins depends on the amount of the Payload
5	Average Diesel use per Hour for each Dumper Truck with a 10-Tonne Payload	25	25	25
6	Average of Diesel Use of each Dumper Truck per 100 km	35	35	35
7	Probability of Bottlenecks During the Operation Time	Blockage 1= 60% Blockage 2= 40%	Blockage 1= 60% Blockage 2= 40%	Blockage 1= 50% Blockage 2= 30% Blockage 3= 60%
8	Average Duration of Blockages	Blockage 1= Triangular (1, 2, 4) Blockage 2= Triangular (1, 2, 3)	Blockage 1= Triangular (1, 2, 4) Blockage 2= Triangular (1, 2, 3)	Blockage 1= Triangular (1, 2, 3) Blockage 2= Triangular (1, 2, 3) Blockage 3= Triangular (3, 5, 6)
9	Min and Max of the Number of Available Dumper Trucks	1-5	1-5	3-7
10	Min and Max of the Payloads (Tonnes) Permitted by Fleet Manager and Drivers	8-12 Tonnes	4-16 Tonnes	8-16 Tonnes
11	Min and Max of the Speed of Accepted by Fleet Manager and Drivers	14-26 Km/h	20-40 Km/h	30-50 Km/h
12	Estimation Material Quantities Loaded in each Dumper Truck	Estimated soil quantity (1.5 tonnes/m³ density) was based on a loader bucket capacity of 3 tonnes (2 m³)	Based on Asphalt Plant Bills	Estimated soil quantity (1.5 tonnes/m³ density) was based on a loader bucket capacity of 3 tonnes (2 m³)
13	Cost of Renting a Dump Truck Per Hour	900,000 Tomans	900,000 Tomans	900,000 Tomans
14	Allowed Work Hours	24 hours a day	24 hours	Only from 23:00 to 07:00 in the morning

The data for these variables were obtained from multiple sources, including project managers, site managers, fleet managers, and drivers' representatives, ensuring that perspectives from all key stakeholders were included. Additionally, structured observations were conducted on-site to gather precise numerical data, such as fuel consumption, travel distances, loading and dumping times, and bottleneck probabilities. This multi-faceted approach provided a robust foundation for evaluating operational efficiency and validating the proposed model.

1. ***Loop Length***

- The total distance covered during hauling operations, referred to as the loop length, is a fundamental factor in evaluating fuel consumption, travel time, and the efficiency of operational workflows.
- In Case 1, the loop length was 6620 meters, representing a moderate distance suitable for observing blockages at specific intersections. In contrast, Case 3 featured the longest loop length of 23000 meters, providing insights into the challenges of long-distance hauling, such as route planning and fuel usage over extended periods. Meanwhile, Case 2, with a shorter loop length of 2660 meters, allowed for a focused analysis of hauling operations with complex unloading dynamics, such as coordinating with an asphalt paver.

2. ***Amount of Material Hauled***

- The type and quantity of material significantly impact hauling logistics. The selected case studies featured two distinct materials: soil in Cases 1 and 3 and asphalt in 2.
- The material quantity varied between cases, with Case 1 and Case 3 involving 900 tonnes each, and Case 2 handling 416 tonnes of asphalt. This variability allowed for testing how payload size influences loading times, truck allocation, and operational efficiency. For example, the heavier soil loads required different hauling strategies compared to the smaller yet more complex asphalt loads.

3. ***Loading and Dumping Times***

- Loading and dumping times are critical variables that directly affect total hauling time and operational delays.
- In Case 1 and Case 3, loading and dumping times were relatively consistent, ranging between 2 and 10 minutes. However, Case 2 introduced variability in unloading times due to the gradual unloading process required by the asphalt paver, ranging from 5 to 28 minutes. This additional complexity provided an opportunity to test strategies for optimising these processes and minimizing delays.

4. ***Fuel Usage***

- Fuel consumption was measured as both average diesel usage per hour and per 100 kilometres. These metrics provided a consistent baseline for comparing operational efficiency across the cases.
- The data collected on fuel consumption, combined with model outputs such as total time and the number of brakes, enabled precise calculations of total diesel use and CO_2 emissions. This approach allowed for a detailed evaluation of how Eco-hauling principles reduced fuel wastage and emissions in different scenarios.

5. ***Probability and Duration of Bottlenecks***

- Bottlenecks were a significant factor in all case studies, varying in probability and duration depending on the scenario.
- In Case 1, two blockages occurred with probabilities of 40–60%, each lasting between 1 and 4 minutes. Case 3 introduced an additional bottleneck with longer durations (3–6 minutes), while Case 2 had fewer bottlenecks but required precise coordination to prevent delays caused by the asphalt paver. These variations allowed for testing the effectiveness of queue management strategies and pre-emptive measures like checkpoints.

6. ***Fleet Dynamics***

- The number of dumper trucks, their payload capacities, and operational speeds varied across the cases, reflecting the unique requirements of each scenario.
- Case 3, for example, featured larger fleets with higher payload capacities (16 tonnes) to manage the longer loop length, whereas Case 2 had smaller payloads (8 tonnes) but required higher speeds (up to 50 km/h) to maintain synchronization with the asphalt paver. These differences provided valuable insights into fleet management strategies and their impact on efficiency.

7. ***Work Hours***

- The operating hours differed significantly across the cases, introducing varying levels of complexity in scheduling and resource allocation.
- Cases 1 and 2 operated 24/7, enabling continuous observation of hauling operations under different conditions. In contrast, Case 3 had restricted night-time operations (23:00–07:00), requiring adjustments to scheduling and fleet utilization to maintain productivity within limited timeframes.

8. Material Type

- The two materials involved—soil and asphalt—presented unique challenges in handling and logistics.
- Soil, as seen in Cases 1 and 3, required efficient loading and dumping processes to minimize delays. Asphalt, handled in Case 2, introduced additional complexity due to its reliance on precise unloading coordination with the asphalt paver, making it an ideal testbed for micro-level optimisation strategies.

9. Truck Speed and Payload Capacity

- The acceptable speeds of dumper trucks (14–50 km/h) and their payload capacities (8–16 tonnes) were essential variables in evaluating hauling efficiency.
- By modelling these factors, the study was able to test how speed and payload optimisations influenced fuel consumption, travel time, and emissions across different loop lengths and material types.
- To estimate the quantity of soil (Earth (Sand, Clay, Silt) with a density of 1.5 Tonnes/M3) that needed to be loaded onto each dumper truck, the loader bucket capacity, which amounted to 3 tonnes or two cubic meters, was considered. To ensure accuracy, data on the load amount in the excavator bucket was collected by measuring the dimensions of the soil in the bucket at ten different time points. The contractor also provided data on the material composition and estimated density.

10. Dumper Trucks Rental Costs

- The majority of the dumper trucks used in the case studies were rented, and since the data collection spanned a few months, the rental rates remained consistent throughout this period. Using cost as a key indicator enabled an accurate estimation of the expenses associated with dumper trucks for each scenario, which was directly linked to their total operational time. This proportional relationship between cost and operational time allowed for a precise evaluation and comparison of the financial implications across different scenarios based on their respective durations.

3-9 Development of Structured Scenarios by Stat-Ease

Based on the empirical data, the subsequent stage involved designing structured scenarios to analyse operational performance for each case systematically. Using Stat-Ease software, 15–17 scenarios were generated by strategically combining key input parameters such as fleet size (number of trucks), number of deliveries, truck speed, and payload capacity.

This structured approach allowed for the controlled exploration of how variations in these parameters affect performance metrics, including total operation time, idle time, diesel consumption, and CO_2 emissions. By systematically altering these variables, the research sought to uncover the interrelationships between input factors and operational efficiency, identifying patterns and trade-offs that inform optimisation strategies.

The outcome of this stage was a clearly defined matrix of input combinations, providing a comprehensive framework for simulating and evaluating scenarios. This matrix not only ensured consistency and clarity in scenario testing but also laid the groundwork for identifying optimised configurations to achieve improved performance and sustainability in hauling operations.

3-10 Overview of Case Studies

The selected case studies were strategically chosen to represent varied, complex, and high-impact construction logistics scenarios. They serve not only as real-world contexts for evaluating carbon emissions in hauling operations but also as targeted environments to demonstrate the practical application and value of the BASE model. Each case involves unique constraints, such as time-sensitive deliveries, uncoordinated subcontractors, and limited site access, which present bottlenecks and inefficiencies commonly found across the industry.

These cases were not selected arbitrarily. They were specifically chosen for their ability to reflect diverse construction contexts—ranging from highway development and paving operations to urban infrastructure upgrades—all of which are heavily dependent on precise logistics management. Their complexity makes them ideal for testing key BASE model interventions, such as checkpoint optimisation, time-blocked scheduling, collaborative planning, and simulation-driven performance forecasting.

Each case study involved structured engagement with project managers, site engineers, fleet managers, and drivers, ensuring a robust, practice-oriented basis for data collection. A mix of site-structured observations and simulation software analysis was applied uniformly across all cases to ensure consistency and empirical depth. This allowed for capturing both observed inefficiencies and testing theoretical improvements using the BASE model.

Collectively, these case studies provide a robust framework for evaluating the BASE model's capacity to address emissions reduction, logistics performance, and collaborative planning across varied construction environments.

Table 3.6: Summary of Case Studies

Case Study	Project Focus	Rationale for Selection	Participants Involved	Data Collection
Case 1	Soil hauling for road construction	Involved uncoordinated subcontractors, overlapping truck movements, and clear bottlenecks	Project Manager, site managers and engineers, fleet managers and drivers	Interview, site-structured observation, simulation in software
Case 2	Asphalt hauling for paving operations	Required synchronisation with paving machine, featured time-sensitive material handling and varied unloading speeds	Project Manager, site managers and engineers, fleet managers and drivers	Interview, site-structured observation, simulation in software
Case 3	Urban road construction with soil and concrete hauling	Characterised by night-time delivery constraints, multiple contractors, and urban congestion	Project Manager, site managers and engineers, fleet managers and drivers	Interview, site-structured observation, simulation in software

3-10-1 Case 1: Soil Hauling with Concurrent Operations

This case involves a road project in Iran that included a soil-hauling operation. Two subcontractors operated concurrently (soil hauling (orange route) and asphalt laying (yellow route)) under the same main contractor. The project required transporting 900 tonnes of soil along a looped route of 6620 meters, with significant bottlenecks at two intersections (Blockage 1 and Blockage 2) (Figures 3.11 and 3.12).

Fig. 3.11: Hauling Path - Case Study 1

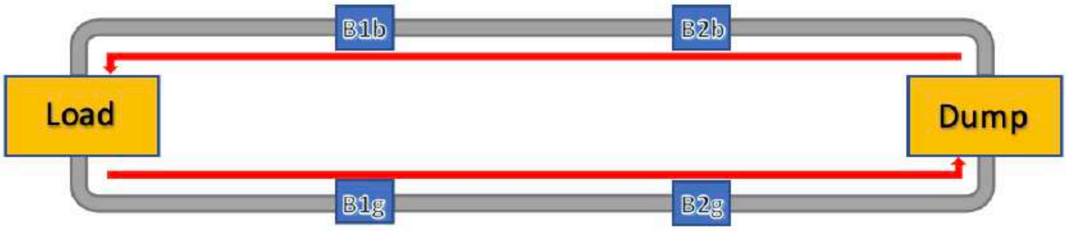


Fig. 3.12: Schematic Illustration of the Hauling Process - Case Study 1

In the next step, a table of scenarios (Table 3.6) is generated using Stat-Ease. This table is constructed based on input data that includes the minimum and maximum values for dumper trucks, their payload capacity, and speed parameters. The generated scenarios are then modelled in AnyLogic, where key variables such as total time, idle time, diesel consumption, CO_2 emissions, and operational costs are calculated. Additionally, the table facilitates a comparative analysis between Eco-hauling and the combined Eco-hauling and Big Room approach, which eliminates bottlenecks to optimise efficiency and sustainability.

Table 3.7: Scenarios Matrix for Eco-Hauling and Big Room Analysis - Case Study 1

Scenario	No of Deliveries	Speed Km/h	Payloads Tonnes	No of Trucks	Eco-hauling						Eco-hauling and Big Room					
					Total Time mins	Idle Time mins	No of Brakes	Diesel Litres	CO2 Kg CO2	Cost Tomans	Total Time mins	Idle Time mins	No of Brakes	Diesel Litres	CO2 Kg CO2	Cost Tomans
1	100	23	9	4												
2	90	26	10	3												
3	82	23	11	4												
4	82	23	11	2												
5	113	20	8	3												
6	82	17	11	2												
7	90	20	10	3												
8	90	20	10	1												
9	100	17	9	2												
10	90	14	10	3												
11	90	20	10	5												
12	100	23	9	2												
13	82	17	11	4												
14	75	20	12	3												
15	100	17	9	4												

The generated scenarios, outlined in Table 3.6, are modelled in AnyLogic to simulate the complexities of hauling operations across the selected case studies. These scenarios, derived from the minimum and maximum values for dumper trucks, payload capacity, and speed parameters, allow for a systematic exploration of operational performance. Within AnyLogic, the model calculates key variables such as total operation time, idle time, diesel consumption, CO_2 emissions, and operational costs, offering insights into the efficiency of each scenario. Furthermore, the model enables a comparative analysis between Eco-hauling and the integrated Eco-hauling and Big Room approach, demonstrating how eliminating bottlenecks can optimise resource use, minimise delays, and enhance sustainability (Figures 3.13 and 3.14). This modelling process provides a robust framework for evaluating and improving construction logistics strategies.

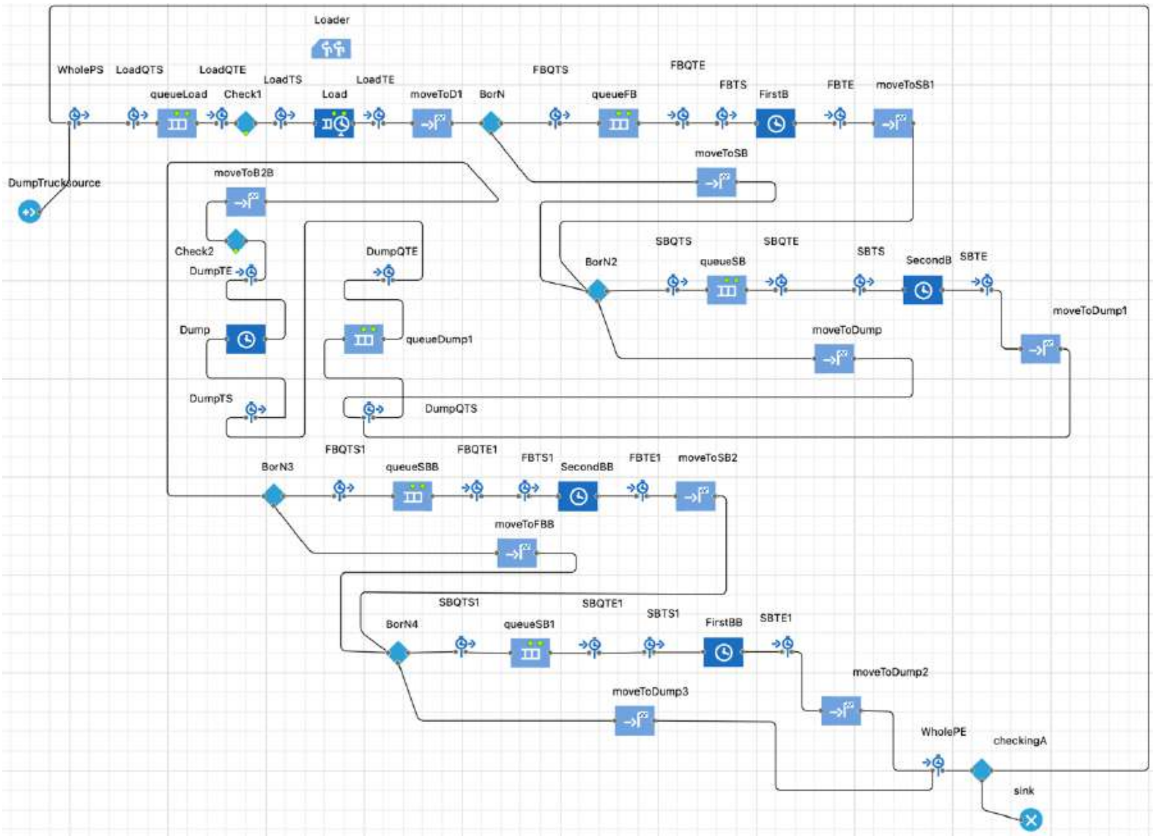


Fig. 3.13: Eco-Hauling Mode Modelled in AnyLogic - Case Study 1

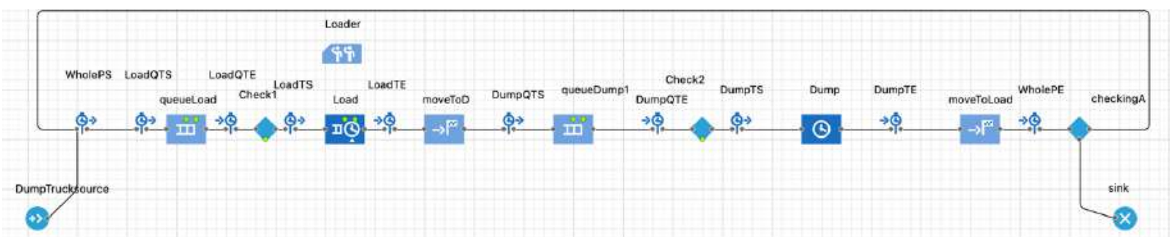


Fig. 3.14: Eco-Hauling and Big Room Mode Modelled in AnyLogic - Case Study1

The Eco-hauling model, in its standalone form, reflects the complexities of real-world construction logistics, where bottlenecks and delays frequently disrupt operations. This model incorporates multiple checkpoints before Blockage 1 and Blockage 2, as well as loading and dumping points where dumper trucks adjust their speed, queue, or wait depending on route conditions. While these checkpoints help mitigate some carbon emissions by enabling drivers to manage bottlenecks more effectively, they cannot eliminate bottlenecks entirely. As a result, delays and congestion persist, leading to idle times and operational inefficiencies. Managing this process flow remains challenging as bottlenecks continue to create unpredictability in the system. These features simulate the inefficiencies caused by unaligned contractor schedules, poor communication, and conflicting priorities.

In contrast, the Eco-hauling and Big Room model integrates collaborative planning to simplify the process and ensure a seamless workflow. This model eliminates unnecessary interruptions by removing bottlenecks and keeping the check checkpoints just before loading and dumping points, allowing dumper trucks to flow continuously through the system. The Big Room approach fosters communication and alignment among stakeholders, ensuring that schedules are coordinated and resources are optimised. This streamlined process reduces idle times, diesel consumption, and emissions while improving overall efficiency. The simplification of the workflow makes the system more predictable, reliable, and easier to manage. By comparing these two models, the benefits of integrating Eco-hauling with the Big Room approach become clear. The removal of delays and the emphasis on collaboration result in a simpler yet more effective operation. This integration enhances performance and supports sustainability goals by reducing resource wastage and environmental impacts. The combined model provides a practical, human-centric solution to the challenges of modern construction logistics.

- *Challenges:*
  - The overlapping routes created frequent blockages, leading to delays, increased idle times, and higher fuel consumption.
  - A lack of effective coordination between subcontractors further exacerbated inefficiencies.
- *BASE Model Application:*
  - Based on Eco-Hauling principles, checkpoints were introduced 300 meters ahead of each blockage and at the loading and dumping points. These

checkpoints allowed drivers to assess the passage status, optimising truck speeds, reducing braking frequency, and minimising fuel wastage. This adjustment improved the hauling process's efficiency while contributing to reduced emissions and a more sustainable operation.

  - A Big Room was established for this case, and the collaborative effort concluded that the stakeholders could operate in two distinct time blocks within a 24-hour day. For instance, the hauling subcontractor may work from 5 a.m. to 4 p.m., while the asphalt laying contractor operates from 4 p.m. to 5 a.m. This strategic scheduling aims to facilitate collaborative efforts, eliminate blockages, and ensure a seamless project workflow.
  - Another key outcome of the Big Room approach was the recognition that the sequential start method for dumper trucks not only reduced engine runtime but also improved operational coordination and fuel efficiency. Instead of all trucks starting their engines simultaneously and waiting in line, this method required the first truck to start its engine and proceed for loading, while the remaining trucks started sequentially based on the loading time of the previous truck. For example, with 5 trucks and a 9-minute loading time per truck, the second truck would start its engine after 9 minutes, the third after 18 minutes, and so on. This approach saved a total of 90 minutes of idle engine time across all trucks, significantly reducing unnecessary diesel consumption and CO_2 emissions. By addressing such inefficiencies collaboratively, the Big Room approach enabled all stakeholders to implement a simple yet effective solution that enhanced both sustainability and overall project efficiency.
  - Structured observations and AnyLogic simulations validated the BASE model, achieving 90% alignment between real-life data and simulation results.

- *Significance*:
  - Case 1 served as a valuable testbed for assessing the BASE model's ability to manage multi-contractor operations, reduce congestion, and improve overall hauling efficiency.

3-10-2 Case 2: Asphalt Hauling with Complex Unloading Dynamics

Case 2 was conducted at the same site as Case 1 but focused on asphalt hauling operations. The project involved transporting 416 tonnes of asphalt from an asphalt plant to a dumping point with an asphalt paver. The loop length was 2660 meters, presenting unique coordination challenges due to the nature of asphalt unloading (Figure 3.15). In Figure 3.16, the red numbers show the locations of dumping points.

Fig 3.15: Asphalt Laying Path - Case Study 2

The red marker indicates the location of the asphalt plant, where asphalt is produced and loaded onto dumper trucks for transportation. The yellow route serves as the hauling path for trucks, facilitating the movement of asphalt from the plant to the dumping point and back. This path is not part of the asphalt paving process. The purple line (1274 meters), however, highlights the section of the route where asphalt is being laid, representing the active paving area. This setup ensures a clear distinction between the hauling operations and the paving activities.

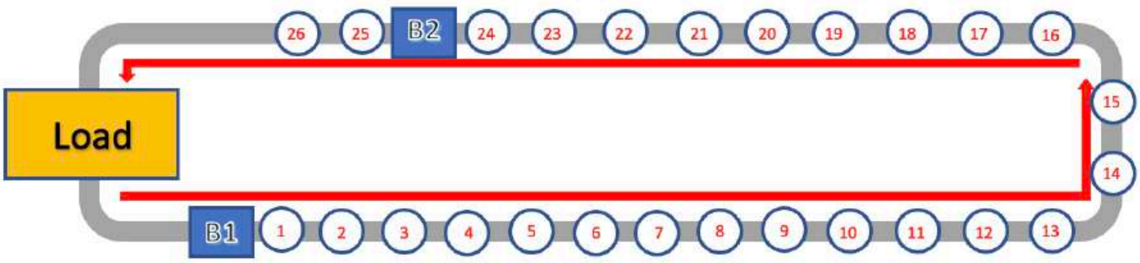


Fig. 3.16: Schematic Illustration of the Hauling Process - Case Study 2

Again, similar to Case 1, a table of scenarios (Table 3.7) is generated using Stat-Ease in the next step. This table is constructed based on input data that includes dumper trucks' minimum and maximum values, payload capacity, and speed parameters. The generated scenarios are then modelled in AnyLogic, where key variables such as total time, idle time, diesel consumption, CO_2 emissions, and operational costs are calculated. The table also facilitates a comparative analysis between Eco-hauling and the combined Eco-hauling and Big Room approach, eliminating bottlenecks to optimise efficiency and sustainability.

Table 3.8: Scenarios Matrix for Eco-Hauling and Big Room Analysis-Case Study 2

Model	No of Deliveries	Speed Km/h	Payloads Tonnes	No of Trucks	Eco-hauling						Eco-hauling and Big Room					
					Total Time mins	Idle Time mins	No of Brakes	Diesel Litres	CO2 Kg CO2	Cost Tomans	Total Time mins	Idle Time mins	No of Brakes	Diesel Litres	CO2 Kg CO2	Cost Tomans
1	**52**	**30**	**8**	**3**												
2	**104**	**30**	**4**	**1**												
3	**26**	**30**	**16**	**5**												
4	**52**	**20**	**8**	**5**												
5	**52**	**30**	**8**	**2**												
6	**52**	**30**	**8**	**5**												
7	**52**	**30**	**8**	**4**												
8	**104**	**40**	**4**	**3**												
9	**26**	**30**	**16**	**1**												
10	**104**	**20**	**4**	**3**												
11	**104**	**30**	**4**	**5**												
12	**52**	**40**	**8**	**1**												
13	**52**	**40**	**8**	**5**												
14	**26**	**40**	**16**	**3**												
15	**52**	**20**	**8**	**1**												

The generated scenarios, outlined in Table 3.7, are modelled in AnyLogic to simulate the complexities of hauling operations across the selected case studies. These scenarios, derived from the minimum and maximum values for dumper trucks, payload capacity, and speed parameters, allow for systematically exploring operational performance. Within AnyLogic, the model calculates key variables such as total operation time, idle time, diesel consumption, CO_2 emissions, and operational costs, offering insights into the efficiency of each scenario. Furthermore, the model enables a comparative analysis between Eco-hauling and the integrated Eco-hauling and Big Room approach, demonstrating how eliminating bottlenecks can optimise resource use, minimise delays, and enhance sustainability (Figures 3.17 and 3.18). This modelling process provides a robust framework for evaluating and improving construction logistics strategies.

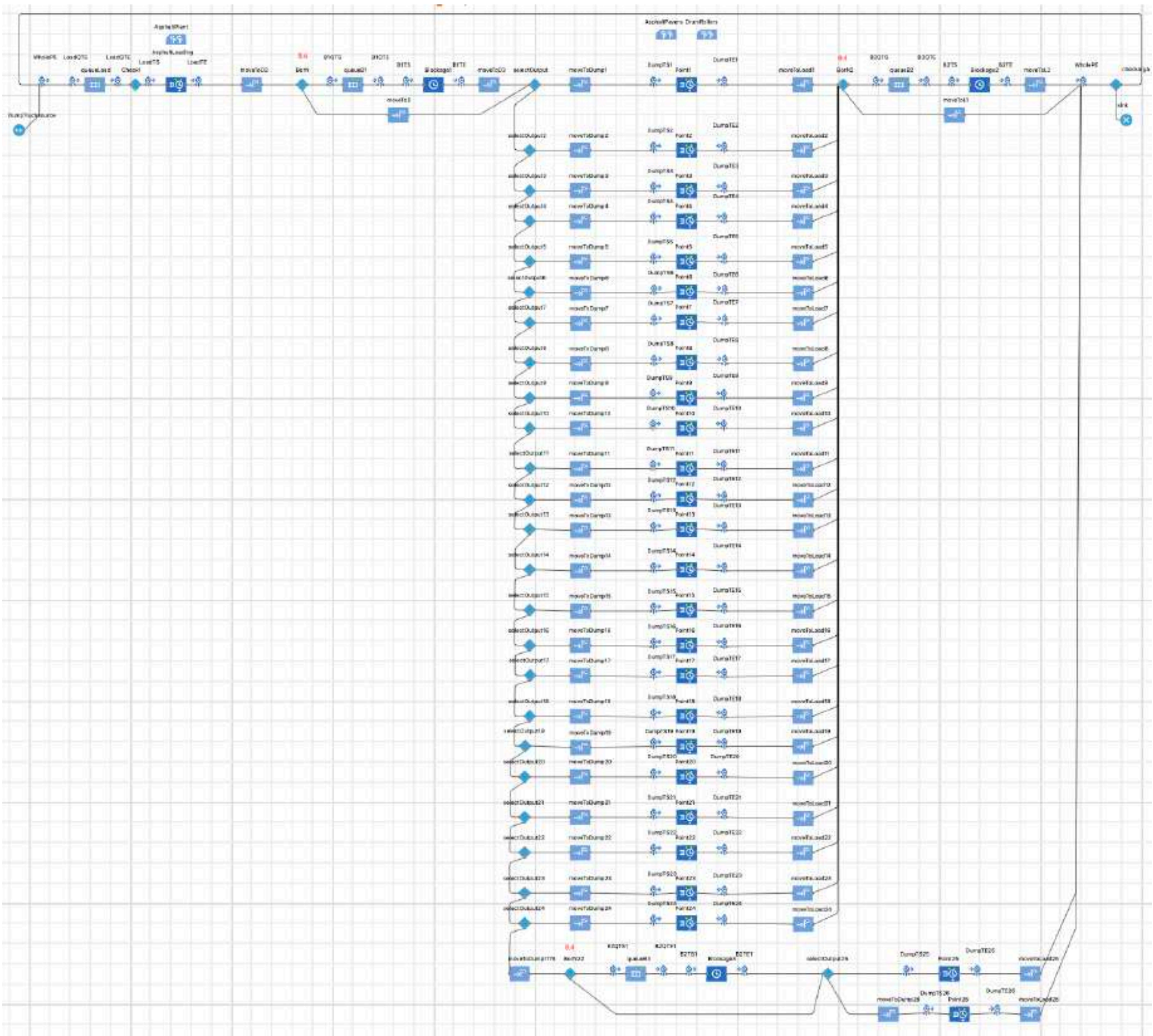


Fig. 3.17: Eco-Hauling Mode Modelled in AnyLogic - Case Study 2

In contrast to Case 1, Case 2 presented a more complex scenario involving asphalt hauling between a plant and a paver. The unique challenge lay in the dynamic relationship between the paver's speed and the flow of dumper trucks, which required precise coordination to avoid interruptions. Unlike the relatively linear operations in Case 1, the model for Case 2 needed to account for the variable unloading pace dictated by the paver, leading to variability in truck movements and potential delays.

The integration of Eco-hauling and the Big Room approach was equally beneficial here, although its effects were more nuanced. The checkpoints allowed drivers to synchronise their movements with the paver, reducing idling and ensuring smoother transitions. This adjustment mitigated delays caused by the paver's variability, improving overall operational flow. Additionally, the Big Room approach provided a platform for stakeholders to coordinate the timing of truck dispatches, paver operations, and asphalt loading, thus addressing the unique challenges posed by the interdependence of these activities.

Unlike Case 1, the post-integration model in Case 2 remained complex and changed minorly, reflecting the inherent intricacies of the operation. However, the integration improved its functionality by introducing greater control and predictability. While the model did not achieve the same degree of simplification as in Case 1, it demonstrated the BASE model's capacity to adapt to more intricate logistics scenarios without compromising its effectiveness.

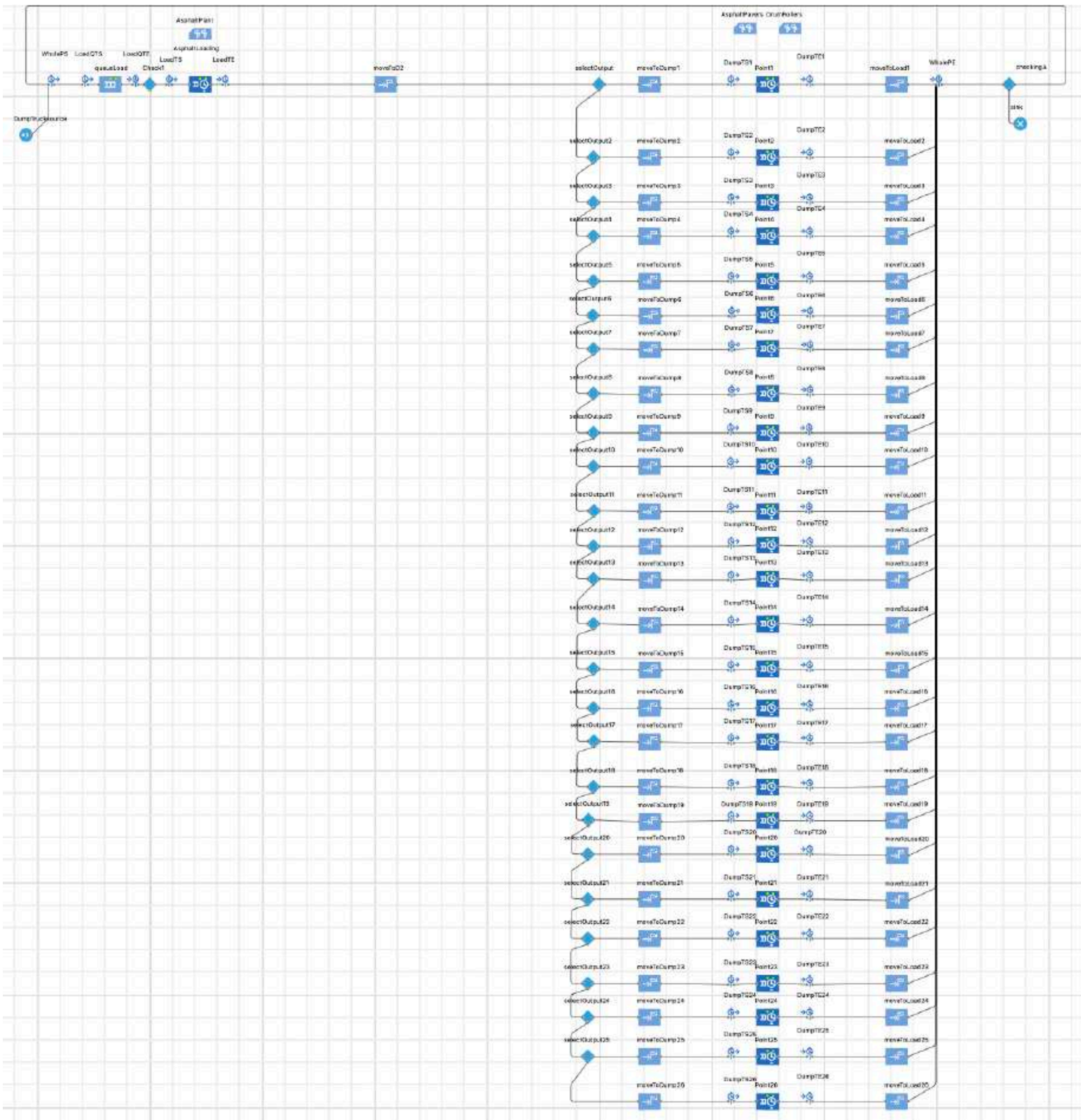


Fig. 3.18: Eco-Hauling and Big Room Mode Modelled in AnyLogic – Case Study 2

- *Challenges:*
    - Trucks needed to synchronise their speed with the asphalt paver during gradual unloading, which introduced significant variability in dumping times.
    - Frequent adjustments in truck movements to align with the paver caused operational delays and increased fuel consumption.

- *BASE Model Application:*
    - Based on Eco-Hauling principles, checkpoints were introduced 300 meters ahead of each blockage and at the loading and dumping points. These checkpoints allowed drivers to assess the passage status, optimising truck speeds, reducing braking frequency, and minimising fuel wastage. This adjustment improved the hauling process's efficiency while contributing to reduced emissions and a more sustainable operation.
    - A Big Room was established for this case, and the collaborative effort concluded that the stakeholders could operate in two distinct time blocks within a 24-hour day. For instance, the hauling subcontractor may work from 5 a.m. to 4 p.m., while the asphalt laying contractor operates from 4 p.m. to 5 a.m. This strategic scheduling aims to facilitate collaborative efforts, eliminate blockages, and ensure a seamless project workflow.
    - Again, another key outcome of the Big Room approach was the recognition that the sequential start method for dumper trucks not only reduced engine runtime but also improved operational coordination and fuel efficiency. Instead of all trucks starting their engines simultaneously and waiting in line, this method required the first truck to start its engine and proceed for loading, while the remaining trucks started sequentially based on the loading time of the previous truck. For example, with 5 trucks and a 9-minute loading time per truck, the second truck would start its engine after 9 minutes, the third after 18 minutes, and so on. This approach saved a total of 90 minutes of idle engine time across all trucks, significantly reducing unnecessary diesel consumption and CO_2 emissions. By addressing such inefficiencies collaboratively, the Big Room approach enabled all stakeholders to implement a simple yet effective solution that enhanced both sustainability and overall project efficiency.

  - Simulations in AnyLogic captured micro-level interactions, validating the BASE model's applicability to scenarios requiring high precision.

- *Significance:*

  - Case 2 highlights the BASE model's ability to manage complex coordination dynamics and improve the efficiency of operations involving time-sensitive processes like asphalt paving.

3-10-3 Case 3: Road Project with Concurrent Operations in a Downtown

This case study revolves around a road construction project located in the heart of the city, where two groups—one responsible for soil hauling and the other for concrete hauling—had to work concurrently under restricted night-time conditions. The project faced significant challenges due to strict city council regulations that limited operations to a specific time window from 11:00 PM to 7:00 AM, prioritising safety and reducing pollution in the densely populated downtown area. Both groups needed to complete their respective tasks within 10 days, making the efficient use of the available time critical.

The soil hauling group was tasked with removing 4,800 tonnes of soil over 10 nights, which translated to 480 tonnes per night. The hauling route covered a loop length of 23,000 metres and included three bottlenecks, one more than in Case 1 and 2, further complicating the operations (Figures 3.19, 3.20 and 3.21). Meanwhile, the concrete hauling group was responsible for transporting concrete from the batching plant to pour into pile holes for reinforcement cages. The concrete group estimated that 3 to 4 hours would be sufficient for nightly operations, given that 5 to 6 cages could be prepared by the reinforcement group each night. However, due to bottlenecks and coordination challenges, their actual work often extended to 6–7 hours. Both groups operated under significant constraints as the soil dumping area and concrete batching plant were located at the same site. This shared location became a point of congestion, adding to the delays. A major issue was the lack of a consistent start time for either group. Depending on circumstances, operations would sometimes begin at 11 PM, 12 AM, or even 1 AM, creating further disruption and inefficiencies. This lack of synchronisation between the soil hauling and concrete hauling groups compounded the delays, as neither contractor's schedule was clearly defined, leading to overlapping tasks and operational conflicts.

The soil hauling group also faced efficiency challenges due to the presence of three bottlenecks on their route, which further impacted their ability to meet the planned target of 480 tonnes per night. Similarly, the concrete hauling group's delays were exacerbated by the bottlenecks and the misalignment of schedules, causing prolonged use of the limited operational window.

This project exemplified the complexities of managing two interdependent operations within limited working hours. The need for precise coordination, efficient bottleneck management, and adherence to environmental and safety regulations made this case particularly challenging. Despite these constraints, both groups worked collaboratively to complete their tasks, leveraging strategies such as checkpoint adjustments and adaptive scheduling to achieve their goals within the set timeframe.

Fig. 3.19: Hauling Path - Case Study 3

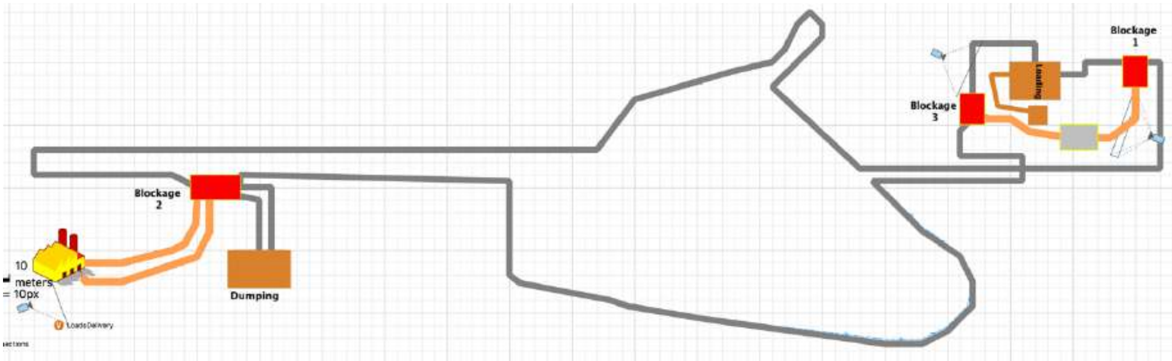


Fig. 3.20: Graphical Hauling Path on AnyLogic- Case Study 3

Fig. 3.21: Schematic Illustration of the Hauling Process- Case Study 3

Again, similar to Case 1and 2, a table of scenarios (Table 3.8) is generated using Stat-Ease in the next step. This table is constructed based on input data that includes dumper trucks' minimum and maximum values, payload capacity, and speed parameters. The generated scenarios are then modelled in AnyLogic, where key variables such as total time, idle time, diesel consumption, CO_2 emissions, and operational costs are calculated. The table also facilitates a comparative analysis between Eco-hauling and the combined Eco-hauling and Big Room approach, eliminating bottlenecks to optimise efficiency and sustainability.

Table 3.9: Scenarios Matrix for Eco-Hauling and Big Room Analysis-Case Study 3

Model	No of Deliveries	Speed Km/h	Payloads Tonnes	No of Trucks	Eco-hauling						Eco-hauling and Big Room					
					Total Time mins	Idle Time mins	No of Brakes	Diesel Litres	CO2 Kg CO2	Cost Tomans	Total Time mins	Idle Time mins	No of Brakes	Diesel Litres	CO2 Kg CO2	Cost Tomans
1	40	40	12	3												
2	40	40	12	7												
3	60	40	8	5												
4	48	45	10	4												
5	34	35	14	6												
6	34	45	14	6												
7	30	40	16	5												
8	34	45	14	4												
9	34	40	14	5												
10	48	45	10	6												
11	34	35	14	4												
12	48	35	10	6												
13	40	40	12	5												
14	40	30	12	5												
15	60	35	8	4												
16	40	50	12	5												
17	40	40	12	4												

The generated scenarios, outlined in Table 3.8, are modelled in AnyLogic to simulate the complexities of hauling operations across the selected case studies. These scenarios, derived from the minimum and maximum values for dumper trucks, payload capacity, and speed parameters, allow for systematically exploring operational performance. Within AnyLogic, the model calculates key variables such as total operation time, idle time, diesel consumption, CO_2 emissions, and operational costs, offering insights into the efficiency of each scenario. Furthermore, the model enables a comparative analysis between Eco-hauling and the integrated Eco-hauling and Big Room approach, demonstrating how eliminating bottlenecks can optimise resource use, minimise delays, and enhance sustainability (Figures 3.22 and 3.23). This modelling process provides a robust framework for evaluating and improving construction logistics strategies.

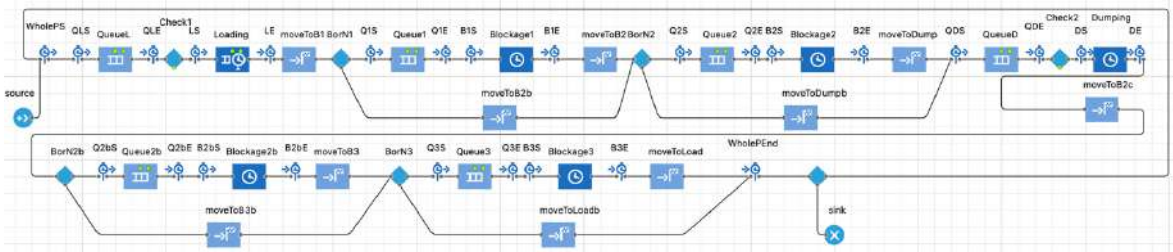


Fig. 3.22: Eco-Hauling Mode Modelled in AnyLogic – Case Study 3

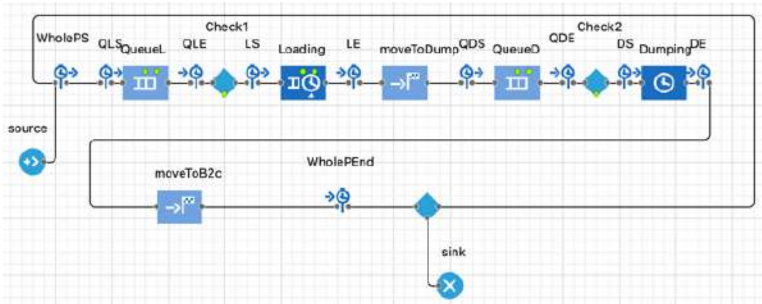


Fig. 3.23: Eco-Hauling and Big Room Mode Modelled in AnyLogic – Case Study 3

In its standalone form for Case Study 3, the Eco-hauling model highlights the complexities of urban construction logistics where multiple bottlenecks and conflicting operations create significant challenges. This model reflects the real-world conditions of hauling operations, incorporating checkpoints at key locations such as before Blockage 1, Blockage 2, and Blockage 3, as well as at loading and dumping points. These checkpoints allow dumper truck drivers to assess route conditions, manage their speed, and queue as needed. While these features help reduce fuel consumption and carbon emissions by enabling proactive navigation through bottlenecks, they do not eliminate bottlenecks or operational inefficiencies entirely.

The three bottlenecks along the 23-kilometre loop further complicate operations, creating unpredictability and frequent delays. The lack of synchronisation between the soil and concrete hauling groups exacerbates these inefficiencies. The Eco-hauling model realistically simulates these challenges, including the disruptions caused by inconsistent start times and poor contractor communication. Consequently, idle times and congestion persist, limiting the model's ability to achieve sustainable and efficient operations.

In contrast, the integrated Eco-hauling and Big Room model simplifies the process and introduces collaborative planning to address these challenges holistically. Integrating the Big Room approach focuses on aligning schedules, improving communication, and optimising resource allocation among all stakeholders. This collaborative planning eliminates unnecessary bottlenecks and prioritises key checkpoints only at loading and dumping points, ensuring a smoother and more predictable flow of operations

- *Challenges:*
  - Strict Regulations: Limited operational hours created time constraints, making efficiency essential.
  - Bottlenecks: The soil hauling route included three bottlenecks, one more than in Case 1 and Case 2.
  - Shared Sites: The shared dumping area and batching plant caused congestion.

  - Coordination Issues: Lack of consistent start times and poorly synchronised operations led to delays.
  - Efficiency Problems: Both groups struggled to complete their tasks within the restricted time window.

- *BASE Model Application:*
  - Based on Eco-Hauling principles, checkpoints were introduced 300 meters ahead of each blockage and at the loading and dumping points. These checkpoints allowed drivers to assess the passage status, optimising truck speeds, reducing braking frequency, and minimising fuel wastage. This adjustment improved the hauling process's efficiency while contributing to reduced emissions and a more sustainable operation.
  - The Big Room outcomes revealed inefficiencies in soil hauling operations, requiring 6 hours nightly to transport 480 tonnes of soil. Using AnyLogic for simulation and Stat-Ease for optimisation, a refined scenario proposed reducing the number of trucks from 7 to 6, increasing payload capacity from 12 to 16 tonnes, and raising the average speed from 40 km/h to 48 km/h. These adjustments cut the operation time from 6 hours to 4 hours, improving efficiency and aligning with sustainability goals by cutting CO_2 emissions by 32%. Without optimisation, dividing the work time into two shifts would not have been feasible. Initially, contractors assumed hauling 480 tonnes would require 7 trucks operating for at least 6 hours, leaving no room for the concrete hauling team. However, applying the BASE model identified the most suitable and optimised scenario within the allowable hours. With this approach, contractors can divide the working period (11 pm to 7 am) into two shifts: soil hauling from 11 pm to 3 am and concrete hauling from 3 am to 7 am. This division eliminates bottlenecks, optimises resource allocation, and reduces idle time. The adoption of this strategy highlights the value of collaborative planning and advanced modelling tools in achieving efficiency and sustainability milestones.
  - An important result of the Big Room approach was the realisation that the sequential start strategy for dumper trucks not only cut down engine idle time but also enhanced coordination and fuel efficiency during operations. Rather than having all trucks start their engines simultaneously and queue unnecessarily, this method instructed the first truck to start and proceed for loading, while the others waited to start based on the loading time of the preceding truck. For instance, with 7 trucks and an 8-minute

loading time per truck, the second truck would start its engine 8 minutes later, the third after 16 minutes, and so on. This strategy collectively reduced engine idle time by 168 minutes, resulting in significant savings in diesel consumption and a decrease in CO_2 emissions. By addressing such inefficiencies through collaborative discussions, the Big Room approach empowered stakeholders to implement this straightforward yet impactful solution, improving both sustainability and operational efficiency.

  - Simulation models in AnyLogic validated these strategies, demonstrating their scalability for long-distance hauling operations.

- *Significance:*
  - Case 3 provides insights into the scalability of the BASE model and its adaptability to large-scale projects with unique operational constraints.
  - Case 3 same as case 1 served as a valuable testbed for assessing the BASE model's ability to manage multi-contractor operations, reduce congestion, and improve overall hauling efficiency.

The three case studies collectively provide a robust methodological framework for evaluating the complexities of construction hauling logistics. Each case was carefully designed to reflect unique operational challenges, from addressing bottlenecks in multi-contractor environments (Case 1) to managing precise unloading dynamics (Case 2) and optimising long-distance hauling under restricted schedules (Case 3). Together, they validate the flexibility and comprehensiveness of the BASE model in addressing diverse logistical scenarios.

A key element of the methodology is its focus on environmental sustainability. Each case incorporated variables like diesel consumption and CO_2 emissions into the analysis, enabling the BASE model to address operational inefficiencies while assessing its potential for reducing environmental impacts. By integrating checkpoints, stakeholder collaboration through the Big Room approach, and simulation tools, the methodology ensures a systematic approach to minimising resource wastage and emissions.

This methodological framework lays the foundation for understanding how the BASE model can streamline construction logistics and improve sustainability. It demonstrates the practicality of combining operational data with simulation outputs, setting the stage for future evaluations and validating its potential to enhance efficiency while reducing the carbon footprint of hauling operations.

3-11 Modelling and Parameters

The modelling process for each scenario incorporates a range of critical input parameters, such as the number of trucks, their payload capacities, average speeds, and the total number of deliveries required. These inputs form the foundation for evaluating and comparing operational performance. Using AnyLogic simulation software, key outputs are calculated, including the total number of brakes (stops), total operation time, and cumulative idle time. These outputs are significant as they directly influence diesel consumption and operational efficiency (Table 3.9).

Table 3.10 Key outputs of each scenario

Element	Explanation
Total Number of brakes	o Per stop at blockages o Per stop at dumping and loading points o Spending more than the maximum expected time at dumping and loading points (Means it was another queue inside the point) o Spending more than twice the mean time at dumping and loading points (Means it was another queue inside the point) o Spending more than 0.1 a minute in queue blocks
Total operation time	Time taken to complete the entire hauling process
Cumulative Idle Time	The times when trucks are not actively hauling include: o Spending time in queues o Spending time in Blockages o Spending more than the mean time in dumping and loading blocks

Once the outputs are obtained, predefined formulas are applied to compute diesel consumption for each scenario, as detailed in Table 3.10. The calculated diesel consumption values are then used to derive the corresponding CO_2 emissions, as illustrated in Table 3.11. This systematic approach ensures a comprehensive evaluation of each scenario, enabling a thorough comparison of efficiency and environmental impacts. The step-by-step methodology provides clarity and ensures that all scenarios are analysed with consistency and precision. The detailed tracking of these parameters allows for a granular understanding of the operational dynamics. By simulating various scenarios, AnyLogic generates valuable data that inform targeted improvements in efficiency and sustainability. This enables stakeholders to assess the trade-offs between operational changes and their impacts on fuel consumption, emissions, and overall project performance. The results provide actionable insights to optimise hauling logistics while minimising environmental impacts.

Table 3.11 Key Outputs and Diesel Consumption Calculation Parameters

	Outputs	**Explanation**
Diesel Consumption (Litres)	**Brakes**	**1. Braking Events Diesel Consumption** The diesel consumed due to braking events can be calculated as follows: **Diesel Consumption (Litres) = Total Brakes × 0.1 × 0.35** Where: Total Brakes: Number of braking events 0.1: Fuel increase factor per stop (10% fuel increase per km) Each stop per km of driving added about 10% to the fuel use just to bring the vehicle speed back to normal (Rylander *et al.*, 2014). 0.35: Diesel consumption (litres) per km to return to normal speed
	Total operation time	**2. Aggregate Diesel Consumption During Operations** To calculate the total diesel consumed during operations, the following steps can be expressed: $\textbf{Aggregate Operation Duration (Hours)} = \frac{\textbf{Total Operation Time (Minutes)} \times \textbf{Number of Trucks}}{60}$ **Diesel Consumption (Litres) = Aggregate Duration (Hours) × 25** Diesel consumption per hour for each dumper truck is based on estimates from the contractor.
	Sequential Start Method	**3. Optimising Engine Runtime Through Sequential Truck Start Method** (Only used in integration of Eco-Hauling and Big Room mode) At the start of hauling, trucks start engines sequentially, reducing idle time, synchronising runtime, and improving fuel efficiency and emissions. Saved Time for n-th Truck = (n−1) × Loading Time per Truck (Minutes) Total Saved Time (Minutes) = $\sum_{i=1}^{n}((i-1) \times Loading\ Time\ per\ Truck)$
	Diesel Consumption Adjustment Based on Payload	Contractors consider 10 tonnes as the average payload to estimate the hourly diesel use. The formula adjusts diesel consumption based on deviations from this 10-tonne average: **According to** Coyle (2007)**, heavy truck fuel consumption increases by approximately 0.112 miles per gallon (mpg) for every additional tonne of payload = 0.047 km/L** Increase or decrease per km = 0.047 L/km × (Payload−10) Tonnes Total distance in km = Number of deliveries (Loops) × Length per loop in km Total added or decreased diesel = Increase or decrease per km × Total distance (km)

3-11-1 Expanded Explanation of Table 3-10

Table 3-11 outlines the fundamental parameters used for analysing hauling operations. These parameters include the number of braking events, total operation time, the sequential start method, and diesel consumption adjustments based on payload. Each parameter is tied to specific formulas, enabling accurate calculation of operational performance and fuel consumption. Below is a detailed explanation of each parameter.

1. *Number of Braking Events*

Braking events are a critical metric that reflects inefficiencies in the hauling process. When trucks decelerate or come to a stop, additional energy is required to accelerate back to operational speed, leading to increased diesel consumption. This parameter focuses on quantifying the fuel consumed as a result of braking.

The formula to calculate diesel consumption due to braking events is:

Diesel Consumption (Litres) = Number of Braking Events × 0.1 × 0.35

Where:

- Number of Braking Events: The total number of stops occurring during hauling.
- 0.1: Represents a 10% increase in fuel consumption per kilometre for each braking event.
- 0.35: Average diesel consumption (litres per kilometre) for heavy trucks.

Example Calculation:

If 80 braking events occur in an operation, the additional diesel consumed is:

Diesel Consumption = 80 × 0.1 × 0.35 = 2.8 litres.

These braking events typically occur at blockages, dumping points, loading points, and queues. Minimising the number of braking events is essential to reducing fuel consumption, which can be achieved through better route planning and coordination between stakeholders.

2. *Total Operation Time*

Total operation time represents the duration required to complete hauling tasks, including loading, travelling, dumping, and returning to the starting point. It serves as a key indicator of operational efficiency and fuel consumption.

The aggregate operation time for all trucks is calculated as:

Aggregate Duration (Hours) = (Total Operation Time (Minutes) × Number of Trucks) ÷ 60

The diesel consumption during operations is then determined using:

Diesel Consumption (Litres) = Aggregate Duration (Hours) × 25

Where:

- 25: Diesel consumption rate in litres per hour for heavy trucks.

Example Calculation:
If the total operation time is 400 minutes and there are 6 trucks:

1. Aggregate Duration = (400 × 6) ÷ 60 = 40 hours.
2. Diesel Consumption = 40 × 25 = 1000 litres.

Reducing total operation time directly impacts fuel consumption. Strategies include optimising schedules, increasing payload capacities, and reducing delays caused by inefficiencies at loading and dumping points.

3. *Sequential Start Method*

The sequential start method reduces idle engine runtime at the start of hauling operations. Instead of starting all engines simultaneously, trucks start sequentially, aligned with loading times. This method reduces overlapping idle time, lowering unnecessary diesel consumption and emissions.

The time saved for each truck is calculated as:
Saved Time for the n-th Truck = (n − 1) × Loading Time per Truck

To calculate the total saved time across all trucks:
Total Saved Time (Minutes) = Sum of ((i − 1) × Loading Time per Truck), where i ranges from 1 to n

Example Calculation:
For 5 trucks with a loading time of 10 minutes each:

- Truck 1: 0 minutes saved
- Truck 2: (2 − 1) × 10 = 10 minutes saved
- Truck 3: (3 − 1) × 10 = 20 minutes saved
- Truck 4: (4 − 1) × 10 = 30 minutes saved
- Truck 5: (5 − 1) × 10 = 40 minutes saved

Total Saved Time:
0 + 10 + 20 + 30 + 40 = 100 minutes.

Diesel Saved (Sequential Start) = 100 ÷ 60 × 25 = 41.67 litres

This approach optimises coordination, reduces idle time, and contributes to overall fuel efficiency.

4. *Diesel Consumption Adjustment Based on Payload*
   Payload adjustments account for the impact of variations in payload weight on fuel consumption. Heavier payloads increase diesel usage, while lighter payloads reduce it.

The adjustment per kilometre is calculated using:
Diesel Adjustment per km (Litres) = 0.047 × (Payload (Tonnes) − 10)

The total diesel adjustment is then determined as:
Total Diesel Adjustment (Litres) = Diesel Adjustment per km × Total Distance (km)

Where:

- Total Distance = Number of Deliveries × Length of Loop

Example Calculation:
If a truck has a payload of 15 tonnes, with 10 deliveries, and each loop is 8 km:

1. Diesel Adjustment per km = 0.047 × (15 − 10) = 0.235 litres/km
2. Total Distance = 10 × 8 = 80 km
3. Total Diesel Adjustment = 0.235 × 80 = 18.8 litres

By carefully managing payload weights, projects can optimise diesel consumption and reduce unnecessary emissions without compromising productivity.

5. *Practical Application of Table 3-11*

Each parameter in Table 3-11 provides a specific formula for calculating operational performance and fuel consumption. These formulas are designed for simulation tools such as AnyLogic and Stat-Ease, which allow stakeholders to test different scenarios and optimise logistics operations. By using these parameters, construction projects can achieve:

- Reduced total diesel consumption
- Lower CO_2 emissions
- Improved operational efficiency

In summary, Table 3-11 offers a clear and actionable methodology for evaluating and improving hauling operations. Each parameter focuses on a specific inefficiency, enabling a targeted approach to sustainability in construction logistics.

3-11-2 Calculating CO_2 Emissions for Each Scenario

To calculate CO_2 emissions for each hauling scenario, the total diesel consumption must first be determined by summing up several key components derived from operational outputs. These components include diesel consumption due to braking events, active operation time, adjustments based on payload variations, and idle time in queues or blockages. Once the total diesel consumption is calculated, it is converted into CO_2 emissions using a standardised emission factor. According to Ji et al. (2014), diesel emits 2.62 kg of CO_2 per litre combusted.

Below is a detailed and sequenced explanation of the calculation process.

Step 1- Diesel Consumed Due to Braking Events:

Braking events contribute to additional diesel consumption as trucks use more fuel to return to their normal operating speed after each stop. This consumption is calculated using the formula:

$$\text{Diesel Consumed (Braking)} = \text{Number of Braking Events} \times 0.1 \times 0.35$$

Here, 0.1 represents a 10% increase in fuel consumption per kilometre due to braking, and 0.35 is the average diesel consumption rate in litres per kilometre for heavy trucks.

For example, if a scenario involves 80 braking events, the diesel consumed is:

$$\text{Diesel Consumed (Braking)} = 80 \times 0.1 \times 0.35 = 2.8 \text{ litres}$$

Step 2- Diesel Consumed During Total Operation Time:

This component measures the diesel used during active hauling operations, including loading, travelling, dumping, and returning. The formula is:

$$\text{Diesel Consumed (Operation Time)} = \text{Aggregate Duration (Hours)} \times 25$$

The aggregate duration is calculated as:

$$\text{Aggregate Duration (Hours)} = (\text{Total Operation Time (Minutes)} \times \text{Number of Trucks}) \div 60$$

Here, 25 litres/hour is the average diesel consumption rate for heavy trucks during active operation.

For example, if the total operation time is 360 minutes (6 hours) with 4 trucks, the calculations are:

$$\text{Aggregate Duration} = (360 \times 4) \div 60 = 24 \text{ hours}$$

$$\text{Diesel Consumed (Operation Time)} = 24 \times 25 = 600 \text{ litres}$$

Step 3 - Diesel Saved Using Sequential Start Method

The Sequential Start Method reduces unnecessary engine runtime at the start of hauling operations. Instead of starting all truck engines simultaneously and waiting for their turn to load, trucks start engines sequentially, aligned with loading times. This method significantly reduces overlapping engine runtime, resulting in lower diesel consumption and emissions.

The saved time for each truck is calculated as:

$$\text{Saved Time for the n-th Truck} = (n-1) \times \text{Loading Time per Truck}$$

To calculate the total saved time across all trucks:

$$\text{Total Saved Time (Minutes)} = \sum_{i=1}^{n}((i-1) \times Loading\ Time\ per\ Truck)$$

Example Calculation:

For 6 Trucks with a Loading Time of 12 Minutes Each:

Truck 1: 0 minutes saved

Truck 2: (2 − 1) × 12 = 12 minutes saved

Truck 3: (3 − 1) × 12 = 24 minutes saved

Truck 4: (4 − 1) × 12 = 36 minutes saved

Truck 5: (5 − 1) × 12 = 48 minutes saved

Truck 6: (6 − 1) × 12 = 60 minutes saved

Total Saved Time:

0 + 12 + 24 + 36 + 48 + 60 = 180 minutes

Diesel Saved (Sequential Start): 180 ÷ 60 × 25 = 75 litres

Step 4- Diesel Adjustment Based on Payload Variations:

Payload adjustments account for the impact of deviations from the standard payload weight (10 tonnes) on fuel consumption. The formula for adjustment per kilometre is:

Diesel Adjustment per km = 0.047 × (Payload (Tonnes) − 10)

The total adjustment is calculated as:

Total Diesel Adjustment = Diesel Adjustment per km × Total Distance (km)

Total Distance = Number of Deliveries × Loop Length

For example, if a truck carries a payload of 15 tonnes with 10 deliveries, and each loop is 8 km:

Diesel Adjustment per km = 0.047 × (15 − 10) = 0.235 litres/km

Total Distance = 10 × 8 = 80 km

Total Diesel Adjustment = 0.235 × 80 = 18.8 litres

Step 5 - Total Diesel Consumption:

The total diesel consumption for a scenario is the sum of the above components:

Total Diesel Consumed =

Diesel Consumed (Braking) +

Diesel Consumed (Operation Time) +

Diesel Saved Using Sequential Start Method +

Diesel Adjustment Based on Payload Variations

For example, using the results above:

Diesel Consumed (Braking) = 2.8 litres
Diesel Consumed (Operation Time) = 600 litres
Diesel Saved Using Sequential Start Method = -75 litres
Diesel Adjustment Based on Payload Variations = 18.8 litres

Total Diesel Consumed = 2.8 + 600 + 18.8 - 75 = 546.6 litres

Convert Diesel Consumption to CO_2 Emissions:
Once the total diesel consumption is calculated, it is converted into CO_2 emissions using the formula:

CO_2 Emissions (kg) = Total Diesel Consumed (Litres) × 2.62

Here, 2.62 kg CO_2/litre is the standardised emission factor for diesel combustion, representing the amount of CO_2 released per litre of diesel burned.

For example, using the total diesel consumption of 641.6 litres:

CO_2 Emissions = 546.6 × 2.62 = **1,432.09 kg CO_2**

This calculation shows that, for this scenario, the operation emits approximately 1,432.09 kg of CO_2.

By following this methodology, each scenario's environmental impact can be quantified. This step-by-step approach ensures that all inefficiencies, such as braking events, payload variations, and idle time, are accurately accounted for. The results enable stakeholders to evaluate the sustainability of different scenarios, identify areas for improvement, and implement strategies to reduce diesel consumption and CO_2 emissions.

3-11-3 Calculating Total Rental Costs for Dumper Trucks

To calculate the total rental cost of dumper trucks for each scenario, a step-by-step approach was followed to ensure accuracy and consistency. First, the total operational time (measured in hours) for each scenario was determined based on the planned activities and the timeline required to complete them. This total operational time reflects the cumulative hours during which the trucks were in use for a given scenario.

Next, this value was multiplied by the number of dumper trucks used in the scenario, accounting for the fleet size required to meet the operational demands. Finally, the resulting product was multiplied by 900,000, representing the hourly rental rate of the trucks in the local currency. This simple yet robust formula made it possible to calculate the total rental cost for each scenario.

By applying this consistent methodology, the analysis ensured that the cost estimation was both precise and comparable across all scenarios. This allowed for meaningful financial comparisons, helping to identify cost-efficient options while maintaining operational effectiveness.

Formula:

Total Rental Cost = Total Operational Time (hours) × Number of Trucks × 900,000

3-12 Analysis and Optimisation Using Stat-Ease Tool

To extract actionable insights and achieve the best possible configurations for sustainable construction logistics, the optimisation stage utilises Stat-Ease tools. After the scenarios have been expanded and simulated, Stat-Ease software is applied to analyse the vast dataset and refine the results into optimal recommendations. This stage is pivotal for transforming raw data into practical strategies by focusing on reducing CO_2 emissions, lowering costs, and improving operational efficiency.

Using advanced optimisation techniques, Stat-Ease tools enable the identification of optimal configurations among hundreds of scenarios. The software employs Response Surface Methodology (RSM) and Design of Experiments (DOE) to systematically evaluate the relationships between input variables—such as truck numbers, payload sizes, and speeds—and output metrics, including fuel consumption, CO_2 emissions, and costs. These tools help pinpoint the combinations of input variables that deliver the best overall performance.

A critical step in optimisation involves applying RSM to explore the effects of multiple variables simultaneously. For instance, RSM can highlight how the interaction between payload size and vehicle speed influences fuel efficiency, allowing researchers to identify the most effective balance. By generating contour plots and surface graphs, Stat-Ease visualises these interactions, making it easier to understand how adjusting specific inputs impacts the desired outcomes. For example, it may reveal that increasing payload slightly while reducing speed leads to significant reductions in fuel consumption and emissions.

Stat-Ease also enables the use of desirability functions to prioritise multiple objectives during optimisation. In this context, goals such as minimising emissions, reducing idle time, and cutting costs are weighted according to their importance. The software then identifies configurations that achieve the highest overall desirability, ensuring that no objective is compromised. This multi-objective approach ensures that the solutions are both sustainable and practical for real-world implementation.

Another key feature of Stat-Ease is its ability to identify bottlenecks and inefficiencies that might not be apparent in initial analyses. For example, it may detect configurations where an increase in operational efficiency leads to unintended increases in CO_2 emissions due to longer engine running times. By addressing these trade-offs, the optimisation process ensures that the final recommendations are not only efficient but also aligned with sustainability goals.

The output of this stage is a set of optimised configurations tailored to the specific constraints and objectives of the project. These configurations are accompanied by detailed insights into why they outperform others, providing stakeholders with a clear rationale for their implementation. For instance, the recommendations might suggest deploying fewer trucks with slightly larger payloads and moderate speeds to achieve maximum fuel efficiency without compromising delivery timelines.

In summary, the optimisation stage using Stat-Ease tools is the culmination of the data-driven approach to sustainable construction logistics. By analysing the expanded and simulated scenarios, this stage refines the data into actionable insights, offering precise configurations that minimise CO_2 emissions, reduce costs, and enhance operational efficiency. This step not only completes the analytical process but also ensures that the research delivers practical, stakeholder-ready solutions for real-world application.

3-13 Simulation Model Validation

Case Study 1 and Case Study 3 were instrumental in validating the proposed modelling approach, providing practical scenarios to test the effectiveness and accuracy of the Eco-hauling principles. These cases were specifically chosen due to their diverse challenges and operational scales, which allowed for a comprehensive evaluation of the model's applicability to real-world construction logistics.

In Case Study 1, the total material hauling requirement was 1,800 tonnes. To facilitate a detailed comparison between real-life operations and the simulation model, the contractor was asked to divide the operation into two distinct phases. In the first phase, 900 tonnes were hauled without the application of any specific strategy, representing the baseline or conventional approach to hauling. This operation served as a control scenario, capturing the inherent inefficiencies and bottlenecks present in typical construction logistics. In the second phase, Eco-hauling principles were introduced. Checkpoints were established 300 meters before critical points in the operation, including the loading and dumping areas, as well as known bottlenecks. These checkpoints aimed to optimise truck movements by reducing braking frequency, minimising idle times, and improving fuel efficiency. By directly comparing these two operational strategies, the effectiveness of the Eco-hauling approach could be rigorously assessed.

In Case Study 3, the soil hauling operation presented a more complex and large-scale scenario. The project involved the removal of 4,800 tonnes of soil over 10 nights, with each night requiring the transportation of 480 tonnes. On the first night, the operation was carried out without any strategic interventions, serving as a baseline similar to the first phase of Case Study 1. On the second night, Eco-hauling principles were applied by introducing checkpoints 300 meters ahead of critical locations, including bottlenecks and loading and dumping points. This approach mirrored the methodology used in Case Study 1, allowing for consistency in the evaluation process.

Four key elements defined each scenario in both case studies: the number of dumper trucks, the payload capacity per truck (measured in tonnes), the average speed of the trucks (measured in kilometres per hour), and the total number of deliveries required to complete the operation. To ensure a fair and accurate comparison between the baseline and Eco-hauling scenarios, the contractor was instructed to maintain the same values for these variables across both operational strategies. By keeping these parameters consistent, the impact of the Eco-hauling principles could be isolated and assessed with greater precision.

Data collection for both the initial and Eco-hauling scenarios involved structured on-site observations. These observations were designed to capture numerical data on key performance indicators, including total operation time, idle time, fuel consumption, and the number of stops or brakes made by the trucks. This data was crucial for understanding the operational dynamics of each scenario and provided a foundation for validating the simulation model. The structured nature of the data collection process ensured reliability and consistency, enabling a robust comparison between real-life operations and simulated outputs.

The Eco-hauling scenarios were then modelled using AnyLogic software, a powerful tool for simulating complex logistics operations. The modelling process involved creating a sample scenario using the same inputs (Number of dumper trucks, payloads, and average speed) that contractors were required to follow. These inputs were incorporated into the software to validate the accuracy and reliability of the model. This validation step was crucial in ensuring that the simulation accurately reflected the real-world behaviours and challenges encountered on-site.

The results from the modelling process demonstrated a high degree of alignment between the real-life data and the simulation outputs. On average, the model achieved an accuracy of 90%, indicating a strong correlation between observed site behaviours and the predictions made by the simulation. This level of accuracy suggests that the model provides a reliable representation of the operational scenarios, capturing the key dynamics and inefficiencies present in construction logistics. The ability of the simulation model to replicate real-life conditions with such precision underscores its utility as a tool for analysing and optimising construction operations.

The comparative analysis of the baseline and Eco-hauling scenarios revealed several important insights. In both Case Study 1 and Case Study 3, the application of Eco-hauling principles resulted in significant improvements in operational efficiency and environmental performance.

1. *Reduction in Total Operation Time:* In both case studies, the introduction of checkpoints reduced total operation time. Trucks spent less time idling at bottlenecks, and their movements were more streamlined, enabling faster completion of hauling tasks.
2. *Improved Fuel Efficiency:* By optimising truck movements and reducing idle times, the Eco-hauling scenarios demonstrated lower fuel consumption compared to the

baseline operations. This reduction in fuel usage not only lowered operational costs but also contributed to a decrease in greenhouse gas emissions.

3. *Minimisation of Bottlenecks:* The strategic placement of checkpoints ahead of critical locations helped to mitigate the impact of bottlenecks. Drivers were able to adjust their speed and prepare for delays in advance, leading to smoother traffic flow and reduced congestion.
4. *Consistency in Performance:* The implementation of Eco-hauling principles introduced a level of predictability and consistency in the operations. Unlike the baseline scenarios, which were characterised by variability and inefficiencies, the Eco-hauling scenarios exhibited more stable and reliable performance metrics.

The findings from Case Study 1 and Case Study 3 highlight the transformative potential of Eco-hauling principles in construction logistics. By addressing key inefficiencies and optimising resource use, this approach offers a practical pathway to achieving more sustainable and cost-effective operations. The high degree of alignment between real-life data and the simulation model further validates the applicability of this methodology to diverse construction scenarios.

Moreover, the use of AnyLogic software proved to be invaluable in analysing and improving construction logistics. The ability to simulate complex operations and test different strategies in a virtual environment provides stakeholders with a powerful decision-making tool. By leveraging simulation and modelling, contractors can identify and implement targeted improvements that enhance both operational efficiency and environmental performance.

3-14 BASE Model Validation

Validation of the BASE simulation model was carried out to ensure its accuracy, credibility, and applicability to real-world construction logistics scenarios. The validation process followed a combination of conceptual, operational, and stakeholder-based techniques, each detailed below.

1- Conceptual Validation

The simulation logic, parameters, and process flows were aligned with actual logistics workflows observed in the case studies. Activities such as truck arrival, queuing, loading/unloading, and site movement were mapped closely to real-world operations. This conceptual grounding ensured that the BASE model accurately reflected the logistics systems it aimed to improve.

2- Operational Validation

Operational validation was conducted by comparing simulation results with empirical data collected from project documentation, including delivery records, fuel consumption logs, and observed time-motion studies. Key outputs such as trip frequency, queue length, delivery time, and fuel usage were cross-referenced. Iterative adjustments were made to improve the consistency between simulated and actual data.

3- Expert Validation

Stakeholder involvement was central to validating the model. Project managers, site engineers, and logistics coordinators participated in structured review sessions where simulation results were presented. Their insights confirmed whether the model accurately represented logistical constraints, workflows, and bottlenecks. Feedback from these sessions informed refinements in model logic and assumptions.

4- Scenario-Based Testing

The BASE model was further validated through scenario testing, comparing baseline (current practice) and intervention (BASE-enhanced) simulations. Performance indicators such as carbon emissions, wait times, and logistics efficiency showed improvements aligned with expected outcomes. These results confirmed the model's responsiveness to change and its practical relevance for decision-making in construction logistics.

This four-pronged validation approach confirmed that the BASE model was both accurate in its representation and effective in simulating the impact of sustainable logistics interventions.

Chapter 4:

Results Analysis

4-1 Introduction

This chapter focuses on analysing the results obtained from the application of the BASE model across three case studies. The primary objective is to evaluate the model's effectiveness in addressing operational inefficiencies, reducing carbon emissions, and improving the overall sustainability of construction logistics. Through a systematic comparison of real-world data and simulation outcomes, this chapter aims to provide a robust validation of the Eco-hauling and Big Room principles.

The results are structured to highlight key performance metrics, including total operation time, fuel consumption, and CO_2 emissions. Each case study serves as a practical example, demonstrating how the BASE model’s integration of Eco-hauling strategies and collaborative approaches can optimise logistics operations under varying conditions. Additionally, the model’s scalability and adaptability are tested across diverse scenarios, reinforcing its potential for broader application in the construction industry.

Each case study highlights unique logistical challenges and operational inefficiencies, providing a rich context for evaluating the BASE model’s performance. Case Study 1 focuses on soil hauling with concurrent operations and tests the impact of checkpoints and collaborative scheduling. Case Study 2 examines the complexities of asphalt hauling, where synchronisation between hauling trucks and paver operations creates significant challenges. Case Study 3 evaluates a large-scale road project with concurrent operations in a downtown area, introducing additional constraints such as bottlenecks, restricted time windows, and shared operational sites. These diverse scenarios provide a comprehensive basis for validating the model across different contexts.

The validation process includes detailed simulations using AnyLogic software, which model the complexities of construction logistics and calculate key performance metrics. The simulation outcomes are then compared with real-world observations to assess the accuracy and reliability of the BASE model. Additionally, practitioner feedback is incorporated as a final step in the validation process, ensuring that the model’s practical applicability aligns with industry needs and expectations. This feedback provides critical insights into the model’s strengths, potential limitations, and opportunities for further refinement.

The chapter concludes with a discussion of the findings and their implications for sustainable construction logistics. These insights aim to contribute to advancing sustainable practices in the construction industry and encourage further adoption of data-driven, collaborative approaches.

4-2 Analysis of Case Study 1

4-2-1 Existing Scenario

This section details the analysis of the current, or "existing," hauling practices observed for Case Study 1. This process involves the transportation of 900 tonnes of soil, relying on conventional hauling methods employed by the contractor. The data was gathered through structured observation, focusing on diesel consumption, CO_2 emissions, idle times, and financial costs (Table 4.1).

Table 4.1: Existing Scenario – Case Study 1

Strategies	Inputs				Outputs					
	No of Deliveries	Speed KM/h	Payload Tonnes	No of Trucks	Total Time Mins	Idle Time Mins	No of Brakes	Diesel Litres	CO2 Kg CO2	Cost Tomans
Existing	90	20	10	5	635	708	649	1345.6	3525.5	47,625,000

The existing scenario provides insight into how material hauling is conducted without strategic interventions, serving as a baseline for assessing the effectiveness of alternative approaches such as Eco-Hauling and the integrated Eco-Hauling and Big Room strategy. By thoroughly understanding this scenario, we can identify inefficiencies, bottlenecks, and opportunities for improvement.

1. Operational Inputs and Characteristics

The existing process involved the following key inputs:

1. *Material Hauled:* A total of 900 tonnes of soil.
2. *Number of Deliveries:* A total of 90 trips were required to transport the 900 tonnes of soil. Each truck carried a payload of 10 tonnes per trip.
3. *Fleet Size:* The contractor used five dumper trucks to complete the operation.
4. *Speed:* Trucks operated at an average speed of 20 km/h.
5. Payload: Each truck carried the standard payload of 10 tonnes per trip.

These inputs are characteristic of traditional hauling operations in construction, where decisions are often based on practical constraints rather than optimised strategies.

2. Operational Outputs and Observed Outcomes

The existing process produced the following results:

1. *Total Operation Time:* The trucks collectively operated for 635 minutes. This includes the time spent driving between the loading and unloading points.
2. *Idle Time:* Trucks were idle for a significant portion of the operation—708 minutes in total. This idle time includes delays at loading/unloading points and waiting in queues.
3. *Number of Brakes Used:* Drivers used the brake pedals 649 times throughout the operation, indicating frequent stop-and-go conditions and inefficient traffic flow.
4. *Diesel Consumption:* A total of 1345.6 litres of diesel was consumed during the operation.
5. *CO_2 Emissions:* Diesel usage resulted in emissions of 3525.5 kilograms of CO_2, contributing significantly to the environmental footprint of the project.
6. *Financial Cost:* The total cost of the operation, driven by rental of dumper trucks, amounted to 47,625,000 Tomans.

3. Detailed Process Description

The hauling process in this scenario followed a straightforward, conventional workflow:

- Soil was excavated and loaded onto dumper trucks at the site.
- Trucks transported the soil to the designated dumping location, operating at an average speed of 20 km/h.
- After unloading, the trucks returned to the loading site to repeat the cycle.

Despite this straightforward workflow, two critical bottlenecks were identified:

Intersections with Other Hauling Routes: Soil and asphalt hauling contractors worked concurrently, with their routes intersecting at two key points (Blockage 1 and Blockage 2). These intersections caused further delays and disrupted the workflow.

These bottlenecks contributed significantly to inefficiencies such as high idle times, frequent braking, and increased diesel consumption.

Also, the following inefficiencies were noted:

1. *Queueing and Bottlenecks:* Trucks were often observed waiting in queues at the loading and unloading points. This waiting time contributed heavily to the total idle time (708 minutes). Inefficient coordination among loading equipment, truck operators, and site managers caused these delays.
2. *Frequent Stop-and-Go Conditions:* The operation was characterized by frequent braking, with drivers using the brakes 649 times during the operation. This is a strong indicator of stop-and-go traffic conditions, likely caused by overlapping tasks, poor scheduling, and uncoordinated site operations.
3. *Unoptimised Payloads and Vehicle Utilisation:* Each truck carried a payload of 10 tonnes, which aligns with its maximum capacity, but there was no evidence of efforts to reduce the number of trips required or optimise the vehicle allocation.
4. *High Diesel Consumption:* The combined effects of prolonged idle time, frequent braking, and inefficient traffic flow led to high diesel usage. The operation consumed 1345.6 litres of diesel, which is both a financial and environmental burden.
5. *Environmental Impact:* CO_2 emissions from this operation totalled 3525.5 kilograms. This represents a significant contribution to the project's overall carbon footprint, highlighting the environmental costs of unoptimised hauling operations.

4. Environmental and Financial Impacts

The inefficiencies in the existing process directly influenced both environmental and financial outcomes:

1. *Environmental Costs:*
   - Carbon Emissions: The 3525.5 kg of CO_2 emitted during the operation underscores the heavy environmental toll of conventional hauling practices. Prolonged idle times and frequent stops were key contributors to this outcome.

- Diesel Dependency: Diesel combustion not only increases CO_2 emissions but also releases other pollutants such as nitrogen oxides (NOx) and particulate matter, which harm air quality.

2. *Financial Costs*:
   - The high diesel consumption (1345.6 litres) translated to elevated operational costs, given the price of fuel.
   - The cost of renting and operating the fleet of five dumper trucks further inflated expenses, resulting in a total cost of 47,625,000 Tomans.

5. Challenges in the Existing Scenario

The challenges observed in the existing scenario highlight systemic inefficiencies that hinder sustainability and cost-effectiveness:

1. *Inefficient Coordination:* The lack of coordination between stakeholders—drivers, site managers, and equipment operators—led to significant idle time and operational delays.
2. *Resource Waste:* Prolonged idle time and frequent braking not only wasted fuel but also accelerated wear and tear on the trucks, potentially increasing maintenance costs.
3. *Lack of Strategic Planning:* The absence of strategic interventions, such as route optimisation, collaborative planning, or dynamic scheduling, limited the potential for improving operational efficiency.
4. *Environmental Neglect:* The operation's high carbon footprint reflects a failure to prioritize sustainability. This is particularly concerning in the context of global efforts to reduce greenhouse gas emissions.

The existing scenario provides a clear picture of the challenges associated with conventional hauling practices. Key inefficiencies—such as high idle times, frequent braking, and uncoordinated operations—resulted in excessive fuel consumption, elevated costs, and significant environmental impacts.

These findings underscore the urgent need for strategic interventions to optimise the hauling process. By addressing these inefficiencies through innovative approaches like Eco-Hauling and collaborative strategies, there is substantial potential to reduce both costs and carbon emissions while improving overall project efficiency.

4-2-2 Comparison Existing Scenario vs. Eco-Hauling vs. Integrated Eco-Hauling and Big Room Strategy

In Case Study 1, the hauling operation for transporting 900 tonnes of soil is evaluated across three distinct strategies: the contractor's existing plan, Eco-Hauling, and the integrated Eco-Hauling and Big Room approach. This section provides a detailed comparative analysis of these strategies, highlighting their impact on key operational metrics such as diesel consumption, CO_2 emissions, idle time, and cost. By maintaining the same inputs across all scenarios, the analysis focuses on how each strategy optimises the outputs and addresses inefficiencies in the baseline process (Table 4.2).

Table 4.2: Comparison of Strategies – Case Study 1

Strategies	Inputs				Outputs					
	No of Deliveries	Speed KM/h	Payload Tonnes	No of Trucks	Total Time Mins	Idle Time Mins	No of Brakes	Diesel Litres	CO2 Kg CO2	Cost Tomans
Existing	90	20	10	5	635	708	649	1345.6	3525.5	47,625,000
Eco-Hauling	90	20	10	5	624	679	594	1320.8	3460.5	46,800,000
Eco-Hauling & Big Room	90	20	10	5	572	408	351	1179.0	3089.0	42,900,000

1. **Baseline (Existing Scenario): Summary of Findings**

As previously discussed, the existing scenario reflects the contractor's conventional plan, which resulted in significant inefficiencies:

- Diesel Consumption: 1,345.6 litres
- CO_2 Emissions: 3,525.5 kilograms
- Idle Time: 708 minutes
- Cost: 47,625,000 Tomans

The high idle times and frequent braking events (649 occurrences) illustrate poor coordination, traffic flow issues, and the absence of strategic planning. These inefficiencies contributed directly to elevated costs and environmental impacts. This scenario serves as the baseline for comparing the alternative strategies.

2. Eco-Hauling Strategy

Eco-Hauling focuses on optimising the transportation process through improved planning and operational efficiency. This strategy leverages techniques such as route optimisation, reduced braking, and minimised idle time to improve fuel efficiency and lower emissions. However, it does not incorporate collaborative stakeholder engagement as seen in the integrated approach.

Key Outputs and Reductions

- Diesel Consumption: 1,320.8 litres (a reduction of 1.85% compared to the baseline)
- CO_2 Emissions: 3,460.5 kilograms (a reduction of 1.84% compared to the baseline)
- Idle Time: 679 minutes (a reduction of 4.1% compared to the baseline)
- Number of Braking Events: 594 (a reduction of 8.5% compared to the baseline)
- Cost: 46,800,000 Tomans (a reduction of 1.73% compared to the baseline)

- **Analysis:**
  1. *Reduction in Diesel Consumption and CO_2 Emissions:* The Eco-Hauling strategy achieved a modest reduction in diesel consumption, down by 24.8 litres (1.85%). This decrease can be attributed to more efficient driving practices, which reduced unnecessary braking and idling. Consequently, CO_2 emissions also saw a proportional reduction of 65 kilograms (1.84%).
  2. *Impact on Idle Time:* Idle time decreased from 708 minutes to 679 minutes (4.1%), indicating a slight improvement in traffic flow and operational efficiency. However, the lack of significant changes suggests that without collaborative planning, major bottlenecks could not be addressed.
  3. *Optimisation of Braking Events:* The number of braking events was reduced by 55 events (8.5%), reflecting smoother traffic flow and more efficient driving practices. This also contributed to reduced fuel consumption and lower wear and tear on the vehicles.
  4. *Cost Implications:* The reduction in diesel consumption resulted in a minor cost saving of 825,000 Tomans (1.73%). The limited impact on cost reflects the strategy's inability to fully address systemic inefficiencies.

- **Limitations:** While Eco-Hauling demonstrates potential for reducing fuel usage and emissions, its impact is constrained by the absence of broader collaborative mechanisms. Issues such as site congestion and task overlap, which require stakeholder input and coordination, remain unresolved.

3. Integrated Eco-Hauling and Big Room Strategy

The integrated approach combines the principles of Eco-Hauling with the Big Room strategy, fostering collaboration among stakeholders to streamline operations. This strategy not only optimises fuel efficiency but also addresses systemic inefficiencies through shared decision-making and better communication.

Key Outputs and Reductions

- Diesel Consumption: 1,179.0 litres (a reduction of 12.4% compared to the baseline).
- CO_2 Emissions: 3,089.0 kilograms (a reduction of 12.4% compared to the baseline).
- Idle Time: 408 minutes (a reduction of 42.4% compared to the baseline).
- Number of Braking Events: 351 (a reduction of 45.9% compared to the baseline).
- Cost: 42,900,000 Tomans (a reduction of 9.9% compared to the baseline).

- **Analysis:**

1. *Significant Reduction in Diesel Consumption and CO_2 Emissions:* The integrated strategy achieved a substantial reduction in diesel consumption, down by 166.6 litres (12.4%). This improvement reflects a combination of fuel-efficient driving practices and reduced idle times, achieved through enhanced planning and coordination. CO_2 emissions decreased by 436.5 kilograms (12.4%), demonstrating the environmental benefits of this approach.
2. *Substantial Decrease in Idle Time:* Idle time was reduced to 408 minutes, a significant improvement of 42.4% compared to the baseline. This reduction highlights the role of collaborative planning in eliminating bottlenecks and improving traffic flow at the loading and unloading sites. By involving all stakeholders in the decision-making process, the integrated approach ensured smoother operations.

3. *Optimisation of Braking Events:* The number of braking events decreased significantly from 649 to 351, a reduction of 45.9%. This reflects smoother traffic flow, better route planning, and enhanced driver practices. The fewer braking events not only reduced fuel consumption but also minimised vehicle wear and tear, contributing to long-term cost savings.
4. *Cost Savings:* The total cost dropped to 42,900,000 Tomans, a significant saving of 4,725,000 Tomans (9.9%) compared to the baseline. The cost reduction was driven by decreased diesel consumption and shorter operational time.

Key Benefits of Collaboration (Big Room Approach):

- Improved Coordination: The Big Room facilitated open communication among drivers, site managers, and equipment operators, enabling them to synchronise tasks and reduce overlaps. This coordination was instrumental in eliminating bottlenecks.
- Shared Problem-Solving: Stakeholders collaborated to identify and resolve operational challenges, such as queueing at loading points and inefficient task scheduling. This proactive approach minimised delays and improved efficiency.
- Enhanced Decision-Making: Stakeholders in the Big Room share their points of view and, through collaborative discussions, work together to identify potential bottlenecks. By pooling their expertise, they collaboratively anticipate operational challenges and design effective strategies to eliminate these issues before the hauling operation begins. This forward-thinking approach minimises delays and ensures that all stakeholders are aligned in their objectives, creating a seamless and efficient hauling process.

4. Comparative Analysis

- *Diesel Consumption and CO_2 Emissions:* The integrated approach delivered the most significant reductions in diesel consumption (12.4%) and CO_2 emissions (12.4%), far outperforming the modest improvements of 1.85% and 1.84%, respectively, achieved by Eco-Hauling. This demonstrates the critical role of collaborative planning in addressing systemic inefficiencies that impact fuel usage.
- *Idle Time:* Idle time was reduced by 42.4% under the integrated strategy, compared to just 4.1% in the Eco-Hauling scenario. The dramatic improvement in idle time

under the integrated approach underscores the importance of stakeholder collaboration in eliminating bottlenecks and ensuring smooth operations.

- *Cost Savings:* The integrated strategy achieved a cost reduction of 9.9%, driven by optimised operations and decreased diesel consumption. In contrast, Eco-Hauling achieved a modest cost reduction of 1.73%, highlighting its limited ability to address root inefficiencies.
- *Overall Efficiency:* The integrated strategy's ability to reduce braking events by 45.9% compared to the baseline further demonstrates its effectiveness in streamlining traffic flow and improving operational efficiency.

The analysis of strategies in Case Study 1 reveals that while Eco-Hauling offers modest improvements over the baseline, its impact is limited by the absence of stakeholder collaboration. In contrast, the integrated Eco-Hauling and Big Room strategy delivers substantial benefits across all metrics, including diesel consumption, CO_2 emissions, idle time, braking events, and cost.

By fostering collaboration and aligning stakeholder efforts, the integrated approach addresses systemic inefficiencies that neither the baseline nor Eco-Hauling could resolve. These findings underscore the importance of integrating collaborative frameworks into construction logistics to achieve both environmental and financial sustainability.

In summary, the integrated Eco-Hauling and Big Room strategy represents the most effective solution for optimising hauling operations, reducing emissions, and cutting costs. This strategy provides a blueprint for sustainable construction practices, demonstrating the value of combining operational efficiency with collaborative decision-making.

4-2-3 Analysis of Initial Scenarios Modelled in AnyLogic - Case Study 1

The subsequent stage of analysis in Case Study 1 involved a structured exploration of 15 scenarios designed using empirical data and generated via Stat-Ease software. The scenarios systematically combined key input parameters, including fleet size (number of trucks), number of deliveries, truck speed, and payload capacity (Table 4.3). This approach enabled a comprehensive evaluation of how variations in these parameters influenced key performance metrics such as total operational time, idle time, diesel consumption, CO_2 emissions, and overall cost.

By examining the interrelationships between these variables, this structured framework provided insight into the patterns, trade-offs, and opportunities for optimisation. The findings from this stage are pivotal in identifying configurations that enhance operational efficiency while advancing sustainability objectives.

Table 4.3: Initial Scenarios Modelled in AnyLogic – Case Study 1

Scenario	No of Deliveries	Speed Km/h	Payloads Tonnes	No of Trucks	Eco-hauling						Eco-hauling and Big Room					
					Total Time mins	Idle Time mins	No of Brakes	Diesel Litres	CO2 Kg CO2	Cost Tomans	Total Time mins	Idle Time mins	No of Brakes	Diesel Litres	CO2 Kg CO2	Cost Tomans
1	100	23	9	4	779	557	623	1289.0	3377.1	T 46,740,000	667	104	314	1076.6	2820.7	T 40,020,000
2	90	26	10	3	896	481	556	1139.5	2985.5	T 40,320,000	749	46	279	938.5	2458.9	T 33,705,000
3	82	23	11	4	652	486	518	1130.3	2961.4	T 39,120,000	552	99	260	939.6	2461.8	T 33,120,000
4	82	23	11	2	1228	376	415	1063.4	2786.1	T 36,840,000	1048	16	169	902.2	2363.8	T 31,440,000
5	113	20	8	3	1193	563	581	1441.3	3776.2	T 53,685,000	1020	33	347	1209.3	3168.3	T 45,900,000
6	82	17	11	2	1359	390	343	1170.0	3065.4	T 40,770,000	1166	5	169	1000.6	2621.6	T 34,980,000
7	90	20	10	3	957	472	469	1212.7	3177.3	T 43,065,000	815	33	274	1020.8	2674.5	T 36,675,000
8	90	20	10	1	2778	400	359	1170.1	3065.7	T 41,670,000	2401	11	180	1006.7	2637.6	T 36,015,000
9	100	17	9	2	1667	488	516	1376.1	3605.3	T 50,010,000	1421	4	205	1157.7	3033.1	T 42,630,000
10	90	14	10	3	1101	498	561	1395.9	3657.3	T 49,545,000	946	40	276	1184.7	3103.9	T 42,570,000
11	90	20	10	5	624	679	594	1320.8	3460.5	T 46,800,000	572	408	351	1179.0	3089.0	T 42,900,000
12	100	23	9	2	1507	472	509	1242.5	3255.3	T 45,210,000	1275	13	205	1036.1	2714.5	T 38,250,000
13	82	17	11	4	704	440	431	1213.9	3180.5	T 42,240,000	614	84	259	1042.9	2732.4	T 36,840,000
14	75	20	12	3	808	404	395	1070.5	2804.6	T 36,360,000	683	28	232	901.1	2360.8	T 30,735,000
15	100	17	9	4	851	533	526	1405.6	3682.6	T 51,060,000	739	86	313	1196.5	3134.8	T 44,340,000

Note: Total time should be multiplied by the number of dumper trucks, but idle time is cumulative.

1. Scenario Design

The scenarios were constructed by systematically altering four primary input factors:

- *Fleet Size (Number of Trucks):* Ranged between 1 to 5 trucks, allowing analysis of fleet efficiency under different configurations.
- *Number of Deliveries:* Spanned between 75 and 113 trips, representing different configurations to analyse and compare performance.
- *Dumper Truck Speed:* Varied between 14 km/h and 26 km/h, representing diverse operational conditions.
- *Payload Capacity:* Adjusted from 8 to 12 tonnes, accommodating different load efficiencies.

These combinations created a matrix of 15 unique scenarios for testing, ensuring robust and consistent exploration of operational dynamics.

2. Performance Metrics Across Scenarios

Each scenario's outcomes were measured against key performance indicators, including total time, idle time, number of braking events, diesel consumption, CO_2 emissions, and cost. Below is a detailed analysis of these metrics across the table:

1. Total Operational Time:

Scenarios with larger fleets and higher payload capacities (e.g., Scenarios 1 and 3) achieved shorter total operational times due to increased hauling efficiency. For instance, Scenario 3 reduced total time to 652 minutes, compared to the longer 2,778 minutes observed in Scenario 8 with only one truck.
Conversely, scenarios with fewer trucks (e.g., Scenario 8) showed significantly longer operation times, indicating the importance of fleet size in balancing efficiency and resource allocation.
Scenario 11 provides another compelling example, achieving 624 minutes with a fleet of 5 trucks and an optimised payload of 10 tonnes under the Big Room strategy. This demonstrates how larger fleets, when effectively managed, can further reduce operational times.

2. Idle Time:

Idle time was dramatically reduced in the Eco-Hauling and Big Room strategy. For instance, Scenario 1, which utilised four trucks, reduced idle time to 104 minutes under the Big Room strategy compared to 557 minutes in the Eco-Hauling scenario. Scenario 9 also stands out, achieving an idle time of just 4 minutes under the Big Room strategy compared to 488 minutes in the Eco-Hauling approach. This highlights the impact of reducing bottlenecks and enhancing scheduling efficiency.

3. *Number of Braking Events:*

The number of braking events was notably reduced under the Eco-Hauling and Big Room strategy across all scenarios. For example, Scenario 1 recorded only 314 braking events, compared to 623 in the Eco-Hauling scenario.
Scenario 4 also achieved significant improvement, reducing braking events to 169 under the Big Room strategy compared to 415 in the Eco-Hauling scenario. This highlights the impact of improved coordination and smoother traffic conditions.
This improvement illustrates the effectiveness of smoother traffic conditions and strategic planning in minimising unnecessary stops

4. Diesel Consumption and CO_2 Emissions:

Scenarios with higher payload capacities and optimised fleet sizes demonstrated significant fuel savings. For instance, Scenario 3 reduced diesel consumption to

939.6 litres under the Big Room strategy, compared to 1,130.3 litres in the Eco-Hauling scenario, representing a marked improvement.

Scenario 10 also highlights the effectiveness of this approach, achieving a diesel consumption of 1,184.7 litres under the Big Room strategy compared to 1,395.9 litres in the Eco-Hauling scenario. CO_2 emissions were similarly reduced, with Scenario 10 recording 3,103.9 kilograms under the Big Room strategy compared to 3,657.3 kilograms under the Eco-Hauling approach.

CO_2 emissions followed a similar trend, with the Eco-Hauling and Big Room approach achieving reductions of up to 15.1% compared to the Eco-Hauling approach. For instance, Scenario 10 reduced emissions to 3,103.9 kilograms compared to 3,657.3 kilograms in the Eco-Hauling approach, a reduction of 15.1%.

5. Cost:

The cost metric showed significant improvements when fleet sizes were optimised. For example, Scenario 7, with its efficient setup of 3 trucks and 10 tonnes payload, achieved a cost of 36,675,000 under the Big Room strategy compared to 43,065,000 under Eco-Hauling. Similarly, Scenario 14, which used 3 trucks and a 12-tonne payload, demonstrated one of the lowest recorded costs at T 30,735,000 under the Big Room strategy, compared to 36,360,000 under Eco-Hauling. Scenario 9 also highlighted substantial savings, achieving 42,630,000 under the Big Room strategy compared to 50,010,000 under Eco-Hauling. These examples emphasise how coordinated efforts and carefully selected configurations can significantly lower costs.

Conversely, scenarios with fewer trucks but extended operation times (e.g., Scenario 8) incurred higher costs due to inefficiencies, underlining the importance of balancing fleet size and operational efficiency.

3. Key Insights

Fleet Size and Efficiency:

Larger fleets generally resulted in shorter operation times and reduced diesel consumption, as evidenced by Scenario 3 and 4. However, diminishing returns were observed beyond an optimal fleet size due to increased coordination complexity.

Payload Optimisation:

Scenarios with optimised payloads, such as 10 tonnes in Scenario 7 and 12 tonnes in Scenario 14, demonstrated the best balance between fuel efficiency and operational performance. Scenario 7 achieved a cost of T 36,675,000 under the Big Room strategy, reflecting efficient use of resources. Similarly, Scenario 14 reduced idle time to 28 minutes and achieved one of the lowest costs (T 30,735,000), showing how maximising payloads can reduce inefficiencies while avoiding overloading or underutilising trucks.

Collaborative Decision-Making:

The Eco-Hauling and Big Room strategy delivered the most significant performance improvements. By involving stakeholders in decision-making, the strategy avoided bottlenecks and reduced idle time, braking events, and fuel consumption. For instance, Scenario 9 achieved substantial cost savings of T 42,630,000, a reduction of 14.8% compared to T 50,010,000 under the Eco-Hauling approach. Additionally, idle time was reduced by 99.2% (from 488 minutes to 4 minutes), braking events were reduced by 60.2% (from 516 to 205), and diesel consumption was reduced by 15.8% (from 1,376.1 litres to 1,157.7 litres). These outcomes highlight the value of collaborative planning and proactive resource management in achieving operational efficiency and sustainability.

Trade-Offs Between Time and Cost:

Scenario 14 presents a compelling example of cost efficiency, achieving T 30,735,000 under the Big Room strategy, which is one of the lowest costs recorded. This result highlights how an optimised payload of 12 tonnes combined with a medium-sized fleet (3 trucks) can effectively reduce operational costs.

Conversely, scenarios with fewer trucks, like Scenario 8, reduced costs on truck rentals but required more time to complete operations. This trade-off resulted in higher emissions and fuel consumption, highlighting the need to balance efficiency with cost considerations.

The scenario analysis underscores the importance of systematic exploration and optimisation in hauling operations. By strategically varying input factors such as fleet size, payload, and truck speed, it is possible to identify configurations that deliver significant improvements in efficiency, cost, and sustainability.

The Eco-Hauling and Big Room strategy consistently outperformed the Eco-Hauling-only approach, demonstrating the critical role of collaborative planning in addressing systemic inefficiencies. By reducing idle time, braking events, and emissions, this strategy not only enhances operational performance but also aligns with broader sustainability objectives.

In conclusion, the insights from this analysis provide a robust foundation for refining hauling operations, enabling decision-makers to optimise resources while minimising environmental impact. The comprehensive evaluation of these scenarios highlights the potential for targeted interventions to achieve balanced, efficient, and sustainable outcomes in construction logistics.

4-2-3-1 Analysis of CO_2 Emissions – Case 1

CO_2 emissions were a critical performance indicator, with reductions achieved primarily through the adoption of the Eco-Hauling and Big Room strategy. It is important to note that at this stage, the analysis is based on a limited set of scenarios. Future stages will use tools like Stat-Ease software to expand the number of scenario outcomes, enabling more detailed exploration and refined analysis. Below is a detailed analysis of emissions across scenarios:

1. Scenarios with Higher Emissions

- Scenarios with fewer trucks and lower payload capacities typically recorded higher emissions due to longer operational times and increased inefficiencies. For instance, Scenario 5, which operated with 3 trucks and an 8-tonne payload, emitted 3,776.2 kg of CO_2 under Eco-Hauling and 3,168.3 kg under the Big Room strategy, achieving a reduction of 16.1%.
- Scenario 9, using 2 trucks with a payload of 9 tonnes, emitted 3,605.3 kg under Eco-Hauling and 3,033.1 kg under the Big Room strategy, representing a 16.0% reduction.
- Scenario 15, operating with 4 trucks and a payload of 9 tonnes, recorded emissions of 3,682.6 kg under Eco-Hauling and 3,134.8 kg under the Big Room strategy, achieving a 14.9% reduction.

2. Scenarios with Lower Emissions

- Lower CO_2 emissions were observed in scenarios where key variables were optimised. Scenarios with moderate fleet sizes (2–3 trucks), higher payloads (11–12 tonnes), and higher speeds (20–23 km/h) significantly reduced emissions.

- Scenario 4, with 2 trucks and a payload of 11 tonnes, achieved emissions of 2,786.1 kg under Eco-Hauling, which dropped to 2,363.8 kg under the Big Room strategy, a reduction of 15.1%. This was due to the balance of fleet size and payload, which avoided overloading or underutilisation.
- Scenario 14, using 3 trucks with a payload of 12 tonnes, achieved the lowest emissions levels of 2,360.8 kg under the Big Room strategy, compared to 2,804.6 kg under Eco-Hauling, a reduction of 15.8%. The larger payload reduced the number of trips required.
- Scenario 3, which employed 4 trucks at 23 km/h with a payload of 11 tonnes, recorded emissions of 2,961.4 kg under Eco-Hauling, reduced to 2,461.8 kg under the Big Room strategy, a 16.9% reduction. The moderate speed and optimised payload contributed to this improvement.

3. *Efficiency of the Big Room Strategy:*

- The Big Room strategy proved pivotal in achieving emissions reductions across all scenarios, with improvements ranging from 14.0% (Scenario 15) to 16.9% (Scenario 3). This approach emphasised proactive bottleneck management, optimised resource allocation, and stakeholder collaboration.
- Scenarios such as Scenario 3, with 4 trucks operating at 23 km/h and a payload of 11 tonnes, achieved the highest emissions reduction of 16.9%, from 2,961.4 kg under Eco-Hauling to 2,461.8 kg under the Big Room strategy.
- Similarly, Scenario 15, operating with 4 trucks and a payload of 9 tonnes, demonstrated a 14.0% reduction, highlighting the impact of collaborative planning in minimising inefficiencies.
- The strategy also ensured smoother traffic flow, reduced idle times, and fewer braking events, which collectively contributed to substantial environmental benefits.

The analysis of CO_2 emissions across scenarios highlights the importance of optimised fleet sizes, payload capacities, and operational speeds in achieving significant emissions reductions. The Eco-Hauling and Big Room strategy proved effective, consistently reducing emissions by approximately 15% across all scenarios.

Future analyses will use tools like Stat-Ease software to expand the range of scenario outcomes, enabling deeper exploration of variables and further refinement of strategies. These findings lay a solid foundation for integrating sustainability into construction logistics while balancing economic and environmental performance.

4-2-4 Optimisation with Response Surface Methodology for Case Study 1

The optimisation stage for Case Study 1 marks a critical phase in translating simulation results into actionable insights. By employing advanced statistical tools such as Response Surface Methodology (RSM) within Stat-Ease software, this stage explores the intricate relationships between input variables—such as truck fleet size, payload capacity, and speed—and output performance metrics, including total time, idle time, cost, braking events, CO_2 emissions, and diesel consumption.

As the scenarios integrating Eco-Hauling and Big Room demonstrated superior performance across all aspects, only these types of scenarios were selected for optimisation and comparison. This focused approach ensures that the analysis targets the configurations with the highest potential for enhancing sustainability and operational efficiency.

This methodology leverages the expanded set of scenarios generated during the simulation stage, enabling a comprehensive evaluation of the effects and interactions of key variables. Surface graphs and 3D plots provide a clear visualisation of these interactions, highlighting the configurations that deliver optimal results. For instance, the influence of payload size and vehicle speed on fuel efficiency and emissions can be systematically assessed, identifying combinations that minimise environmental impact without compromising performance.

The primary objectives of this section are to:

1. Analyse each output metric (total time, idle time, cost, braking events, CO_2 emissions, and diesel consumption) in detail using RSM visualisations.
2. Identify trends, trade-offs, and interactions that impact performance.
3. Provide a foundation for comparing these results with the optimised scenarios identified in subsequent stages.

By focusing on the six key performance indicators and leveraging the synergies of integrated scenarios, this analysis bridges the gap between raw simulation data and practical, optimised solutions. The insights gained from this process will inform configurations that balance sustainability, cost, and operational efficiency, ensuring they are ready for real-world implementation.

4-2-4-1 Analysis of Total Time Surface Graph for Integration of Eco-Hauling and Big Room Approach

This surface graph illustrates the relationship between payload (tonnes), number of trucks, and total operational time (minutes) in the integration of Eco-Hauling and the Big Room approach. By examining the interactions among these variables, we can identify key configurations that optimise total time, improve operational efficiency and CO_2 emissions (Figure 4.1).

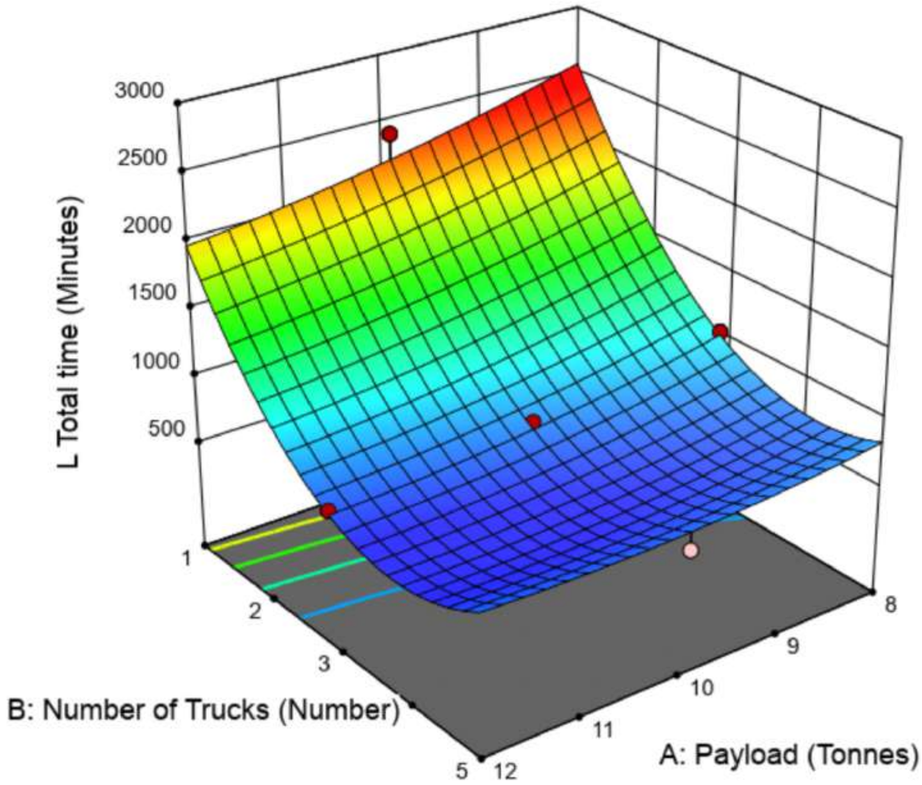


Fig. 4.1: Surface Graph of Total Time for the Integration of Eco-Hauling and Big Room – Case 1

When the payload size increases from approximately 8 tonnes to 12 tonnes, the total operational time drops significantly. This is because fewer trips are needed to transport the same volume of material, leading to improved efficiency. For example, payloads closer to 12 tonnes consistently result in total times below 1,000 minutes, whereas payloads of 8 tonnes often exceed 2,500 minutes. The increase in payload capacity demonstrates its strong influence on reducing overall time and the associated CO_2 emissions, as fewer trips mean reduced fuel consumption and environmental impact.

Adding more trucks also plays a crucial role in lowering total operational time. Increasing the fleet size from 1 to 5 trucks sharply reduces the total time required. However, the benefits diminish beyond 4–5 trucks, as further increases in fleet size do not yield proportional improvements. For smaller payloads, like 8–9 tonnes, adding more trucks becomes essential to compensate for the additional trips required. For instance, moving from 1 to 4 trucks can cut operational time significantly, but increasing to 5 trucks provides minimal additional benefit. Moreover, optimised fleet sizes not only enhance time efficiency but also lower CO_2 emissions by preventing inefficiencies associated with underutilised trucks.

The most efficient configurations for reducing total operational time involve payloads between 10–12 tonnes and 3–5 trucks. These combinations strike the ideal balance between workload distribution and operational efficiency, ensuring minimal total time without overburdening resources. Larger payloads have a stronger impact on reducing total time compared to simply adding more trucks, highlighting the importance of payload optimisation. These configurations also result in reduced CO_2 emissions, as they minimise fuel consumption and the total number of trips required.

Although speed is not explicitly shown in this graph, it plays a crucial role in determining total operational time. Higher speeds directly reduce travel duration, leading to faster operations. However, in scenarios with higher numbers of trucks, increased speed can cause bottlenecks as multiple trucks arrive simultaneously at loading or dumping points, disrupting the flow and creating congestion. This effect has been considered in the optimisation process to balance speed with operational harmony, ensuring that faster speeds do not compromise efficiency or lead to unintended increases in CO_2 emissions due to idling.

- **Practical Implications:**

  1. *Configuration Recommendations:*

     Payloads of 10–12 tonnes and 3–5 trucks are ideal for achieving time efficiency and reducing environmental impact. These configurations reduce total operational time and contribute to significant CO_2 emissions reductions by lowering the number of trips required.

  2. *Operational Efficiency:*

     Minimising total time enhances overall efficiency, enabling faster project completion and reducing fuel consumption. These improvements directly align with sustainability goals by reducing emissions and energy use.

  3. *Trade-Offs:*

     While increasing payload and fleet size improves performance, excessive fleet sizes (beyond 5 trucks) offer diminishing returns and may introduce new inefficiencies, such as congestion at loading and dumping points, potentially leading to higher CO_2 emissions.

4. *Alignment with Sustainability Goals:*

   Efficient configurations not only optimise time but also support decarbonisation efforts in the construction industry. The Eco-Hauling and Big Room approach demonstrates its effectiveness in lowering emissions and improving environmental performance.

In summary, this analysis underscores the importance of balancing payload size, fleet size, and speed to optimise total operational time and reduce CO_2 emissions. By adopting the Eco-Hauling and Big Room approach, stakeholders can achieve operational efficiency while contributing to sustainability objectives and cost savings.

4-2-4-2 Analysis of Idle Time Surface Graph for Integration of Eco-Hauling and Big Room Approach

This surface graph illustrates the relationship between payload (tonnes), number of trucks, and idle time (minutes) in the integration of Eco-Hauling and the Big Room approach. Idle time significantly affects operational efficiency, fuel consumption, and CO_2 emissions, making its optimisation crucial for sustainable construction logistics (Figure 4.2).

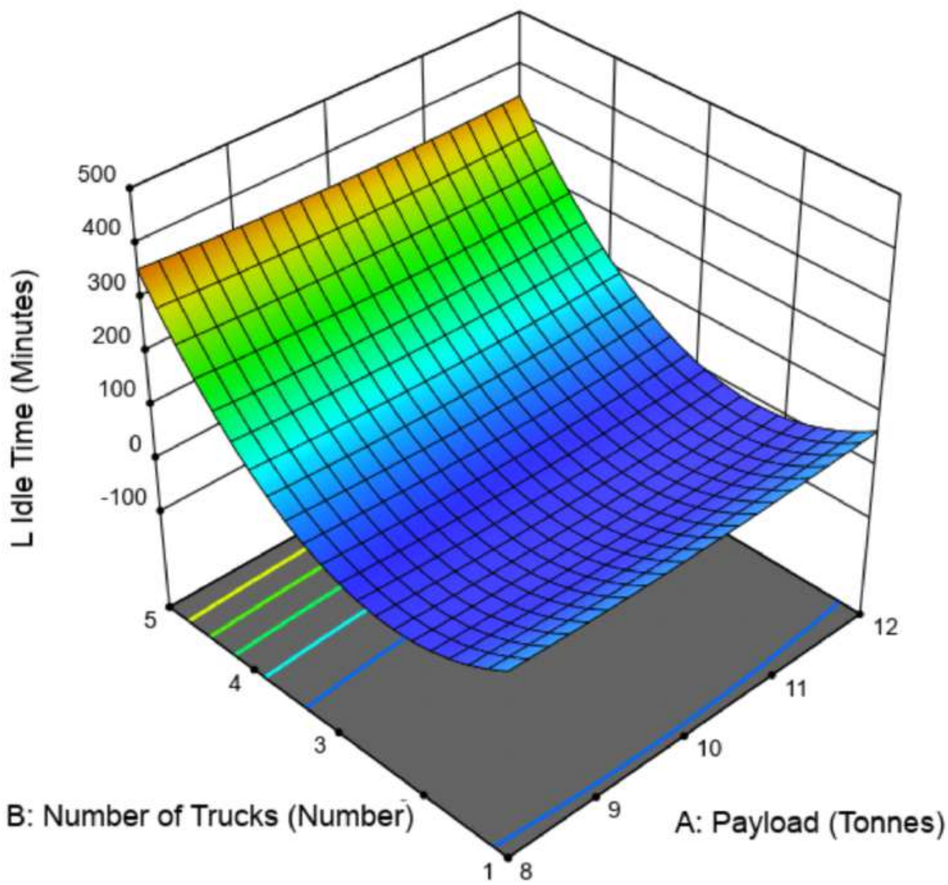


Fig. 4.2: Surface Graph of Idle Time for the Integration of Eco-Hauling and Big Room – Case 1

As payload size increases from 8 tonnes to 12 tonnes, idle time decreases significantly. Larger payloads reduce the number of trips required to transport the same volume of material, thereby minimising waiting periods at loading and dumping points. For instance, payloads near 12 tonnes consistently show idle times dropping below 50 minutes, while smaller payloads around 8 tonnes result in idle times exceeding 300 minutes. This reduction in idle time directly contributes to lower CO_2 emissions, as vehicles spend less time idling and consuming fuel inefficiently.

The number of trucks plays a critical role in influencing idle time. Fleets with fewer trucks (1–3) experience significantly higher idle times due to longer waiting periods at loading and dumping points. Conversely, increasing the fleet size to 4–5 trucks reduces idle time considerably. However, beyond 5 trucks, the reduction in idle time plateaus, indicating diminishing returns. Properly optimised fleet sizes not only improve time efficiency but also help reduce CO_2 emissions by avoiding unnecessary idling caused by overloading logistical infrastructure.

Although speed is not explicitly represented in this graph, it indirectly influences idle time. Higher speeds can reduce travel durations, potentially decreasing idle periods. However, in scenarios with larger fleets, increased speed may lead to congestion as multiple trucks arrive simultaneously at loading or dumping points. This highlights the importance of harmonising speed with fleet size and payload to minimise both idle time and CO_2 emissions. The optimisation process considers these dynamics to ensure balanced and efficient operations.

The most effective configurations for minimising idle time involve payloads between 10–12 tonnes and 3–5 trucks. These setups strike a balance between reducing the number of trips and avoiding congestion, leading to smoother operations and lower emissions. Configurations with smaller payloads or fewer trucks tend to experience higher idle times due to inefficient distribution of workload and longer operational durations.

- **Practical Implications**

1. *Configuration Recommendations:*

   Payloads of 10–12 tonnes and 3–5 trucks are optimal for reducing idle time and emissions. These setups ensure efficient operations and minimise fuel wastage.

2. *Environmental Benefits:*

   Reducing idle time directly lowers CO_2 emissions, aligning with sustainability objectives by decreasing fuel consumption and environmental impact.

3. *Operational Flow Improvements:*

   Minimised idle times enhance logistical flow, reducing bottlenecks and enabling faster project completion. This also results in financial savings through reduced fuel usage.

4. *Trade-Offs:*

   While increasing fleet size reduces idle time, excessive fleet sizes (beyond 5 trucks) may lead to diminishing returns and congestion, negating the benefits of reduced idle time and potentially increasing emissions.

The analysis underscores the importance of optimising payload size, fleet size, and speed to minimise idle time and associated CO_2 emissions. By leveraging the Eco-Hauling and Big Room approach, stakeholders can achieve operational efficiency while advancing sustainability goals. These insights offer actionable recommendations for reducing environmental impact and improving resource allocation in construction logistics.

4-2-4-3 Analysis of Brakes Events Surface Graph for Integration of Eco-Hauling and Big Room Approach

This surface graph highlights the relationship between payload (tonnes)**,** number of trucks, and the number of braking events in the integration of Eco-Hauling and the Big Room approach. Reducing braking events is crucial for improving fuel efficiency, minimising wear and tear on vehicles, and enhancing overall operational flow. Moreover, braking events directly impact fuel consumption and CO_2 emissions, making them a key parameter in sustainable construction logistics (Figure 4.3).

When the payload size increases from 8 tonnes to 12 tonnes, the number of braking events decreases consistently. Larger payloads reduce the frequency of trips, leading to fewer interactions with traffic and logistics bottlenecks that typically cause braking events. For example, payloads closer to 12 tonnes show braking events dropping below 100, while smaller payloads around 8 tonnes result in braking events exceeding 400. This reduction also lowers CO_2 emissions, as smoother operations with fewer braking events minimise fuel wastage caused by frequent acceleration and deceleration.

The number of trucks significantly influences the frequency of braking events. Fleets with fewer trucks (1–3) experience a higher number of braking events due to longer operational times and increased traffic encounters during each trip. Conversely, as the fleet size increases to 4–5 trucks, braking events are noticeably reduced due to more distributed workloads and improved synchronisation among trucks. This reduction in braking events also contributes to lower CO_2 emissions, as optimised fleet sizes ensure smoother traffic flow and reduced idling periods caused by stop-and-go movements.

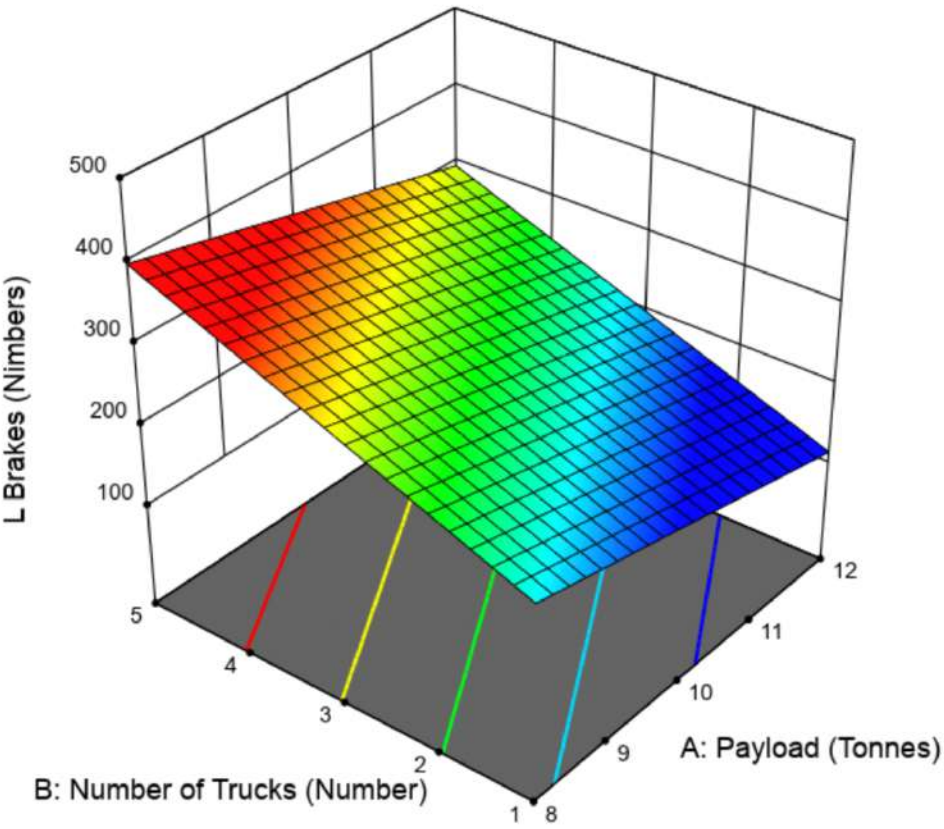


Fig. 4.3: Surface Graph of the Number of Brakes for the Integration of Eco-Hauling and Big Room – Case 1

Although speed is a factor influencing braking events, its impact in this scenario is relatively low. Higher speeds can lead to fewer braking events as trucks maintain a steadier flow, but this effect diminishes when trucks operate in synchronised patterns within optimal payload and fleet configurations. Additionally, increased speed in scenarios with larger fleets may lead to bottlenecks at loading and dumping points, indirectly increasing braking events. This highlights the importance of balancing speed with payload and fleet size to reduce braking events and the associated CO_2 emissions**.**

The optimal configurations for minimising braking events occur with payloads between 10–12 tonnes and 3–5 trucks**.** These setups balance the operational load, reduce the number of trips required, and enhance traffic flow, leading to fewer braking events. On the other hand, configurations with smaller payloads or fewer trucks encounter higher braking frequencies due to increased congestion and inefficiencies in trip distribution. These optimised configurations also align with sustainability goals by significantly reducing CO_2 emissions**.**

- **Practical Implications**

1. *Configuration Recommendations***:**

   Payloads of 10–12 tonnes and 3–5 trucks are optimal for minimising braking events. These settings ensure fewer trips, steady operations, and better coordination, reducing the need for frequent braking and lowering CO_2 emissions**.**

2. *Operational Flow Improvements***:**

   Reducing braking events not only saves fuel but also decreases vehicle wear and tear, lowering maintenance costs. Additionally, smoother operations reduce delays caused by stop-and-go movements, further contributing to reduced emissions.

3. *Trade-Offs***:**

   While increasing payload and fleet size improves braking performance, excessive fleet sizes (beyond 5 trucks) offer diminishing returns and may introduce new inefficiencies, such as congestion at loading and dumping points, which can negatively impact CO_2 emissions.

4. *Alignment with Sustainability Goals*:

   Fewer braking events align with sustainability objectives by reducing fuel consumption, emissions, and the environmental impact of vehicle operations. The integration of Eco-Hauling and the Big Room approach supports these goals by fostering efficient and collaborative operations.

The analysis underscores the importance of balancing payload size, fleet configurations, and speed to minimise braking events and associated CO_2 emissions. By adopting the Eco-Hauling and Big Room approach, stakeholders can enhance operational flow and sustainability while reducing costs and environmental impacts. These insights demonstrate how optimised configurations contribute to both operational efficiency and the decarbonisation of construction logistics.

4-2-4-4 Analysis of Diesel Consumption Surface Graph for Integration of Eco-Hauling and Big Room Approach

This surface graph illustrates the relationship between payload (tonnes), number of trucks, and diesel consumption (litres) in the integration of Eco-Hauling and the Big Room approach. Diesel consumption is a critical metric in sustainable construction logistics, directly influencing operational costs and CO_2 emissions. Understanding its dependency on operational parameters enables stakeholders to design more efficient strategies (Figure 4.4).

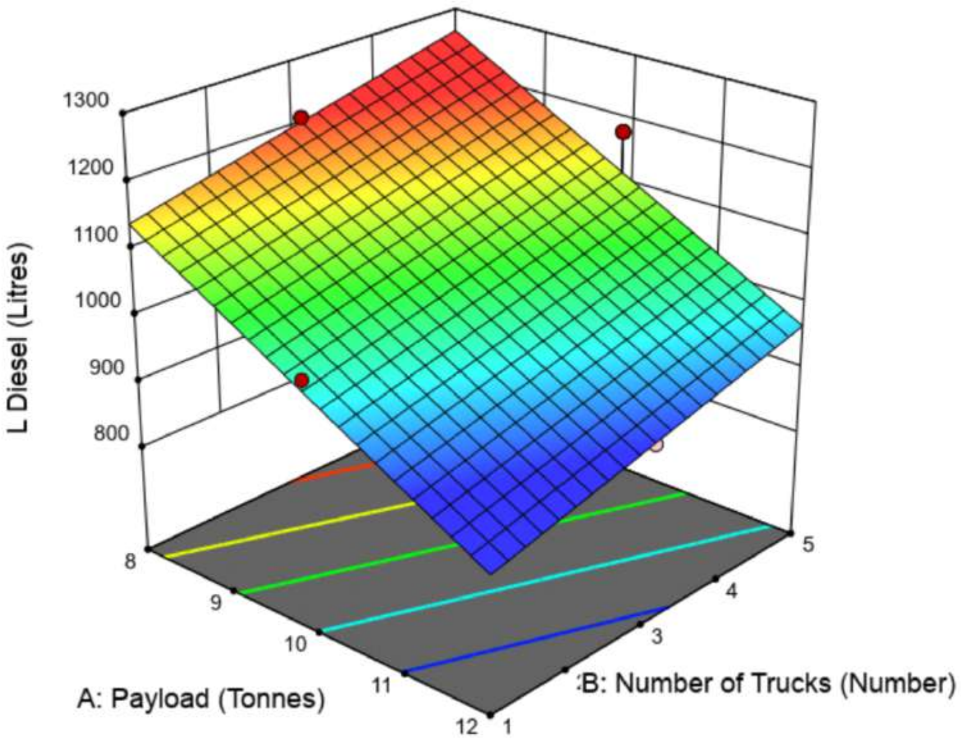


Fig. 4.4: Surface Graph of the Diesel Consumption for the Integration of Eco-Hauling and Big Room – Case 1

As payload size increases from 8 tonnes to 12 tonnes, diesel consumption decreases consistently. Larger payloads reduce the number of trips required to transport the same volume of material, leading to more fuel-efficient operations. For instance, payloads near 12 tonnes show diesel consumption dropping below 900 litres, while smaller payloads of around 8 tonnes result in diesel consumption exceeding 1,300 litres. This efficiency is primarily due to the reduced frequency of trips, which minimises cumulative fuel usage and contributes to lower CO_2 emissions.

The number of trucks also significantly affects diesel consumption. Fleets with fewer trucks (1–3) tend to have higher diesel consumption because each truck must complete more trips, leading to extended operational durations. Conversely, increasing the fleet size to 4–5 trucks reduces diesel consumption by distributing the workload more evenly, thereby enhancing efficiency. However, beyond 5 trucks, the reduction in diesel consumption diminishes, indicating that excessive fleet sizes may not yield proportional benefits. Properly optimised fleet sizes not only lower fuel usage but also align with sustainability goals by reducing CO_2 emissions.

Although speed is not explicitly shown in this graph, it has a significant impact on diesel consumption. Lower speeds tend to increase fuel usage due to extended travel times and inefficient engine performance. For example, scenarios with slower speeds often exhibit higher diesel consumption even with optimal payloads and fleet sizes. Conversely, higher speeds reduce diesel consumption by shortening travel durations and improving engine efficiency. However, excessive speeds may lead to safety concerns and operational disruptions, such as congestion at loading and dumping points. This highlights the need to balance speed with other operational variables to achieve optimal diesel consumption and minimise CO_2 emissions.

The most efficient configurations for minimising diesel consumption involve payloads between 10–12 tonnes and 3–4 trucks. These setups balance the operational load, reduce the number of trips, and optimise fuel efficiency. Smaller payloads or fewer trucks often result in higher diesel consumption due to increased operational demands and longer durations. These optimised configurations also align with sustainability goals by significantly lowering CO_2 emissions and operational costs.

- **Practical Implications**

1. *Configuration Recommendations:*

   Payloads of 10–12 tonnes and 3–4 trucks are ideal for reducing diesel consumption and emissions. These setups minimise fuel usage while maintaining operational efficiency.

2. *Environmental Benefits:*

   Lower diesel consumption directly reduces CO_2 emissions, supporting decarbonisation efforts and aligning with regulatory sustainability targets.

3. *Operational Flow Improvements:*

   Efficient fuel usage enhances logistical flow, reduces delays, and contributes to cost savings through decreased fuel expenditure.

4. *Trade-Offs:*

   While increasing payload and fleet size improves diesel efficiency, excessive fleet sizes (beyond 5 trucks) may lead to diminishing returns and operational inefficiencies, such as congestion.

The analysis underscores the importance of optimising payload size, fleet size, and speed to minimise diesel consumption and associated CO_2 emissions. By adopting the Eco-Hauling and Big Room approach, stakeholders can achieve operational efficiency while advancing sustainability goals. These insights provide actionable recommendations for reducing environmental impact and improving resource allocation in construction logistics.

4-2-4-5 Analysis of CO_2 Emissions Surface Graph for Integration of Eco-Hauling and Big Room Approach

This surface graph illustrates the relationship between payload (tonnes), number of trucks, and CO_2 emissions (kilograms) in the integration of Eco-Hauling and the Big Room approach. CO_2 emissions are a critical metric in sustainable construction logistics, directly linked to operational efficiency and environmental impact. Understanding the factors influencing emissions is essential for designing strategies that align with decarbonisation goals (Figure 4.5).

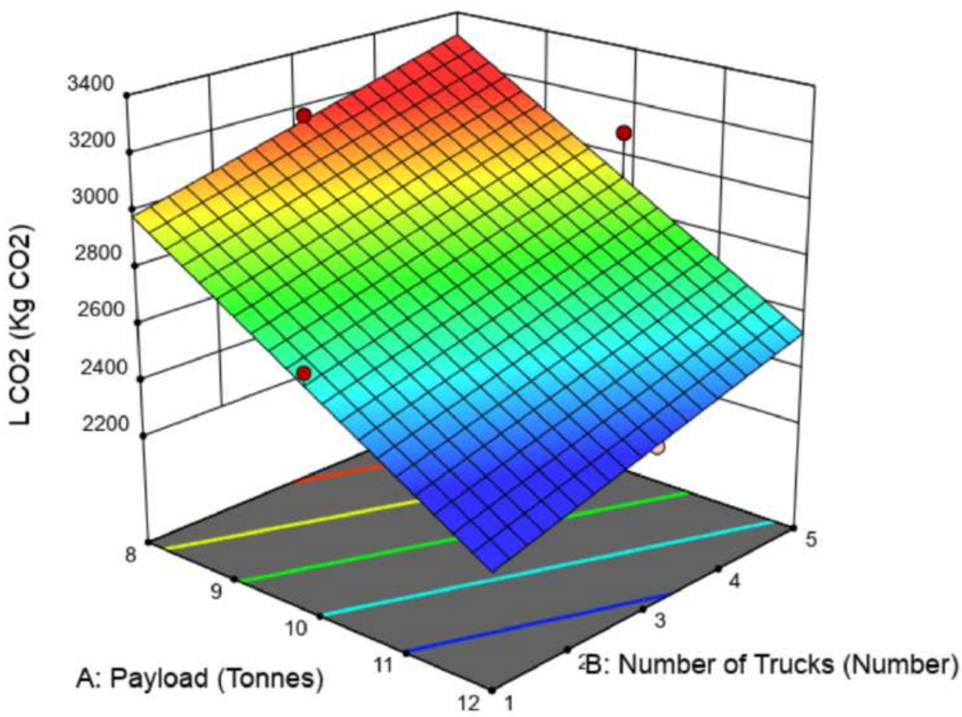


Fig. 4.5: Surface Graph of the CO_2 Emissions for the Integration of Eco-Hauling and Big Room – Case 1

As payload size increases from 8 tonnes to 12 tonnes, CO_2 emissions decrease significantly. Larger payloads reduce the number of trips required to transport the same material volume, leading to fewer emissions overall. For instance, payloads near 12 tonnes show CO_2 emissions dropping below 2,200 kilograms, while smaller payloads around 8 tonnes result in emissions exceeding 3,200 kilograms. This reduction demonstrates the efficiency of optimising payload sizes to minimise emissions and fuel consumption.

The number of trucks also plays a significant role in determining CO_2 emissions. Fleets with fewer trucks (1–3) generally exhibit higher emissions due to prolonged operational times and increased fuel consumption per truck. Conversely, increasing the fleet size to 4–5 trucks reduces emissions by distributing the workload more evenly, resulting in shorter operational durations and fewer emissions. However, excessive fleet sizes beyond 5 trucks lead to diminishing returns and potential inefficiencies, such as congestion, that could counteract emission reductions.

Although speed is not explicitly represented in this graph, it directly affects CO_2 emissions by influencing fuel efficiency. Lower speeds increase emissions due to prolonged travel times and less efficient engine performance. On the other hand, higher speeds reduce travel durations, improving engine efficiency and lowering emissions. However, excessive speeds may create safety risks and disrupt operational harmony, such as causing bottlenecks at loading and dumping points. Balancing speed with other variables ensures that CO_2 emissions are minimised without compromising operational integrity.

The optimal configurations for minimising CO_2 emissions involve payloads between 10–12 tonnes and 3–4 trucks. These setups achieve the best balance of operational efficiency and emissions reductions by reducing the number of trips and ensuring smoother operations. Configurations with smaller payloads or fewer trucks tend to exhibit higher emissions due to increased trip frequency and longer operational durations.

- **Practical Implications**

1. *Configuration Recommendations:*

   Payloads of 10–12 tonnes and 3–4 trucks are optimal for reducing CO_2 emissions. These configurations minimise the number of trips and optimise fuel efficiency, aligning with sustainability objectives.

2. *Environmental Benefits:*

   Reduced CO_2 emissions contribute directly to decarbonisation efforts, helping to meet regulatory targets and minimise environmental impact.

3. *Operational Flow Improvements:*

   Lower emissions are indicative of efficient logistical flow, reduced delays, and better utilisation of resources. This also results in cost savings through decreased fuel usage.

4. *Trade-Offs:*

   While increasing payload and fleet size improves emission efficiency, excessive fleet sizes (beyond 5 trucks) may lead to operational challenges such as congestion, negating the benefits of reduced emissions.

The analysis highlights the importance of optimising payload size, fleet size, and speed to minimise CO_2 emissions and fuel consumption. By adopting the Eco-Hauling and Big Room approach, stakeholders can achieve significant emissions reductions while improving operational efficiency. These insights provide a robust framework for sustainable construction logistics, supporting environmental and economic goals.

4-2-4-6 Analysis of Rental Costs Surface Graph for Integration of Eco-Hauling and Big Room Approach

This surface graph illustrates the relationship between payload (tonnes), number of trucks, and rental costs (currency) in the integration of Eco-Hauling and the Big Room approach. Rental cost is a critical performance metric in construction logistics, directly linked to fleet size, operational efficiency, and scheduling. Understanding how these variables interact helps in designing cost-effective logistics strategies (Figure 4.6).

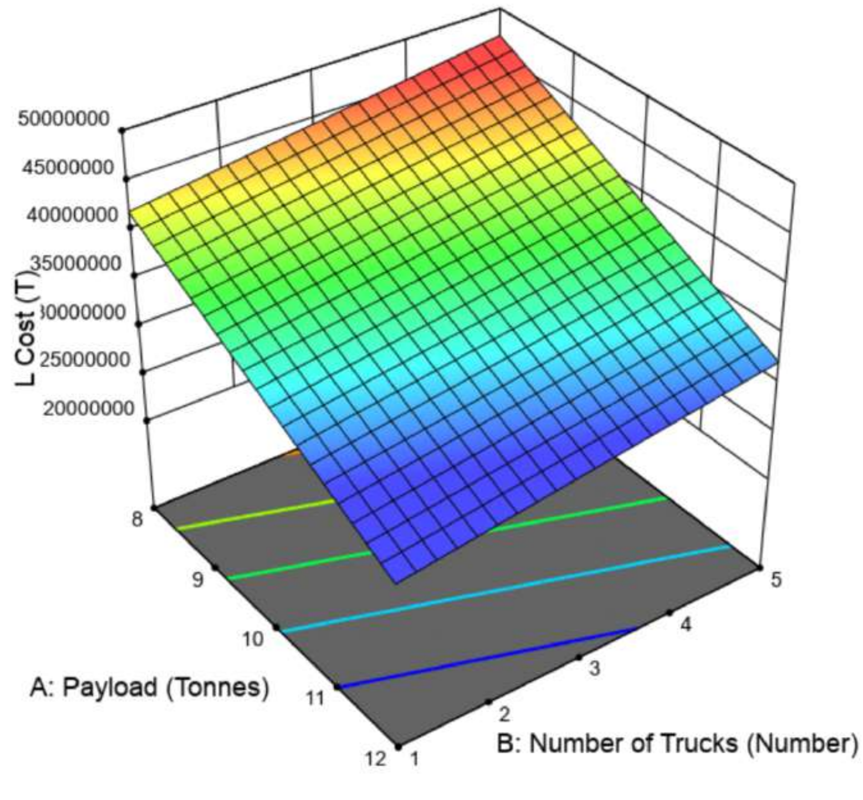


Fig. 4.6: Surface Graph of Rental Costs Emissions for the Integration of Eco-Hauling and Big Room – Case 1

As payload size increases from 8 tonnes to 12 tonnes, rental costs decrease significantly. Larger payloads allow for fewer trips to transport the same material volume, reducing the total rental time for trucks and hence the overall costs. For example, payloads near 12 tonnes exhibit lower rental costs compared to smaller payloads of 8 tonnes, where more trips and extended rental durations are required. This reduction underscores the importance of optimising payload sizes to achieve cost efficiency.

The number of trucks is another significant factor influencing rental costs. Fleets with fewer trucks (1–3) tend to have higher costs due to longer operational times required to complete the workload. However, increasing the fleet size to 3–4 trucks generally reduces rental costs by ensuring faster project completion. Beyond 4 trucks, the benefits diminish due to increased coordination complexity and underutilisation of resources, which can result in unnecessary costs.

Although speed is not explicitly depicted in this graph, it indirectly affects rental costs. Higher speeds reduce travel and operational durations, thereby lowering rental costs by minimising the time trucks are in use. Conversely, lower speeds increase costs due to extended operational times. However, excessive speeds can disrupt the balance of operations, causing inefficiencies such as congestion or higher fuel consumption, which may negate cost benefits. Ensuring an optimal speed that aligns with payload and fleet size is crucial for minimising costs.

The optimal configurations for minimising rental costs involve payloads between 10–12 tonnes and 3–4 trucks. These setups strike the right balance between reducing the number of trips and achieving efficient operations. Configurations with smaller payloads or fewer trucks often result in higher costs due to longer operational durations and less efficient resource utilisation.

- **Practical Implications**

1. *Configuration Recommendations:*

   Payloads of 10–12 tonnes and 3–4 trucks are ideal for reducing rental costs, ensuring fewer trips and faster completion times.

2. *Cost Efficiency:*

   Lower rental costs directly contribute to overall project savings, freeing up resources for other project needs.

3. *Operational Efficiency:*

   Efficient configurations reduce delays and improve scheduling, further lowering costs and enhancing project timelines.

4. *Trade-Offs:*

   While increasing payload size and fleet size improves cost efficiency, excessive fleet sizes (beyond 4 trucks) can lead to operational challenges and diminishing returns.

The analysis demonstrates the importance of balancing payload size, fleet size, and speed to minimise rental costs while maintaining operational efficiency. By leveraging the Eco-Hauling and Big Room approach, stakeholders can achieve significant cost savings and improve logistical flow. These insights support the development of cost-effective, sustainable construction logistics strategies.

4-2-5 Optimised Scenarios Analysis - Case 1

Using Stat-Ease optimisation tools has led to the identification of three optimised scenarios based on varying importance weightings between time and carbon emissions (Table 4.4). Cutting-edge tool such as Stat-Ease allowed for the evaluation of over 320 configurations, significantly expanding the scenario pool and improving the ability to identify and optimise solutions tailored to specific operational needs.

Table 4.4: Optimised Scenarios – Case Study 1

Strategies	Inputs				Outputs					
	No of Deliveries	Speed KM/h	Payload Tonnes	No of Trucks	Total Time Mins	Idle Time Mins	No of Brakes	Diesel Litres	CO2 Kg CO2	Cost Tomans
Time 50% - Carbon 50%	75	24	12	4	494	35	159	875.5	2293.7	29,640,000
Time 0% - Carbon 100%	75	26	12	1	1816	0	150	808.6	2118.5	27,240,000
Time 100% - Carbon 0%	75	26	12	5	460	362	294	1015.2	2659.7	34,500,000

These scenarios provide contractors with tailored configurations to address specific project priorities, whether focusing on reducing CO_2 emissions, minimising total time, or achieving a balanced approach. By leveraging these suggestions, contractors can optimise their operations to align with environmental, economic, and project-specific goals. The table summarises the optimised inputs and outputs for each scenario, demonstrating how different configurations impact key performance metrics.

The optimised scenarios suggest varying approaches based on the priority given to time and carbon emissions. Below is a comprehensive analysis of the three configurations:

1. Balanced Importance Weightings (50% Time, 50% Carbon)

- *Inputs:* This configuration involves 4 trucks operating at a speed of 24 km/h, with a payload capacity of 12 tonnes per truck. The number of deliveries is 75.
- *Outputs:*
  - Total Time: 494 minutes, indicating efficient operations.
  - Idle Time: 35 minutes, showcasing minimal delays and bottlenecks.
  - Braking Events: 159, reflecting smooth traffic flow.
  - Diesel Consumption: 875.5 litres, representing efficient fuel usage.
  - CO_2 Emissions: 2,293.7 kg, striking a balance between environmental impact and operational efficiency.
  - Cost: 29,640,000 Tomans, highlighting cost-effectiveness while maintaining environmental considerations.

This configuration represents a balanced approach that achieves reasonable reductions in both time and carbon emissions. Contractors prioritising both operational efficiency and sustainability can benefit from this scenario.

2. Carbon-Focused Configuration (100% Carbon, 0% Time)

- *Inputs:* This configuration uses a single truck operating at 26 km/h with a payload of 12 tonnes, completing 75 deliveries.
- *Outputs:*
  - *Total Time:* 1,816 minutes, significantly longer due to the reduced fleet size.
  - *Idle Time:* 0 minutes, demonstrating efficient use of the single truck with no waiting time.
  - *Braking Events:* 150, slightly lower than the balanced configuration.
  - *Diesel Consumption:* 808.6 litres, the lowest among the three scenarios.
  - *CO_2 Emissions:* 2,118.5 kg, representing the most substantial emissions reduction.
  - *Cost:* 27,240,000 Tomans, the most cost-effective scenario.

This scenario prioritises carbon reduction at the expense of operational time. It is ideal for projects with strict environmental requirements and flexible timelines. Contractors focused on minimising environmental impact will find this configuration particularly beneficial.

3. Time-Focused Configuration (100% Time, 0% Carbon)

- *Inputs:* This setup involves 5 trucks operating at 26 km/h, with a payload of 12 tonnes, completing 75 deliveries.
- *Outputs:*
    - Total Time: 460 minutes, the shortest operational duration.
    - Idle Time: 362 minutes, reflecting potential inefficiencies due to over-deployment of trucks.
    - Braking Events: 294, the highest among the three scenarios.
    - Diesel Consumption: 1,015.2 litres, the highest fuel usage.
    - CO_2 Emissions: 2,659.7 kg, higher than the other configurations.
    - Cost: 34,500,000 Tomans, the most expensive scenario.

This scenario prioritises time efficiency, making it suitable for projects with tight deadlines. However, the trade-off includes higher emissions and costs, which may not align with sustainability goals.

- **Comparative Analysis**

1. *Environmental Impact:*

- The carbon-focused scenario achieves the lowest CO_2 emissions (2,118.5 kg), demonstrating its alignment with decarbonisation goals.
- The time-focused scenario results in the highest emissions (2,659.7 kg), making it less environmentally friendly.

2. *Operational Time:*

- The time-focused scenario achieves the shortest operational duration (460 minutes), ideal for projects with strict deadlines.

- o The carbon-focused scenario has the longest operational time (1,816 minutes), highlighting its trade-off for emissions reduction.

3. *Cost Efficiency:*

- o The carbon-focused scenario is the most cost-effective (27,240,000 Tomans), driven by lower fuel consumption and reduced fleet size.
- o The time-focused scenario incurs the highest cost (34,500,000 Tomans), reflecting the trade-off for prioritising time.

4. *Idle Time:*

- o The carbon-focused scenario eliminates idle time entirely, reflecting optimal resource utilisation.
- o The time-focused scenario shows high idle time (362 minutes), indicating inefficiencies due to over-deployment of trucks.

5. *Braking Events:*

- o The balanced scenario maintains a moderate number of braking events (159), reflecting smooth operations.
- o The time-focused scenario exhibits the highest number of braking events (294), potentially increasing wear and tear on vehicles.

Ultimately, the optimised scenarios provide contractors with actionable insights into balancing time, carbon emissions, and costs. Each configuration aligns with specific project priorities:

- The balanced configuration offers a harmonious approach, addressing both environmental and operational goals by ensuring moderate reductions in total time, idle time, and emissions. For instance, this configuration achieves a total operational time of 494 minutes and limits CO_2 emissions to 2,293.7 kg, making it an efficient yet environmentally considerate choice for contractors.
- The carbon-focused configuration excels in minimising emissions and costs, making it ideal for environmentally sensitive projects. It achieves the lowest CO_2 emissions at 2,118.5 kg and a total cost of 27,240,000 Tomans. However, this comes with a

trade-off in total operational time, which is extended to 1,816 minutes due to the use of a single truck.

- The time-focused configuration prioritises operational speed, catering to projects with tight deadlines but higher environmental trade-offs. This setup achieves the shortest total time of 460 minutes but results in the highest CO_2 emissions of 2,659.7 kg and the greatest diesel consumption at 1,015.2 litres. This configuration is suited for time-sensitive projects where speed is prioritised over sustainability.

By leveraging these insights, contractors can select configurations that best align with their project goals and stakeholder expectations, ensuring efficient, cost-effective, and sustainable construction logistics. Furthermore, these findings support broader sustainability goals, including decarbonisation and regulatory compliance, while fostering enhanced collaboration among stakeholders. The cost efficiencies observed highlight tangible benefits that reinforce the practicality of these strategies.

While this analysis has been conducted on a limited set of scenarios, future work will involve expanded scenario evaluations using advanced tools like Stat-Ease. This will allow for deeper exploration and refinement of configurations, ensuring even more precise alignment with project objectives and long-term sustainability.

4-2-6 Comparison of Balanced Configuration with Existing Scenario

Among the three optimised scenarios—Time 50% - Carbon 50%, Time 0% - Carbon 100%, and Time 100% - Carbon 0%—the balanced configuration (Time 50% - Carbon 50%) has been chosen for comparison with the existing scenario (Table 4.5).

Table 4.5: Suggested Scenario vs Existing Scenario – Case Study 1

Strategies	Inputs				Outputs					
	No of Deliveries	Speed KM/h	Payload Tonnes	No of Trucks	Total Time Mins	Idle Time Mins	No of Brakes	Diesel Litres	CO2 Kg CO2	Cost Tomans
Existing	90	20	10	5	635	708	649	1345.6	3525.5	47,625,000
Time 50% - Carbon 50%	75	24	12	4	494	35	159	875.5	2293.7	29,640,000

This decision is driven by its ability to address both environmental and operational priorities simultaneously, making it the most practical and adaptable solution for construction logistics. While the carbon-focused scenario excels in minimising emissions and costs, and the time-focused scenario prioritises speed, the balanced configuration provides a middle ground, ensuring significant improvements in all key performance metrics without heavily compromising one objective over the other.

By comparing the balanced configuration with the contractor's existing approach, we can highlight how the BASE model integrates optimisation to achieve a harmonious balance between efficiency, sustainability, and cost-effectiveness.

- **Comparative Analysis of Outputs**

1. Total Time

- Existing Scenario: Total operational time stands at 635 minutes.
- Balanced Configuration: Total time is reduced to 494 minutes, reflecting a 22.2% reduction.
- Analysis: The reduction in total time demonstrates the effectiveness of the balanced configuration in streamlining operations. By optimising fleet size (4 trucks) and payloads (12 tonnes), unnecessary delays and inefficiencies are eliminated, leading to faster project completion.

2. Idle Time

- Existing Scenario: Idle time is 708 minutes.
- Balanced Configuration: Idle time is drastically reduced to 35 minutes, representing a 95.1% reduction.
- Analysis: This dramatic decrease highlights the importance of coordination and flow management in the balanced configuration. Optimised resource allocation ensures trucks spend minimal time waiting at loading and unloading points, preventing congestion and delays.

3. Braking Events

- Existing Scenario: 649 braking events are recorded.
- Balanced Configuration: Braking events are reduced to 159, an improvement of 75.5%.

- Analysis: The smoother traffic flow achieved through better planning and fewer bottlenecks is evident in this reduction. Reduced braking not only improves operational efficiency but also minimises vehicle wear and tear, contributing to cost savings.

4. Diesel Consumption

- Existing Scenario: Diesel consumption is 1,345.6 litres.
- Balanced Configuration: Diesel consumption drops to 875.5 litres, a 34.9% reduction.
- Analysis: Lower fuel usage is directly linked to the optimised number of trucks and improved operational flow. This reduction contributes to both cost savings and environmental benefits, showcasing the dual advantage of efficiency and sustainability.

5. CO_2 Emissions

- Existing Scenario: CO_2 emissions are 3,525.5 kilograms.
- Balanced Configuration: Emissions are reduced to 2,293.7 kilograms, achieving a 35% reduction.
- Analysis: The substantial reduction in CO_2 emissions highlights the environmental impact of the balanced configuration. By minimising idle time and diesel consumption, the BASE model significantly lowers greenhouse gas emissions, aligning with global sustainability and decarbonisation goals.

6. Cost

- Existing Scenario: Total cost is 47,625,000 Tomans.
- Balanced Configuration: Cost is reduced to 29,640,000 Tomans, achieving a 37.8% saving.

- Analysis: The cost-effectiveness of the balanced configuration is evident, driven by reduced fuel consumption, fewer braking events, and lower idle time. This outcome demonstrates how optimised operations can deliver substantial financial benefits alongside environmental and efficiency improvements.

The comparison between the balanced configuration and the existing scenario underscores the transformative potential of the BASE model in construction logistics. The balanced configuration emerges as the optimal choice, addressing both environmental and operational objectives. Key takeaways include:

1. *Enhanced Efficiency:* A 22.2% reduction in total operational time and a staggering 95.1% reduction in idle time highlight the efficiency gains achieved through better coordination and resource utilisation.

2. *Environmental Benefits:* A 35% reduction in CO_2 emissions and a 34.9% decrease in diesel consumption demonstrate the alignment of the balanced configuration with sustainability and decarbonisation goals.

3. *Cost Savings:* With a 37.8% reduction in costs, the balanced configuration proves its financial viability, making it an attractive choice for contractors aiming to optimise operations.

By leveraging the insights from this analysis, contractors can adopt the BASE model to significantly improve construction logistics. This approach not only enhances project performance but also contributes to broader sustainability efforts by reducing greenhouse gas emissions and aligning with regulatory compliance. Moving forward, the findings reinforce the importance of data-driven decision-making and collaborative planning in achieving a sustainable and efficient built environment.

4-3 Analysis of Case Study 2

4-3-1 Existing Scenario

This section details the analysis of the current, or "existing," hauling practices observed for Case Study 2. This process involves the transportation of asphalt using conventional hauling methods employed by the contractor. The data was gathered through structured observation, focusing on diesel consumption, CO_2 emissions, idle times, and financial costs (Table 4.6).

Table 4.6: Existing Scenario-Case Study 2

Strategies	Inputs				Outputs					
	No of Deliveries	Speed KM/h	Payload Tonnes	No of Trucks	Total Time Mins	Idle Time Mins	No of Brakes	Diesel Litres	CO2 Kg CO2	Cost Tomans
Existing	26	30	16	5	674	2164	168	1431.7	3751.1	50,550,000

The existing scenario provides insight into how asphalt hauling is conducted without strategic interventions, serving as a baseline for assessing the effectiveness of alternative approaches such as Eco-Hauling and the integrated Eco-Hauling and Big Room strategy. By thoroughly understanding this scenario, we can identify inefficiencies, bottlenecks, and opportunities for improvement.

1. Operational Inputs and Characteristics

The existing process involved the following key inputs:

1. *Material Hauled:* A total of 416 tonnes of asphalt.
2. *Number of Deliveries:* A total of 26 trips were required to transport the asphalt. Each truck carried a payload of 16 tonnes per trip.
3. *Fleet Size:* The contractor used five dumper trucks to complete the operation.
4. *Speed:* Trucks operated at an average speed of 30 km/h.
5. *Payload:* Each truck carried the standard payload of 16 tonnes per trip.

These inputs are characteristic of traditional hauling operations in construction, where decisions are often based on practical constraints rather than optimised strategies.

2. Operational Outputs and Observed Outcomes

In contrast to Case 1, Case 2 presented a more complex scenario involving asphalt hauling between a plant and a paver. The unique challenge lay in the dynamic relationship between the paver's speed and the flow of dumper trucks, which required precise coordination to avoid interruptions. Unlike the relatively linear operations in Case 1, the model for Case 2 needed to account for the variable unloading pace dictated by the paver, leading to variability in truck movements and potential delays.
The existing process produced the following results:

1. *Total Operation Time:* The trucks collectively operated for 674 minutes.
2. *Idle Time:* Trucks were idle for a significant portion of the operation—2,164 minutes in total. This idle time includes delays at loading/unloading points and waiting in queues.
3. *Number of Brakes Used:* Drivers used the brake pedals 168 times throughout the operation, indicating frequent stop-and-go conditions and inefficient traffic flow.
4. *Diesel Consumption:* A total of 1,431.7 litres of diesel was consumed during the operation.
5. *CO_2 Emissions:* Diesel usage resulted in emissions of 3,751.1 kilograms of CO_2, contributing significantly to the environmental footprint of the project.
6. *Financial Cost:* The total cost of the operation, driven by the rental of dumper trucks, amounted to 50,550,000 Tomans.

3. Detailed Process Description

The hauling process in Case 2 followed a more complex workflow compared to the straightforward operations observed in Case 1:

1. Asphalt Loading: Asphalt is loaded onto dumper trucks at the plant, with each truck carrying a payload of 16 tonnes.

2. Transportation: Trucks transport the asphalt to the designated paver location at an average speed of 30 km/h. During this process, trucks navigate two critical bottlenecks along the route:

   Blockages Caused by Route Intersections: Soil-hauling contractors and asphalt-hauling contractors operate concurrently, with their routes intersecting at two points (Blockage 1 and Blockage 2). These intersections create additional delays, increasing idle time.

3. Unloading and Paver Coordination: Upon arrival at the paver, the unloading pace is dictated by the paver's speed, which varies dynamically based on the construction workflow. Trucks often wait for the paver to progress, resulting in additional idle times.
4. Return Trip: After unloading, trucks return to the asphalt plant to repeat the cycle. This journey is also subject to delays caused by the bottlenecks mentioned above.

The unique challenges of this process lie in its interdependencies, particularly the need to align truck dispatch schedules and unloading times with the variable pace of the paver. The dynamic nature of the paver’s speed, dictated by construction workflow demands, introduces complexities that ripple across the entire hauling operation. Without precise synchronisation, trucks often arrive at the unloading point either too early, resulting in extended idle times as they wait for the paver to progress, or too late, causing interruptions in the paving process.

These delays not only disrupt the smooth flow of operations but also exacerbate inefficiencies across several performance metrics. Prolonged idle times, which totaled 2,164 minutes in the observed scenario, significantly increase fuel consumption as trucks remain running while stationary. Frequent braking events, caused by stop-and-go traffic conditions near bottlenecks and intersections, contribute further to operational inefficiency. These braking events, recorded at 168 occurrences, reflect poor traffic flow management and unnecessary wear and tear on vehicles.

The inefficiencies stemming from this lack of coordination directly influence diesel consumption, which reached a high of 1,431.7 litres in this scenario. The corresponding CO_2 emissions totalled 3,751.1 kilograms, underscoring the environmental impact of unoptimised operations. This substantial carbon footprint highlights the failure to mitigate emissions through more strategic planning and better resource management.

Moreover, the reliance on diesel not only increases greenhouse gas emissions but also releases harmful pollutants like nitrogen oxides (NOx) and particulate matter, further degrading air quality.

These inefficiencies underline the importance of implementing strategic interventions to streamline the process. Effective measures, such as synchronised dispatch schedules, real-time communication between paver operators and truck drivers, and dynamic scheduling tools, could drastically reduce idle times, unnecessary braking, and fuel consumption. By addressing these systemic challenges, construction logistics can become significantly more efficient, sustainable, and cost-effective.

4. Environmental and Financial Impacts

The inefficiencies in the existing process directly influenced both environmental and financial outcomes:

1. *Environmental Costs:*
   - Carbon Emissions: The 3,751.1 kg of CO_2 emitted during the operation underscores the heavy environmental toll of conventional hauling practices. Prolonged idle times and frequent stops were key contributors to this outcome.
   - Diesel Dependency: Diesel combustion not only increases CO_2 emissions but also releases other pollutants such as nitrogen oxides (NOx) and particulate matter, which harm air quality.
2. Financial Costs:
   - The high diesel consumption (1,431.7 litres) translated to elevated operational costs, given the price of fuel.
   - The cost of renting and operating the fleet of five dumper trucks further inflated expenses, resulting in a total cost of 50,550,000 Tomans.

5. Challenges in the Existing Scenario

The challenges observed in the existing scenario highlight systemic inefficiencies that hinder sustainability and cost-effectiveness:

1. *Inefficient Coordination:* The lack of coordination between stakeholders—drivers, site managers, and equipment operators—led to significant idle time and operational delays.
2. *Resource Waste:* Prolonged idle time and frequent braking not only wasted fuel but also accelerated wear and tear on the trucks, potentially increasing maintenance costs.
3. *Lack of Strategic Planning:* The absence of strategic interventions, such as route optimisation, collaborative planning, or dynamic scheduling, limited the potential for improving operational efficiency.
4. *Environmental Neglect:* The operation's high carbon footprint reflects a failure to prioritise sustainability. This is particularly concerning in the context of global efforts to reduce greenhouse gas emissions.

The existing scenario provides a clear picture of the challenges associated with conventional hauling practices. Key inefficiencies—such as high idle times, frequent braking, and uncoordinated operations—resulted in excessive fuel consumption, elevated costs, and significant environmental impacts.

These findings underscore the urgent need for strategic interventions to optimise the hauling process. By addressing these inefficiencies through innovative approaches like Eco-Hauling and collaborative strategies, there is substantial potential to reduce both costs and carbon emissions while improving overall project efficiency.

4-3-2 Comparison Existing Scenario vs. Eco-Hauling vs. Integrated Eco-Hauling and Big Room Strategy - Case Study 2

This comparative analysis evaluates three hauling strategies used in Case Study 2 for transporting 416 tonnes of asphalt: the contractor's Existing Scenario, the optimised Eco-Hauling Strategy, and the Integrated Eco-Hauling and Big Room Strategy (Table 4.7).

Table 4.7: Comparison of Strategies in Case Study 2

Strategies	Inputs				Outputs					
	No of Deliveries	Speed KM/h	Payload Tonnes	No of Trucks	Total Time Mins	Idle Time Mins	No of Brakes	Diesel Litres	CO2 Kg CO2	Cost Tomans
Existing	26	30	16	5	674	2164	168	1431.7	3751.1	50,550,000
Eco-Hauling	26	30	16	5	645	2047	137	1370.1	3589.7	48,375,000
Eco-Hauling & Big Room	26	30	16	5	630	1817	82	1303.6	3415.5	47,250,000

The study focuses on key performance metrics, including diesel consumption, CO_2 emissions, idle time, braking events, and costs, to understand the operational efficiency and environmental impacts of each strategy. By maintaining consistent inputs across scenarios, the analysis isolates the effects of strategic interventions on key outputs, providing valuable insights for optimising construction logistics.

1. Baseline (Existing Scenario): Summary of Findings

The Existing Scenario reflects the contractor’s conventional hauling practices, characterised by a lack of strategic planning and coordination. These inefficiencies resulted in:

- Diesel Consumption: 1,431.7 litres
- CO_2 Emissions: 3,751.1 kilograms
- Idle Time: 2,164 minutes
- Braking Events: 168 occurrences
- Cost: 50,550,000 Tomans

Frequent braking events and prolonged idle times highlighted traffic flow issues, bottlenecks, and uncoordinated operations, leading to high fuel usage and environmental impact. This scenario serves as the baseline for comparison.

2. Eco-Hauling Strategy

The Eco-Hauling strategy introduced operational efficiency through better scheduling and route optimisation but lacked collaborative stakeholder engagement.

Key Outputs and Reductions:

- Diesel Consumption: 1,370.1litres (a reduction of 4.3% reduction compared to the baseline)
- CO_2 Emissions: 3,589.7kilograms (a reduction of 4.3% reduction compared to the baseline)
- Idle Time: 2,047 minutes (a reduction of 5.4% reduction compared to the baseline)
- Braking Events: 137 occurrences (a reduction of 18.5% reduction)
- Cost: 48,375,000 Tomans (a reduction of 4.3% reduction)
- **Analysis:**

    1. *Fuel Efficiency and Emissions Reduction:* The strategy reduced diesel consumption by 61.6 litres, leading to a proportional reduction in CO_2 emissions of 161.4 kilograms. These improvements reflect smoother traffic flow and less unnecessary idling.
    2. *Idle Time Decrease:* Idle time decreased by 117 minutes, reflecting improved scheduling but leaving bottlenecks unresolved.
    3. Reduced Braking Events: Braking events dropped by 31 occurrences, indicating more efficient vehicle movements and reduced stop-and-go conditions.
    4. *Cost Savings:* Costs decreased by 2,175,000 Tomans, reflecting fuel savings and reduced idle time.

- **Limitations:** The Eco-Hauling strategy showed limited ability to address systemic inefficiencies, such as bottlenecks and overlapping tasks, due to the absence of collaborative planning.

3. Integrated Eco-Hauling and Big Room Strategy

This strategy combined eco-friendly practices with the collaborative Big Room approach, achieving substantial improvements in all metrics.

Key Outputs and Reductions:

- Diesel Consumption: 1,303.6 litres (a reduction of 8.9% reduction compared to the baseline)
- CO_2 Emissions: 3,415.5 kilograms (a reduction of 8.9% reduction compared to the baseline)
- Idle Time: 1,817 minutes (a reduction of 16% reduction compared to the baseline)
- Braking Events: 82 occurrences (a reduction of 51.2% reduction compared to the baseline)
- Cost: 47,250,000 Tomans (a reduction of 6.5% reduction compared to the baseline)
- **Analysis:**

1. *Diesel and Emissions Reduction:* Diesel usage decreased by 128.1 litres, reducing CO_2 emissions by 335.6 kilograms. These improvements highlight the efficiency gains from synchronised operations and reduced bottlenecks.
2. *Significant Idle Time Reduction:* Idle time was cut by 347 minutes, reflecting the benefits of proactive bottleneck management and synchronised dispatching.
3. *Optimised Braking Events:* Braking events fell by 86 occurrences, indicating smooth traffic flow and enhanced operational harmony.
4. *Cost Efficiency:* Costs decreased by 3,300,000 Tomans, underscoring the financial benefits of reduced idle time, improved fuel efficiency, and streamlined operations.

Key Benefits of Collaboration:

- *Streamlined Coordination:* The Big Room fosters real-time communication between drivers, site managers, and equipment operators, ensuring tasks are synchronized effectively. This collaboration helps avoid overlaps and ensures smooth workflow, significantly reducing operational bottlenecks.
- *Collaborative Problem-Solving:* Through shared discussions, stakeholders address key operational issues, such as queuing at loading points and suboptimal scheduling.

This joint effort allows for quick identification of inefficiencies and the implementation of timely solutions, enhancing overall productivity.

- *Proactive Decision-Making:* In the Big Room, stakeholders collectively evaluate potential challenges before operations commence. By leveraging diverse expertise, they anticipate bottlenecks and design targeted strategies to resolve them. This unified planning approach ensures seamless hauling operations, minimizes delays, and aligns all parties towards common goals.

4. Comparative Analysis

- *Diesel Consumption and CO_2 Emissions:* The integrated strategy achieved the largest reductions, with 8.9% improvements in both metrics, compared to 4.3% reductions under Eco-Hauling. Diesel consumption dropped by 128.1 litres, and CO_2 emissions decreased by 335.6 kilograms, showcasing the environmental and fuel efficiency benefits of collaborative planning. Eco-Hauling achieved modest reductions of 61.6 litres of diesel and 161.4 kilograms of CO_2 emissions, reflecting its limited impact on systemic inefficiencies.
- *Idle Time:* Idle time decreased by 16% with the integrated strategy, equivalent to 347 fewer minutes, far surpassing the 5.4% reduction (117 minutes) achieved by Eco-Hauling. The collaborative approach effectively addressed bottlenecks and synchronised operations, while Eco-Hauling's impact was constrained by the lack of stakeholder involvement.
- *Braking Events:* The integrated strategy reduced braking events by 51.2% (86 fewer occurrences), compared to the 18.5% reduction (31 fewer occurrences) achieved by Eco-Hauling. This improvement underscores the role of stakeholder collaboration in streamlining operations and minimising unnecessary stops.
- Cost: The integrated strategy achieved a 6.5% reduction in costs (3,300,000 Tomans saved), outperforming the 4.3% improvement (2,175,000 Tomans saved) under Eco-Hauling. Cost savings were driven by reduced fuel consumption, fewer delays, and better resource allocation.

The comparative analysis highlights the transformative potential of collaborative and eco-friendly strategies in construction logistics. The Integrated Eco-Hauling and Big Room Strategy delivered substantial improvements across all key performance metrics. It achieved a 6.5% reduction in total time by eliminating bottlenecks and synchronizing operations, thereby reducing delays and enhancing workflow efficiency. Idle time saw a 16% reduction, as real-time coordination and proactive bottleneck management minimized unnecessary waiting periods, contributing significantly to operational efficiency. Braking events were reduced by 51.2%, ensuring smoother traffic flow, reducing stop-and-go movements, and minimizing vehicle wear. Additionally, the strategy led to an 8.9% reduction in CO_2 emissions through optimised fuel usage, significantly lowering the environmental footprint of hauling operations. Financially, the strategy achieved a 6.5% reduction in costs by cutting fuel consumption, shortening idle times, and minimizing operational delays. This comprehensive improvement underscores the effectiveness of combining operational efficiency with collaboration in achieving sustainable construction logistics.

By addressing inefficiencies through collaboration and strategic interventions, the integrated strategy enhances both operational efficiency and environmental performance. These findings underscore the value of adopting advanced frameworks like the BASE model to achieve sustainable and efficient construction logistics. The integrated strategy not only aligns with global sustainability goals but also sets a new standard for balancing economic and environmental performance in construction operations.

4-3-3 Analysis of Initial Scenarios Modelled in AnyLogic - Case Study 2

Case Study 2 provides a detailed exploration of the operational performance of asphalt hauling operations, focusing on the transportation of 416 tonnes of asphalt over a 2660-meter loop. This case study analysed 17 distinct scenarios to assess the effectiveness of Eco-hauling alone and the combined Eco-hauling and Big Room approach (Table 4.8).

Table 4.8: Initial Scenarios Modelled in AnyLogic – Case Study 2

Scenario	No of Deliveries	Speed Km/h	Payloads Tonnes	No of Trucks	Eco-hauling						Eco-hauling and Big Room					
					Total Time mins	Idle Time mins	No of Brakes	Diesel Litres	CO2 Kg CO2	Cost Tomans	Total Time mins	Idle Time mins	No of Brakes	Diesel Litres	CO2 Kg CO2	Cost Tomans
1	52	30	8	3	636	621	261	789.7	2069.0	T 28,620,000	636	567	154	776.0	2033.1	T 28,620,000
2	104	30	4	1	2203	276	306	842.1	2206.3	T 33,045,000	1995	68	208	752.0	1970.2	T 29,925,000
3	26	30	16	5	645	2047	137	1370.1	3589.7	T 48,375,000	630	1817	82	1303.6	3415.5	T 47,250,000
4	52	20	8	5	641	1731	272	1330.5	3485.9	T 48,075,000	637	1630	211	1286.7	3371.1	T 47,775,000
5	52	30	8	2	736	182	165	604.7	1584.3	T 22,080,000	688	80	111	559.5	1465.8	T 20,640,000
6	52	30	8	5	632	1762	270	1311.7	3436.6	T 47,400,000	636	1690	212	1284.7	3365.9	T 47,700,000
7	52	30	8	4	633	1178	262	1049.8	2750.4	T 37,980,000	645	1176	158	1046.1	2740.7	T 38,700,000
8	104	40	4	3	916	863	494	1075.8	2818.5	T 41,220,000	926	866	415	1075.5	2817.8	T 41,670,000
9	26	30	16	1	1032	82	80	454.4	1190.6	T 15,480,000	959	9	52	423.0	1108.3	T 14,385,000
10	104	20	4	3	914	661	457	1072.0	2808.6	T 41,130,000	929	677	296	1075.1	2816.7	T 41,805,000
11	104	30	4	5	915	2551	592	1840.5	4822.1	T 68,625,000	927	2538	508	1829.2	4792.5	T 69,525,000
12	52	40	8	1	1376	132	155	564.4	1478.7	T 20,640,000	1278	34	105	521.8	1367.1	T 19,170,000
13	52	40	8	5	631	1785	269	1309.6	3431.1	T 47,325,000	636	1723	212	1284.7	3365.9	T 47,700,000
14	26	40	16	3	642	956	129	828.6	2171.0	T 28,890,000	641	894	77	815.5	2136.7	T 28,845,000
15	52	20	8	1	1472	132	155	604.4	1583.5	T 22,080,000	1375	34	105	562.2	1472.9	T 20,625,000
16	52	30	8	1	1408	132	155	577.7	1513.5	T 21,120,000	1311	34	105	535.5	1403.0	T 19,665,000
17	26	20	16	2	628	250	93	548.2	1436.4	T 18,840,000	623	235	78	540.2	1415.4	T 18,690,000

Note: Total time should be multiplied by the number of dumper trucks, but idle time is cumulative.

1. Scenario Design

The scenarios in Case Study 2 were systematically designed by altering four primary input factors:

- *Fleet Size (Number of Trucks):* The fleet size ranged from 1 to 5 trucks, allowing an in-depth analysis of efficiency under different fleet configurations.
- *Number of Deliveries:* The number of deliveries varied between 26 and 104 trips, reflecting diverse operational conditions and requirements.
- *Dumper Truck Speed:* Speeds were adjusted between 20 km/h and 40 km/h, representing various scenarios of operational constraints and efficiencies.
- *Payload Capacity:* Payloads ranged from 4 tonnes to 16 tonnes, simulating the impact of load efficiency on operational performance.

These combinations created a matrix of 17 unique scenarios for testing, ensuring a robust and consistent exploration of operational dynamics.

2. Performance Metrics Across Scenarios

Key performance metrics, including total time, idle time, number of brakes, diesel consumption, CO_2 emissions, and operational costs, were examined to determine how the interventions impacted the environmental and economic outcomes of the hauling operations. The following analysis dives deep into the data presented in the table and compares the results to highlight significant trends and insights.

1. Total Time: A Measure of Overall Operation Duration

Total time, which represents the duration of operations across all trucks in the loop, varied across scenarios based on payload, speed, and the number of trucks. Analysing total time allows us to see how efficiently the overall hauling operation was conducted.

- *Scenario 1:*
    - Total time remained constant at 636 minutes for both Eco-hauling and the integrated approach. This suggests that the improvements in idle time and braking events did not significantly alter the overall duration of operations, likely due to consistent payload sizes and loop length.

- *Scenario 9:*
    - Total time reduced slightly from 1032 minutes (Eco-hauling) to 959 minutes, indicating that bottleneck elimination and better coordination contributed to more efficient hauling cycles. Despite the limited number of trucks, better route management enabled smoother operations.
- *Scenario 12:*
    - A reduction from 1376 minutes to 1278 minutes was observed, indicating that careful scheduling and routing optimisation directly impacted the total time needed for operations. This scenario benefitted from higher payloads, requiring fewer trips to complete the task.

Key Observations on Total Time:

- Scenarios involving higher payloads and fewer trucks demonstrated more pronounced reductions in total time, as fewer trips were needed.
- Improvements in total time were less significant in scenarios where speed limitations or payload sizes already constrained operations.

2. Idle Time: Tackling Operational Inefficiencies

Idle time, which represents periods where trucks are stationary and not productive, is a critical inefficiency in hauling operations. Reducing idle time leads to lower fuel consumption, emissions, and overall costs. The integrated approach showed substantial reductions across all scenarios.

- *Scenario 9:*
    - Idle time dropped dramatically from 82 minutes to just 9 minutes, reflecting the significant impact of eliminating bottlenecks at intersections and optimising truck movement. This scenario shows how collaborative planning can drastically minimise unproductive waiting periods.
- *Scenario 12:*
    - Idle time decreased from 132 minutes to 34 minutes, demonstrating the benefits of improved scheduling and a reduction in overlapping activities. The optimised loading and unloading process was particularly effective in this scenario.

- *Scenario 5:*
  - Idle time reduced from 182 minutes to 80 minutes, highlighting how better sequencing of truck dispatches and unloading processes can cut down unproductive waiting times.

Key Observations on Idle Time:

- Scenarios with fewer trucks and lower payloads tended to show the most dramatic reductions in idle time due to more flexible scheduling.
- The reductions in idle time directly influenced other metrics, such as diesel consumption and emissions, by ensuring trucks spent less time idling.

3. Number of Brakes: Indicator of Smooth Operations

The number of braking events is a key indicator of the smoothness of operations. Frequent braking events suggest stop-and-go movements, which increase fuel consumption and reduce efficiency. The data shows a consistent reduction in braking events across scenarios.

- *Scenario 1:*
  - Braking events decreased significantly from 261 to 154, reflecting better synchronisation and the introduction of checkpoint strategies to maintain smoother truck movements.
- *Scenario 9:*
  - Braking events were reduced from 80 to 52, showcasing the impact of smoother traffic flows and optimised unloading processes. Fewer bottlenecks translated into fewer stop-and-go operations.
- *Scenario 13:*
  - A reduction from 269 to 212 braking events was observed, indicating improvements in route management and fewer delays at critical points in the loop.

Key Observations on Braking:

- Scenarios with higher speeds and fewer bottlenecks saw the most significant reductions in braking events.

- Fewer braking events not only improve fuel efficiency but also reduce wear and tear on vehicles, leading to lower maintenance costs over time.

4. Diesel Consumption: A Measure of Efficiency

Diesel consumption is directly tied to the operational efficiency of hauling processes. Reducing diesel usage lowers both costs and CO_2 emissions. The integrated approach achieved consistent savings across scenarios.

- *Scenario 5:*
  - Diesel consumption decreased from 604.7 litres to 559.5 litres, representing a 7.5% reduction. This scenario benefitted from reduced idle times and fewer braking events.
- *Scenario 12:*
  - Fuel consumption dropped from 564.4 litres to 521.8 litres, showcasing a 7.5% savings. Improved coordination ensured that trucks operated more efficiently with fewer delays.
- *Scenario 9:*
  - *Diesel usage fell from 454.4 litres to 423.0 litres, marking a 6.9% reduction. The substantial reduction in idle time played a major role in achieving these savings.*

Key Observations on Diesel Consumption:

- Scenarios with higher payloads but fewer trips were consistently more fuel-efficient, as fewer trips reduced overall diesel usage.
- Diesel consumption closely followed the trends in idle time and braking events, emphasising the relationship between operational efficiency and fuel use.

5. Operational Costs: Economic Benefits of Efficiency

Operational costs provide a direct measure of the financial impact of hauling inefficiencies. By reducing idle time, diesel consumption, and braking events, the integrated approach delivered notable cost savings.

- *Scenario 5:*
  - Costs decreased from 22,080,000 to 20,640,000, reflecting a reduction of approximately 6.5%. The lower operational time and more efficient operations contributed to these savings.
- *Scenario 12:*
  - Costs dropped from 20,640,000 to 19,170,000, representing a 7.1% reduction. This scenario benefitted from streamlined scheduling and a reduction in delays.
- *Scenario 9:*
  - Costs fell from 15,480,000 to 14,385,000, marking the largest percentage decrease in cost (7.1%) among all scenarios. This reflects the cumulative impact of reductions in idle time and braking events.

Key Observations on Costs:

- Lower total time and reduced idle time were the primary drivers of cost savings.
- Scenarios with fewer trucks or higher payloads benefitted from economies of scale, leading to more significant cost reductions.

4-3-3-1 Scenarios with Divergent Outcomes:

Scenarios 6, 8, 10, and 11 exhibit distinctive outcomes when comparing Eco-hauling and the integrated approach. By examining key metrics such as total time, idle time, diesel consumption, and costs, these scenarios highlight both the opportunities and limitations of collaborative strategies in complex operational contexts.

1. Scenario 6:

   - In Eco-hauling, total time was 632 minutes, with idle time at 1762 minutes, diesel consumption at 1311.7 litres, and costs at T 47,400,000. The large fleet size (5 trucks) at moderate speed and payload contributed to inefficiencies.
   - With the integration approach, total time increased marginally to 636 minutes, idle time reduced slightly to 1690 minutes, and diesel consumption dropped to 1284.7 litres. Costs rose marginally to T 47,700,000, indicating limited benefits in this configuration.

2. Scenario 8:

- For Eco-hauling, total time was 916 minutes, with idle time at 863 minutes, diesel consumption at 1075.8 litres, and costs at T 41,220,000. High speed combined with low payloads resulted in frequent trips and high idle times.
- With integration, total time increased slightly to 926 minutes, idle time remained similar at 866 minutes, and diesel consumption saw negligible change at 1075.5 litres. Costs increased to T 41,670,000, reflecting the inefficiencies of high-speed, low-payload operations.

3. Scenario 10**:**

- Under Eco-hauling, total time was 914 minutes, idle time was 661 minutes, diesel consumption was 1072.0 litres, and costs were T 41,130,000. The low-speed configuration created bottlenecks, limiting operational efficiency.
- With integration, total time increased to 929 minutes, idle time rose to 677 minutes, diesel consumption increased to 1075.1 litres, and costs rose to T 41,805,000, showing that reduced speeds limit the benefits of collaborative strategies.

4. Scenario 11:

- In Eco-hauling, total time was 915 minutes, idle time was 2551 minutes, diesel consumption was 1829.2 litres, and costs were T 68,625,000. The combination of a large fleet and high delivery frequency amplified inefficiencies.
- With integration, total time rose slightly to 927 minutes, idle time decreased marginally to 2538 minutes, but diesel consumption increased to 1840.5 litres. Costs rose to T 69,525,000, highlighting the challenges of applying collaborative strategies to high-frequency scenarios.

Key Observations:

- Across these scenarios, Eco-hauling and the integrated approach yielded marginal differences, with minor improvements in idle time and fuel efficiency offset by increases in total time and costs.

- Scenarios with high delivery frequency, low payloads, or reduced speeds exhibited constrained benefits from integration, as inherent inefficiencies persisted despite collaborative strategies.

Scenarios featuring smaller fleets, higher payloads, and optimised speed configurations demonstrated more pronounced gains in idle time reduction, fuel savings, and cost efficiency. These configurations reveal the potential of integration strategies when applied to simpler, optimised contexts.

The findings emphasise the importance of matching the operational approach to the scenario's specific characteristics to achieve maximum efficiency gains.

The complex nature of Case Study 2 highlights the limited effectiveness of the integration of Eco-hauling and the Big Room approach when scenarios are restricted in number or scope. Scenarios with high delivery frequencies, reduced speeds, or low payloads constrain the potential benefits of these strategies, as inherent inefficiencies persist despite collaborative efforts. However, this does not undermine the capability of the BASE model itself.

By leveraging the full potential of the BASE model to identify optimised scenarios, its ability to select the most suitable configurations is evident. The BASE model excels in aligning operational parameters with sustainability goals, showcasing its strength in guiding decision-making towards efficiency and reduced emissions.

Key Insights of Initial Scenarios

Fleet Size and Efficiency: Scenarios with fewer trucks demonstrated greater operational efficiency. A smaller fleet size, combined with higher payloads, resulted in reduced total time, idle time, and fuel consumption, highlighting the importance of strategic fleet sizing.

Payload Optimisation: Scenarios with higher payloads consistently performed better in terms of efficiency and cost savings. These scenarios required fewer trips, reducing idle time and braking events, while maximising resource utilisation.

Collaborative Decision-Making: The integration of collaborative scheduling and the Big Room approach played a critical role in improving performance metrics. Enhanced communication among stakeholders helped address bottlenecks and streamline operations.

Trade-Offs Between Time and Cost: While total time reductions were achieved in many scenarios, some involved trade-offs, as prioritising cost reductions occasionally resulted in marginal increases in operational time. These trade-offs must be considered to balance operational goals effectively.

Complexity of Case Study 2: Compared to Case Study 1, the integrated approach in Case Study 2 was less effective. This can largely be attributed to the more complex nature of the operations in Case Study 2, which involved dynamic interactions between trucks and the asphalt paver and additional bottlenecks at intersections. These complexities limited the full realisation of the benefits observed in simpler scenarios.

The findings from Case Study 2 provide valuable insights into the role of collaborative planning and optimisation in improving construction logistics. In 13 scenarios, enhancements were observed in key performance metrics, including total time, idle time, braking events, diesel consumption, and operational costs. However, the degree of improvement varied depending on operational parameters such as payload size, the number of trucks, and the complexity of the route. Scenarios with fewer trucks or larger payloads demonstrated the most significant gains, underscoring the importance of carefully balancing these factors to maximise efficiency.

Scenarios 6, 8, 10, and 11 show the limitations of Eco-Hauling and Big Room. The effectiveness of integrating these methods remains questioned. Yet, it is worth noting that these are the initial scenarios, not all the options.

Despite these limitations, the analysis highlights the considerable potential of adopting collaborative and optimisation-driven strategies in construction logistics. By addressing inefficiencies and refining operations, these techniques can deliver meaningful improvements in both economic and environmental performance, paving the way for more sustainable construction practices.

4-3-3-2 Analysis of CO_2 Emissions

In Case Study 2, the scenario involved asphalt hauling between a plant and a paver. Unlike the relatively straightforward operations in Case 1, this case required a model capable of addressing the dynamic and interdependent relationship between the paver's variable speed and the flow of dumper trucks. These complexities demanded a more sophisticated approach that combined the efficiency of Eco-hauling with the collaborative power of the Big Room approach. Together, these strategies provided significant improvements across key operational metrics, particularly in reducing idle time and operational costs. However, their impact on CO_2 emissions proved to be more nuanced, with some scenarios failing to achieve consistent reductions.

One of the most critical metrics in evaluating sustainability is CO_2 emissions, as they directly measure the environmental impact of operations. The Eco-hauling model contributed significantly to emission reductions by optimising routes and minimising fuel consumption. By ensuring trucks operated at efficient speeds and reducing idle times, Eco-hauling helped limit the overall carbon footprint of the hauling operations.

When the Big Room approach was integrated with Eco-hauling, additional improvements were observed in many scenarios. Enhanced coordination between stakeholders allowed for better scheduling of truck dispatches, aligning them more closely with the paver's variable speed. This reduced unnecessary movements and prolonged idling, further lowering CO_2 emissions. However, the integration did not always lead to consistent reductions. In certain cases, increased coordination efforts introduced minor inefficiencies. For example, trucks occasionally experienced delays at checkpoints or required additional movements to align with updated schedules. These inefficiencies, while small, contributed to marginal increases in CO_2 emissions in specific scenarios.

The variability in outcomes highlights the complexities of integrating multiple dynamic systems. While the Big Room approach improved overall operational efficiency, the interplay between truck movements, paver speed, and stakeholder coordination sometimes led to unintended consequences. For instance, prolonged synchronisation efforts at checkpoints could result in additional idling, negating the emissions savings achieved through route optimisation. Similarly, the need for real-time adjustments occasionally caused trucks to travel extra distances, slightly increasing fuel consumption and emissions.

These challenges underline the importance of continuous refinement of the integrated model. Future iterations of the Eco-hauling and Big Room approach must focus on mitigating these minor inefficiencies to ensure consistent reductions in CO_2 emissions across all scenarios. This could involve enhanced predictive algorithms to optimise truck dispatching further, reducing the likelihood of delays or extra movements. Additionally, improved real-time communication tools could help stakeholders coordinate more effectively, minimising synchronisation delays.

1. *Scenario-Specific Insights*

- Scenarios with Higher Emissions:

  Scenarios involving fewer trucks and lower payload capacities often recorded higher emissions due to longer operational times and increased inefficiencies. For instance:

  - Scenario 6, which operated with 5 trucks and an 8-tonne payload, emitted 3436.6 kg of CO_2 under Eco-hauling and 3365.9 kg under the Big Room strategy, achieving a reduction of 2.1%.
  - Scenario 11, using 5 trucks with a payload of 4 tonnes, emitted 4822.1 kg under Eco-hauling and 4792.5 kg under the Big Room strategy, representing a reduction of 0.6%.

2. *Scenarios with Lower Emissions:*

   Lower CO_2 emissions were observed in scenarios where key variables were optimised. Scenarios with moderate fleet sizes (2–3 trucks), higher payloads (8–16 tonnes), and balanced speeds significantly reduced emissions. For example:

   - Scenario 5, with 2 trucks and a payload of 8 tonnes, achieved emissions of 1584.3 kg under Eco-hauling, which dropped to 1465.8 kg under the Big Room strategy, a reduction of 7.5%.
   - Scenario 9, using 1 truck with a payload of 16 tonnes, recorded emissions of 1190.6 kg under Eco-hauling, reduced to 1108.3 kg under the Big Room strategy, a reduction of 6.9%.
   - Scenario 17, which employed 2 trucks at 20 km/h with a payload of 16 tonnes, recorded emissions of 1436.4 kg under Eco-hauling, reduced to 1415.4 kg under the Big Room strategy, a 1.5% reduction.

The impact of the Eco-hauling and Big Room approach on CO_2 emissions reveals both its potential and its challenges. While the combined model achieved significant reductions in many scenarios, the occasional increases in emissions highlight the complexities of aligning dynamic systems with environmental goals. These findings reinforce the importance of ongoing refinement and innovation. By addressing the minor inefficiencies observed, future iterations of this integrated approach can deliver consistent and meaningful reductions in CO_2 emissions, aligning operational efficiency with sustainability objectives.

Furthermore, expanding the range of scenarios and operational configurations would allow for a more thorough exploration of the model's capabilities. Broader scenario testing would provide opportunities to fine-tune operational strategies and better utilise the flexibility of the BASE model.

The potential to transform construction logistics into a more environmentally responsible practice remains substantial, provided these challenges are met with targeted solutions.

4-3-4 Optimisation with Response Surface Methodology for Case Study 2

The optimisation stage for Case Study 2 represents a pivotal moment in transitioning from simulation outcomes to actionable recommendations. By employing advanced analytical methods such as Response Surface Methodology (RSM) within Stat-Ease software, this stage explores the complex interactions between input variables—such as fleet size, payload capacity, and speed—and key performance metrics, including total time, idle time, operational costs, braking events, CO_2 emissions, and diesel consumption.

Case Study 2 focuses on the transportation of 416 tonnes of asphalt over a 2660-meter loop in a dynamic construction environment. Unlike Case Study 1, where operational parameters were more straightforward, the complexity of Case Study 2 lies in its varied truck configurations, payloads ranging from 4 to 16 tonnes, and speeds between 20 km/h and 40 km/h. These variations add layers of operational challenges, such as bottlenecks at loading and unloading points, as well as the critical issue of synchronisation between dumper trucks and the asphalt paver.

Maintaining a steady supply of asphalt without interruptions is essential for ensuring the quality of paving operations, but mismatches in timing can lead to delays, idle time, and inefficiencies that ripple through the entire operation.

Unlike Case Study 1, where the integration of Eco-Hauling and the Big Room approach consistently delivered superior performance across all scenarios, Case Study 2 exhibited varied outcomes. Of the 17 scenarios analysed, 13 scenarios demonstrated improved performance when integrating the Eco-Hauling and Big Room strategies, while the remaining four scenarios displayed constrained benefits due to the inherent complexities of the operations.

Despite this, we focus solely on the scenarios that integrated the Eco-Hauling and Big Room approach for optimisation. This decision is justified by the fact that these scenarios represent the configurations with the greatest potential for achieving sustainability goals and operational efficiency. While the remaining four scenarios provide valuable insights into the limits of integration, they do not offer the same level of opportunity for meaningful advancements in performance.

This methodology capitalises on the diverse set of scenarios generated during the simulation phase, enabling a detailed evaluation of key variable interactions and their influence on performance. Surface graphs and 3D plots provide a visual representation of these relationships, illustrating how changes in operational parameters affect sustainability and efficiency. For example, the interplay between payload size and vehicle speed can reveal configurations that reduce environmental impact while maintaining high-performance standards.

The primary objectives of this section are to:

1. Analyse Key Metrics: Evaluate total time, idle time, operational costs, braking events, CO_2 emissions, and diesel consumption in detail using surface graph visualisations.
2. Identify Critical Interactions: Highlight trends, trade-offs, and synergies that influence performance outcomes.
3. Optimise Configurations: Establish a foundation for identifying configurations that balance operational efficiency, cost, and sustainability.

By delving into the six critical performance indicators and leveraging the insights from the integrated scenarios, this analysis bridges the gap between raw data and practical, optimised solutions. The findings will guide the identification of operational configurations that support sustainability goals while ensuring economic and logistical feasibility for real-world implementation.

4-3-4-1 Analysis of Total Time Surface Graph for Integration of Eco-Hauling and Big Room Approach

The surface graph for Total Time provides critical insights into the relationship between payload and the number of trucks under the integrated Eco-Hauling and Big Room approach. This metric is vital for assessing overall operational efficiency, as it reflects the duration required to complete the transportation of asphalt in different configurations (Figure 4.7).

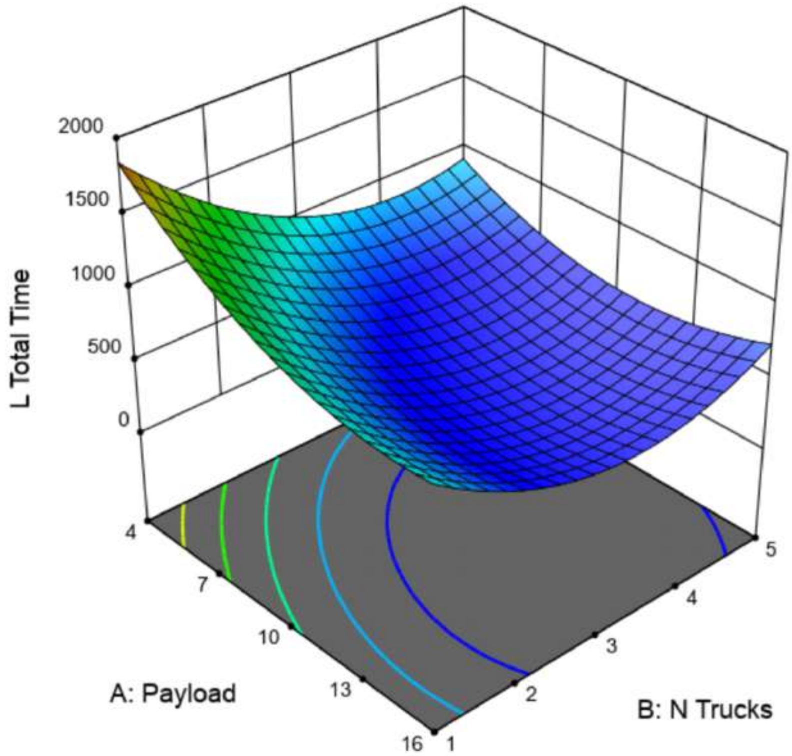


Fig. 4.7: Surface Graph of Total Time for the Integration of Eco-Hauling and Big Room – Case 2

The effect of payload on total time is evident in the graph. Configurations with smaller payloads (4–7 tonnes) result in significantly higher total times. This is because smaller payloads necessitate more trips to transport the same volume of asphalt, leading to prolonged operational durations. In contrast, scenarios with larger payloads (13–16 tonnes) show a substantial reduction in total time. Fewer trips are required, which streamlines the transportation cycle, particularly when the number of trucks is optimised.

Fleet size also plays a critical role in determining total time. Smaller fleets (1–2 trucks) exhibit significantly higher total times, even with larger payloads. This is due to the increased workload per truck, resulting in longer operational cycles. On the other hand, larger fleets (4–5 trucks) demonstrate marked improvements in total time. The workload is distributed more effectively among the trucks, reducing waiting times at loading and unloading points. However, it is worth noting that the benefits of adding more trucks diminish when fleet sizes become excessive, as congestion at key points starts to offset the advantages.

The graph reveals an optimal configuration where the lowest total time is observed. This occurs when payloads are between 13–16 tonnes and the fleet size is in the range of 3–4 trucks. Beyond these values, further increases in fleet size provide diminishing returns due to operational bottlenecks. Synchronisation challenges between dumper trucks and the asphalt paver emerge as a significant issue in scenarios with either too few or too many trucks. Inadequate fleet sizes result in delays in asphalt supply to the paver, whereas excessive fleets lead to congestion at unloading points, increasing total time.

Although speed is not represented directly in this graph, it remains a critical variable and is considered during optimisation as a fourth dimension. The effect of speed on total time varies depending on the payload and fleet size. For scenarios with smaller fleets and lower payloads, increasing speed significantly reduces total time. Faster truck movement enables quicker cycles, which compensates for the smaller payload capacities and limited fleet sizes. Conversely, in scenarios with larger fleets and higher payloads, increasing speed can lead to an increase in total time. Higher speeds exacerbate synchronisation issues and create inefficiencies at loading and unloading points, as trucks arrive too quickly for the system to handle effectively. This interplay underscores the importance of balancing speed with payload and fleet size to achieve optimal performance.

The trends observed in the graph highlight several trade-offs. Larger payloads reduce total time but require optimised fleet sizes to maintain efficiency. Similarly, smaller fleets demand higher payloads to avoid excessive cycle times. These results underscore the operational complexity of Case Study 2, demonstrating the need for precise adjustments to address synchronisation issues and bottlenecks.

In comparison to Case Study 1, where total time reductions were more consistent across scenarios due to simpler operational dynamics, Case Study 2 requires more intricate adjustments. The additional complexity arises from the need to synchronise trucks with the asphalt paver and manage congestion at key points.

- **Practical Implications**

  1. *Configuration Recommendations*:
     - Payloads of 13–16 tonnes and 3–4 trucks are ideal for achieving time efficiency. These configurations significantly reduce total operational time by minimising the number of trips required, helping to streamline logistics.
  2. *Environmental Benefits:*
     - By reducing the number of trips required and minimising total time, these configurations help lower fuel consumption and CO_2 emissions. This contributes to sustainability objectives and aligns with efforts to reduce the environmental footprint of construction logistics.
  3. *Operational Efficiency:*
     - Minimising total time not only enhances project efficiency but also reduces fuel consumption. This directly supports sustainability goals by decreasing overall energy use and lowering emissions.
  4. *Trade-Offs:*
     - While increasing payload and fleet size improves total time performance, exceeding 4–5 trucks introduce inefficiencies such as congestion at loading and unloading points. This can negate the benefits of optimisation by increasing overall cycle time.

In summary, the analysis of total time underscores the critical need for balanced configurations in payload size, fleet size, and speed. By adopting these optimal strategies, stakeholders can achieve operational efficiency, cost savings, and significant sustainability gains.

4-3-4-2 Analysis of Idle Time Surface Graph for Integration of Eco-Hauling and Big Room Approach

The surface graph for Idle Time offers a detailed look into the interaction between payload and the number of trucks and their influence on idle time under the integrated Eco-Hauling and Big Room approach. Idle time serves as a crucial metric for operational efficiency, as it reflects periods of inactivity that contribute to delays and inefficiencies (Figure 4.8).

The graph demonstrates that idle time decreases as payload increases. Configurations with smaller payloads (4–7 tonnes) result in significantly higher idle time due to the increased number of trips required and the frequent waiting periods at loading and unloading points. In contrast, larger payloads (13–16 tonnes) lead to a considerable reduction in idle time, as fewer trips are needed to transport the same volume of asphalt. However, the number of trucks also plays a significant role in influencing idle time.

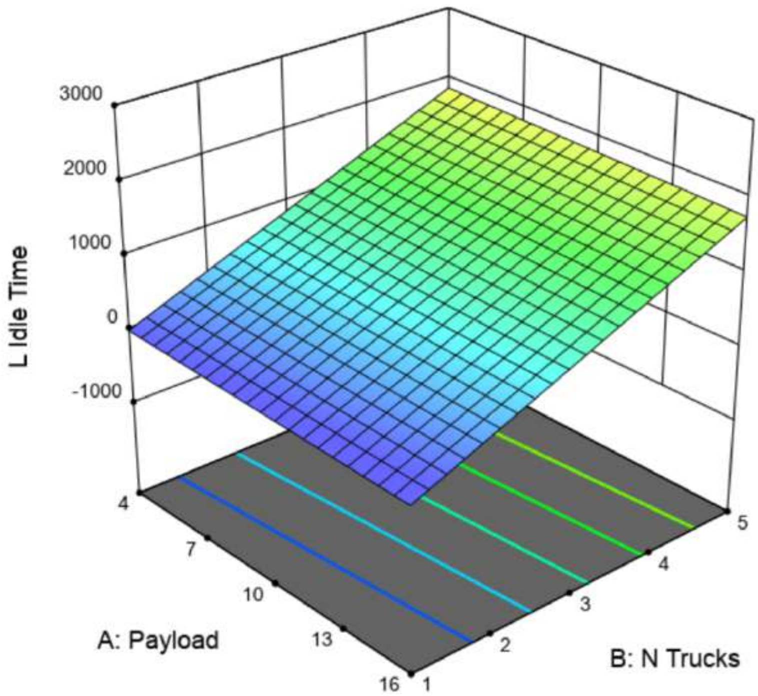


Fig. 4.8: Surface Graph of Idle Time for the Integration of Eco-Hauling and Big Room – Case 2

Smaller fleets (1–2 trucks) exhibit lower idle time in scenarios with larger payloads. This is because the limited number of trucks ensures a steady workflow with minimal bottlenecks. However, for smaller payloads, idle time increases even for smaller fleets, as the trucks spend more time waiting due to the increased cycle frequency. Larger fleets (4–5 trucks), on the other hand, show higher idle time overall, particularly with smaller payloads. This is due to congestion and inefficiencies caused by too many trucks competing for limited loading and unloading resources.

The optimal configuration for minimising idle time is observed when payloads are between 13–16 tonnes and fleet size is 2–3 trucks. These configurations ensure a smooth flow of operations with minimal waiting periods. Beyond these values, idle time starts to increase due to excessive competition at key points in the operation.

Speed, though not directly represented in the graph, plays an important role in influencing idle time. Higher speeds lead to higher idle time, as trucks arrive too quickly for the system to handle, causing congestion at loading and unloading points. Conversely, lower speeds result in lower idle time, as trucks arrive in a more controlled and synchronised manner, ensuring smoother operations and reducing waiting periods.

The trends in the graph highlight several operational trade-offs. While increasing payloads reduces idle time, it also requires careful management of fleet size to avoid congestion. Similarly, smaller fleets are more efficient for larger payloads but less so for smaller payloads. These findings demonstrate the need for precise optimisation of operational parameters to achieve efficiency.

In comparison to Case Study 1, where idle time reductions were more uniform across scenarios, Case Study 2 presents additional complexities. The synchronisation of trucks with the asphalt paver and the management of loading and unloading points are critical factors that influence idle time in this case.

- **Practical Implications**

1. *Configuration Recommendations:*
   - Payloads of 13–16 tonnes and fleet sizes of 2–3 trucks are ideal for minimising idle time. These configurations streamline operations and reduce waiting periods.
2. *Operational Efficiency:*
   - Reducing idle time directly enhances overall operational efficiency by eliminating unnecessary delays. This leads to faster project completion and lower operational costs.
3. *Environmental Benefits:*
   - Minimising idle time reduces unnecessary fuel consumption and associated CO_2 emissions, contributing directly to environmental sustainability by optimising resource use.
   -
4. *Trade-Offs:*
   - While larger payloads and smaller fleets improve idle time performance, excessive fleet sizes (4–5 trucks) or smaller payloads increase idle time due to congestion and inefficiencies at loading and unloading points.

In summary, the analysis of idle time highlights the importance of balancing payload size, fleet size, and speed to minimise operational delays. By focusing on these optimal configurations, stakeholders can achieve more efficient operations and significant cost savings.

4-3-4-3 Analysis of Brakes Events Surface Graph for Integration of Eco-Hauling and Big Room Approach

The surface graph for Number of Brakes provides valuable insights into the relationship between payload and the number of trucks under the integrated Eco-Hauling and Big Room approach. The number of braking events is a crucial metric for assessing operational smoothness and efficiency, as frequent braking indicates interruptions, inefficiencies, and potential wear-and-tear on machinery (Figure 4.9).

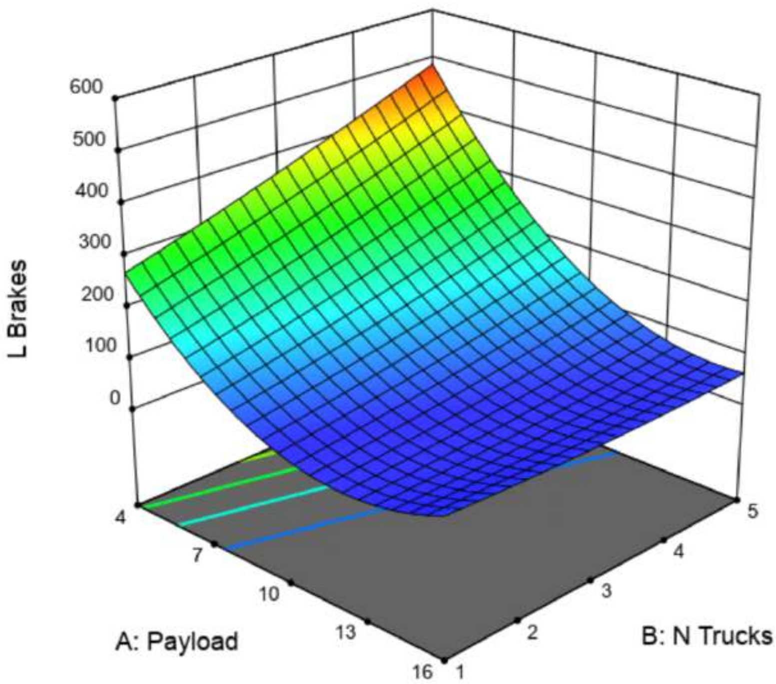


Fig. 4.9: Surface Graph of Brakes Events for the Integration of Eco-Hauling and Big Room – Case 2

The impact of payload on the number of brakes is evident in the graph. Configurations with smaller payloads (4–7 tonnes) exhibit significantly higher braking events. This is attributed to the increased number of trips required to transport the asphalt, resulting in more frequent stops and starts. Conversely, larger payloads (13–16 tonnes) lead to a substantial reduction in the number of braking events. Fewer trips mean fewer interruptions, resulting in smoother and more efficient operations.

Fleet size also plays a critical role in determining the number of braking events. Smaller fleets (1–2 trucks) demonstrate fewer braking events overall, particularly with larger payloads. This is due to less congestion and more predictable movement patterns within the operation. On the other hand, larger fleets (4–5 trucks) show an increase in braking events, especially with smaller payloads. The higher number of trucks leads to competition for loading and unloading points, causing more frequent braking.

The graph indicates an optimal configuration for minimising braking events. This occurs when payloads are between 13–16 tonnes and fleet sizes are 2–3 trucks. These configurations balance the workload and ensure smoother operations with fewer interruptions. However, excessive fleet sizes lead to diminishing returns due to congestion and inefficiencies.

Although speed is not explicitly represented in this graph, it remains a critical variable influencing braking events. When speed increases, scenarios with lower payloads show a sharp rise in the number of braking events. This is due to the increased number of trips required to transport the asphalt in these configurations, which results in more frequent acceleration and deceleration. However, for other configurations, such as those with higher payloads and optimised fleet sizes, changes in speed have a negligible impact on the number of brakes. Moderate speeds generally promote smoother and more controlled operations.

The trends observed in the graph highlight several trade-offs. While larger payloads reduce braking events, they require careful fleet size management to avoid congestion. Similarly, smaller fleets are more efficient for braking performance but may face capacity limitations. These findings underline the importance of fine-tuning operational parameters to optimise performance.

In comparison to Case Study 1, where the number of braking events was uniformly lower across scenarios, Case Study 2 presents added challenges. The complexities of synchronising truck movements and managing congestion at loading and unloading points significantly influence braking performance.

- **Practical Implications**

  1. *Configuration Recommendations:*
     - Payloads of 13–16 tonnes and fleet sizes of 2–3 trucks are recommended to minimise braking events. These configurations promote smoother operations and reduce mechanical wear-and-tear.
  2. *Environmental Benefits:*
     - Reducing braking events directly decreases fuel consumption and emissions. Smoother operations minimise energy waste associated with frequent acceleration and deceleration, contributing to environmental sustainability.

3. *Operational Efficiency:*
    - Minimising braking events enhances operational efficiency by reducing delays and maintaining consistent movement patterns. This leads to faster project completion and lower maintenance costs.
4. *Trade-Offs:*
    - While larger payloads and smaller fleets improve braking performance, excessive fleet sizes (4–5 trucks) or smaller payloads lead to higher braking events due to congestion and inefficiencies at key points.

In summary, the analysis of braking events underscores the need for balanced configurations in payload size, fleet size, and speed to optimise operational smoothness. By focusing on these optimal strategies, stakeholders can achieve reduced mechanical wear, fuel savings, and environmental benefits.

4-3-4-4 Analysis of Diesel Consumption Surface Graph for Integration of Eco-Hauling and Big Room Approach

The surface graph for Diesel Consumption provides critical insights into the relationship between payload and the number of trucks under the integrated Eco-Hauling and Big Room approach. Diesel consumption is a key metric for evaluating both operational efficiency and environmental impact, as it directly correlates to fuel costs and CO_2 emissions (Figure 4.10).

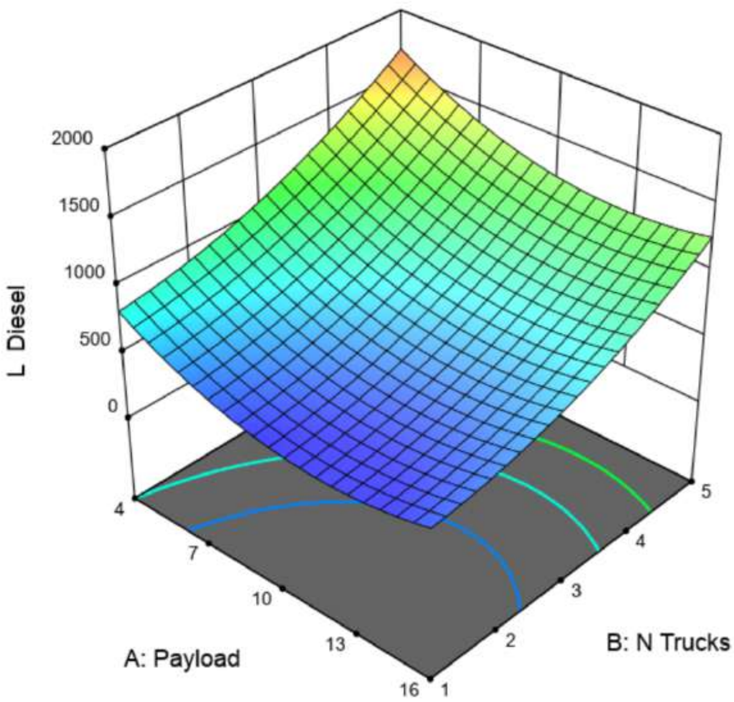


Fig. 4.10: Surface Graph of Diesel Consumption for the Integration of Eco-Hauling and Big Room – Case 2

The impact of payload on diesel consumption is evident in the graph. Configurations with smaller payloads (4–7 tonnes) exhibit significantly higher diesel usage due to the increased number of trips required to transport the same volume of asphalt. Conversely, larger payloads (13–16 tonnes) result in lower diesel consumption as fewer trips are necessary, optimising fuel efficiency.

Fleet size also plays a crucial role in diesel consumption. Smaller fleets (1–2 trucks) show lower diesel consumption overall, particularly with larger payloads. The reduced number of vehicles contributes to less cumulative fuel usage. On the other hand, larger fleets (4–5 trucks) demonstrate higher diesel consumption, especially with smaller payloads. The increased number of vehicles amplifies fuel usage, particularly in scenarios with suboptimal payload configurations.

The graph indicates an optimal configuration for minimising diesel consumption. This occurs when payloads are between 13–16 tonnes and fleet sizes are 2–3 trucks. These configurations strike a balance between the number of trips and the fleet size, ensuring fuel efficiency and reduced environmental impact. Beyond this range, diesel consumption increases due to inefficiencies associated with excessive fleet sizes or smaller payloads.

Speed, though not explicitly represented in this graph, has a moderate influence on diesel consumption. When speed increases, scenarios with higher payloads and a greater number of trucks show a slight rise in diesel usage. This is attributed to the increased engine demand during rapid acceleration and deceleration in these configurations. However, for other configurations, such as those with smaller payloads and fewer trucks, changes in speed have a negligible impact on diesel consumption. Moderate speeds continue to optimise fuel efficiency by promoting smoother and more consistent operations.

The trends observed in the graph highlight several trade-offs. While larger payloads reduce diesel consumption, they require careful fleet size management to maximise efficiency. Similarly, smaller fleets are advantageous for fuel usage but may face limitations in handling larger operational demands. These findings underline the importance of optimising operational parameters to achieve both economic and environmental goals.

In comparison to Case Study 1, where diesel consumption trends were more predictable, Case Study 2 presents additional complexities. The dynamic interactions between payload, fleet size, and operational factors significantly influence fuel usage, necessitating a more nuanced approach to optimisation.

- **Practical Implications**

  1. *Configuration Recommendations:*
     - Payloads of 13–16 tonnes and fleet sizes of 2–3 trucks are recommended to minimise diesel consumption. These configurations optimise fuel efficiency by reducing the number of trips and balancing vehicle usage.
  2. *Environmental Benefits:*
     - Minimising diesel consumption directly reduces CO_2 emissions and contributes to sustainability objectives. Efficient configurations lower the carbon footprint of construction operations while reducing fuel costs.
  3. *Operational Efficiency:*
     - Reducing diesel consumption enhances overall operational efficiency by lowering fuel costs and improving resource utilisation. This directly supports both economic and environmental goals.
  4. *Trade-Offs:*
     - While larger payloads and smaller fleets improve diesel efficiency, excessive fleet sizes (4–5 trucks) or smaller payloads lead to higher fuel consumption due to inefficiencies and increased operational demand.

In summary, the analysis of diesel consumption underscores the need for balanced configurations in payload size, fleet size, and speed to optimise fuel efficiency. By adopting these optimal strategies, stakeholders can achieve significant cost savings, reduce environmental impact, and enhance overall operational performance.

4-3-4-5 Analysis of CO_2 Emissions Surface Graph for Integration of Eco-Hauling and Big Room Approach

The surface graph for CO_2 Emissions provides critical insights into the relationship between payload and the number of trucks under the integrated Eco-Hauling and Big Room approach. CO_2 emissions are a direct indicator of the environmental impact of operations, making this metric essential for assessing sustainability (Figure 4.11).

The impact of payload on CO_2 emissions is clearly visible in the graph. Configurations with smaller payloads (4–7 tonnes) result in significantly higher emissions due to the increased number of trips required to transport the same volume of asphalt. In contrast, larger payloads (13–16 tonnes) lead to a substantial reduction in emissions as fewer trips are needed, optimising the overall fuel efficiency of operations.

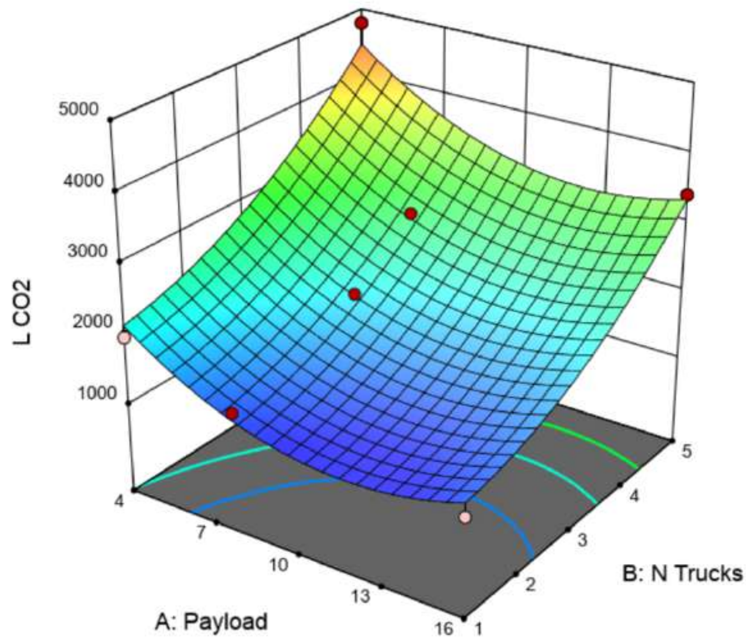


Fig. 4.11: Surface Graph of CO_2 Emissions for the Integration of Eco-Hauling and Big Room – Case 2

Fleet size also has a notable effect on CO_2 emissions. Smaller fleets (1–2 trucks) exhibit lower emissions overall, particularly with larger payloads. This is due to the reduced number of vehicles contributing to cumulative emissions. Conversely, larger fleets (4–5 trucks) result in higher emissions, especially with smaller payloads. The increased number of vehicles amplifies fuel usage and associated emissions in these configurations.

The graph highlights an optimal configuration for minimising CO_2 emissions. This occurs when payloads are between 13–16 tonnes and fleet sizes are 2–3 trucks. These configurations balance the number of trips and fleet size, ensuring maximum fuel efficiency and reduced environmental impact. Beyond this range, emissions increase due to inefficiencies caused by excessive fleet sizes or smaller payloads.

Speed, while not explicitly represented in this graph, has a moderate influence on CO_2 emissions. When speed increases, scenarios with higher payloads and a greater number of trucks show a slight rise in emissions. This is due to increased engine demand during rapid acceleration and deceleration in these configurations. However, for other configurations, such as those with smaller payloads and fewer trucks, changes in speed have a negligible impact on emissions. Moderate speeds remain optimal for minimising environmental impact by promoting smoother and more efficient operations.

The trends observed in the graph underscore several trade-offs. While larger payloads reduce CO_2 emissions, they require careful fleet size management to maximise efficiency. Similarly, smaller fleets are advantageous for reducing emissions but may face limitations in handling larger operational demands. These findings highlight the importance of fine-tuning operational parameters to balance economic and environmental goals.

In comparison to Case Study 1, where CO_2 emissions followed more predictable trends, Case Study 2 introduces additional complexities. The dynamic interactions between payload, fleet size, and operational factors significantly influence emissions, necessitating a more detailed approach to optimisation.

- **Practical Implications**

1. *Configuration Recommendations:*
   - Payloads of 13–16 tonnes and fleet sizes of 2–3 trucks are recommended to minimise CO_2 emissions. These configurations optimise fuel usage and reduce the environmental footprint of operations.
2. *Environmental Benefits:*
   - Minimising CO_2 emissions directly contributes to sustainability objectives. Efficient configurations lower the carbon footprint of construction logistics while supporting decarbonisation efforts in the industry.
3. *Operational Efficiency:*
   - Reducing CO_2 emissions aligns with operational efficiency by improving resource utilisation and reducing fuel consumption. This supports both economic and environmental goals.
4. *Trade-Offs:*
   - While larger payloads and smaller fleets improve emissions performance, excessive fleet sizes (4–5 trucks) or smaller payloads lead to higher emissions due to inefficiencies and increased operational demand.

In summary, the analysis of CO_2 emissions underscores the critical need for balanced configurations in payload size, fleet size, and speed to optimise environmental performance. By adopting these optimal strategies, stakeholders can achieve substantial sustainability gains while maintaining operational efficiency.

4-3-4-6 Analysis of Rental Costs Surface Graph for Integration of Eco-Hauling and Big Room Approach

The surface graph for Rental Costs provides critical insights into the relationship between payload and the number of trucks under the integrated Eco-Hauling and Big Room approach.

Rental cost is a key metric for assessing the financial feasibility of operations, as it directly correlates to the efficiency of resource utilisation and operational configuration (Figure 4.12).

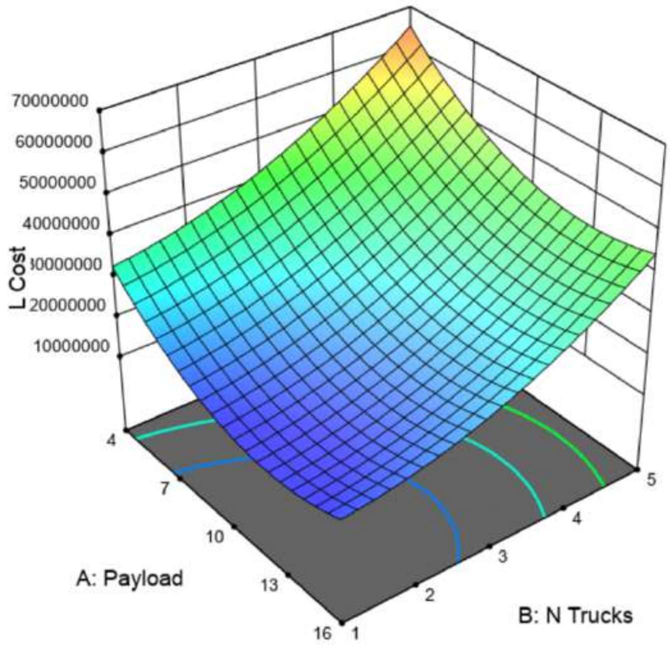


Fig. 4.12: Surface Graph of Rental Costs for the Integration of Eco-Hauling and Big Room – Case 2

The impact of payload on rental cost is evident in the graph. Configurations with smaller payloads (4–7 tonnes) result in significantly higher costs due to the increased number of trips required to transport the same volume of asphalt. In contrast, larger payloads (13–16 tonnes) lead to a reduction in rental costs as fewer trips are needed, maximising resource efficiency. Fleet size also plays a crucial role in determining rental costs. Smaller fleets (1–2 trucks) show lower costs overall, particularly with larger payloads. This is due to the reduced number of vehicles contributing to cumulative rental expenses. On the other hand, larger fleets (4–5 trucks) demonstrate higher costs, especially with smaller payloads. The increased number of vehicles amplifies rental expenses in these configurations, particularly when payloads are not optimised.

The graph indicates an optimal configuration for minimising rental costs. This occurs when payloads are between 13–16 tonnes, and fleet sizes are 2–3 trucks. These configurations balance the number of trips and fleet size, ensuring cost-efficiency. Beyond this range, rental costs increase due to inefficiencies associated with excessive fleet sizes or smaller payloads. Speed, while not explicitly represented in this graph, has a moderate influence on rental costs. When speed increases, scenarios with higher payloads and a greater number of trucks show a slight rise in rental expenses due to increased operational strain. However, speed changes have a negligible impact on rental cost for other configurations, such as those with smaller payloads and fewer trucks. Moderate speeds are optimal for maintaining cost-efficiency by promoting smoother and more consistent operations.

The trends observed in the graph highlight several trade-offs. While larger payloads reduce rental costs, they require careful fleet size management to maximise efficiency. Similarly, smaller fleets are advantageous for cost reduction but may face limitations in handling larger operational demands. These findings underscore the importance of optimising operational parameters to balance financial and operational goals.

In comparison to Case Study 1, where rental cost trends were more predictable, Case Study 2 introduces additional complexities. The dynamic interactions between payload, fleet size, and operational factors significantly influence rental expenses, requiring a more nuanced approach to optimisation.

- **Practical Implications**

1. *Configuration Recommendations:*
    - Payloads of 13–16 tonnes and fleet sizes of 2–3 trucks are recommended to minimise rental costs. These configurations optimise resource utilisation and reduce cumulative expenses.
2. *Environmental Benefits:*
    - Minimising rental costs aligns with reducing unnecessary resource usage, which indirectly supports sustainability objectives by promoting efficient operations.
3. *Operational Efficiency:*
    - Reducing rental costs enhances overall operational efficiency by improving resource allocation and minimising financial waste. This directly supports both economic and operational goals.
4. *Trade-Offs:*
    - While larger payloads and smaller fleets improve cost-efficiency, excessive fleet sizes (4–5 trucks) or smaller payloads lead to higher expenses due to inefficiencies and increased operational demand.

In summary, the analysis of rental cost underscores the critical need for balanced configurations in payload size, fleet size, and speed to optimise financial performance. By adopting these optimal strategies, stakeholders can save significant costs while maintaining operational efficiency.

4-3-5 Optimised Scenarios Analysis - Case 2

Employing Stat-Ease optimisation tools, three optimised scenarios were identified based on weightings of varying importance between time and carbon emissions. Advanced tools like Stat-Ease enabled the evaluation of over 1,350 configurations, greatly expanding the scenario pool and enhancing the ability to identify and optimise solutions tailored to specific operational needs. These scenarios provide contractors with tailored configurations to address specific project priorities, whether focusing on reducing CO_2 emissions, minimising total time, or achieving a balanced approach. By leveraging these suggestions, contractors can optimise their operations to align with environmental, economic, and project-specific goals (Table 4.9). The table summarises the optimised inputs and outputs for each scenario, demonstrating how different configurations impact key performance metrics:

Table 4.9: Optimised Scenarios – Case Study 2

Strategies	Inputs				Outputs					
	No of Deliveries	Speed KM/h	Payload Tonnes	No of Trucks	Total Time Mins	Idle Time Mins	No of Brakes	Diesel Litres	CO2 Kg CO2	Cost Tomans
Time 50% - Carbon 50%	26	20	16	2	623	235	78	540.2	1415.4	18,690,000
Time 0% - Carbon 100%	26	20	16	1	991	0	52	434.5	1138.5	14,865,000
Time 100% - Carbon 0%	26	20	16	4	602	812	101	1024.9	2685.3	36,120,000

The optimised scenarios suggest varying approaches based on the priority given to time and carbon emissions. Below is a comprehensive analysis of the three configurations:

1. Balanced Importance Weightings (50% Time, 50% Carbon)

- *Inputs:* This configuration involves 2 trucks operating at a speed of 20 km/h, with a payload capacity of 16 tonnes per truck. The number of deliveries is 26.
- *Outputs:*
  - Total Time: 623 minutes, showcasing efficient operations.
  - Idle Time: 235 minutes, reflecting moderate waiting times.
  - Braking Events: 78, representing smooth traffic flow.
  - Diesel Consumption: 540.2 litres, reflecting efficient fuel usage.
  - CO_2 Emissions: 1,415.4 kg, balancing environmental impact and operational efficiency.

- Cost: 18,690,000 Tomans, demonstrating cost-effectiveness while maintaining environmental considerations.

This configuration represents a balanced approach that achieves reasonable reductions in both time and carbon emissions. Contractors prioritising both operational efficiency and sustainability can benefit from this scenario.

2. Carbon-Focused Configuration (100% Carbon, 0% Time)

- *Inputs:* This configuration uses a single truck operating at 20 km/h with a payload of 16 tonnes, completing 26 deliveries.
- *Outputs:*
  - Total Time: 991 minutes, significantly longer due to the reduced fleet size.
  - Idle Time: 0 minutes, demonstrating efficient use of the single truck with no waiting time.
  - Braking Events: 52, slightly lower than the balanced configuration.
  - Diesel Consumption: 434.5 litres, the lowest among the three scenarios.
  - CO_2 Emissions: 1,138.5 kg, representing the most substantial emissions reduction.
  - Cost: 14,865,000 Tomans, the most cost-effective scenario.

This scenario prioritises carbon reduction at the expense of operational time. It is ideal for projects with strict environmental requirements and flexible timelines. Contractors focused on minimising environmental impact will find this configuration particularly beneficial.

3. Time-Focused Configuration (100% Time, 0% Carbon)

- *Inputs:* This setup involves 4 trucks operating at 20 km/h, with a payload of 16 tonnes, completing 26 deliveries.
- *Outputs:*
  - Total Time: 602 minutes, the shortest operational duration.
  - Idle Time: 812 minutes, indicating potential inefficiencies due to over-deployment of trucks.
  - Braking Events: 101, the highest among the three scenarios.

- Diesel Consumption: 1,024.9 litres, the highest fuel usage.
- CO_2 Emissions: 2,685.3 kg, higher than the other configurations.
- Cost: 36,120,000 Tomans, the most expensive scenario.

This scenario prioritises time efficiency, making it suitable for projects with tight deadlines. However, the trade-off includes higher emissions and costs, which may not align with sustainability goals.

- **Comparative Analysis**

1. Environmental Impact:

- The carbon-focused scenario achieves the lowest CO_2 emissions (1,138.5 kg), demonstrating its alignment with decarbonisation goals.
- The time-focused scenario results in the highest emissions (2,685.3 kg), making it less environmentally friendly.

2. Operational Time:

- The time-focused scenario achieves the shortest operational duration (602 minutes), ideal for projects with strict deadlines.
- The carbon-focused scenario has the longest operational time (991 minutes), highlighting its trade-off for emissions reduction.

3. Cost Efficiency:

- The carbon-focused scenario is the most cost-effective (14,865,000 Tomans), driven by lower fuel consumption and reduced fleet size.
- The time-focused scenario incurs the highest cost (36,120,000 Tomans), reflecting the trade-off for prioritising time.

4. Idle Time:

- The carbon-focused scenario eliminates idle time entirely, reflecting optimal resource utilisation.
- The time-focused scenario shows high idle time (812 minutes), indicating inefficiencies due to over-deployment of trucks.

5. Braking Events:

- The balanced scenario maintains a moderate number of braking events (78), reflecting smooth operations.
- The time-focused scenario exhibits the highest number of braking events (101), potentially increasing wear and tear on vehicles.

Finally, the optimised scenarios provide contractors with actionable insights into balancing time, carbon emissions, and costs. Each configuration aligns with specific project priorities:

- The balanced configuration offers a harmonious approach, addressing both environmental and operational goals by ensuring moderate reductions in total time, idle time, and emissions. For instance, this configuration achieves a total operational time of 623 minutes and limits CO_2 emissions to 1,415.4 kg, making it an efficient yet environmentally considerate choice for contractors.
- The carbon-focused configuration excels in minimising emissions and costs, making it ideal for environmentally sensitive projects. It achieves the lowest CO_2 emissions at 1,138.5 kg and a total cost of 14,865,000 Tomans. However, this comes with a trade-off in total operational time, which is extended to 991 minutes due to the use of a single truck.
- The time-focused configuration prioritises operational speed, catering to projects with tight deadlines but higher environmental trade-offs. This setup achieves the shortest total time of 602 minutes but results in the highest CO_2 emissions of 2,685.3 kg and the greatest diesel consumption at 1,024.9 litres. This configuration is suited for time-sensitive projects where speed is prioritised over sustainability.

By leveraging these insights, contractors can select configurations that best align with their project goals and stakeholder expectations, ensuring efficient, cost-effective, and sustainable construction logistics. Case Study 2 initially involved an analysis of 17 scenarios, which provided limited insights and optimisation options. However, the application of advanced tools like Stat-Ease expanded the scenario pool to over 1,350 configurations, significantly enhancing the ability to explore and identify optimal solutions. This demonstrates the robust potential of the BASE model when fully utilised, allowing contractors to make well-informed decisions tailored to specific project needs. By addressing the unique challenges of Case Study 2—such as the synchronisation of dumper trucks with asphalt pavers and the management of smaller delivery cycles—these tailored configurations provide actionable strategies to achieve operational efficiency and sustainability effectively.

4-3-6 Comparison of Balanced Scenario with Existing Scenario

Among the three optimised scenarios—Time 50% - Carbon 50%, Time 0% - Carbon 100%, and Time 100% - Carbon 0%—the balanced configuration (Time 50% - Carbon 50%) has been chosen for comparison with the existing scenario. This decision is driven by its ability to simultaneously address environmental and operational priorities, making it the most practical and adaptable solution for construction logistics. While the carbon-focused scenario excels in minimising emissions and costs, and the time-focused scenario prioritises speed, the balanced configuration provides a middle ground, ensuring significant improvements in all key performance metrics without heavily compromising one objective over the other (Table 4.10).

Table 4.10: Suggested Scenario vs Existing Scenario – Case Study 2

Strategies	Inputs				Outputs					
	No of Deliveries	Speed KM/h	Payload Tonnes	No of Trucks	Total Time Mins	Idle Time Mins	No of Brakes	Diesel Litres	CO2 Kg CO2	Cost Tomans
Existing	26	30	16	5	674	2164	168	1431.7	3751.1	50,550,000
Time 50% - Carbon 50%	26	20	16	2	623	235	78	540.2	1415.4	18,690,000

By comparing the balanced configuration with the contractor's existing approach, we can highlight how the BASE model integrates optimisation to achieve a harmonious balance between efficiency, sustainability, and cost-effectiveness.

- **Comparative Analysis of Outputs**

1. *Total Time*
   - Existing Scenario: Total operational time stands at 674 minutes.

- Balanced Configuration: Total time is reduced to 623 minutes, reflecting a 7.6% reduction.
- Analysis: The reduction in total time demonstrates the effectiveness of the balanced configuration in streamlining operations. By optimising fleet size (2 trucks) and payloads (16 tonnes), unnecessary delays and inefficiencies are reduced, leading to faster project completion.

2. *Idle Time*
   - Existing Scenario: Idle time is 2,164 minutes.
   - Balanced Configuration: Idle time is drastically reduced to 235 minutes, representing an 89.1% reduction.
   - Analysis: This dramatic decrease highlights the importance of coordination and flow management in the balanced configuration. Optimised resource allocation ensures trucks spend minimal time waiting at loading and unloading points, preventing congestion and delays.
3. *Braking Events*
   - Existing Scenario: 168 braking events are recorded.
   - Balanced Configuration: Braking events are reduced to 78, an improvement of 53.6%.
   - Analysis: The smoother traffic flow achieved through better planning and fewer bottlenecks is evident in this reduction. Reduced braking improves operational efficiency and minimises vehicle wear and tear, contributing to cost savings.
4. *Diesel Consumption*
   - Existing Scenario: Diesel consumption is 1,431.7 litres.
   - Balanced Configuration: Diesel consumption drops to 540.2 litres, a 62.3% reduction.

- Analysis: Lower fuel usage is directly linked to the optimised number of trucks and improved operational flow. This reduction contributes to both cost savings and environmental benefits, showcasing the dual advantage of efficiency and sustainability.

5. *CO_2 Emissions*
   - Existing Scenario: CO_2 emissions are 3,751.1 kilograms.
   - Balanced Configuration: Emissions are reduced to 1,415.4 kilograms, achieving a 62.3% reduction.
   - Analysis: The substantial reduction in CO_2 emissions highlights the environmental impact of the balanced configuration. The BASE model significantly lowers greenhouse gas emissions by minimising idle time and diesel consumption, aligning with global sustainability and decarbonisation goals.
6. *Cost*
   - Existing Scenario: Total cost is 50,550,000 Tomans.
   - Balanced Configuration: Cost is reduced to 18,690,000 Tomans, achieving a 63% saving.
   - Analysis: The cost-effectiveness of the balanced configuration is evident, driven by reduced fuel consumption, fewer braking events, and lower idle time. This outcome demonstrates how optimised operations can deliver substantial financial benefits alongside environmental and efficiency improvements.

The comparison between the balanced configuration and the existing scenario underscores the transformative potential of the BASE model in construction logistics. The balanced configuration emerges as the optimal choice, addressing both environment and operational objectives. Key takeaways include:

1. *Enhanced Efficiency*: A 7.6% reduction in total operational time and an 89.1% reduction in idle time highlight the efficiency gains achieved through better coordination and resource utilisation.

2. *Environmental Benefits*: A 62.3% reduction in CO_2 emissions and a 62.3% decrease in diesel consumption demonstrate the alignment of the balanced configuration with sustainability and decarbonisation goals.

3. *Cost Savings*: With a 63% reduction in costs, the balanced configuration proves its financial viability, making it an attractive choice for contractors aiming to optimise operations.

By leveraging the insights from this analysis, contractors can adopt the BASE model to significantly improve construction logistics. This approach enhances project performance and contributes to broader sustainability efforts by reducing greenhouse gas emissions and aligning with regulatory compliance. Moving forward, the findings reinforce the importance of data-driven decision-making and collaborative planning in achieving a sustainable and efficient built environment.

4-4 Analysis of Case Study 3

4-4-1 Existing Scenario

This section analyses the existing hauling practices observed in Case Study 3. Data was collected through structured observation, with particular attention given to diesel consumption, CO_2 emissions, idle times, and associated financial costs, as summarized in Table 4.11.

Table 4.11: Existing Scenario-Case Study 3

Strategies	Inputs				Outputs					
	No of Deliveries	Speed KM/h	Payload Tonnes	No of Trucks	Total Time Mins	Idle Time Mins	No of Brakes	Diesel Litres	CO2 Kg CO2	Cost Tomans
Existing	40	40	12	7	356	448	298	1134.2	2971.5	37,380,000

The existing scenario for Case Study 3 involves a road construction project in the heart of a city, requiring concurrent operations between two groups: soil hauling and concrete hauling. This setup operates under strict constraints, including night-time working hours (11:00 PM to 7:00 AM) mandated by city council regulations, aimed at ensuring safety and reducing environmental impact in the densely populated downtown area. The soil hauling group was tasked to remove 4,800 tonnes of soil over 10 nights, translating to 480 tonnes per night.

1. Operational Inputs and Characteristics

The existing configuration employs the following inputs:

1. *Material Hauled:* A total of 416 tonnes of soil.
2. *Number of Deliveries:* A total of 40 trips were required to transport the asphalt. Each truck carried a payload of 12 tonnes per trip.
3. *Speed:* Trucks operated at an average speed of 40 km/h.
4. *Payload:* Each truck carried the standard payload of 12 tonnes per trip.
5. *Number of Trucks:* The contractor used seven dumper trucks to complete the operation.

These inputs are designed to handle the dual operations efficiently but face challenges due to bottlenecks shared resources, and limited time windows.

2. Operational Outputs and Observed Outcomes

The outputs of the existing scenario include the following performance metrics:

1. *Total Operation Time:* The trucks collectively operated for 356 minutes.
2. *Idle Time:* Trucks were idle for a significant portion of the operation 448 minutes in total. This time includes delays at loading/unloading points and waiting in queues.
3. *Number of Brakes Used:* Drivers used the brake pedals 298 times throughout the operation, indicating frequent stop-and-go conditions and inefficient traffic flow.
4. *Diesel Consumption:* A total of 1,134.2 litres of diesel was consumed.

5. *CO_2 Emissions:* Diesel usage resulted in emissions of 2,971.5 kilograms of CO_2, contributing significantly to the environmental footprint of the project.
6. *Financial Cost: The total cost of the operation, driven by the rental of dumper trucks, amounted to* 37,380,000 *Tomans.*

The current setup reflects significant inefficiencies that limit the project's overall performance and sustainability. These inefficiencies include:

1. High Idle Time:
   - At 448 minutes, idle time accounts for a substantial portion of the operational window. This is primarily due to congestion at shared sites, misalignment of schedules between soil and concrete hauling groups, and delays caused by bottlenecks along the hauling route.
   - Such prolonged idle times lead to wasted fuel and increased emissions, highlighting the need for better coordination and scheduling.
2. Excessive Number of Braking Events:
   - With 298 braking events, the scenario indicates frequent interruptions and traffic flow disruptions. This reflects operational inefficiencies stemming from bottlenecks and uncoordinated activities between the two groups.
   - The frequent braking contributes to higher wear and tear on vehicles, elevated maintenance costs, and inefficient energy usage.
3. Diesel Consumption and CO_2 Emissions:
   - Diesel consumption stands at 1,134.2 litres, translating to CO_2 emissions of 2,971.5 kg. These figures indicate a substantial environmental footprint for the project.
   - The lack of synchronisation between the groups and bottleneck-induced delays further exacerbates fuel wastage and emissions, underscoring the need for optimised resource allocation.
4. High Operational Costs:
   - The total cost of 37,380,000 Tomans reflects the financial strain of these inefficiencies. Excess fuel usage, extended idle times, and vehicle wear all contribute to elevated costs.

5. Coordination Challenges:
    - The absence of a consistent start time for operations—ranging from 11 PM to 1 AM—creates scheduling conflicts and reduces the effective working window. This lack of coordination is a critical bottleneck that affects both groups' ability to meet their nightly targets.

3. Detailed Process Description

The soil hauling operation follows a detailed route that incorporates key operational steps and challenges:

1. Loading Zone:
    - Trucks begin their journey at the loading zone, where soil is loaded onto the vehicles. This area often experiences delays due to limited space and high activity levels. Coordination between trucks at this point is crucial to avoid congestion.
2. Route Through Blockage 1:
    - After loading, trucks proceed through Blockage 1, the first critical bottleneck on the route. This area is frequently blocked by concrete hauling trucks, creating delays and compounding congestion issues for both groups.
3. Mid-Route Transit and Blockage 2:
    - Trucks then navigate approximately half of the 23,000-metre loop to reach Blockage 2, which is located near the dumping point. This point serves as the entry to the shared space used by both the soil hauling and concrete hauling groups, where the concrete batching plant is located for loading and soil dumping activities take place. The shared entry and exit points at this location intensify congestion, creating significant delays for both groups.

4. Dumping Area:
    - Upon reaching the dumping site, soil is unloaded.
5. Return Journey Through Blockage 3:
    - After unloading, trucks return to the loading zone, encountering Blockage 2 again on the way, before facing Blockage 3. Blockage 3 further complicates operations, as the return path intersects with incoming concrete hauling trucks entering the site, increasing the risk of traffic jams and further delays.

These interdependent routes highlight the complexity of managing two concurrent operations within a limited time window. Bottlenecks shared resources, and unsynchronised schedules exacerbate delays and inefficiencies, underscoring the need for advanced optimisation strategies to streamline operations and minimise disruptions.

4. Environmental and Financial Impacts

The existing scenario for Case Study 3 presents significant environmental and financial challenges:

1. Environmental Impacts

- High Emissions: The scenario generates 2,971.5 kg of CO_2 emissions, reflecting the environmental cost of inefficiencies, including extended idle times and frequent braking events.
- These emissions highlight the urgent need for more sustainable practices, particularly in the context of downtown construction where air quality regulations are often stringent.
- Fuel Inefficiency: Diesel consumption at 1,134.2 litres is a direct consequence of mismanaged scheduling and frequent vehicle stops due to bottlenecks. This not only increases the environmental footprint but also exacerbates operational costs.

2. Financial Impacts

- Elevated Costs: With a total cost of 37,380,000 Tomans, the inefficiencies in the existing scenario drive up operational expenses, primarily due to excessive fuel consumption and vehicle wear and tear.
- The financial burden is further amplified by the need for frequent maintenance due to high braking events and extended operational times.

Addressing these environmental and financial issues requires a focus on optimisation strategies that streamline operations, reduce fuel consumption, and minimise emissions, thereby aligning with both regulatory and sustainability goals.

5. Challenges in the Existing Scenario

The existing scenario faces several challenges that hinder operational efficiency:

1. *Limited Working Hours:* Night-time restrictions (11:00 PM to 7:00 AM) significantly constrain the operational window, leaving little room for error or delays.
2. *Unsynchronised Operations:* The lack of a consistent start time for both soil and concrete hauling operations leads to scheduling conflicts and overlapping tasks, causing delays and inefficiencies.
3. *Shared Resources:* The shared use of the batching plant and dumping area by both groups creates congestion and bottlenecks, particularly during peak activity periods.
4. *Bottleneck Challenges:* Three critical bottlenecks along the soil hauling route slow down operations and lead to significant idle times.
5. *Coordination Complexity:* The interdependent nature of soil and concrete hauling operations necessitates precise coordination, which is currently lacking. This results in overlapping schedules and inefficient use of resources.
6. *Environmental and Financial Constraints:* High emissions and elevated costs underscore the inefficiencies in the current configuration, highlighting the need for optimised operations that balance environmental and financial goals.

By addressing these challenges through the BASE model and advanced optimisation tools, the project can achieve a more sustainable and efficient operational framework.

The existing scenario provides a baseline for evaluating optimisation strategies in Case Study 3. While the current configuration meets operational requirements, its inefficiencies in time management, fuel consumption, and emissions highlight the need for improved coordination and optimisation. However, the application of advanced tools like Stat-Ease offers the potential to address these challenges by:

- Reducing idle time through enhanced scheduling and resource allocation.
- Minimising braking events by addressing bottlenecks and optimising traffic flow.
- Lowering fuel consumption and emissions through better coordination and reduced delays.
- Improving cost efficiency by addressing operational inefficiencies.

With these improvements, the BASE model can help align project operations with both environmental and financial sustainability objectives, making it a critical tool for overcoming the challenges of concurrent operations in constrained environments like downtown construction projects.

4-4-2 Comparison Existing Scenario vs. Eco-Hauling vs. Integrated Eco-Hauling and Big Room Strategy - Case Study 3

This section compares three different hauling strategies used in Case Study 3: the Existing Scenario, the Eco-Hauling strategy, and the Integrated Eco-Hauling and Big Room strategy. These strategies are evaluated based on key metrics such as total operation time, idle time, braking events, diesel consumption, CO_2 emissions, and costs (Table 4.12). The unique challenges of Case Study 3, such as the strict 11:00 PM to 7:00 AM operation window and the interdependency between soil and concrete hauling groups, are incorporated into this analysis.

Table 4.12: Comparison of Strategies in Case Study 3

Strategies	Inputs				Outputs					
	No of Deliveries	Speed KM/h	Payload Tonnes	No of Trucks	Total Time Mins	Idle Time Mins	No of Brakes	Diesel Litres	CO2 Kg CO2	Cost Tomans
Existing	40	40	12	7	356	448	298	1134.2	2971.5	37,380,000
Eco-Hauling	40	40	12	7	292	376	229	945.1	2476.0	30,660,000
Eco-Hauling & Big Room	40	40	12	7	257	19	86	794.2	2080.7	26,985,000

1. Existing Scenario: Challenges and Outcomes

The existing hauling process served as the baseline for comparison. This approach followed traditional methods without any strategic intervention or optimization. As a result, the operations were inefficient and costly.

1. *Diesel Usage:* Trucks consumed 1,134.2 litres of diesel each night, contributing to high fuel costs and increased emissions.
2. *CO_2 Emissions:* A total of 2,971.5 kilograms of carbon dioxide was emitted per night, highlighting the significant environmental impact.
3. *Idle Time:* Trucks spent 448 minutes idle due to frequent delays caused by three major bottlenecks along the 23,000-meter loop.
4. *Braking Events:* There were 298 occurrences of braking, indicating stop-and-go movements and inefficient traffic flow.
5. *Total Time:* The operation required 356 minutes to complete each night, often disrupting the limited operational window.
6. *Cost:* The financial cost of these operations amounted to 37,380,000 Tomans per night.

Overall, inefficiencies in this scenario were exacerbated by the shared soil dumping area and concrete batching plant, which created congestion and delayed operations for both hauling groups.

2. Eco-Hauling Strategy: Incremental Improvements

The Eco-Hauling strategy introduced basic operational improvements, such as route optimization and better scheduling. While it addressed some inefficiencies, it lacked a collaborative framework to fully resolve issues arising from shared bottlenecks and interdependent operations.

Key Results and Reductions:

1. *Diesel Usage:* Consumption was reduced to 945.1 litres per night, achieving a 16.7% reduction compared to the baseline.
2. *CO_2 Emissions:* Emissions dropped to 2,476.0 kilograms, reflecting a similar 16.7% reduction.

3. *Idle Time:* Decreased to 376 minutes, showing a 16.1% improvement over the existing scenario.
4. *Braking Events:* Reduced to 229 occurrences, a 23.2% improvement.
5. *Total Time:* The operation time shortened to 292 minutes, representing an 18.0% reduction.
6. *Cost:* Expenses dropped to 30,660,000 Tomans, saving 18.0% in costs.

Analysis:

The introduction of Eco-Hauling enabled more efficient route planning, which reduced delays caused by bottlenecks. However, the scheduling challenges between the soil and concrete hauling groups persisted. Additionally, while bottleneck 3 was partially alleviated, it continued to slow down soil dumping activities.

3. Integrated Eco-Hauling and Big Room Strategy

This strategy built upon the Eco-Hauling improvements by integrating a collaborative Big Room approach. This method allowed all stakeholders, including the soil and concrete hauling groups, to synchronize their schedules and manage bottlenecks proactively. The results demonstrated significant improvements across all metrics.

Key Results and Reductions:

- *Diesel Usage:* Consumption fell to 794.2 litres per night, a substantial 30.0% reduction from the baseline.
- *CO_2 Emissions:* Emissions were reduced to 2,080.7 kilograms, a 30.0% improvement.
- *Idle Time:* Dropped drastically to just 19 minutes, achieving a 95.8% reduction.
- *Braking Events:* Reduced to 86 occurrences, showing a 71.1% improvement.
- *Total Time:* The operation time was cut to 257 minutes, a 27.8% reduction compared to the existing scenario.
- *Cost:* Expenses decreased to 26,985,000 Tomans, saving 27.8%.

Analysis:

The collaborative approach was particularly effective in addressing the unique constraints of Case Study 3. Proactive communication and checkpoint adjustments ensured both hauling groups could operate efficiently within the restricted 8-hour window. By reducing congestion at the shared dumping and batching site, the strategy drastically minimized idle time and enhanced throughput.

4. Comparison and Insights

- *Environmental Impact:* The integrated strategy delivered the most significant reduction in CO_2 emissions (30.0%), making it the most environmentally sustainable option. The Eco-Hauling strategy achieved moderate improvements, while the existing scenario had the highest emissions due to inefficiencies.
- *Cost Savings:* The integrated strategy reduced costs by 27.8%, making it the most cost-effective solution. Eco-Hauling offered some financial relief with an 18.0% cost reduction, but the existing scenario remained the most expensive.
- *Operational Efficiency:* Total operation time and idle time were significantly reduced under the integrated strategy. Idle time, in particular, dropped to just 19 minutes, highlighting the effectiveness of synchronized operations and proactive bottleneck management.

The comparative analysis of Case Study 3 highlights the critical importance of strategic interventions in construction logistics. The existing scenario underscored the inefficiencies of unoptimized hauling operations, characterized by high idle times, excessive fuel consumption, and significant environmental and financial costs. While the Eco-Hauling strategy introduced incremental improvements through better route management and scheduling, it fell short of addressing the systemic challenges posed by bottlenecks and uncoordinated schedules.

The Integrated Eco-Hauling and Big Room strategy demonstrated transformative potential, combining route optimization with real-time collaboration among stakeholders. This approach not only minimized bottlenecks and idle times but also achieved substantial reductions in CO_2 emissions, fuel consumption, and operational costs. By fostering synchronized operations, the integrated strategy achieved a 30% reduction in emissions, a 27.8% decrease in costs, and an impressive 95.8% drop-in idle time compared to the baseline.

These findings emphasize the importance of collaborative frameworks and eco-friendly strategies in addressing the complexities of urban construction projects. In Case Study 3, challenges such as strict regulatory time windows and shared bottlenecks were effectively resolved through the integrated BASE model.

By combining the collaborative power of the Big Room with advanced simulation tools like AnyLogic, optimization via Stat-Ease, and the eco-conscious principles of Eco-Hauling, the BASE model offers a transformative solution for decarbonizing construction logistics. It enhances efficiency, reduces costs, and aligns construction practices with global sustainability goals. The success of the BASE model in Case Study 3 sets a benchmark for achieving operational excellence while maintaining environmental responsibility in similar projects.

4-4-3 Analysis of Initial Scenarios Modelled in AnyLogic - Case Study 3

Stat-Ease meticulously developed scenarios for Case Study 3 to assess the performance, sustainability, and financial implications of hauling operations under varying conditions. Each scenario was designed to represent a unique combination of critical operational factors, including the number of trucks deployed, payload capacity, average speed, and delivery frequency. This detailed analysis aimed to identify the most efficient and sustainable hauling practices by accounting for key variables that directly influence operational outcomes (Table 4.13).

Table 4.13: Initial Scenarios Modelled in AnyLogic - Case Study 3

Scenario	No of Deliveries	Speed Km/h	Payloads Tonnes	No of Trucks	Eco-hauling						Eco-hauling and Big Room					
					Total Time mins	Idle Time mins	No of Brakes	Diesel Litres	CO2 Kg CO2	Cost Tomans	Total Time mins	Idle Time mins	No of Brakes	Diesel Litres	CO2 Kg CO2	Cost Tomans
1	40	40	12	3	624	239	217	873.0	2287.1	T 28,080,000	543	3	80	760.7	1992.9	T 24,435,000
2	40	40	12	7	292	376	229	945.1	2476.0	T 30,660,000	257	19	86	794.2	2080.7	T 26,985,000
3	60	40	8	5	529	361	322	985.4	2581.7	T 39,675,000	464	4	126	830.6	2176.1	T 34,800,000
4	48	45	10	4	515	267	250	867.1	2271.8	T 30,900,000	450	14	102	743.6	1948.2	T 27,000,000
5	34	35	14	6	308	268	173	921.2	2413.5	T 27,720,000	279	15	73	807.7	2116.2	T 25,110,000
6	34	45	14	6	289	318	202	874.7	2291.7	T 26,010,000	251	19	74	737.7	1932.8	T 22,590,000
7	30	40	16	5	309	212	142	840.7	2202.7	T 23,175,000	277	10	62	742.0	1944.2	T 20,775,000
8	34	45	14	4	399	232	191	816.8	2140.0	T 23,940,000	349	8	70	714.2	1871.2	T 20,940,000
9	34	40	14	5	336	240	170	851.1	2229.9	T 25,200,000	303	11	71	753.8	1975.0	T 22,725,000
10	48	45	10	6	368	375	322	931.3	2440.0	T 33,120,000	313	11	102	761.1	1994.1	T 28,170,000
11	34	35	14	4	438	234	189	881.7	2310.0	T 26,280,000	392	8	70	785.9	2059.1	T 23,520,000
12	48	35	10	6	397	359	318	1003.6	2629.4	T 35,730,000	353	9	101	861.0	2255.8	T 31,770,000
13	40	40	12	5	372	237	251	869.2	2277.2	T 27,900,000	337	16	86	769.7	2016.5	T 25,275,000
14	40	30	12	5	430	290	215	988.8	2590.5	T 32,250,000	386	15	86	871.8	2284.0	T 28,950,000
15	60	35	8	4	683	329	379	1023.6	2681.8	T 40,980,000	611	15	130	887.4	2324.9	T 36,660,000
16	40	50	12	5	356	291	212	834.5	2186.3	T 26,700,000	307	13	85	707.2	1852.7	T 23,025,000
17	40	40	12	4	484	270	263	901.3	2361.3	T 29,040,000	408	6	82	755.8	1980.1	T 24,480,000

Note: Total time should be multiplied by the number of dumper trucks, but idle time is cumulative.

1. Scenario Design

Using AnyLogic, these scenarios simulated the complexities of an urban road construction project, incorporating:

1. *Number of deliveries:* Ranged from 30 to 60 deliveries per scenario.
2. *Speed:* Varied between 30 km/h and 50 km/h to evaluate the impact of operational speed on efficiency and emissions.
3. *Payload capacity:* Adjusted between 8 tonnes and 16 tonnes, reflecting different truck configurations.
4. *Number of trucks:* Varied between 3 and 7 trucks to assess how fleet size influenced bottlenecks and costs.
5. *Operational time:* The scenarios recorded total operational times ranging from 251 minutes to 529 minutes, reflecting the influence of route optimisation and collaboration on performance.

Characteristics:

- *Restricted operational hours:* Operations were limited to the hours between 11:00 PM and 7:00 AM, in line with city council regulations prioritising safety and noise control.
- *Bottlenecks:* Three significant bottlenecks were included to reflect real-world congestion points that could delay operations.
- *Interdependency:* Soil and concrete hauling groups shared resources and facilities, creating conflicts and coordination challenges.
- *Environmental and cost considerations:* Scenarios prioritised reducing diesel consumption, CO_2 emissions, and operational costs while maintaining efficiency.

A total of 17 scenarios were modelled, exploring the interplay of these variables to identify configurations that balance operational efficiency, environmental sustainability, and cost-effectiveness.

2. Performance Metrics Across Scenarios

The performance of each scenario was assessed against critical metrics, offering insights into their operational effectiveness, environmental impact, and financial viability. This section provides an expanded and comprehensive analysis with examples and patterns observed across scenarios:

1. *Diesel Consumption and CO_2 Emissions*

   Diesel consumption and CO_2 emissions were directly influenced by factors such as payload, truck numbers, and operational inefficiencies.

- *Highest Diesel Consumption:* Scenario 15 recorded the highest diesel consumption at 1,023.6 litres, translating to 2,681.8 kg of CO_2 emissions. This scenario, with 60 deliveries and smaller payloads, highlighted the inefficiency caused by increased delivery frequencies without proper synchronisation.
- *Lowest Diesel Consumption:* Scenario 8 demonstrated excellent efficiency with diesel usage at 71112 litres, resulting in 1,871.2 kg of CO_2 emissions due to the application of the Eco-Hauling and Big Room Strategy.
- *Optimised Consumption:* Scenario 6 achieved a balance of diesel usage (737.7 litres) and emissions (1,932.8 kg) by leveraging payloads of 14 tonnes with six trucks.
- *Best Environmental Performance:* Scenario 16 achieved the lowest emissions of 1,852.7 kg CO_2, facilitated by higher speed (50 km/h) and a focus on minimising idle times and braking events.
- *Best Reduction Between Strategies:* Comparing Eco-Hauling and Eco-Hauling and Big Room, Scenario 8 highlights a diesel reduction of 131.5 litres (18.4%) and a CO_2 reduction of 355.8 kg (16%) due to enhanced collaboration and optimised scheduling.

2. *Idle Time*

   Idle time served as a critical measure of inefficiency, influenced by bottlenecks and poor coordination.

- *Excessive Idle Time:* Baseline scenarios, such as Scenario 10, recorded idle times of 375 minutes due to uncoordinated schedules between soil and concrete hauling groups. This led to significant delays at shared facilities.
- *Minimal Idle Time:* Scenario 1 achieved an idle time of just 3 minutes through the Eco-Hauling and Big Room Strategy, showcasing the impact of real-time coordination and proactive planning.

- *Moderate Improvement:* Scenario 13 reduced idle time to 16 minutes, even with 40 deliveries, due to enhanced scheduling and reduced congestion at bottlenecks.
- *Best Reduction Between Strategies:* Scenario 8 demonstrated a reduction of 224 minutes (96.6%) in idle time between the Eco-Hauling and Eco-Hauling & Big Room approaches, highlighting the effectiveness of collaborative planning.

3. *Operational Time*

Operational time is a crucial factor in meeting the regulatory time window of 11:00 PM to 7:00 AM.

- *Longest Operational Time:* Scenario 3 required 529 minutes to complete 60 deliveries, far exceeding the available window. This was due to smaller payloads and increased delivery numbers, which intensified bottleneck effects.
- *Shortest Operational Time:* Scenario 6 completed operations in just 251 minutes by balancing payload size (14 tonnes) and truck numbers (6), showcasing the value of efficient planning.
- *Speed Impact:* Scenario 16 demonstrated the benefits of higher average speeds (50 km/h), completing operations in 307 minutes while maintaining a manageable payload size.
- *Best Reduction Between Strategies:* Scenario 8 demonstrated a reduction of 50 minutes (12.5%) in operational time between Eco-Hauling and Eco-Hauling & Big Room strategies, ensuring completion within the regulatory time window.

4. *Braking Events*

Braking events reflected inefficiencies caused by bottlenecks, traffic flow disruptions, and poor route planning.

- *High Braking Frequency:* Scenario 15 recorded 379 braking events, illustrating the challenges posed by unoptimised routes and frequent congestion.
- *Lowest Braking Events:* Scenario 7, with 30 deliveries and larger payloads (16 tonnes), achieved a significant reduction to 62 braking events through effective route optimisation.
- *Balanced Approach:* Scenario 4 recorded 102 braking events, striking a balance between moderate payloads and speeds to minimise disruptions.

- *Best Reduction Between Strategies:* Scenario 8 reduced braking events by 121 (63.4%) between the Eco-Hauling and Eco-Hauling & Big Room strategies, highlighting the impact of enhanced route planning and coordination.

5. *Rental Costs*

Rental costs were a direct result of inefficiencies, diesel consumption, and operational delays.

- *Highest Rental Cost:* Scenario 15 incurred the highest cost of 40,980,000 Tomans, driven by excessive idle times, braking events, and diesel consumption.
- *Lowest Rental Cost:* Scenario 8 demonstrated significant savings, reducing costs to 20,940,000 Tomans through synchronised schedules and optimised operations.
- *Moderate Costs:* Scenario 5 balanced operational variables effectively, achieving a cost of 25,110,000 Tomans while maintaining a payload size of 14 tonnes.
- *Best Reduction Between Strategies:* Scenario 8 achieved a rental cost reduction of 2,995,000 Tomans (12.5%) between Eco-Hauling and Eco-Hauling & Big Room strategies, demonstrating the financial benefits of improved coordination and operational efficiency.

3. Key Insights of Initial Scenarios

- Collaboration as a Driver of Efficiency

The introduction of the Eco-Hauling and Big Room Strategy showcased the transformative potential of collaborative planning. Scenarios employing this approach consistently outperformed others in reducing idle times, braking events, and operational costs. For example, Scenario 1's drastic reduction in idle time (3 minutes) exemplifies how real-time coordination can mitigate bottlenecks and optimise throughput.

- The Role of Optimised Variables

Balancing operational variables such as truck numbers, payload size, and average speed was critical to achieving efficiency. Scenario 6 demonstrated this by achieving a low operational time (251 minutes) and cost (22,590,000 Tomans) while maintaining environmental sustainability.

- Environmental Sustainability as a Priority

  The scenarios highlighted the tangible environmental benefits of adopting Eco-Hauling principles. Scenario 16's emissions of 1,852.7 kg CO_2 underscore the potential for minimising environmental impact through strategic adjustments to speed and payload size.

- Financial Implications of Inefficiencies

  Scenarios that failed to address bottlenecks and synchronisation challenges incurred significantly higher costs. Scenario 15, with prolonged idle times and high diesel usage, serves as a cautionary example of the financial repercussions of inefficiency.

Eventually, the analysis of these initial scenarios underscores the importance of strategic planning and collaboration in urban construction logistics. By employing tools like AnyLogic and principles embedded in the BASE model, significant improvements in operational efficiency, environmental impact, and cost savings can be achieved. Scenarios utilising the Eco-Hauling and Big Room Strategy set a benchmark for sustainable practices, demonstrating that balancing operational performance with environmental and financial considerations is not only achievable but essential for the future of urban construction.

4-4-3-1 Analysis of CO_2 Emissions

The performance of each scenario was assessed against critical metrics, offering insights into their operational effectiveness, environmental impact, and rental cost implications. This section focuses on CO_2 emissions, exploring their trends and impacts across the scenarios in detail.

1. **Understanding CO_2 Emissions Trends**

   CO_2 emissions provide a clear measure of the environmental sustainability of each scenario. By examining these emissions across different configurations, we can identify patterns, improvements, and opportunities for further optimisation. The variations in CO_2 emissions are driven by factors such as the number of deliveries, payload sizes, average speed, and operational inefficiencies.

- *High CO_2 Emissions*

The highest CO_2 emissions were observed in scenarios where inefficiencies were most pronounced:

- Scenario 15 recorded emissions of 2,681.8 kg CO_2, the highest among all cases. This outcome was due to a combination of smaller payloads (8 tonnes per truck), requiring more trips, and longer operational times of 683 minutes. The high diesel consumption of 1,023.6 litres reflects these inefficiencies.
- Scenario 12 was another high-emission case, producing 2,629.4 kg CO_2. With 48 deliveries and a payload of 10 tonnes, inefficiencies arose from moderate payload capacities and lower speeds (35 km/h), contributing to prolonged operations and higher fuel use.

- *Moderate CO_2 Emissions*

Scenarios with balanced operational inputs achieved moderate emissions:

- Scenario 6 demonstrated emissions of 1,932.8 kg CO_2**,** reflecting the benefits of optimised payload sizes (14 tonnes) and operational speeds (45 km/h). This scenario balanced fuel consumption at 737.7 litres and reduced the number of trips required.
- Scenario 5 displayed slightly higher emissions at 2,413.5 kg CO_2. Despite similar payloads and deliveries as Scenario 6, inefficiencies in route coordination and timing increased emissions slightly.

- *Low CO_2 Emissions*

Scenarios with optimised strategies and reduced inefficiencies achieved the lowest emissions:

- Scenario 16 achieved the lowest emissions of 1,852.7 kg CO_2, showcasing the importance of higher speeds (50 km/h) and optimised payloads (12 tonnes). With reduced operational times (307 minutes) and idle times (13 minutes), this scenario set the benchmark for environmental efficiency.
- Scenario 8 followed closely with emissions of 1,871.2 kg CO_2, benefiting from the Eco-Hauling and Big Room Strategy. Reduced idle times (8 minutes) and efficient coordination minimised fuel consumption to 714.2 litres.

2. **Best Reduction Between Strategies**

The transition from Eco-Hauling to the Eco-Hauling and Big Room Strategy consistently resulted in reduced emissions.
Key examples include:

Scenario 2: CO_2 emissions were reduced from 2,476.0 kg CO_2 under Eco-Hauling to 2,080.7 kg CO_2, a 15.9% reduction. This was achieved by improving coordination and cutting idle times from 376 minutes to just 19 minutes.

Scenario 8: Emissions dropped by 268.8 kg CO_2 (12.6%), reflecting the benefits of streamlined operations and collaborative planning.

Scenario 10: The integrated strategy reduced emissions from 2,440.0 kg CO_2 to 1,994.1 kg CO_2, a reduction of 18.3%. Enhanced scheduling and fewer braking events played a significant role.

3. **Key Insights**

- Lower speeds (<40 km/h) and smaller payloads (<12 tonnes) consistently led to higher emissions, as seen in Scenarios 15 and 12, due to the increased number of trips and longer operational times.
- Balanced payload sizes (14 tonnes) and higher speeds (45-50 km/h) resulted in optimised emissions. Scenarios 6 and 16 highlight how these adjustments can achieve significant environmental benefits.

The Eco-Hauling and Big Room Strategy proved critical in reducing emissions by minimising idle times and enhancing operational synchronisation. Scenarios 8 and 2 demonstrated the environmental advantages of adopting collaborative approaches, achieving reductions in emissions and improved operational efficiency.
High idle times directly correlated with increased emissions. For example, Scenario 10, with 375 minutes of idle time, produced emissions of 2,440.0 kg CO_2. By contrast, Scenario 1, with just 3 minutes of idle time, achieved emissions of 1,992.9 kg CO_2, highlighting the importance of minimising idle times to reduce environmental impact.
Transitioning from Eco-Hauling to the integrated strategy reduced emissions by an average of 15% across scenarios. This underscores the value of collaborative frameworks in achieving sustainability goals by streamlining operations and enhancing coordination.

Transitioning from Eco-Hauling to the integrated strategy reduced emissions by an average of 15% across scenarios, underscoring the value of collaborative frameworks in achieving sustainability goals.

4-4-4 Optimisation with Response Surface Methodology for Case Study 3

The optimisation stage for Case Study 3 represents a pivotal moment in transitioning from simulation outcomes to actionable recommendations. Using Stat-Ease, a total of 945 scenarios were generated, forming the basis for detailed surface graphs and enabling an in-depth exploration of operational variables. By employing advanced analytical methods such as Response Surface Methodology (RSM) within Stat-Ease software, this stage explores the complex interactions between input variables—such as fleet size, payload capacity, and speed—and key performance metrics, including total time, idle time, rental costs, braking events, CO_2 emissions, and diesel consumption.

Case Study 3 revolves around the complexities of urban construction logistics, specifically focusing on the concurrent operations of soil and concrete hauling. The urban setting and strict regulatory constraints, which limit operations to night-time hours (11:00 PM to 7:00 AM), add layers of challenges to the operation.

The project scope involves transporting 4,800 tonnes of soil over a 10-night period and delivering concrete to reinforce pile holes. These dual operations necessitate meticulous planning and execution to meet strict deadlines while adhering to environmental and regulatory requirements.

Operational constraints are significant, with the project route spanning a 23,000-meter loop that includes three bottlenecks. These bottlenecks, combined with shared facilities for soil dumping and concrete batching, often lead to congestion and delays. The need to manage these constraints effectively is critical for the success of the project.

Variable parameters also play a crucial role in determining operational outcomes. Payload sizes range from 8 to 16 tonnes, while speeds vary between 30 and 50 km/h. Fleet sizes are another variable, with configurations involving 3 to 7 trucks. These parameters require careful adjustment to optimise performance across various metrics.

Coordination challenges further complicate the scenario. The synchronisation of soil and concrete hauling groups is essential to prevent resource conflicts and operational delays. Without precise timing and effective communication, the risk of inefficiencies increases, impacting both project timelines and environmental performance.

The inherent complexities of Case Study 3 demand advanced analytical techniques to identify optimised solutions. Unlike the simpler operations observed in Case Study 1, the interplay of bottlenecks, shared resources, and timing challenges requires a detailed and sophisticated approach to achieve sustainable and efficient outcomes.

Stat-Ease generated a total of 945 scenarios, providing a comprehensive dataset that enabled the creation of detailed surface graphs. These scenarios explore diverse combinations of input variables, offering a robust foundation for optimisation and analysis.

As with Case Study 2, this analysis focuses solely on the scenarios that integrated the Eco-Hauling and Big Room Strategy. This decision is justified by the superior performance exhibited in these scenarios, which align with the goals of sustainability and operational efficiency. Although certain scenarios under Eco-Hauling alone displayed improvements, the integrated approach consistently demonstrated the greatest potential for balancing environmental and logistical objectives.

The methodology leverages the diverse scenarios generated during the simulation phase, enabling a detailed evaluation of variable interactions. Surface graphs and 3D plots are employed to visually represent these relationships, illustrating how changes in fleet size, payload, and speed influence the key performance indicators.

The primary objectives of this section are to:

1. *Analyse Key Metrics:* Evaluate total time, idle time, rental costs, braking events, CO_2 emissions, and diesel consumption in detail using surface graph visualisations.
2. *Identify Critical Interactions:* Highlight trends, trade-offs, and synergies that influence performance outcomes.
3. *Optimise Configurations:* Establish a foundation for identifying configurations that balance operational efficiency, cost, and sustainability.

By delving into the six critical performance indicators and leveraging the insights from the integrated scenarios, this analysis bridges the gap between raw data and practical, optimised solutions. The findings aim to guide the identification of operational configurations that support sustainability goals while ensuring economic and logistical feasibility for real-world implementation.

4-4-4-1 Analysis of Total Time Surface Graph for Integration of Eco-Hauling and Big Room Approach

The surface graph for Total Time provides crucial insights into the interplay between payload and fleet size under the integrated Eco-Hauling and Big Room Strategy. This metric is instrumental in assessing overall operational efficiency, as it reflects the time required to complete hauling operations in Case Study 3. The graph visually demonstrates how varying combinations of payload and fleet size impact the total operational time, providing actionable insights for optimising performance (Figure 4.13).

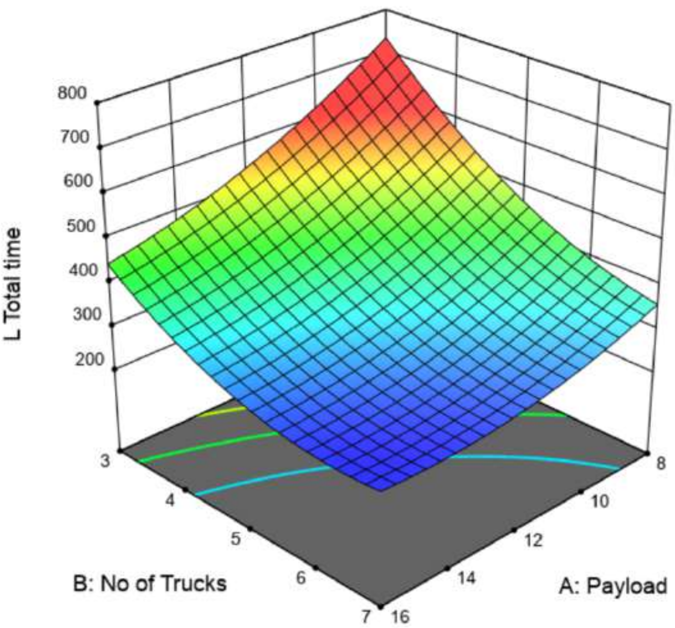


Fig. 4.13: Surface Graph of Total Time for the Integration of Eco-Hauling and Big Room – Case 3

Payload capacity significantly influences total time. Smaller payloads, ranging from 8 to 10 tonnes, result in markedly higher total times due to the increased number of trips required to transport the same volume of materials. These configurations exacerbate inefficiencies, as they necessitate more frequent cycles, leading to extended operational durations. For example, scenarios utilising 8-tonne payloads consistently display a steep increase in total time, particularly when paired with smaller fleet sizes.

Conversely, larger payloads, particularly those between 14 and 16 tonnes, demonstrate a marked reduction in total time. These configurations require fewer trips, thereby streamlining the transportation cycle and minimising operational disruptions. The efficiency gains associated with larger payloads are amplified when combined with the Big Room

Strategy, which optimises coordination and mitigates delays at critical bottlenecks. This synergy between payload size and strategic planning highlights the importance of aligning logistical parameters to achieve operational goals.

Fleet size plays an equally critical role in determining total time. Scenarios involving fleet sizes of 6 to 7 trucks demonstrate the lowest total times. These configurations effectively distribute the workload, reducing bottlenecks and ensuring faster operational cycles. The surface graph clearly indicates that larger fleet sizes, when combined with optimised payloads, maximise efficiency by enabling quicker completion of hauling operations.

While fleet sizes below 5 trucks still perform well under certain configurations, they tend to require more time overall, as fewer trucks must handle the same workload. The graph also underscores that smaller fleets paired with smaller payloads result in significantly higher total times, making these combinations less efficient.

The surface graph reveals a nuanced relationship between payload and fleet size. Optimal configurations emerge when payloads are between 14 and 16 tonnes and fleet sizes range from 6 to 7 trucks. These settings strike a balance between payload efficiency and fleet capacity, ensuring that the benefits of larger payloads are maximised without introducing inefficiencies due to overcapacity or underutilisation of resources. This interplay underscores the necessity of adopting a holistic approach to operational planning, where multiple variables are optimised concurrently to achieve the best outcomes.

Although speed is not explicitly represented in the surface graph, it remains a critical variable affecting total time. Higher speeds can significantly reduce total time in scenarios with smaller fleets and lower payloads, enabling quicker cycles. However, in scenarios involving larger fleets and higher payloads, increasing speed may introduce inefficiencies, such as misalignment at loading and unloading points. This interplay highlights the need for a balanced approach, where speed is adjusted in conjunction with payload and fleet size to optimise performance.

- **Practical Implications**

  1. *Configuration Recommendations:*

     - Payloads of 14 to 16 tonnes and fleet sizes of 6 to 7 trucks are ideal for achieving time efficiency. These configurations minimise the number of trips required while maintaining smooth operations.
     - Smaller fleet sizes below 5 trucks should only be considered in scenarios with reduced payload demands or specific operational constraints.

2. *Environmental Benefits:*
    - Reducing total time directly lowers diesel consumption and CO_2 emissions by minimising operational durations and idle times. This contributes significantly to achieving sustainability goals.
3. *Operational Efficiency:*
    - Minimising total time enhances overall project efficiency, reducing costs associated with prolonged operations and ensuring compliance with regulatory time constraints.
4. *Trade-Offs:*
    - Increasing payloads and fleet size improves total time performance up to a certain threshold. Beyond this, resource constraints or congestion may reduce efficiency.
    - Balancing speed with payload and fleet size is crucial to avoid inefficiencies stemming from misaligned cycles.

The analysis of total time underscores the necessity of balancing payload capacity, fleet size, and speed. Optimal configurations deliver significant gains in efficiency, sustainability, and operational performance. By leveraging the insights provided by the surface graph, stakeholders can identify actionable strategies to achieve their objectives while addressing the complexities of urban construction logistics in Case Study 3. The findings emphasise the critical role of strategic planning and collaboration in optimising total time and advancing sustainability goals.

4-4-4-2 Analysis of Idle Time Surface Graph for Integration of Eco-Hauling and Big Room Approach

The surface graph for Idle Time provides a detailed representation of how payload and fleet size impact inefficiencies within the hauling operations in Case Study 3. Idle time, a critical performance metric, directly correlates with delays and resource underutilisation. Reducing idle time is essential for enhancing operational efficiency and minimising environmental impacts (Figure 4.14).

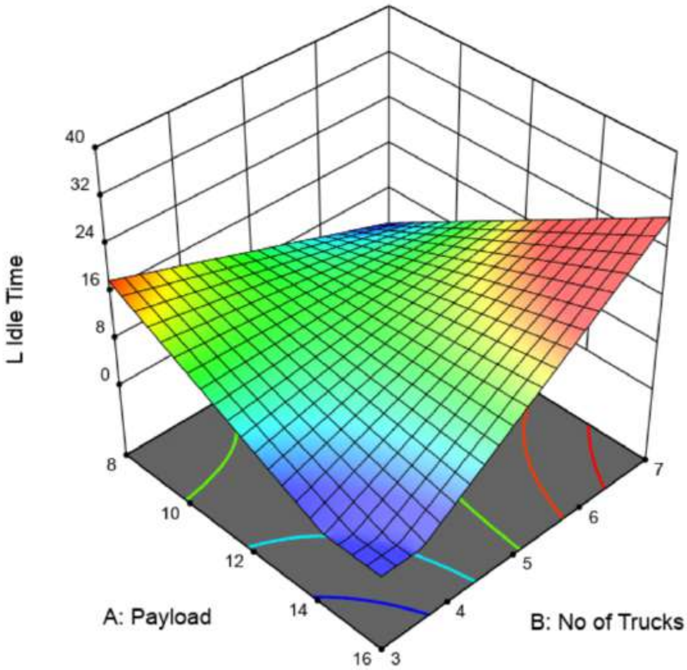


Fig. 4.14: Surface Graph of Idle Time for the Integration of Eco-Hauling and Big Room – Case 3

Payload size plays a significant role in determining idle time. Smaller payloads, such as 8 to 10 tonnes, tend to generate higher idle times. This is primarily due to the increased number of trips required to complete the hauling tasks. Each additional trip introduces opportunities for delays, particularly at loading and unloading points, leading to higher cumulative idle time.

In contrast, larger payloads, especially those between 14 and 16 tonnes, significantly reduce idle time. By decreasing the number of trips required, these configurations streamline operations and minimise waiting periods. The surface graph highlights this trend, showing a clear decrease in idle time as payload sizes increase.

Fleet size has a nuanced effect on idle time. For smaller fleets with the highest payloads, idle time is reduced to nearly zero. This outcome is due to the efficiency of larger payloads in requiring fewer trips, which minimises waiting periods even with fewer trucks. In these scenarios, the operational flow is smooth, with no significant delays caused by fleet size limitations.

Conversely, larger fleets paired with smaller payloads show minimal idle time. This combination benefits from increased truck availability, which helps to distribute workloads efficiently even when payloads are lower. However, the graph reveals that when fleet sizes reach 6 to 7 trucks combined with high payloads (14 to 16 tonnes), idle times increase significantly due to congestion and synchronisation challenges. On the other hand, 6 to 7 trucks paired with lower payloads (8 to 10 tonnes) achieve lower idle times, demonstrating that reduced payloads alleviate coordination difficulties in larger fleets. These scenarios demonstrate how certain configurations can overcome limitations posed by individual variables.

Nevertheless, intermediate configurations, such as moderate payloads paired with smaller fleets, tend to result in higher idle times. These setups fail to optimise either variable, leading to inefficiencies. Similarly, very large fleets with moderate payloads introduce coordination challenges, where the increased number of trucks creates congestion at loading and unloading points.

The interaction between payload and fleet size is a key determinant of idle time. The surface graph reveals that configurations involving payloads of 14 to 16 tonnes combined with fleet sizes of 6 to 7 trucks lead to significantly higher idle times. This outcome is attributed to the increased congestion and synchronisation challenges associated with these settings. In contrast, fleet sizes of 6 to 7 trucks paired with lower payloads of 8 to 10 tonnes achieve much lower idle times, as the reduced payload demands allow for smoother operations and reduced coordination difficulties.

Interestingly, the surface graph also reveals that extreme configurations, such as the smallest fleet sizes paired with the highest payloads, achieve near-zero idle times. This result highlights the importance of payload efficiency in reducing delays. Similarly, the largest fleets with the smallest payloads also perform well, underscoring the flexibility of operational strategies to adapt to varying constraints.

Speed significantly influences operational metrics such as diesel consumption and idle time, and its impact varies depending on payload and fleet size configurations. For scenarios with smaller fleets and lower payloads, lower speeds lead to higher total times and, consequently, higher diesel consumption. Conversely, increasing speed in these configurations reduces total time, enabling quicker cycles and improved efficiency.

On the other hand, scenarios with larger fleets and higher payloads exhibit the opposite trend. Lower speeds in these configurations help reduce total time by enabling better synchronisation of operations and minimising coordination challenges. However, increasing speed in these setups results in higher total times due to misalignment at loading and unloading points, which exacerbates inefficiencies and increases fuel consumption.

- **Practical Implications**

  1. *Configuration Recommendations:*
     - Optimal configurations involve smaller payloads of 8 to 10 tonnes combined with fleet sizes of 6 to 7 trucks. These setups minimise idle time by ensuring smoother coordination and reducing congestion at critical points.
     - Smaller fleets below 5 trucks can be effectively utilised with higher payloads to achieve near-zero idle times.
     - Larger fleets exceeding 6 trucks perform well even with smaller payloads, provided congestion is managed effectively.
  2. *Environmental Benefits:*
     - Reducing idle time lowers diesel consumption and CO_2 emissions by limiting unnecessary engine idling. This contributes to achieving sustainability targets while reducing operational costs.
  3. *Operational Efficiency:*
     - Minimising idle time enhances the productivity of hauling operations, ensuring that resources are utilised effectively and project deadlines are met.
  4. *Trade-Offs:*
     - Extreme configurations, such as minimal fleets with maximum payloads or maximum fleets with minimal payloads, can achieve low idle times but may require additional planning to avoid other inefficiencies.
     - Intermediate configurations with moderate payloads and fleet sizes should be carefully evaluated to avoid higher idle times caused by mismatched variables.

The analysis of idle time highlights the importance of balancing payload and fleet size to achieve operational efficiency. By focusing on optimal configurations, stakeholders can reduce delays, improve resource utilisation, and enhance sustainability outcomes. The findings emphasise the need for strategic planning to minimise idle time and its associated environmental and economic impacts. Through careful adjustment of these variables, Case Study 3 demonstrates the potential for achieving both efficiency and sustainability in urban construction logistics.

4-4-4-3 Analysis of Brake Events Surface Graph for Integration of Eco-Hauling and Big Room Approach

The surface graph for Brake Events offers critical insights into the operational efficiency and safety aspects of hauling operations in Case Study 3. Frequent braking events can increase fuel consumption, wear and tear on vehicles, and overall inefficiencies. Therefore, minimising brake events is crucial for improving both environmental and operational outcomes (Figure 4.15).

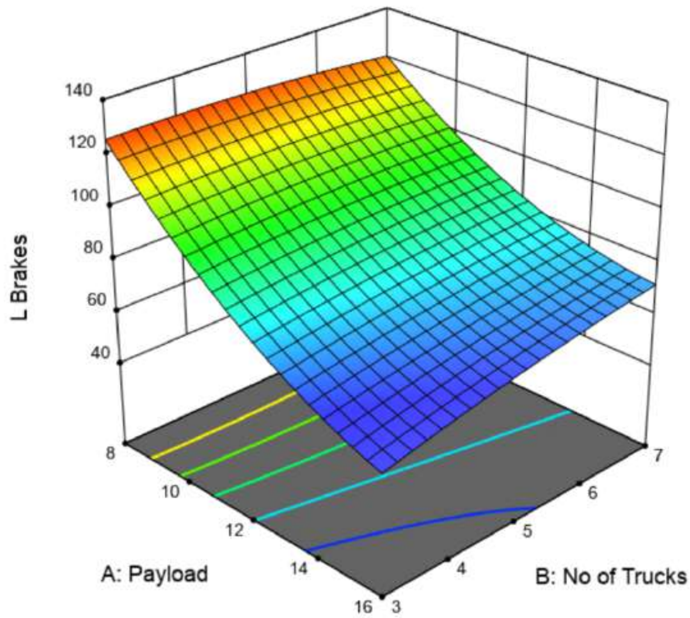


Fig. 4.15: Surface Graph of Brake Events for the Integration of Eco-Hauling and Big Room – Case 3

Payload capacity has a clear and significant influence on the number of brake events. Smaller payloads, particularly those ranging from 8 to 10 tonnes, are associated with higher braking frequencies. This is due to the increased number of trips required to transport the same material volume, which results in more interactions at bottlenecks and loading/unloading points.

Conversely, larger payloads, particularly those between 14 and 16 tonnes, demonstrate a marked reduction in braking events. With fewer trips needed, these configurations streamline operations and reduce interactions at critical points along the route. The surface graph clearly shows that increasing payload size correlates with fewer brake events, contributing to smoother and more efficient operations.

Fleet size also plays a pivotal role in the frequency of brake events. Smaller fleets with 3 to 4 trucks, when paired with higher payloads, show the lowest braking frequencies. This configuration minimises the number of trips required and ensures smoother operations, reducing the need for frequent stops and starts.

Additionally, speed, while not explicitly represented in the surface graph, influences brake events in nuanced ways. For smaller fleets with lower payloads, lower speeds lead to higher braking frequencies due to prolonged travel times and increased stop-and-go interactions. Conversely, higher speeds reduce braking in these configurations by enabling quicker and more continuous cycles.

For larger fleets with higher payloads, lower speeds help to synchronise operations and reduce braking frequencies. However, higher speeds in these scenarios lead to increased braking events due to the difficulty of coordinating multiple trucks at bottlenecks and critical points. These speed dynamics are essential for understanding the broader operational context of brake events.

The interaction between payload and fleet size is critical in determining the number of brake events. Optimal configurations emerge when payloads are set at 14 to 16 tonnes and fleet sizes range from 6 to 7 trucks for minimising braking events. However, smaller fleets of 3 to 4 trucks with higher payloads also show low braking frequencies, indicating flexibility in operational strategies depending on resource availability. These combinations minimise the frequency of braking by reducing the total number of trips required and improving resource allocation.

In contrast, configurations involving smaller payloads and smaller fleets result in significantly higher brake events. These setups amplify inefficiencies, as each truck must make more trips, increasing the likelihood of stops at bottlenecks and other critical points. Similarly, very large fleets with smaller payloads can lead to coordination challenges, where increased vehicle interactions contribute to higher braking frequencies.

- **Practical Implications**

  1. *Configuration Recommendations:*
     - Optimal configurations involve payloads of 14 to 16 tonnes and fleet sizes of 6 to 7 trucks. These setups minimise braking events and enhance operational efficiency.

  - Smaller fleets below 5 trucks should be paired with higher payloads to reduce the frequency of trips and associated brake events.
2. *Environmental and Cost Benefits***:**
  - Reducing brake events directly lowers diesel consumption and CO_2 emissions by minimising stop-and-go activities. Additionally, it reduces wear and tear on vehicles, leading to lower maintenance costs and extended vehicle lifespans.
3. *Operational Efficiency***:**
  - Minimising braking events enhances the smoothness of operations, reducing delays and ensuring better adherence to project timelines.
4. *Trade-Offs***:**
  - While larger fleets with higher payloads reduce brake events, they may require advanced coordination to avoid other inefficiencies such as congestion.
  - Smaller fleets with lower payloads should only be utilised under specific operational constraints, as they tend to increase braking frequencies significantly.

The analysis of brake events highlights the importance of balancing payload capacity and fleet size to achieve operational and environmental efficiency. By focusing on optimal configurations, stakeholders can minimise braking frequencies, improve fuel efficiency, and reduce maintenance costs. The findings underscore the value of strategic planning in addressing the complexities of urban construction logistics, as demonstrated in Case Study 3.

4-4-4-4 Analysis of Diesel Consumption Surface Graph for Integration of Eco-Hauling and Big Room Approach

The surface graph for Diesel Consumption provides valuable insights into the interplay between payload, fleet size, and operational speed in Case Study 3. Diesel consumption is a critical metric for assessing operational efficiency and environmental impact. Minimising diesel use is pivotal for reducing costs and CO_2 emissions, aligning with sustainability goals (Figure 4.16).

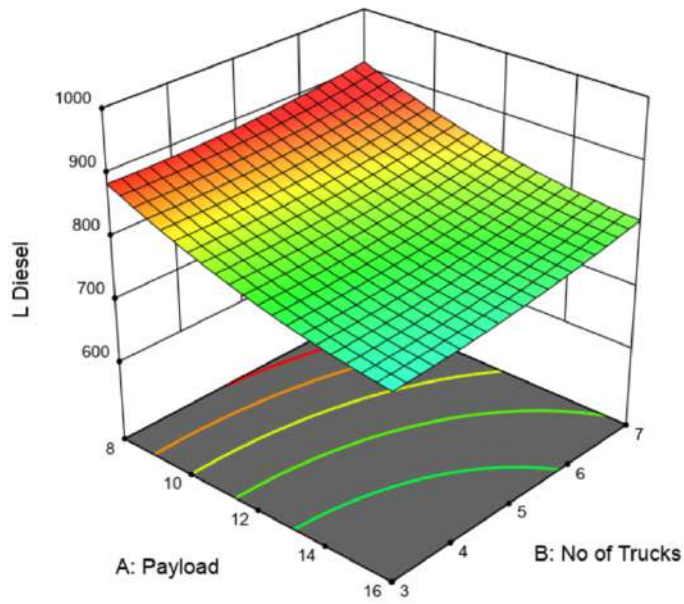


Fig. 4.16: Surface Graph of Diesel Consumption for the Integration of Eco-Hauling and Big Room – Case 3

Payload size significantly affects diesel consumption. Smaller payloads, particularly those ranging from 8 to 10 tonnes, result in higher diesel use. This is because the increased number of trips required to transport the same material volume leads to greater fuel consumption overall. Frequent starts, stops, and accelerations in these scenarios amplify diesel use.

In contrast, larger payloads, particularly those between 14 and 16 tonnes, reduce diesel consumption. By decreasing the number of trips required, these configurations streamline operations and minimise fuel use. The surface graph highlights this trend, showing a clear reduction in diesel consumption as payload sizes increase. This underscores the importance of optimising payload capacities to enhance fuel efficiency.

Fleet size also plays a critical role in determining diesel consumption. Smaller fleets with 3 to 4 trucks, when paired with higher payloads, show lower diesel use. This is because fewer trips are required, resulting in more efficient operations and reduced fuel consumption.
However, as fleet size increases to 6 or 7 trucks, diesel consumption increases, particularly when combined with lower payloads. This is due to the inefficiencies arising from more frequent vehicle interactions and coordination challenges, which lead to higher idle times and increased fuel use. Larger fleets can lead to coordination challenges, increasing idle times and overall fuel consumption. The graph illustrates that smaller fleets with higher payloads achieve lower diesel use, while larger fleets require careful management to avoid inefficiencies.
Although speed is not explicitly visible in the surface graph, it is considered as a dimension in the optimisation process. Speed significantly influences diesel consumption across all scenarios:

- Higher speeds generally lead to lower diesel use across configurations. Faster operations minimise travel times and stop-and-go interactions, reducing fuel consumption.
- Lower speeds, in contrast, result in higher diesel use for all scenarios. Prolonged operational durations and frequent stops increase fuel consumption, particularly for the largest fleets with lower payloads.

In scenarios with larger fleets and higher payloads, lower speeds can provide operational stability and reduce coordination issues. However, excessive reduction in speed may still result in higher diesel consumption due to inefficiencies and prolonged cycles.
The interaction between payload, fleet size, and speed is critical in determining diesel consumption. Optimal configurations emerge when payloads are set at 14 to 16 tonnes, fleet sizes are adjusted to 3 to 4 trucks, and operational speeds are maintained at moderate levels. These settings minimise fuel use by ensuring smooth and efficient operations while avoiding unnecessary accelerations and braking.
In contrast, configurations involving smaller payloads and smaller fleets exhibit significantly higher diesel consumption. These setups require more trips and are less efficient overall. Similarly, very large fleets with smaller payloads can lead to higher diesel use due to coordination challenges and increased vehicle interactions.

- **Practical Implications**

1. *Configuration Recommendations:*
   - Optimal configurations involve payloads of 14 to 16 tonnes, fleet sizes of 3 to 4 trucks, and moderate operational speeds. These setups minimise diesel consumption and enhance overall efficiency.
   - Smaller fleets below 5 trucks should be paired with higher payloads and higher speeds to reduce the frequency of trips and associated diesel use.
2. *Environmental and Cost Benefits:*
   - Reducing diesel consumption directly lowers CO_2 emissions and operational costs, contributing to sustainability goals and improving project feasibility.
3. *Operational Efficiency:*
   - Minimising diesel use enhances the cost-effectiveness of hauling operations while ensuring compliance with environmental regulations.
4. *Trade-Offs:*
   - While larger fleets with higher payloads reduce diesel consumption, they may require advanced coordination to avoid other inefficiencies, such as congestion.
   - Smaller fleets with lower payloads should only be utilised under specific operational constraints, as they tend to increase diesel use significantly.

The analysis of diesel consumption highlights the importance of balancing payload capacity, fleet size, and speed to achieve operational and environmental efficiency. By focusing on optimal configurations, stakeholders can minimise fuel use, reduce emissions, and enhance sustainability outcomes.

4-4-4-5 Analysis of CO_2 Emissions Surface Graph for Integration of Eco-Hauling and Big Room Approach

The surface graph for CO_2 emissions provides critical insights into the environmental impact of various payload, fleet size, and operational speed configurations in Case Study 3. Minimising CO_2 emissions is a key objective for achieving sustainability goals while maintaining operational efficiency (Figure 4.17).

Payload size has a substantial impact on CO_2 emissions. Smaller payloads, particularly those ranging from 8 to 10 tonnes, result in higher CO_2 emissions due to the increased number of trips required to transport the same volume of materials. Each additional trip amplifies fuel consumption, which directly correlates with higher emissions. This trend is evident in the surface graph, where emissions are highest for lower payload configurations.

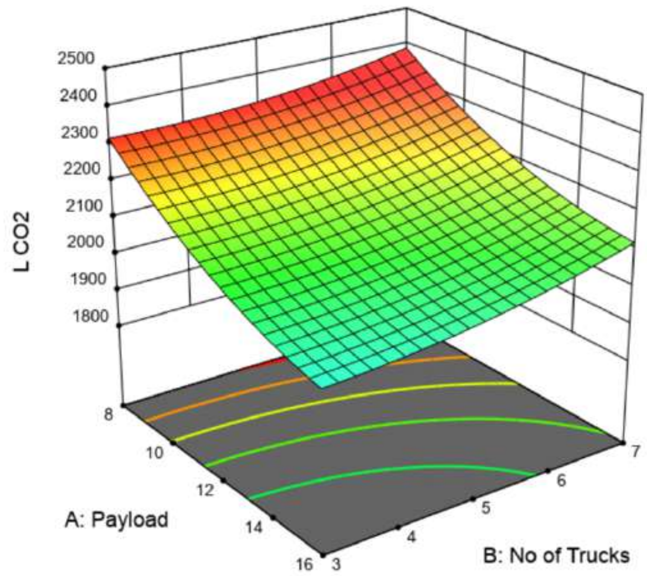


Fig. 4.17: Surface Graph of CO_2 for the Integration of Eco-Hauling and Big Room – Case 3

In contrast, larger payloads, particularly those between 14 and 16 tonnes, significantly reduce CO_2 emissions. By decreasing the total number of trips required, these configurations streamline operations and reduce overall fuel consumption. The surface graph shows that increasing payload size results in lower emissions, reinforcing the importance of optimising payloads to minimise environmental impact.

Fleet size also critically affects CO_2 emissions. Smaller fleets with 3 to 4 trucks paired with higher payloads achieve the lowest emissions. This is due to the reduced number of trips and efficient distribution of workloads, which minimise fuel use and associated emissions.

Conversely, as fleet size increases to 6 or 7 trucks, CO_2 emissions rise, particularly when combined with lower payloads. Larger fleets introduce coordination challenges and increase vehicle interactions, which can lead to higher fuel consumption and emissions. The surface graph demonstrates that smaller fleets with higher payloads consistently achieve better environmental performance, whereas larger fleets require careful management to avoid inefficiencies.

Although speed is not explicitly visible in the surface graph, it plays a significant role in determining CO_2 emissions.

The effect of speed mirrors its impact on diesel consumption:

- Higher speeds generally lead to lower CO_2 emissions across configurations. By reducing travel times and stop-and-go cycles, higher speeds decrease overall fuel consumption, thereby lowering emissions.
- Lower speeds result in higher CO_2 emissions for all scenarios. Prolonged operational durations and increased idling lead to higher fuel use, particularly for larger fleets with lower payloads.

For scenarios with larger fleets and higher payloads, moderate speeds help maintain operational stability while minimising emissions. Excessive speeds, however, may result in coordination challenges and inefficiencies that counteract the benefits of reduced travel times.

The interaction between payload, fleet size, and speed is crucial in determining CO_2 emissions. Optimal configurations emerge when payloads are set at 14 to 16 tonnes, fleet sizes are adjusted to 3 to 4 trucks, and operational speeds are maintained at moderate levels. These settings minimise emissions by ensuring efficient operations while avoiding unnecessary accelerations and braking.

In contrast, configurations involving smaller payloads and larger fleets exhibit significantly higher CO_2 emissions. These setups require more trips and are less efficient overall. Similarly, very large fleets with smaller payloads exacerbate emissions due to increased vehicle interactions and idle times.

- **Practical Implications**

  1. *Configuration Recommendations:*
     - Optimal configurations involve payloads of 14 to 16 tonnes, fleet sizes of 3 to 4 trucks, and moderate operational speeds. These setups minimise CO_2 emissions and enhance overall efficiency.
     - Smaller fleets should be paired with higher payloads to reduce the frequency of trips and associated emissions.
  2. *Environmental Benefits:*
     - Reducing CO_2 emissions directly contributes to sustainability goals, aligning with environmental regulations and improving the ecological footprint of operations.

3. *Operational Efficiency:*
   - Minimising emissions enhances cost-effectiveness by reducing fuel consumption and aligning operations with sustainability objectives.
4. *Trade-Offs:*
   - While larger fleets with higher payloads reduce emissions in some cases, they may require advanced coordination to avoid inefficiencies, such as increased idle times.
   - Smaller fleets with lower payloads should only be utilised under specific constraints, as they tend to increase emissions significantly.

The analysis of CO_2 emissions underscores the significance of strategic planning in optimising payload capacity, fleet size, and speed. Smaller fleets of 3 to 4 trucks paired with larger payloads consistently show the lowest emissions, offering a balance between operational efficiency and environmental sustainability. Higher operational speeds further reduce emissions by minimising fuel consumption and travel times, though caution is required to avoid inefficiencies in larger fleets.

4-4-4-6 Analysis of Rental Cost Emissions Surface Graph for Integration of Eco-Hauling and Big Room Approach

The surface graph for rental costs provides vital insights into the economic impact of different payloads, fleet sizes, and operational speed configurations in Case Study 3. Rental costs directly correlate with the operational efficiency of hauling operations, making them a critical metric for project planning and optimisation (Figure 4.18).

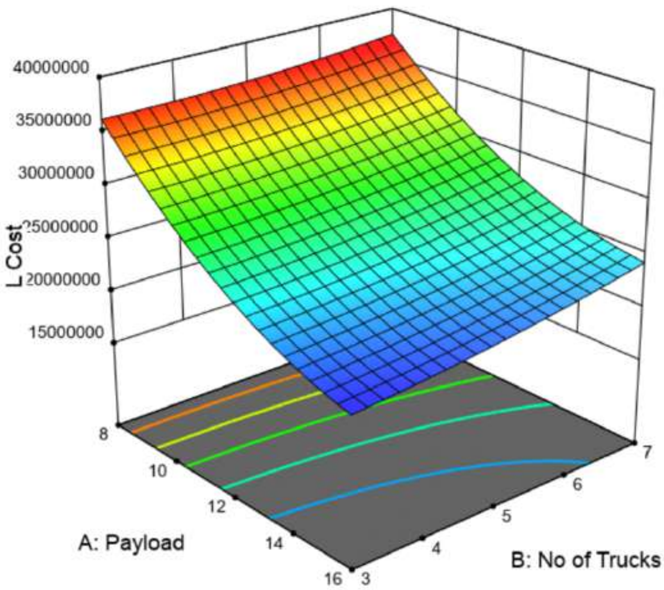


Fig. 4.18: Surface Graph of Rental Cost for the Integration of Eco-Hauling and Big Room – Case 3

Payload capacity significantly influences rental costs. Smaller payloads, particularly those ranging from 8 to 10 tonnes, lead to higher rental costs. This is primarily due to the increased number of trips required to transport the same volume of materials. Each additional trip prolongs operational time, thereby increasing equipment rental duration and costs.

In contrast, larger payloads, particularly those between 14 and 16 tonnes, demonstrate a marked reduction in rental costs. By reducing the total number of trips required, these configurations shorten operational durations, minimising rental time and costs. The surface graph clearly shows that increasing payload size reduces rental costs, emphasising the importance of payload optimisation for cost efficiency.

Fleet size also plays a critical role in determining rental costs. Smaller fleets with 3 to 4 trucks achieve lower rental costs, especially when paired with higher payloads. This is due to the reduced number of trips and shorter overall operational times, which decrease rental durations.

Conversely, as fleet size increases to 6 or 7 trucks, rental costs rise, particularly when combined with lower payloads. Larger fleets introduce inefficiencies such as higher idle times and increased vehicle interactions, which prolong operational times and elevate rental expenses. The surface graph highlights that smaller fleets with optimised payloads consistently achieve lower rental costs, while larger fleets require careful management to avoid excessive costs.

Speed indirectly impacts rental costs through its effect on operational time. Higher speeds generally lead to lower rental costs across configurations by reducing total operational durations. Faster operations enable quicker task completion, minimising equipment usage and associated rental expenses.

In contrast, lower speeds result in higher rental costs for all scenarios. Prolonged travel times and stop-and-go movements increase the total operational duration, leading to longer equipment rental periods. This effect is particularly pronounced for larger fleets with lower payloads, where coordination challenges exacerbate delays and elevate costs.

The interaction between payload, fleet size, and speed is crucial in determining rental costs. Optimal configurations emerge when payloads are set at 14 to 16 tonnes, fleet sizes are adjusted to 3 to 4 trucks, and operational speeds are maintained at moderate levels. These settings minimise costs by ensuring efficient operations and reducing idle times.

In contrast, configurations involving smaller payloads and larger fleets exhibit significantly higher rental costs. These setups require more trips and longer operational durations, increasing overall expenses. Similarly, very large fleets with smaller payloads exacerbate costs due to increased vehicle interactions and inefficiencies.

- **Practical Implications**
  1. *Configuration Recommendations:*
     - Optimal configurations involve payloads of 14 to 16 tonnes, fleet sizes of 3 to 4 trucks, and moderate operational speeds. These setups minimise rental costs and enhance overall efficiency.
     - Smaller fleets should be paired with higher payloads to reduce the frequency of trips and associated rental durations.
  2. *Cost Efficiency:*
     - Reducing rental costs directly contributes to project profitability by minimising equipment usage and optimising operational time.
  3. *Operational Efficiency:*
     - Minimising rental costs enhances project feasibility by aligning operational strategies with budgetary constraints.
  4. *Trade-Offs:*
     - While larger fleets with higher payloads can improve operational flexibility, they may increase rental costs if not carefully managed.
     - Smaller fleets with lower payloads should only be utilised under specific constraints, as they tend to elevate costs significantly.

The analysis of rental costs underscores the importance of strategic planning in optimising payload capacity, fleet size, and speed. Smaller fleets of 3 to 4 trucks paired with larger payloads consistently show the lowest rental costs, offering a balance between operational efficiency and cost-effectiveness. Higher operational speeds further reduce rental costs by minimising equipment usage and travel times, though caution is required to avoid inefficiencies in larger fleets.

By adopting optimal configurations, stakeholders can achieve substantial cost savings while improving the efficiency and feasibility of hauling operations. This analysis highlights the potential of integrating economic considerations into construction logistics, paving the way for more cost-effective urban projects as demonstrated in Case Study 3.

4-4-5 Optimised Scenarios Analysis - Case 3

The analysis of optimised scenarios in Case Study 3 offers critical insights into balancing time efficiency, carbon reduction, and overall operational costs. Employing Stat-Ease software, the initial 17 scenarios were expanded into a comprehensive dataset of over 900 scenarios, allowing for a detailed exploration of the operational dynamics. Case Study 3, situated in a complex urban environment, features unique challenges such as night-time operational restrictions, multiple bottlenecks, and the concurrent hauling of soil and concrete. These characteristics necessitate a nuanced approach to optimisation to address the intertwined goals of efficiency, sustainability, and cost-effectiveness. Using three distinct strategies—Time 50% - Carbon 50%, Time 0% - Carbon 100%, and Time 100% - Carbon 0%—this section evaluates the interplay of operational inputs and outputs to identify the most effective configurations for achieving project objectives (Table 4.14).

Table 4.14: Optimised Scenarios – Case Study 2

Strategies	Inputs				Outputs					
	No of Deliveries	Speed KM/h	Payload Tonnes	No of Trucks	Total Time Mins	Idle Time Mins	No of Brakes	Diesel Litres	CO2 Kg CO2	Cost Tomans
Time 50% - Carbon 50%	30	48	16	6	244	108	84	761.1	1994.2	21,960,000
Time 0% - Carbon 100%	30	50	16	3	391	4	61	674.1	1766.3	17,595,000
Time 100% - Carbon 0%	30	50	16	7	241	278	114	837.7	2194.9	25,305,000

Strategy 1: Balanced Importance Weightings (Time 50% - Carbon 50%)

This strategy represents a balanced approach, prioritising equal weightage to time efficiency and carbon reduction. The inputs for this configuration include:

- *Number of deliveries:* 30. This reflects the total trips required to complete the hauling task under the balanced strategy.
- *Speed:* 48 km/h. A moderate speed balancing fuel efficiency and operational time.
- *Payload:* 16 tonnes. Maximises material transport per trip, reducing overall trips and emissions.
- *Fleet size:* 6 trucks. Ensures workload distribution while minimising idle times.

The outputs reveal a strong balance between operational performance and environmental impact:

- *Total time:* 244 minutes. Represents a balance between quick operations and environmental goals.
- *Idle time:* 108 minutes. Moderate idle time reflects efficient fleet coordination.
- *Number of brakes:* 84. Indicates manageable stops and starts within operations.
- *Diesel consumption:* 761.1 litres. Demonstrates controlled fuel use for balanced efficiency.
- *CO_2 emissions:* 1,994.2 kg. Balanced emissions align with moderate environmental goals.
- *Cost:* 21,960,000 Tomans. Mid-range cost balancing operational needs and environmental considerations.

This scenario demonstrates that balancing both time and carbon objectives is feasible. The moderate idle time and relatively low number of brakes contribute to efficient operations, while diesel consumption and CO_2 emissions remain controlled. However, the cost is mid-range compared to the other strategies, indicating room for optimisation.

Strategy 2: Carbon-Focused Configuration (Time 0% - Carbon 100%)

This strategy prioritises carbon reduction above all other objectives. The operational inputs include:

- *Number of deliveries:* 30. Maintains consistency across all scenarios for comparative analysis.
- *Speed:* 50 km/h. Slightly higher speed prioritises efficient travel.
- *Payload:* 16 tonnes. High payload reduces the number of trips, lowering emissions.
- *Fleet size:* 3 trucks. A smaller fleet maximises efficiency while reducing coordination complexity.

The outputs showcase the environmental benefits of this approach:

- *Total time:* 391 minutes. The longest duration, reflecting the focus on carbon reduction over speed.
- *Idle time:* 4 minutes. Minimal idle time highlights operational efficiency in fuel use.
- *Number of brakes:* 61. Lower braking events reduce fuel waste and wear.

- *Diesel consumption:* 674.1 litres. The lowest consumption, aligned with sustainability goals.
- *CO_2 emissions:* 1,766.3 kg. The lowest emissions, emphasising the strategy's environmental focus.
- *Cost:* 17,595,000 Tomans. Lowest cost, making this strategy highly cost-effective.

This scenario achieves the lowest CO_2 emissions and diesel consumption, highlighting its effectiveness in minimising environmental impact. The minimal idle time and reduced number of brakes further enhance its efficiency. However, the total time is significantly higher, making this configuration less suitable for projects with strict time constraints. The cost is the lowest among the three strategies, making it highly cost-effective for environmentally focused operations.

Strategy 3: Time-Focused Configuration (Time 100% - Carbon 0%)

This strategy prioritises time efficiency, aiming to minimise the total operational duration. The inputs for this configuration are:

- *Number of deliveries:* 30. Consistent deliveries prioritise operational speed.
- *Speed:* 50 km/h. High speed reflects prioritisation of rapid operations.
- *Payload:* 16 tonnes. Optimised payload for fewer trips under tight time constraints.
- *Fleet size:* 7 trucks. Larger fleet size aims to minimise total operational time.

The outputs reflect its focus on time efficiency:

- *Total time:* 241 minutes. The shortest duration, ideal for time-critical projects.
- *Idle time:* 278 minutes. High idle time suggests inefficiencies in fleet utilisation.
- *Number of brakes:* 114. Increased braking indicates less coordinated operations.
- *Diesel consumption:* 837.7 litres. Highest fuel use due to prioritisation of speed.
- *CO_2 emissions:* 2,194.9 kg. The highest emissions, reflecting trade-offs for time efficiency.
- *Cost:* 25,305,000 Tomans. The highest cost, driven by larger fleet size and rapid operations.

This configuration achieves the shortest total time, making it ideal for projects with tight deadlines. However, the high idle time and number of brakes indicate inefficiencies in coordination and resource utilisation. Diesel consumption and CO_2 emissions are the highest among the three strategies, and the cost is also the highest, suggesting that this approach prioritises time at the expense of environmental and financial considerations.

- **Comparative Analysis**

1. *Time Efficiency:*

- The Time 100% - Carbon 0% strategy is the fastest, completing operations in just 241 minutes.
- The Time 50% - Carbon 50% strategy is moderately fast at 244 minutes.
- The Time 0% - Carbon 100% strategy is the slowest at 391 minutes.

2. *Environmental Impact:*

- The Time 0% - Carbon 100% strategy achieves the lowest CO_2 emissions (1,766.3 kg) and diesel consumption (674.1 litres).
- The Time 50% - Carbon 50% strategy offers a balanced environmental performance with 1,994.2 kg CO_2 emissions.
- The Time 100% - Carbon 0% strategy has the highest environmental impact, with 2,194.9 kg CO_2 emissions.

3. *Cost:*

- The Time 0% - Carbon 100% strategy is the most cost-effective at 17,595,000 Tomans.
- The Time 50% - Carbon 50% strategy has a mid-range cost of 21,960,000 Tomans.
- The Time 100% - Carbon 0% strategy is the most expensive at 25,305,000 Tomans.

The optimised scenarios offer contractors actionable insights for balancing time, carbon emissions, and costs. Each configuration corresponds to specific project priorities:

- The Time 50% - Carbon 50% strategy offers a balanced approach, suitable for projects requiring moderate efficiency and environmental performance.

- The Time 0% - Carbon 100% strategy is ideal for projects prioritising sustainability and cost-effectiveness.
- The Time 100% - Carbon 0% strategy is best suited for time-critical projects but comes with higher environmental and financial costs.

The optimised scenarios in Case Study 3 demonstrate the trade-offs between time efficiency, carbon reduction, and cost. By leveraging the capabilities of the BASE model and employing Stat-Ease software, the initial 17 scenarios were expanded to over 900, offering a granular understanding of the interactions between operational variables. This extensive dataset enabled the identification of optimal configurations that balance environmental sustainability, operational efficiency, and financial feasibility.

The ability to simulate such a large number of scenarios is pivotal for projects with complex constraints, such as Case Study 3. The urban setting, night-time restrictions, and concurrent hauling operations required a highly nuanced approach to optimisation. The BASE model provided a robust framework for evaluating the dynamic relationships between payload, fleet size, speed, and their impacts on key performance indicators like CO_2 emissions, idle time, and costs.

Through this comprehensive analysis, the BASE model has proven invaluable in guiding stakeholders towards the most effective strategies for achieving their objectives. Whether prioritising carbon reduction, time efficiency, or cost-effectiveness, the insights derived from these simulations empower decision-makers to make informed choices that align with project priorities and broader sustainability goals. These findings underline the transformative potential of integrating advanced modelling tools in urban construction logistics, paving the way for smarter, greener, and more efficient operations.

4-4-6 Comparison of Balanced Scenario with Existing Scenario

Among the three strategies presented- Balanced Importance Weightings, Carbon-Focused Configuration and Time-Focused Configuration - the balanced configuration (Time 50% - Carbon 50%) has been selected for comparison with the existing scenario (Table 4.15).

This choice is driven by its ability to address both environmental and operational priorities, making it a practical and adaptable solution for urban construction logistics. While the existing scenario reflects conventional practices with higher operational costs and environmental impacts, the balanced configuration leverages the BASE model’s optimisation to significantly improve performance across key metrics.

Table 4.15: Suggested Scenario vs Existing Scenario – Case Study 3

Strategies	Inputs				Outputs					
	No of Deliveries	Speed KM/h	Payload Tonnes	No of Trucks	Total Time Mins	Idle Time Mins	No of Brakes	Diesel Litres	CO2 Kg CO2	Cost Tomans
Existing	40	40	12	7	356	448	298	1134.2	2971.5	37,380,000
Time 50% - Carbon 50%	30	48	16	6	244	108	84	761.1	1994.2	21,960,000

- **Comparative Analysis of Outputs**

1. Total Time

- Existing Scenario: The total operational time is 356 minutes.
- Balanced Configuration: The total time is reduced to 244 minutes, reflecting a 31.5% reduction.
- Analysis: The reduction in total time highlights the efficiency of the balanced configuration. By optimising fleet size (6 trucks) and payloads (16 tonnes), unnecessary delays are minimised, ensuring faster project completion. This improvement is particularly significant in urban construction projects with tight schedules.

2. Idle Time

- Existing Scenario: Idle time is 448 minutes.
- Balanced Configuration: Idle time drops to 108 minutes, representing a 75.9% reduction.
- Analysis: This dramatic decrease underscores the importance of coordination and flow management in the balanced configuration. Effective resource allocation minimises truck wait times at loading and unloading points, preventing congestion and ensuring smoother operations.

3. Braking Events

- Existing Scenario: The existing approach records 298 braking events.
- Balanced Configuration: Braking events are reduced to 84, an improvement of 71.8%.
- Analysis: Smoother traffic flow achieved through better planning and reduced bottlenecks is evident in this reduction. Fewer braking events enhance operational efficiency and reduce vehicle wear and tear, contributing to long-term cost savings.
- 4. Diesel Consumption

- Existing Scenario: Diesel consumption is 1,134.2 litres.
- Balanced Configuration: Diesel consumption decreases to 761.1 litres, achieving a 32.9% reduction.
- Analysis: Lower fuel consumption reflects the benefits of optimised fleet operations and reduced idle times. This improvement not only reduces operational costs but also contributes to environmental goals by lowering greenhouse gas emissions.

5. CO_2 Emissions

- Existing Scenario: CO_2 emissions amount to 2,971.5 kilograms.
- Balanced Configuration: Emissions are reduced to 1,994.2 kilograms, reflecting a 32.9% reduction.
- Analysis: The significant reduction in CO_2 emissions highlights the environmental advantages of the balanced configuration. By minimising fuel use and idle time, the BASE model aligns with sustainability and decarbonisation objectives.

6. Cost

- Existing Scenario: Total cost is 37,380,000 Tomans.
- Balanced Configuration: Cost is reduced to 21,960,000 Tomans, achieving a 41.3% saving.
- Analysis: The cost-effectiveness of the balanced configuration is evident, driven by reduced fuel consumption, fewer braking events, and shorter idle times. These financial benefits demonstrate how optimised operations can deliver significant economic savings alongside environmental improvements.

The comparison between the balanced configuration and the existing scenario underscores the transformative potential of the BASE model in urban construction logistics. Key takeaways include:

1. *Enhanced Efficiency:* A 31.5% reduction in total operational time and a 75.9% reduction in idle time highlight the efficiency gains achieved through better coordination and resource utilisation.

2. *Environmental Benefits:* A 32.9% reduction in CO_2 emissions and diesel consumption aligns the balanced configuration with global sustainability and decarbonisation goals.
3. *Cost Savings:* With a 41.3% reduction in costs, the balanced configuration proves its financial viability, making it an attractive choice for contractors aiming to optimise operations.

The findings from this analysis demonstrate how the balanced configuration outperforms the existing scenario across all critical metrics. By leveraging the BASE model, the balanced configuration effectively integrates environmental sustainability with operational efficiency, paving the way for smarter, greener construction logistics. The BASE model's capability to expand the initial scenarios into over 900 configurations enabled a thorough exploration of operational variables, identifying the most effective strategies for reducing CO_2 emissions and improving overall efficiency.

A key achievement of the balanced configuration is its ability to reduce CO_2 emissions by 32.9% compared to the existing scenario. This significant reduction is made feasible through the BASE model's optimisation of fleet size, payload, and speed, which collectively minimise fuel consumption and idle times. The structured simulation provided by the BASE model allows for the identification of inefficiencies in the existing scenario, such as excessive idle times and high diesel consumption, and the design of targeted solutions to address these issues.

The comparative results underline the practicality of adopting the balanced configuration for urban construction projects. By significantly lowering emissions and operational costs while maintaining high efficiency, the BASE model proves its utility as a powerful tool for achieving sustainability goals. This approach not only aligns with decarbonisation objectives but also delivers tangible economic and operational benefits, demonstrating how advanced modelling can bridge the gap between sustainability aspirations and real-world implementation.

4-5 Validation of the BASE Model

The validation process for the BASE model is robustly supported through a combination of real-world comparisons, simulation accuracy checks, and stakeholder endorsements. These efforts collectively ensure that the model is reliable, practical, and capable of delivering actionable insights for improving construction logistics operations. Below are the key pillars of the validation process:

1. Comparison with Real-World Observations

Case Study 1 and Case Study 3 were pivotal in validating the BASE model against real-world data. These cases provided diverse operational scales and challenges, ensuring the model was tested comprehensively in different settings.

- **Case Study 1**: This smaller-scale hauling operation involved 1,800 tonnes of material transported over two distinct phases. In the first phase, 900 tonnes were hauled without applying any specific strategies, serving as a baseline to capture inefficiencies like excessive idle times and bottlenecks. In the second phase, Eco-hauling principles were implemented by introducing checkpoints 300 meters before critical points, including bottlenecks, loading areas, and dumping points. The checkpoints aimed to streamline operations, minimise braking events, and optimise truck movements. This structured comparison allowed for a rigorous evaluation of the model's practical application. The results showed significant improvements in fuel efficiency, reductions in total operation time, and better management of bottlenecks, validating the BASE model's effectiveness.
- **Case Study 3**: A more complex scenario, this study involved the removal of 4,800 tonnes of soil over 10 nights, with 480 tonnes transported nightly. Similar to Case Study 1, the first night was conducted without interventions to establish a baseline, while the second night applied Eco-hauling principles. The consistency in approach—maintaining the same number of trucks, payload capacities, and speeds across both scenarios—ensured the data accurately reflected the impact of the strategies. Checkpoints ahead of critical locations effectively reduced idle times, improved fuel efficiency, and minimised braking events. These operational improvements aligned closely with the simulation predictions, achieving an average accuracy of 90% between real-life data and the BASE model's outputs. This high accuracy reinforced the model's credibility in replicating and predicting operational dynamics.

By testing the model in both small-scale and large-scale operations, the validation process demonstrated its adaptability and reliability. The ability of the BASE model to deliver measurable improvements across diverse scenarios underscores its utility as a tool for optimising construction logistics.

2. Statistical and Sensitivity Analysis

The use of Stat-Ease software allowed the expansion of 17 initial scenarios into over 900 configurations, providing a rich dataset for detailed evaluation. This broad scope enabled a comprehensive sensitivity analysis of key variables such as fleet size, payload capacity, and speed.

- Sensitivity Testing: Varying input parameters such as fleet size and payload capacity consistently revealed logical trends. For example, increasing payload sizes reduced the total number of trips, which in turn decreased fuel consumption and emissions. Conversely, smaller payloads required more trips, increasing operational inefficiencies. Similarly, fleet size adjustments highlighted the importance of balancing the number of trucks to minimise idle times while avoiding excessive operational costs.
- Statistical Validation: The high correlation between simulated outputs and real-world data further strengthened the model's reliability. The consistency in results across different configurations provided evidence of the model's robustness, ensuring its applicability to varied construction scenarios.

3. Integration with Simulation Tools

The BASE model's integration with AnyLogic software provided a dynamic platform for simulation and validation. AnyLogic's capabilities in modelling complex logistics operations ensured that the BASE model could be rigorously tested against practical scenarios.

- Real-Time Adjustments: AnyLogic simulations allowed for dynamic testing of various strategies, such as the introduction of checkpoints and speed adjustments. This flexibility enabled stakeholders to observe the immediate impacts of different interventions on operational metrics.
- Operational Metrics: Metrics such as total operation time, idle time, fuel consumption, and CO_2 emissions were accurately reflected in the simulation outputs, aligning closely with on-site observations. This alignment validated the BASE model's ability to predict and optimise real-world operations effectively.

4. Stakeholder Feedback and Industry Validation

Stakeholder feedback was obtained through the Big Room approach implemented in each case study. This collaborative platform involved officials, contractors, and logistics experts reviewing the model's outputs and providing practical insights.

- Confirmation of Practicality: Stakeholders confirmed that the strategies suggested by the BASE model, such as checkpoint placements and speed optimisations, were feasible and practical for implementation in real-world settings. Their feedback validated the model's alignment with operational realities.
- Collaboration Benefits: The Big Room discussions highlighted the BASE model's collaborative nature, ensuring that the strategies addressed the needs and constraints of all involved parties. This feedback loop further strengthened the model's applicability and relevance.

5. Comparative Validation Through Eco-Hauling Principles

The comparative analysis between baseline and Eco-hauling scenarios highlighted the transformative potential of the BASE model. Key findings include:

- Reduction in Operational Time: The introduction of checkpoints significantly reduced total operation time by streamlining truck movements and minimising bottlenecks.
- Improved Fuel Efficiency: Optimised truck movements demonstrated lower fuel consumption, leading to cost savings and reduced greenhouse gas emissions.
- Enhanced Predictability: The implementation of structured strategies reduced variability and inefficiencies, ensuring more consistent and reliable performance.

These results validated the BASE model's ability to deliver substantial improvements in both operational efficiency and environmental sustainability.

Eventually, the BASE model has been comprehensively validated through real-world observations, sensitivity analyses, simulation integration, and stakeholder endorsements. By achieving a high degree of accuracy and aligning its outputs with observed behaviours, the model has proven its reliability and practicality for optimising construction logistics. This robust validation framework highlights the transformative potential of the BASE model in reshaping construction operations for better efficiency and sustainability.

The BASE model's ability to expand initial scenarios into over 900 configurations provides a unique advantage. This extensive dataset enables a granular understanding of the interactions between variables such as fleet size, payload, and speed, which are critical for identifying optimal configurations. The use of Stat-Ease and AnyLogic tools ensures that these configurations are not only theoretically sound but also practically implementable, bridging the gap between simulation and real-world applicability.

A particularly significant outcome is the BASE model's demonstrated capacity to reduce CO_2 emissions and fuel consumption without compromising operational efficiency. For example, through its integration in Case Studies 1 and 3, the model achieved an accuracy of 90% in replicating real-world operations while highlighting actionable strategies for emission reduction. This level of precision validates its role as a reliable tool for achieving decarbonisation goals in the construction sector.

Furthermore, the collaborative validation process via the Big Room approach ensures that the BASE model's recommendations align with industry needs and stakeholder constraints. This inclusivity fosters trust and ensures the model's solutions are both feasible and widely adoptable, further enhancing its utility.

In summary, the BASE model stands out as a comprehensive framework for advancing sustainable, efficient, and cost-effective construction logistics. By integrating advanced simulation tools, real-world data, and stakeholder feedback, it provides actionable insights that address both operational challenges and environmental imperatives. The model's scalability and adaptability position it as a cornerstone for future advancements in sustainable construction practices.

4-6 Comparative Evaluation of the BASE Model

4-6-1 Summary of BASE Model Performance

The BASE model was applied across three diverse case studies and consistently demonstrated significant improvements in operational efficiency, environmental performance, and cost-effectiveness. These outcomes were validated through Discrete Event Simulation (DES), optimisation via Response Surface Methodology (RSM), and stakeholder feedback. Key improvements from the balanced optimised scenario, when compared with the existing contractor approach, include:

- CO_2 emissions reduced by up to 35%
- Diesel consumption reduced by approximately 35%
- Idle time reduced by over 90%
- Operational costs reduced by 30–40%
- Operational time reduced by 20–25%

These consistent improvements across all three cases confirm the BASE model's adaptability and scalability in various construction logistics settings.

4-6-2 Comparison with Existing Methods and Techniques

Traditional construction logistics planning often relies on static scheduling, reactive coordination, and manual decision-making, with limited integration of real-time optimisation, emissions data, or stakeholder collaboration. Even established practices like Lean Construction, while effective at reducing waste, typically lack embedded mechanisms for emissions measurement or dynamic simulation.

Compared to such conventional approaches, the BASE model offers a multi-layered improvement:

Integration of Simulation and Optimisation: Unlike single-method approaches, the BASE model combines DES and RSM, enabling detailed performance forecasting and optimisation of logistics variables.

Sustainability-Driven: Most existing models do not incorporate CO_2 emissions as a core performance metric. BASE directly integrates environmental outcomes into logistics decision-making.

Stakeholder Collaboration: Through the Big Room approach, the BASE model facilitates joint planning and bottleneck resolution, a capability largely absents in conventional models.

Adaptability: The model was tested on varied construction contexts, from soil to asphalt hauling and urban logistics, outperforming traditional plans in each case.

4-6-3 Contribution to Practice and Research

The BASE model represents an advancement in sustainable construction logistics by aligning operational efficiency with environmental responsibility and collaborative planning. Its systemic integration of simulation, optimisation, and stakeholder engagement distinguishes it from existing frameworks. As such, the BASE model not only addresses limitations in current practices but also offers a validated, practical roadmap for achieving decarbonisation goals in the built environment.

This comparative evaluation confirms that the BASE model outperforms traditional approaches in key sustainability and operational metrics, thus supporting its broader adoption in both academic and industry contexts.

4-7 Conclusion: CO_2 Reduction in Case Studies

The BASE model has demonstrated its exceptional capacity for advancing environmental sustainability and achieving significant CO_2 reductions across all case studies. By addressing the critical inefficiencies inherent in traditional construction logistics, the integration of Eco-hauling and the Big Room strategy within the BASE model provides a comprehensive and practical framework for achieving decarbonisation while maintaining operational efficiency.

- **CO_2 Reduction Across Scales**: Across all three case studies, the integration of Eco-hauling and the Big Room strategy within the BASE model achieved remarkable reductions in CO_2 emissions, tailored to the specific operational contexts:
    - In Case Study 1, the baseline scenario recorded CO_2 emissions of 3,525.5 kg. By implementing the 50%-50% balanced configuration, emissions were reduced to 2,293.7 kg, representing a 35% reduction. This substantial improvement was achieved through the introduction of checkpoints and collaborative planning, which optimised truck movements and minimised unnecessary idling.
    - In Case Study 2, the baseline scenario recorded CO_2 emissions of 3,751.1 kg. Under the 50%-50% balanced configuration, CO_2 emissions were reduced to 1,415.4 kg, representing a 62.3% reduction. This dramatic improvement was enabled by optimised fleet size, reduced idle time, and collaborative strategies that aligned operational priorities with sustainability objectives.
    - In Case Study 3, the baseline scenario generated CO_2 emissions of 2,971.5 kg. The 50%-50% configuration reduced emissions to 1,994.2 kg, a 32.9% reduction. By optimising fleet sizes and payloads, coupled with the strategic planning facilitated by

the Big Room, idle times were significantly reduced, and operational efficiency was enhanced. This collaborative approach proved effective in streamlining urban logistics while addressing the stringent regulatory and environmental constraints of the scenario.

The BASE model bridges tactical and operational dimensions, delivering scalable solutions adaptable to various logistical challenges:

Eco-hauling focuses on technical optimisations like equipment assignments and speed adjustments, ensuring precise and efficient operations. However, fragmented decision-making can hinder its effectiveness. The Big Room approach resolves this challenge by fostering collaborative alignment. By uniting stakeholders, it ensures that tactical adjustments are not only theoretically optimal but also practically viable, aligning technical improvements with on-site realities.

While Eco-hauling identifies inefficiencies, the Big Room approach facilitates real-time collaboration and problem-solving to resolve bottlenecks effectively. This operational coordination reduces delays and emissions, ensuring streamlined workflows. By integrating both strategies, the BASE model enhances adaptability and addresses complex logistical challenges effectively.

From small rural projects in Case Study 1 to medium-scale operations in Case Study 2 and the complex urban environment of Case Study 3, the BASE model consistently delivered sustainable solutions tailored to unique challenges. Collaborative decision-making reinforced operational efficiency and environmental goals, demonstrating the model's scalability and adaptability to diverse settings.

By enabling significant CO_2 reductions across all case studies, it showcases the potential of data-driven strategies to harmonise operational efficiency with decarbonisation objectives. The integration of advanced tools like AnyLogic and Stat-Ease, combined with real-world validations and collaborative frameworks, ensures that the BASE model is both practical and impactful. This cross-case analysis underscores the model's ability to address inefficiencies, reduce greenhouse gas emissions, and deliver scalable solutions adaptable to various logistical challenges. As the construction industry intensifies its focus on sustainability, the BASE model offers a clear pathway to achieving green, efficient, and cost-effective operations, setting a benchmark for future advancements in sustainable logistics.

Chapter 5:

Conclusion and Summary

5-1 Introduction

This chapter encapsulates the key findings and contributions of this research, providing a holistic reflection on the integration of Eco-hauling principles with collaborative strategies to optimise construction logistics. The study has addressed critical challenges in sustainable construction by developing and evaluating an innovative model that synthesises environmental considerations with operational efficiency. The conclusions drawn here aim to reinforce the significance of the proposed approach in reducing carbon emissions and promoting sustainability in construction logistics.

The chapter summarises the core research findings, demonstrating how the integration of Eco-hauling and Big Room approach overcomes traditional inefficiencies and bottlenecks in construction transportation. It reflects on the practical implications of the research outcomes for industry stakeholders, highlighting their potential to guide sustainable practices and decision-making. Furthermore, the chapter discusses the theoretical advancements introduced by this study, situating them within the broader discourse on sustainable construction.

In addition to summarising the research's practical and academic contributions, this chapter also acknowledges the limitations of the current study and encourages further exploration of emerging technologies, advanced simulation tools, and Big Room-based frameworks. Ultimately, the research reinforces the importance of integrating Eco-hauling with the Big Room approach in addressing the urgent need for decarbonisation in the built environment. Finally, suggestions for future research will be brought up to inspire continued innovation in this area.

5-2 Conclusion

This research has developed and validated the BASE model—a novel, integrated approach to sustainable construction logistics that combines Eco-hauling strategies, collaborative planning, simulation, and optimisation. Through empirical evidence gathered from three real-world case studies, the study has demonstrated the BASE model's ability to reduce CO_2 emissions, improve logistics efficiency, and enhance stakeholder coordination. By embedding environmental metrics directly into planning processes and enabling collaborative decision-making, the model addresses the critical need for decarbonisation in the construction sector.

The BASE model represents a significant advancement over traditional planning methods by integrating Discrete Event Simulation (DES) and Response Surface Methodology (RSM) with the Big Room approach. This integration offers a practical, replicable, and scalable solution that aligns with industry and policy-level sustainability goals. The research not only closes gaps in the literature but also provides a framework that construction professionals can adopt to operationalise low-carbon logistics in diverse project contexts.

Key conclusions emerging from the findings include:

1. The BASE model delivered consistent and measurable improvements across all three case studies, including average reductions of 32.8% in CO_2 emissions, 33.1% in diesel consumption, 93.2% in idle time, 35.5% in operational costs, and 22.7% in operational time.
2. The use of AnyLogic for Discrete Event Simulation enabled detailed modelling of site-specific logistics configurations, offering insights into time-based inefficiencies and allowing for precise intervention planning.
3. The integration of Stat-Ease's RSM tool allowed for rigorous scenario optimisation, enabling planners to identify variable interactions and select configurations that balanced emissions, cost, and time.
4. The collaborative Big Room approach addressed fragmented communication and enabled a shared understanding among stakeholders, directly supporting smoother logistics execution and informed decision-making.
5. The model proved adaptable across varied contexts, from soil and asphalt hauling to complex urban logistics, highlighting its scalability and generalisability for different project types.

6. The BASE model functioned not as a static toolkit but as a dynamic, decision-support system that encourages stakeholder-driven innovation and ongoing performance refinement.

Beyond its practical relevance, the study contributes methodologically by demonstrating how simulation, optimisation, and collaboration can function synergistically within a decision-support environment. It advances the theoretical understanding of sustainable logistics by illustrating how dynamic modelling and real-time stakeholder engagement can lead to better environmental and operational outcomes.

Overall, this study reinforces the importance of shifting from fragmented, reactive logistics planning to integrated, proactive, and sustainability-driven approaches. The BASE model provides a timely and adaptable roadmap for organisations seeking to meet decarbonisation targets while improving project efficiency and coordination. As the industry faces growing environmental responsibilities, the insights and tools developed through this research offer a robust foundation for innovation, policy alignment, and long-term impact in construction logistics.

5-3 Contribution to Knowledge

This study makes a distinctive and original contribution to the field of sustainable construction logistics by introducing and validating the BASE model—a novel, integrated system combining simulation, optimisation, and collaboration to support low-carbon logistics planning.

While previous frameworks often treat logistics, simulation, and stakeholder engagement as separate entities, the BASE model is the first to systematically unify:

- **Eco-hauling principles** aimed at reducing carbon emissions and improving fuel efficiency,
- **Collaborative planning through the Big Room approach** to overcome siloed decision-making,
- **Discrete Event Simulation (DES) using AnyLogic** to visualise and analyse construction logistics in real-time,
- **Response Surface Methodology (RSM) via Stat-Ease** for systematic optimisation across multiple operational variables.

This integrated approach advances beyond the state-of-the-art by addressing three key limitations of existing literature:

1. The lack of dynamic, emissions-oriented logistics models that account for real-time variability and trade-offs.
2. The absence of operational frameworks that engage diverse stakeholders in a shared planning environment.
3. The underutilisation of hybrid simulation-optimisation methods in the context of decarbonising construction logistics.

In contributing this model, the study bridges theoretical, methodological, and practical gaps in the field. It moves beyond descriptive or linear models by offering an interactive, data-driven, and replicable decision-support system. The BASE model has been empirically validated through three case studies with complex logistical constraints, making it both academically rigorous and practically implementable.

Furthermore, this research contributes to methodological innovation by demonstrating how multimodal tools can be used collectively to simulate, optimise, and validate sustainable logistics operations. It also enhances the discourse on stakeholder-led digital transformation by embedding collaboration as a functional component within the model.

In summary, the BASE model stands as a unique contribution that supports both academic advancement and industry application. It paves the way for future research on AI-enhanced optimisation, collaborative platforms, and policy-aligned logistics planning in the construction sector and beyond.

5-3-1 Theoretical Contributions

From a theoretical perspective, this study introduces a novel integration of Eco-hauling principles with collaborative strategies, significantly advancing the discourse on reducing carbon emissions in construction projects. By merging environmentally conscious logistics with enhanced stakeholder collaboration, the research creates a framework that optimises operational efficiency and minimises environmental impacts. This synthesis bridges the critical gap in existing knowledge, demonstrating the potential of combining sustainable hauling practices with collective decision-making to streamline construction processes and support net-zero goals.

Integrating Eco-hauling principles with the Big Room approach underscores the importance of collaborative planning in reducing CO2 emissions. This approach tackles inefficiencies such as excessive fuel use, idling, and redundant operations, providing a clear pathway to achieving decarbonisation targets. The study further highlights the synergistic role of simulation tools like AnyLogic and Stat-Ease in identifying optimal logistics scenarios, emphasising the value of data-driven, holistic methodologies for sustainable construction logistics.

The study lays a solid foundation for future academic inquiries into the intersection of sustainability and logistics by addressing both theoretical and practical dimensions.

It encourages further exploration of predictive analytics, real-time data integration, and advanced optimisation techniques to enhance decision-making and operational outcomes.

Finally, this study developed a model to reduce carbon emissions in construction projects effectively. Each component of the BASE model addresses specific challenges in sustainable logistics while also exhibiting certain limitations. Eco-hauling excels in planning to reduce CO_2 emissions and identifying bottlenecks within hauling operations; however, it falls short in resolving these inefficiencies due to the absence of a collaborative framework.

This is where the Big Room approach becomes indispensable, complementing Eco-hauling by fostering collaboration and enabling stakeholders to collectively address bottlenecks effectively.

Similarly, AnyLogic demonstrates exceptional capabilities in modelling the hauling process with high precision, but it is constrained when it comes to scaling up to large batches of scenarios, such as 200 to 500. At this juncture, Stat-Ease proves invaluable by expanding the scope of scenarios modelled in AnyLogic, enabling more comprehensive analyses and optimisations.

Together, these components form an interdependent cycle, where each contributes to and compensates for the limitations of the others. This synergistic integration ensures that the BASE model functions as a holistic framework for achieving sustainable logistics, harmonising advanced modelling, collaborative decision-making, and strategic planning.

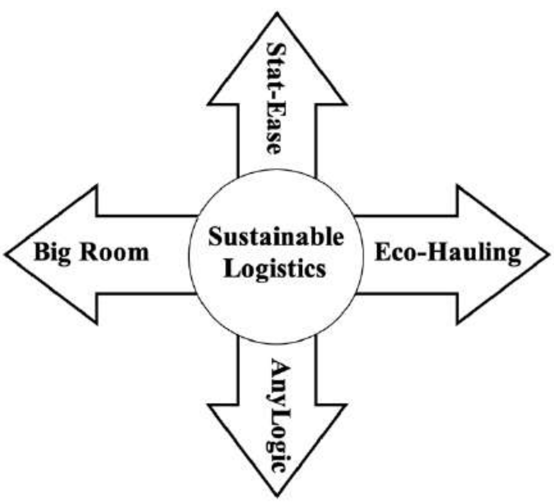


Fig. 3.3: The BASE Model: Big Room, AnyLogic, Stat-Ease, and Eco-Hauling for Sustainable Logistics

5-3-2 Practical Implications

For industry practitioners, this research provides a transformative perspective on managing construction projects sustainably. The findings identify actionable strategies for minimising CO2 emissions, such as route optimisation, reducing idle times, and fostering stakeholder collaboration through virtual Big Rooms. This innovative approach ensures that carbon-intensive activities, such as inefficient material transport and vehicle idling, are addressed effectively, enabling organisations to align with global sustainability goals.

The integration of Eco-hauling with collaborative frameworks not only enhances operational efficiency but also directly reduces fuel consumption and CO2 emissions. By optimising logistics workflows, the study delivers practical solutions that improve project timelines, reduce costs, and increase environmental accountability. As demonstrated in the study, advanced simulation tools enable construction managers to predict and mitigate emissions accurately, fostering data-driven decision-making processes.

These practical implications extend beyond operational improvements, providing a roadmap for compliance with stringent environmental regulations and certifications. The strategies proposed are especially valuable for organisations aiming to achieve net-zero emissions, offering a scalable model that aligns environmental sustainability with industry demands.

Ultimately, a six-step framework was developed as a practical guide for construction practitioners, demonstrating how to effectively adopt the BASE model by integrating advanced tools, collaborative strategies, and data-driven insights to achieve sustainable logistics and reduce CO_2 emissions (Figure 5.1).

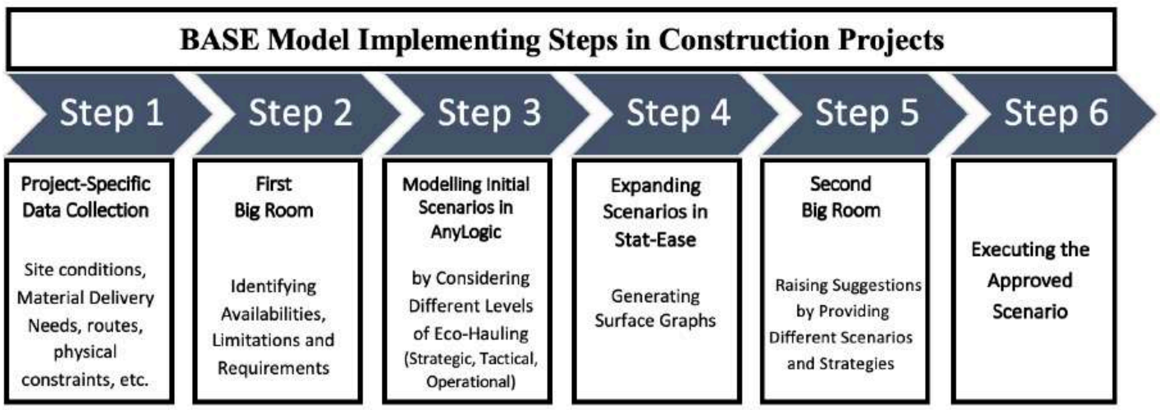


Fig. 5.1: BASE Model Implementation Steps

5-4 Limitations

While the research presents significant contributions, it also acknowledges certain limitations. The case studies, while diverse, were context-specific and may require further validation across different geographical and regulatory environments. The unique conditions of these environments, such as regulatory frameworks, stakeholder dynamics, and infrastructure maturity, may impact the generalisability of the findings.

Additionally, this study did not fully explore integrating renewable energy sources, such as electric construction machinery and biofuels. This omission leaves room for further research on how alternative energy technologies could complement the proposed strategies and enhance carbon reduction outcomes.

5-5 Suggestions for Future Research

The findings of this research open several avenues for future investigations aimed at enhancing the scope, applicability, and impact of sustainable construction logistics. The following recommendations outline key directions for advancing this field:

1. *Integration of Emerging Technologies:* Future research should enhance the BASE model by incorporating real-time data streams through IoT, and applying AI and machine learning to automate scenario prediction and adaptive optimisation. This would enable more responsive and accurate logistics planning aligned with real-time site conditions and sustainability targets.
2. *Exploration of Alternative Energy Sources:* The role of biofuels, renewable energy solutions, and hybrid technologies in supporting sustainable hauling operations should be a focal point for further research.
3. *Social and Behavioural Dimensions:* There is a pressing need to examine how human factors, such as organisational culture, stakeholder collaboration, and workforce training, influence the adoption of sustainable practices. Studies in this area could provide valuable insights into overcoming barriers to implementation and fostering a culture of sustainability within construction projects.
4. *Multimodal Transportation Systems:* Research on integrating multimodal transportation methods—combining road, rail, and water logistics—could offer solutions for minimising emissions and maximising resource efficiency. This area is particularly relevant for projects involving long-distance hauling.

5. *Scalability and Contextual Validation:* Conducting longitudinal studies across diverse geographical and regulatory contexts can validate the scalability and adaptability of the Eco-hauling and Big Room model. Such research would ensure its relevance and effectiveness in varying conditions.
6. *Advanced Simulation and Modelling Techniques:* The development of more sophisticated simulation models, incorporating real-time data and multi-objective optimisation, could enhance the accuracy and reliability of emissions forecasting. Future studies should also explore the use of System Dynamics to model the complex, interdependent relationships in construction logistics, offering insights into how different variables interact over time to influence outcomes. Integrating these techniques with collaborative platforms could further streamline decision-making.
7. *Using BASE Model for Long-Term Applications:* Future research should investigate the application of the BASE model for long-term sustainable logistics, particularly in industries such as quarrying. This approach could demonstrate how the model's principles can be adapted to large-scale operations with prolonged timelines, providing insights into sustained CO2 reduction, operational efficiency, and collaborative decision-making over extended periods.
8. *Policy and Regulatory Frameworks:* Future investigations should consider the impact of government policies, incentives, and regulatory measures on the adoption of sustainable logistics practices. Exploring how these frameworks can accelerate decarbonisation efforts is crucial for industry-wide implementation. These recommendations aim to support the transition toward sustainable, data-driven, and collaborative logistics planning in the construction sector.

- **Mandate carbon reporting in logistics operations**: Regulatory bodies should introduce requirements for monitoring and reporting emissions as part of project logistics plans.
- **Provide incentives for digital sustainability tools**: Funding and tax incentives can be offered to organisations that implement advanced simulation and emissions-optimised logistics planning.
- **Include collaborative planning in sustainability assessment schemes**: Procurement policies and environmental certification bodies should recognise structured stakeholder collaboration (e.g., Big Room sessions) as a sustainability enabler.

- **Support cross-industry research partnerships**: Policymakers should encourage partnerships between academia, industry, and government to advance tools like the BASE model and align them with net-zero policy goals.
- **Embed simulation and optimisation in national construction strategies**: National and regional construction frameworks should explicitly recommend integrated digital tools for decarbonisation planning in logistics.

These recommendations are designed to translate the outcomes of this research into real-world transformation. Their adoption can accelerate the shift toward more sustainable, predictable, and cooperative logistics practices in construction and infrastructure delivery.

References

Abbasi, S., Katayoon Taghizade, ;, Noorzai, E. and Asce, M. (2020), “BIM-Based Combination of Takt Time and Discrete Event Simulation for Implementing Just in Time in Construction Scheduling under Constraints”, *Journal of Construction Engineering and Management*, American Society of Civil Engineers (ASCE), Vol. 146 No. 12, doi: 10.1061/(ASCE)CO.1943-7862.0001940.

Åberg, A., Hansen, T.K., Linde, K., Nielsen, A.K., Damborg, R., Widd, A., Abildskov, J., *et al.* (2015), “A Framework for Modular Modeling of the Diesel Engine Exhaust Gas Cleaning System”, *Computer Aided Chemical Engineering*, Elsevier B.V., Vol. 37, pp. 455–460, doi: 10.1016/B978-0-444-63578-5.50071-2.

Abourizk, S. and Asce, M. (2010), “Role of Simulation in Construction Engineering and Management”, *Journal of Construction Engineering and Management*, American Society of Civil Engineers (ASCE), Vol. 136 No. 10, pp. 1140–1153, doi: 10.1061/(ASCE)CO.1943-7862.0000220.

Adamu, I. and Howell, G. (2012), “APPLYING LAST PLANNER® IN THE NIGERIAN CONSTRUCTION INDUSTRY”.

El Afifi, M.I. and Abdelrazik, W.A. (2023), “Renewable Energy Sources Applications in Currently Occupied Structures”.

Agalianos, K., Ponis, S.T., Aretoulaki, E., Plakas, G. and Efthymiou, O. (2020), “Discrete Event Simulation and Digital Twins: Review and Challenges for Logistics”, *Procedia Manufacturing*, Elsevier, Vol. 51, pp. 1636–1641, doi: 10.1016/J.PROMFG.2020.10.228.

Ahmadabadi, A.A. and Heravi, G. (2019), “The effect of critical success factors on project success in Public-Private Partnership projects: A case study of highway projects in Iran”, *Transport Policy*, Pergamon, Vol. 73, pp. 152–161, doi: 10.1016/J.TRANPOL.2018.07.004.

Ahn, C.R., Asce, M., Lee, S., Peña, F. and Peña-Mora, P. (2015), “Application of Low-Cost Accelerometers for Measuring the Operational Efficiency of a Construction Equipment Fleet”, *Journal of Computing in Civil Engineering*, American Society of Civil Engineers (ASCE), Vol. 29 No. 2, doi: 10.1061/(ASCE)CP.1943-5487.0000337.

Ahn, C.R., Lewis, P., Golparvar-Fard, M. and Lee, S. (2013), “Integrated Framework for Estimating, Benchmarking, and Monitoring Pollutant Emissions of Construction Operations”, *Journal of Construction Engineering and Management*, American Society of Civil Engineers, Vol. 139 No. 12, p. A4013003, doi: 10.1061/(ASCE)CO.1943-7862.0000755.

Akbarnezhad, A. and Xiao, J. (2017), “Estimation and Minimization of Embodied Carbon of Buildings: A Review”, *Buildings 2017, Vol. 7, Page 5*, Multidisciplinary Digital Publishing Institute, Vol. 7 No. 1, p. 5, doi: 10.3390/BUILDINGS7010005.

Akhatova, A., Kranzl, L., Schipfer, F. and Heendeniya, C.B. (2022), “Agent-Based Modelling of Urban District Energy System Decarbonisation—A Systematic Literature Review”, *Energies 2022, Vol. 15, Page 554*, Multidisciplinary Digital Publishing Institute, Vol. 15 No. 2, p. 554, doi: 10.3390/EN15020554.

Akintoye, A., McIntosh, G. and Fitzgerald, E. (2000), “A survey of supply chain collaboration and management in the UK construction industry”, *European Journal of Purchasing & Supply Management*, Pergamon, Vol. 6 No. 3–4, pp. 159–168, doi: 10.1016/S0969-7012(00)00012-5.

Alam, M.S. and McNabola, A. (2014a), “A critical review and assessment of Eco-Driving policy & technology: Benefits & limitations”, *Transport Policy*, Pergamon, Vol. 35, pp. 42–49, doi: 10.1016/J.TRANPOL.2014.05.016.

Alam, M.S. and McNabola, A. (2014b), “A critical review and assessment of Eco-Driving policy & technology: Benefits & limitations”, *Transport Policy*, Pergamon, Vol. 35, pp. 42–49, doi: 10.1016/J.TRANPOL.2014.05.016.

Alarcón, L.F., Diethelm, S., Rojo, O. and Calderon, R. (2005), “Assessing the Impacts of Implementing Lean Construction”.

Alharahsheh, H.H. and Pius, A. (2020), “A Review of key paradigms: positivism VS interpretivism”, *Global Academic Journal of Humanities and Social Sciences*, Vol. 2 No. 3, pp. 39–43, doi: 10.36348/gajhss.2020.v02i03.001.

Alhava, O., Laine, E. and Kiviniemi, A. (2015a), *Intensive Big Room Process for Co-Creating Value in Legacy Construction Projects*, *Journal of Information Technology in Construction (ITcon)*, Vol. 20.

Alhava, O., Laine, E. and Kiviniemi, A. (2015b), “Intensive big room process for co-creating value in legacy construction projects”, *ITcon Vol. 20, Special Issue ECPPM 2014 - 10th European Conference on Product and Process Modelling, Pg. 146-158, Http://Www.Itcon.Org/2015/11*, Vol. 20 No. 11, pp. 146–158.

Allison, C.K. and Stanton, N.A. (2019), “Eco-driving: the role of feedback in reducing emissions from everyday driving behaviours”, *Theoretical Issues in Ergonomics Science*, Taylor & Francis, Vol. 20 No. 2, pp. 85–104, doi: 10.1080/1463922X.2018.1484967.

Aravindh, M.D., Nakkeeran, G., Krishnaraj, L. and Arivusudar, N. (2022), “Evaluation and optimization of lean waste in construction industry”, *Asian Journal of Civil Engineering*, Springer Science and Business Media Deutschland GmbH, Vol. 23 No. 5, pp. 741–752, doi: 10.1007/S42107-022-00453-9/FIGURES/7.

Araya, F. (2022), “Integration of discrete event simulation with other modeling techniques to simulate construction engineering and management: an overview”, doi: 10.7764/RDLC.21.2.338.

Arogundade, S., Dulaimi, M. and Ajayi, S. (2021), “The Role of Contractors in Reducing Carbon during Construction-A Preliminary Study”.

Arvitrida, N.I. (2018), “A review of agent-based modeling approach in the supply chain collaboration context”, *IOP Conference Series: Materials Science and Engineering*, IOP Publishing, Vol. 337 No. 1, p. 012015, doi: 10.1088/1757-899X/337/1/012015.

Athanassiadis, D., Lidestav, G. and Nordfjell, T. (2002), “Energy use and emissions due to the manufacture of a forwarder”, *Resources, Conservation and Recycling*, Elsevier, Vol. 34 No. 3, pp. 149–160, doi: 10.1016/S0921-3449(01)00100-8.

Austern, G., Capeluto, I.G. and Grobman, Y.J. (2018), “Rationalization methods in computer aided fabrication: A critical review”, *Automation in Construction*, Elsevier, Vol. 90, pp. 281–293, doi: 10.1016/J.AUTCON.2017.12.027.

Awardee, E., Wu, G., Barth, M. and Boriboonsomsin, K. (2012), “ENERGY INNOVATIONS SMALL GRANT TRANSPORTATION PROGRAM FINAL REPORT Eco-Routing Navigation System for Electric Vehicles”.

Awwad, R., Asce, A.M., Caesar, ;, Shdid, A., Asce, M. and Tayeh, R. (2017), “Agent-Based Model for Simulating Construction Safety Climate in a Market Environment”, *Journal of Computing in Civil Engineering*, American Society of Civil Engineers (ASCE), Vol. 31 No. 1, doi: 10.1061/(ASCE)CP.1943-5487.0000612.

Azari, R. and Kim, Y.-W. (2014), “Development and Validation of a Framework for Evaluation of Integrated Design Teams of Sustainable High-performance Buildings”, American Society of Civil Engineers, pp. 584–593, doi: 10.1061/9780784413517.060.

Aziz, R.F. and Hafez, S.M. (2013), “Applying lean thinking in construction and performance improvement”, *Alexandria Engineering Journal*, Elsevier B.V., Vol. 52 No. 4, pp. 679–695, doi: 10.1016/J.AEJ.2013.04.008.

Bahramian, M. and Yetilmezsoy, K. (2020), “Life cycle assessment of the building industry: An overview of two decades of research (1995–2018)”, *Energy and Buildings*, Elsevier, Vol. 219, p. 109917, doi: 10.1016/J.ENBUILD.2020.109917.

Ballard, G. (1998), “POSITIVE VS NEGATIVE ITERATION IN DESIGN”.

Ballard, G., Harper, N. and Zabelle, T. (2003), “Learning to see work flow: An application of lean concepts to precast concrete fabrication”, *Engineering, Construction and Architectural Management*, Vol. 10 No. 1, pp. 6–14, doi: 10.1108/09699980310466505.

Ballard, G. and Howell, G. (2003), “Lean project management”, *Building Research and Information : The International Journal of Research, Development and Demonstration*, Vol. 31 No. 2, pp. 119–133, doi: 10.1080/09613210301997.

Ballard, G., Koskela, L., Howell, G. and Zabelle, T. (2001), *PRODUCTION SYSTEM DESIGN IN CONSTRUCTION*.

Ballard, G., Tommelein, I., Koskela, L. and Howell, G. (2002), “Lean construction tools and techniques”.

Banks, J., Carson, J.S., Nelson, B.L. and Nicol, D.M. (2010), *Discrete-Event System Simulation*, Prentice-Hall.

Bao, Z. and Lu, W. (2020), “Developing efficient circularity for construction and demolition waste management in fast emerging economies: Lessons learned from Shenzhen, China”, *Science of The Total Environment*, Elsevier, Vol. 724, p. 138264, doi: 10.1016/J.SCITOTENV.2020.138264.

Barati, K. and Shen, X. (2016), “Emissions Modelling of Earthmoving Equipment”, *33rd International Symposium on Automation and Robotics in Construction*.

Barati, K. and Shen, X. (2017), “Optimal Driving Pattern of On-Road Construction Equipment for Emissions Reduction”, *Procedia Engineering*, No longer published by Elsevier, Vol. 180, pp. 1221–1228, doi: 10.1016/J.PROENG.2017.04.283.

Barbosa, G., Andrade, F., Biotto, C. and Mota, B. (2013), “HEIJUNKA SYSTEM TO LEVEL TELESCOPIC FORKLIFT ACTIVITIES USING TABLETS IN CONSTRUCTION SITE”.

Barkenbus, J.N. (2009), “Eco-driving: An overlooked climate change initiative”, *Energy Policy*, Elsevier, Vol. 38 No. 2, pp. 762–769, doi: 10.1016/J.ENPOL.2009.10.021.

Batty, M. (2012), “A generic framework for computational spatial modelling”, *Agent-Based Models of Geographical Systems*, Springer Netherlands, pp. 19–50, doi: 10.1007/978-90-481-8927-4_2/FIGURES/5_2.

Belaïd, F. (2022), “How does concrete and cement industry transformation contribute to mitigating climate change challenges?”, *Resources, Conservation & Recycling Advances*, Elsevier, Vol. 15, p. 200084, doi: 10.1016/J.RCRADV.2022.200084.

Benjaafar, S., Li, Y. and Daskin, M. (2013), “Carbon footprint and the management of supply chains: Insights from simple models”, *IEEE Transactions on Automation Science and Engineering*, Vol. 10 No. 1, pp. 99–116, doi: 10.1109/TASE.2012.2203304.

Berardi, U. (2017), “A cross-country comparison of the building energy consumptions and their trends”, *Resources, Conservation and Recycling*, Elsevier, Vol. 123, pp. 230–241, doi: 10.1016/J.RESCONREC.2016.03.014.

Bertagnolli, F. (2022), “Lean Management”.

Bhandari, K., Gangopadhyay, S. and Shukla, A. (2011), “Carbon footprint: a tool to quantify the impact of road construction on the environment”, *Journal of the Eastern Asia Society for Transportation Studies*, Vol. 9.

Bolade-Oladepo, Ojelabi, R. and Ogunde, A.O. (2023), “A Decade Trend Analysis of the Literature on Lean Construction (2012-2022): A Systematic Bibliometric Approach”, *IOSR Journal of Engineering (IOSRJEN) Www.Iosrjen.Org ISSN*, Vol. 13, pp. 2278–8719.

Bonnet-Masimbert, P.A., Gauvin, F., Brouwers, H.J.H. and Amziane, S. (2020), "Study of modifications on the chemical and mechanical compatibility between cement matrix and oil palm fibres", *Results in Engineering*, Elsevier B.V., Vol. 7, doi: 10.1016/j.rineng.2020.100150.

Bouhmoud, H., Loudyi, D. and Azhar, S. (2022), "Building information modeling (BIM) for lifecycle carbon emission: scientometric and scoping literature reviews", *Smart and Sustainable Built Environment*, Emerald Publishing, Vol. 13 No. 6, pp. 1349–1369, doi: 10.1108/SASBE-05-2022-0086/FULL/XML.

Boyd C. and Paulson Jr. (1976), "Designing to Reduce Construction Costs", doi: https://doi.org/10.1061/JCCEAZ.0000639.

Boysen, N., Fedtke, S. and Schwerdfeger, S. (2020), "Last-mile delivery concepts: a survey from an operational research perspective", *OR Spectrum 2020 43:1*, Springer, Vol. 43 No. 1, pp. 1–58, doi: 10.1007/S00291-020-00607-8.

Brander, M. (2012), "GHGs-CO2-CO2e-and-Carbon-What-Do-These-Mean-v2.1", *Ecometria*, available at: https://ecometrica.com/assets/GHGs-CO2-CO2e-and-Carbon-What-Do-These-Mean-v2.1.pdf (accessed 5 August 2021).

Briscoe, G.H., Dainty, A.R.J., Millett, S.J. and Neale, R.H. (2004), "Client-led strategies for construction supply chain improvement", *Construction Management and Economics*, Vol. 22 No. 2, pp. 193–201, doi: 10.1080/0144619042000201394.

Bruce, Hobson, Morgan and Child. (2001), "PM—Power and Machinery".

Bui, T.T.P., MacGregor, C., Domingo, N. and Wilkinson, S. (2023), "Collaboration and integration towards zero carbon refurbishment: A New Zealand case study", *Energy for Sustainable Development*, Elsevier, Vol. 74, pp. 361–371, doi: 10.1016/J.ESD.2023.04.005.

Cabeza, L.F., Bai, Q., Bertoldi, P., Kihila, J.M., Lucena, A.F.P., Mata, É., Mirasgedis, S., *et al.* (2022), "9 Buildings Coordinating Lead Authors: Lead Authors: Contributing Authors: Review Editors: Chapter Scientist: Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P", doi: 10.1017/9781009157926.011.

Cao, T., Durbin, T.D., Russell, R.L., Cocker, D.R., Scora, G., Maldonado, H. and Johnson, K.C. (2016), "Evaluations of in-use emission factors from off-road construction equipment", *Atmospheric Environment*, Pergamon, Vol. 147, pp. 234–245, doi: 10.1016/J.ATMOSENV.2016.09.042.

Carr, M. (2018), "An Intro to the Last Planner® System ".

Cassandras, C.G. and Lafortune, S. (1999), "Introduction to Discrete-Event Simulation", Springer, Boston, MA, pp. 591–661, doi: 10.1007/978-1-4757-4070-7_10.

Cavalliere, C., Habert, G., Dell'Osso, G.R. and Hollberg, A. (2019), "Continuous BIM-based assessment of embodied environmental impacts throughout the design process", *Journal of Cleaner Production*, Elsevier, Vol. 211, pp. 941–952, doi: 10.1016/J.JCLEPRO.2018.11.247.

Chastas, P., Theodosiou, T., Bikas, D. and Kontoleon, K. (2017), "Embodied Energy and Nearly Zero Energy Buildings: A Review in Residential Buildings", *Procedia Environmental Sciences*, Elsevier, Vol. 38, pp. 554–561, doi: 10.1016/J.PROENV.2017.03.123.

Chavada, R., Dawood, N. and Kassem, M. (2012), "CONSTRUCTION WORKSPACE MANAGEMENT: THE DEVELOPMENT AND APPLICATION OF A NOVEL nD PLANNING APPROACH AND TOOL", Vol. 17, pp. 213–236.

Chen, Y., Wu, Y., Chen, N., Kang, C., Du, J. and Luo, C. (2022), "Calculation of Energy Consumption and Carbon Emissions in the Construction Stage of Large Public Buildings and an Analysis of Influencing Factors Based on an Improved STIRPAT Model", *Buildings 2022, Vol. 12, Page 2211*, Multidisciplinary Digital Publishing Institute, Vol. 12 No. 12, p. 2211, doi: 10.3390/BUILDINGS12122211.

Construction Task Force. (1998), “Rethinking Construction – The Egan Report - Constructing Excellence”, *1998*, available at: https://constructingexcellence.org.uk/rethinking-construction-the-egan-report/ (accessed 5 January 2025).

Corona, E., Eros, F. and Diee, P. (2013), “A Review of Lean-Kanban Approaches in the Software Development”.

Cox, A. and Townsend, M. (1997), “Latham as half-way house: A relational competence approach to better practice in construction procurement”, *Engineering, Construction and Architectural Management*, MCB UP Ltd, Vol. 4 No. 2, pp. 143–158, doi: 10.1108/EB021045/FULL/PDF.

Coyle, M. (2007), “EFFECTS OF PAYLOAD ON THE FUEL CONSUMPTION OF TRUCKs”, *Imise Limited* , available at: https://imise.co.uk/wp-content/uploads/2017/09/RR5-Effects-of-Payload-on-the-Fuel-Consumption-of-Trucks.pdf?utm_source=chatgpt.com (accessed 16 December 2024).

Creswell, J.W. (1999), “Mixed-Method Research: Introduction and Application”, *Handbook of Educational Policy*, Academic Press, pp. 455–472, doi: 10.1016/B978-012174698-8/50045-X.

Danesh, N. and Jalali, M. (2020), *Comprehensive Advocacy Document for Air Pollution Control and Reducing Its Health Impacts*.

Danielsen, S.W. and Kuznetsova, E. (2015), “Environmental impact and sustainability in aggregate production and use”, *Engineering Geology for Society and Territory - Volume 5: Urban Geology, Sustainable Planning and Landscape Exploitation*, Springer International Publishing, pp. 41–44, doi: 10.1007/978-3-319-09048-1_7.

Dave, B., Pikas, E., Kerosuo, H. and Mäki, T. (2015), “ViBR – Conceptualising a Virtual Big Room through the Framework of People, Processes and Technology”, *Procedia Economics and Finance*, Elsevier, Vol. 21, pp. 586–593, doi: 10.1016/S2212-5671(15)00216-6.

Delbridge, V., Harman, O., Oliveira-Cunha, J. and Venables, A. (2022), *Sustainable Urbanisation in Developing Countries: Cities as Places to Live KEY MESSAGES*.

Demircan Çakar, N., Gedikli, A., Erdoğan, S. and Yıldırım, D.Ç. (2021), “A comparative analysis of the relationship between innovation and transport sector carbon emissions in developed and developing Mediterranean countries”, *Environmental Science and Pollution Research*, Springer Science and Business Media Deutschland GmbH, Vol. 28 No. 33, pp. 45693–45713, doi: 10.1007/S11356-021-13390-Y/TABLES/11.

Detty, R.B., Yingling, J.C., Detty{, R.B. and Yingling{, J.C. (2000), “International Journal of Production Research Quantifying benefits of conversion to lean manufacturing with discrete event simulation: A case study Quantifying bene® ts of conversion to lean manufacturing with discrete event simulation: a case study”, Vol. 38 No. 2, pp. 429–445, doi: 10.1080/002075400189509.

Ding, Z., Gong, W., Li, S. and Wu, Z. (2018), “System Dynamics versus Agent-Based Modeling: A Review of Complexity Simulation in Construction Waste Management”, *Sustainability 2018, Vol. 10, Page 2484*, Multidisciplinary Digital Publishing Institute, Vol. 10 No. 7, p. 2484, doi: 10.3390/SU10072484.

Dipotet L, G. (2010), *Gestion-Energetica-Obras-m-Tierra-v-Ii*.

Doney, S.C., Fabry, V.J., Feely, R.A. and Kleypas, J.A. (2008), “Ocean Acidification: The Other CO 2 Problem”, doi: 10.1146/annurev.marine.010908.163834.

Du, Q., Bao, T., Li, Y., Huang, Y. and Shao, L. (2019), “Impact of prefabrication technology on the cradle-to-site CO2 emissions of residential buildings”, *Clean Technologies and Environmental Policy*, Springer Verlag, Vol. 21 No. 7, pp. 1499–1514, doi: 10.1007/S10098-019-01723-Y/FIGURES/5.

Du, Q., Shao, L., Zhou, J., Huang, N., Bao, T. and Hao, C. (2019), "Dynamics and scenarios of carbon emissions in China's construction industry", *Sustainable Cities and Society*, Elsevier, Vol. 48, p. 101556, doi: 10.1016/J.SCS.2019.101556.

Dubey, R., Gunasekaran, A., Papadopoulos, T. and Childe, S.J. (2015), "Green supply chain management enablers: Mixed methods research", *Sustainable Production and Consumption*, Elsevier, Vol. 4, pp. 72–88, doi: 10.1016/J.SPC.2015.07.001.

Dubois, A. and Gadde, L.E. (2002), "Systematic combining: an abductive approach to case research", *Journal of Business Research*, Elsevier, Vol. 55 No. 7, pp. 553–560, doi: 10.1016/S0148-2963(00)00195-8.

Eadie, R., Browne, M., Odeyinka, H., McKeown, C. and McNiff, S. (2013), "BIM implementation throughout the UK construction project lifecycle: An analysis", *Automation in Construction*, Elsevier, Vol. 36, pp. 145–151, doi: 10.1016/J.AUTCON.2013.09.001.

Eaidgah, Y., Maki, A.A., Kurczewski, K. and Abdekhodaee, A. (2016), "Visual management, performance management and continuous improvement A lean manufacturing approach", *International Journal of Lean Six Sigma*, Vol. 7 No. 2, pp. 187–210, doi: 10.1108/IJLSS-09-2014-0028.

Ebbs, P. and Pasquire, C. (2019), *A Facilitator's Guide to the Last Planner® System A Facilitators' Guide to the Last Planner® System: A Repository of Facilitation Tips for Practitioners*.

Ebbs, P.J., Pasquire, C.L. and Daniel, E.I. (2018), "The last planner® system path clearing approach in action: A case study", *IGLC 2018 - Proceedings of the 26th Annual Conference of the International Group for Lean Construction: Evolving Lean Construction Towards Mature Production Management Across Cultures and Frontiers*, The International Group for Lean Construction, Vol. 2, pp. 724–733, doi: 10.24928/2018/0433.

Ebrahimi, B., Wallbaum, H., Jakobsen, P.D. and Booto, G.K. (2020), "Regionalized environmental impacts of construction machinery", *International Journal of Life Cycle Assessment*, Springer, Vol. 25 No. 8, pp. 1472–1485, doi: 10.1007/S11367-020-01769-X/FIGURES/4.

EIA. (2020), "Where greenhouse gases come from - U.S. Energy Information Administration (EIA)", available at: https://www.eia.gov/energyexplained/energy-and-the-environment/where-greenhouse-gases-come-from.php (accessed 29 June 2022).

van Eldik, M.A., Vahdatikhaki, F., dos Santos, J.M.O., Visser, M. and Doree, A. (2020), "BIM-based environmental impact assessment for infrastructure design projects", *Automation in Construction*, Elsevier, Vol. 120, p. 103379, doi: 10.1016/J.AUTCON.2020.103379.

EPA. (2005), *Clean Construction USA* .

EPA. (2009), *POTENTIAL FOR REDUCING GREENHOUSE GAS EMISSIONS IN THE CONSTRUCTION SECTOR. Climate Change | US EPA*.

ERA. (2019), *CARBON FOOTPRINT OF CONSTRUCTION EQUIPMENT RESEARCH REPORT CARBON FOOTPRINT OF CONSTRUCTION EQUIPMENT RESEARCH REPORT CARBON FOOTPRINT OF CONSTRUCTION EQUIPMENT 2 3*.

Ercan, T., Zhao, Y., Tatari, O. and Pazour, J.A. (2015), "Optimization of transit bus fleet's life cycle assessment impacts with alternative fuel options", *Energy*, Elsevier Ltd, Vol. 93, pp. 323–334, doi: 10.1016/j.energy.2015.09.018.

Esau, R., Jungclaus, M., Olgyay, V. and Rempher, A. (2021), "Reducing Embodied Carbon in Buildings Low-Cost, High-Value Opportunities Contacts Copyrights and Citation".

Fakhimi, M., Anagnostou, A., Stergioulas, L. and Taylor, S.J.E. (2015), "A hybrid agent-based and Discrete Event Simulation approach for sustainable strategic planning and simulation analytics”, *Proceedings - Winter Simulation Conference*, Institute of Electrical and Electronics Engineers Inc., Vol. 2015-January, pp. 1573–1584, doi: 10.1109/WSC.2014.7020009.

Falakeh, S., Sallerström, P., Carlsson, A. and Anderberg, S. (2023), “Reduced Greenhouse Gas Emissions from Transport Infrastructure Construction Reaching the Swedish Transport Administration’s climate reduction targets with greenhouse gas reduction measures in the production phase of the most recurring materials”.

Fang, Q., Chen, X., Castro-Lacouture, D. and Li, C. (2023), “Intervention and management of construction workers’ unsafe behavior: A simulation digital twin model”, *Advanced Engineering Informatics*, Elsevier, Vol. 58, p. 102182, doi: 10.1016/J.AEI.2023.102182.

Farmer, G.T. and Cook, J. (2013), “Carbon Dioxide, Other Greenhouse Gases, and the Carbon Cycle”, *Climate Change Science: A Modern Synthesis*, Springer, Dordrecht, pp. 199–215, doi: 10.1007/978-94-007-5757-8_9.

Fathi, S., Fathi, S. and Balali, V. (2023), “Time–Space Conflict Management in Construction Sites Using Discrete Event Simulation (DES) and Path Planning in Unity”, *Applied Sciences (Switzerland)*, Multidisciplinary Digital Publishing Institute (MDPI), Vol. 13 No. 14, doi: 10.3390/app13148128.

Fellows, Richard. and Liu, Anita. (2022), “Research methods for construction”, Wiley-Blackwell, p. 372.

Ferdosi, H., Abbasianjahromi, H., Banihashemi, S. and Ravanshadnia, M. (2023), “BIM applications in sustainable construction: scientometric and state-of-the-art review”, *International Journal of Construction Management*, Taylor & Francis, Vol. 23 No. 12, pp. 1969–1981, doi: 10.1080/15623599.2022.2029679.

Forrester, J.W. (1994), “System dynamics, systems thinking, and soft OR”, *System Dynamics Review*, John Wiley & Sons, Ltd, Vol. 10 No. 2–3, pp. 245–256, doi: 10.1002/SDR.4260100211.

Forrester, J.W. (2009), “Some Basic Concepts in System Dynamics”.

Forth, K., Borrmann, A. and Hollberg, A. (2023), “Interactive visualization of uncertain embodied GHG emissions for design decision support in early stages using open BIM”, *Life-Cycle of Structures and Infrastructure Systems - Proceedings of the 8th International Symposium on Life-Cycle Civil Engineering, IALCCE 2023*, CRC Press/Balkema, pp. 3634–3641, doi: 10.1201/9781003323020-445/INTERACTIVE-VISUALIZATION-UNCERTAIN-EMBODIED-GHG-EMISSIONS-DESIGN-DECISION-SUPPORT-EARLY-STAGES-USING-OPEN-BIM-FORTH-BORRMANN-HOLLBERG.

Frey, H.C., Rasdorf, W. and Lewis, P. (2010), “Comprehensive field study of fuel use and emissions of nonroad diesel construction equipment”, *Transportation Research Record*, National Research Council, No. 2158, pp. 69–76, doi: 10.3141/2158-09.

Friedlingstein, P., Jones, M.W., Andrew, R.M., Hauck, J., Olsen, A., Peters, G.P., Peters, W., *et al.* (2020), “Shin-Ichiro Nakaoka 26”, *Earth Syst. Sci. Data*, Vol. 12, p. 63, doi: 10.5194/essd-12-3269-2020.

Gallaire, H., Minker, J. and Nicolas, J.M. (1984), “Logic and Databases: A Deductive Approach”, *ACM Computing Surveys (CSUR)*, ACMPUB27New York, NY, USA, Vol. 16 No. 2, pp. 153–185, doi: 10.1145/356924.356929/ASSET/2C6C6575-43CD-40B9-BCA0-1ECE5ABD4AE3/ASSETS/356924.356929.FP.PNG.

Galsworth, G.D.. (1997), “Visual systems : harnessing the power of the visual workplace”, American Management Association, p. 320.

Garcés, G. and Peña, C. (2023), “A Review on Lean Construction for Construction Project Management”, *Revista Ingenieria de Construccion*, Potificia Universidad Catolica de Chile, Vol. 38 No. 1, pp. 43–60, doi: 10.7764/RIC.00051.21.

Gettu, N. and Buttlar, W.G. (2024), "Critical Parameters Affecting the Carbon Footprint of Asphalt Mixes", *RILEM Bookseries*, Springer Science and Business Media B.V., Vol. 48, pp. 374–383, doi: 10.1007/978-3-031-53389-1_35/FIGURES/6.

Ghaffarianhoseini, A., Tookey, J., Ghaffarianhoseini, A., Naismith, N., Azhar, S., Efimova, O. and Raahemifar, K. (2016), "Building Information Modelling (BIM) uptake: Clear benefits, understanding its implementation, risks and challenges", doi: 10.1016/j.rser.2016.11.083.

Gharibeh, H.F., Yazdankhah, A.S., Azizian, M.R. and Farrokhifar, M. (2021), "Online Energy Management Strategy for Fuel Cell Hybrid Electric Vehicles with Installed PV on Roof", *IEEE Transactions on Industry Applications*, Institute of Electrical and Electronics Engineers Inc., Vol. 57 No. 3, pp. 2859–2869, doi: 10.1109/TIA.2021.3061323.

Ghisellini, P., Ripa, M. and Ulgiati, S. (2018), "Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector. A literature review", *Journal of Cleaner Production*, Elsevier, Vol. 178, pp. 618–643, doi: 10.1016/J.JCLEPRO.2017.11.207.

Giesekam, J., Barrett, J., Taylor, P. and Owen, A. (2014), "The greenhouse gas emissions and mitigation options for materials used in UK construction", doi: 10.1016/j.enbuild.2014.04.035.

GlobalABC. (2020), "Global Alliance for Buildings and Construction 2020 GLOBAL STATUS REPORT FOR BUILDINGS AND CONSTRUCTION Towards a zero-emissions, efficient and resilient buildings and construction sector EXECUTIVE SUMMARY 2020 GLOBAL STATUS REPORT FOR BUILDINGS AND CONSTRUCTION Towards a zero-emissions, efficient and resilient buildings and construction sector".

Gokberk Bayhan, H., Demirkesen, S., Zhang, C. and Tezel, A. (2022), "A Lean Construction and BIM Interaction Model for the Construction Industry".

Goldsman, D. and Goldsman, P. (2015), "Discrete-Event Simulation", Springer, London, pp. 103–109, doi: 10.1007/978-1-4471-5634-5_10.

Golhar, D.Y. and Stamm, C.L. (1991), "The just-in-time philosophy: A literature review", *THE INTERNATIONAL JOURNAL OF PRODUCTION RESEARCH*, Taylor & Francis Group, Vol. 29 No. 4, pp. 657–676, doi: 10.1080/00207549108930094.

Golzarpoor, H., González, V. and Poshdar, M. (2013), "IMPROVING CONSTRUCTION ENVIRONMENTAL METRICS THROUGH INTEGRATION OF DISCRETE EVENT SIMULATION AND LIFE CYCLE ANALYSIS".

González, V. and Echaveguren, T. (2012), "Exploring the environmental modeling of road construction operations using discrete-event simulation", *Automation in Construction*, Elsevier, Vol. 24, pp. 100–110, doi: 10.1016/J.AUTCON.2012.02.011.

Greer, F. and Horvath, A. (2024), "Exploring the significance of transportation emissions in upfront embodied carbon in buildings", *Building and Environment*, Pergamon, Vol. 269, p. 112457, doi: 10.1016/J.BUILDENV.2024.112457.

Greif, M. (1991), "The visual factory: Building participation through shared information", *The Visual Factory: Building Participation through Shared Information*, Taylor and Francis, pp. 1–281, doi: 10.1201/9780203719114/VISUAL-FACTORY-MICHEL-GREIF/ACCESSIBILITY-INFORMATION.

Groenewolt, A., Schwinn, T., Nguyen, L. and Menges, A. (2018), "An interactive agent-based framework for materialization-informed architectural design", *Swarm Intelligence*, Springer New York LLC, Vol. 12 No. 2, pp. 155–186, doi: 10.1007/S11721-017-0151-8/FIGURES/16.

Guggemos, A.A. and Horvath, A. (2005), "Comparison of Environmental Effects of Steel- and Concrete-Framed Buildings", *Journal of Infrastructure Systems*, American

Society of Civil Engineers, Vol. 11 No. 2, pp. 93–101, doi: 10.1061/(ASCE)1076-0342(2005)11:2(93).
Guggemos, A.A. and Horvath, A. (2006), "Decision-Support Tool for Assessing the Environmental Effects of Constructing Commercial Buildings", *Journal of Architectural Engineering*, American Society of Civil Engineers, Vol. 12 No. 4, pp. 187–195, doi: 10.1061/(ASCE)1076-0431(2006)12:4(187).
Guna, T.H., Suparno and Kertati, I. (2024), "Breaking down barriers: Overcoming silo mentality in bureaucratic reform", *Journal of Sustainability, Society, and Eco-Welfare*, Institute for Advanced Science, Social, and Sustainable Future, Vol. 2 No. 1, pp. 16–28, doi: 10.61511/JSSEW.V2I1.2024.884.
Hajdukiewicz, M., Byrne, D., Keane, M.M. and Goggins, J. (2015), "Real-time monitoring framework to investigate the environmental and structural performance of buildings", *Building and Environment*, Pergamon, Vol. 86, pp. 1–16, doi: 10.1016/J.BUILDENV.2014.12.012.
Hajji, A.M. and Larasati, A. (2016), "ARTICLES YOU MAY BE INTERESTED IN E3-A user's interface for quantifying total cost, diesel consumption, and emissions from bulldozers and its comparison to field data AIP Conference Emission inventory of HC and CO of heavy construction equipment by using NONROAD engine modelling for toll road project in Indonesia AIP Conference", *Proceedings*, Vol. 1778, p. 20006, doi: 10.1063/1.4965742.
Hajji, A.M., Michael, ; and Lewis, P. (2017), "How to estimate green house gas (GHG) emissions from an excavator by using CAT's performance chart Articles You May Be Interested In E3-A user's interface for quantifying total cost, diesel consumption, and emissions from bulldozers and its comparison to field data Wear model of an excavator bucket AIP Conference Proceedings", *AIP Conf. Proc*, Vol. 1887, p. 20047, doi: 10.1063/1.5003530.
Halfen, M., Treiber, M., Brux, T. and Schwab, D. (2023), "Mobile Fast-charging Solutions for the Electrified Construction Site", *ATZheavy Duty Worldwide 2023 16:2*, Springer, Vol. 16 No. 2, pp. 38–43, doi: 10.1007/S41321-023-1026-0.
Hamdan, H.A.M., Andersen, P.H. and de Boer, L. (2021), "Stakeholder collaboration in sustainable neighborhood projects—A review and research agenda", *Sustainable Cities and Society*, Elsevier, Vol. 68, p. 102776, doi: 10.1016/J.SCS.2021.102776.
Haris, N.I.N., Al Edrus, S.S.A.O., Abdul Raof, N., Wondi, M.H., Khan, W.R., Sien, L.S., Ilyas, R.A., *et al.* (2024), "Toward low-carbon cities: A review of circular economy integration in urban waste management and its impact on carbon emissions", *Wiley Interdisciplinary Reviews: Energy and Environment*, John Wiley & Sons, Ltd, Vol. 13 No. 5, p. e535, doi: 10.1002/WENE.535.
Harrison, H., Birks, M., Franklin, R. and Mills, J. (2017), "Case Study Research: Foundations and Methodological Orientations", *Forum Qualitative Sozialforschung / Forum: Qualitative Social Research*, Vol. 18 No. 1, doi: 10.17169/FQS-18.1.2655.
Hassan, M.K. (2013), "Applying Lean Six Sigma for Waste Reduction in a Manufacturing Environment", *SSRN Electronic Journal*, Elsevier BV, doi: 10.2139/SSRN.4920215.
Havn, E. (1994), "J.P. Womack, D.T. Jones, and D. Ross, The Machine that Changed the World, Rawson Associates, New York, 1990, 323 PP., $24.95", *International Journal of Human Factors in Manufacturing*, John Wiley & Sons, Ltd, Vol. 4 No. 3, pp. 341–343, doi: 10.1002/HFM.4530040310.
Heidari, B. and Marr, L.C. (2015), "Real-time emissions from construction equipment compared with model predictions", *Journal of the Air and Waste Management Association*, Taylor and Francis Inc., Vol. 65 No. 2, pp. 115–125, doi: 10.1080/10962247.2014.978485.
Hennig, W. (2008), "Ford eco-driving: Best practice training and evaluation", available at: https://scholar.google.com/scholar?q=Hennig%2C%20W.%2C%202008.%20Ford%2

0eco-driving%3A%20best%20practice%20training%20and%20evaluation%2C%20November%2012. (accessed 8 January 2025).

Heppenstall, A.J.J., Crooks, A.T., See, L.M. and Batty, M. (2012), “Agent-based models of geographical systems”, *Agent-Based Models of Geographical Systems*, Springer Netherlands, pp. 1–759, doi: 10.1007/978-90-481-8927-4/COVER.

Hertwich, E.G. and Peters, G.P. (2009), “Carbon footprint of nations: A global, trade-linked analysis”, *Environmental Science and Technology*, Vol. 43 No. 16, pp. 6414–6420, doi: 10.1021/ES803496A.

Hertwich, E.G. and Wood, R. (2018), “The growing importance of scope 3 greenhouse gas emissions from industry”, *Environmental Research Letters*, IOP Publishing, Vol. 13 No. 10, p. 104013, doi: 10.1088/1748-9326/AAE19A.

Hong, J., Shen, G.Q., Feng, Y., Lau, W.S.T. and Mao, C. (2015), “Greenhouse gas emissions during the construction phase of a building: a case study in China”, *Journal of Cleaner Production*, Elsevier, Vol. 103, pp. 249–259, doi: 10.1016/J.JCLEPRO.2014.11.023.

Hong, T., Ji, C., Jang, M. and Park, H. (2013), “Assessment Model for Energy Consumption and Greenhouse Gas Emissions during Building Construction”, *Journal of Management in Engineering*, American Society of Civil Engineers, Vol. 30 No. 2, pp. 226–235, doi: 10.1061/(ASCE)ME.1943-5479.0000199.

Huaman-Orosco, C., Erazo-Rondinel, A.A. and Herrera, R.F. (2022), “Barriers to Adopting Lean Construction in Small and Medium-Sized Enterprises—The Case of Peru”, *Buildings*, MDPI, Vol. 12 No. 10, p. 1637, doi: 10.3390/BUILDINGS12101637/S1.

Huang, Y., Ng, E.C.Y., Zhou, J.L., Surawski, N.C., Chan, E.F.C. and Hong, G. (2018), “Eco-driving technology for sustainable road transport: A review”, *Renewable and Sustainable Energy Reviews*, Pergamon, Vol. 93, pp. 596–609, doi: 10.1016/J.RSER.2018.05.030.

Huang, Y.A., Weber, C.L. and Matthews, H.S. (2009), “Categorization of scope 3 emissions for streamlined enterprise carbon footprinting”, *Environmental Science and Technology*, American Chemical Society, Vol. 43 No. 22, pp. 8509–8515, doi: 10.1021/ES901643A/SUPPL_FILE/ES901643A_SI_001.PDF.

Huovila, P. and Koskela, L. (1998), “Contribution of the Principles of Lean Construction to Meet the Challenges of Sustainable Development”.

Iacovidou, E., Hahladakis, J.N. and Purnell, P. (2020), “A systems thinking approach to understanding the challenges of achieving the circular economy”, *Environmental Science and Pollution Research 2020 28:19*, Springer, Vol. 28 No. 19, pp. 24785–24806, doi: 10.1007/S11356-020-11725-9.

Ibrahim, H., Ghandour, M., Dimitrova, M., Ilinca, A. and Perron, J. (2011), “Integration of Wind Energy into Electricity Systems: Technical Challenges and Actual Solutions”, *Energy Procedia*, Elsevier, Vol. 6, pp. 815–824, doi: 10.1016/J.EGYPRO.2011.05.092.

Iwao, S. (2017), “Revisiting the existing notion of continuous improvement (Kaizen): literature review and field research of Toyota from a perspective of innovation”, *Evolutionary and Institutional Economics Review 2017 14:1*, Springer, Vol. 14 No. 1, pp. 29–59, doi: 10.1007/S40844-017-0067-4.

Jabri, A. and Zayed, T. (2017), “Agent-based modeling and simulation of earthmoving operations”, *Automation in Construction*, Elsevier, Vol. 81, pp. 210–223, doi: 10.1016/J.AUTCON.2017.06.017.

Jackson, D. and Ascui, F. (2019), *Achieving Infrastructure Emission Reductions through Supply Chain Collaboration: Challenges and Opportunities*.

Jafary Nasab, T., Monavari, S.M., Jozi, S.A. and Majedi, H. (2020), “Assessment of carbon footprint in the construction phase of high-rise constructions in Tehran”, *International Journal of Environmental Science and Technology*, Springer, Vol. 17 No. 6, pp. 3153–3164, doi: 10.1007/S13762-019-02557-3/FIGURES/5.

Jaijith, A. (2020), “Construction Equipment Management in Project Site”, *International Research Journal of Engineering and Technology*.

Jalaei, F., Zoghi, M. and Khoshand, A. (2021), “Life cycle environmental impact assessment to manage and optimize construction waste using Building Information Modeling (BIM)”, *International Journal of Construction Management*, Taylor & Francis, Vol. 21 No. 8, pp. 784–801, doi: 10.1080/15623599.2019.1583850.

Jamil, A.H.A. and Fathi, M.S. (2016), “The Integration of Lean Construction and Sustainable Construction: A Stakeholder Perspective in Analyzing Sustainable Lean Construction Strategies in Malaysia”, *Procedia Computer Science*, Elsevier, Vol. 100, pp. 634–643, doi: 10.1016/J.PROCS.2016.09.205.

Jaques, R. (2000), “Construction Site Waste Generation—The Influence of Design and Procurement”, *Architectural Science Review*, Taylor & Francis Group, Vol. 43 No. 3, pp. 141–145, doi: 10.1080/00038628.2000.9696897.

Jassim, H.S.H., Krantz, J., Lu, W. and Olofsson, T. (2020), “A model to reduce earthmoving impacts”, *Journal of Civil Engineering and Management*, Vilnius Gediminas Technical University, Vol. 26 No. 6, pp. 490–512, doi: 10.3846/JCEM.2020.12641.

Jeong, J., Hong, T., Ji, C., Kim, J., Lee, M., Jeong, K. and Lee, S. (2017), “An integrated evaluation of productivity, cost and CO2 emission between prefabricated and conventional columns”, *Journal of Cleaner Production*, Elsevier, Vol. 142, pp. 2393–2406, doi: 10.1016/J.JCLEPRO.2016.11.035.

Ji, C., Hong, T. and Park, H.S. (2014), “Comparative analysis of decision-making methods for integrating cost and CO2 emission – focus on building structural design –”, *Energy and Buildings*, Elsevier, Vol. 72, pp. 186–194, doi: 10.1016/J.ENBUILD.2013.12.045.

Jianhua, L., Genchuan, L., Daiquan, L., Wenlei, L., Bowen, F., Zhong, B., Jing, J., *et al.* (2018), “Study of Collaborative Management for Transportation Construction Project Based on BIM Technology”, doi: 10.1088/1757-899X/322/5/052060.

Joensuu, T., Edelman, H. and Saari, A. (2020), “Circular economy practices in the built environment”, *Journal of Cleaner Production*, Elsevier, Vol. 276, p. 124215, doi: 10.1016/J.JCLEPRO.2020.124215.

Jogdand, O.K. (2020), “Study on the Effect of Global Warming and Greenhouse Gases on Environmental System”, *Green Chemistry and Sustainable Technology*, Apple Academic Press, pp. 275–306, doi: 10.1201/9780367808310-12.

Jose, L.P. (2001), *Detailed Haul Units Performance Model*, Virginia Polytechnic Institute State University, Blacksburg, Virginia.

Joshi, H.S., Jayarajan, S., Vaidyanathan, K. and Devkar, G. (2020a), “Quantitative framework for measuring effectiveness of big room”, *IGLC 28 - 28th Annual Conference of the International Group for Lean Construction 2020*, The International Group for Lean Construction, pp. 277–288, doi: 10.24928/2020/0119.

Joshi, H.S., Jayarajan, S., Vaidyanathan, K. and Devkar, G. (2020b), “Quantitative Framework for Measuring Effectiveness of Big Room”, *IGLC 28 - 28th Annual Conference of the International Group for Lean Construction 2020*, The International Group for Lean Construction, pp. 277–288, doi: 10.24928/2020/0119.

Junnila, S., Horvath, A. and Guggemos, A.A. (2006), “Life-Cycle Assessment of Office Buildings in Europe and the United States”, *Journal of Infrastructure Systems*, American Society of Civil Engineers, Vol. 12 No. 1, pp. 10–17, doi: 10.1061/(ASCE)1076-0342(2006)12:1(10).

Juntunen, J., Kiviniemi, A. and Alhava, O. (2015), “The Use of Modified PPC Measurement in Design Management”.
Kaboli, A.S. and Carmichael, D.G. (2016), “An examination of the DRET model and the influence of payload, haul grade and truck type on earthmoving emissions”, *International Journal of Construction Management*, Taylor and Francis Ltd., Vol. 16 No. 2, pp. 95–108, doi: 10.1080/15623599.2015.1130600.
Kamat, V.R., Asce, M., Martinez, J.C., Fischer, ; Martin, Mani Golparvar-Fard, ;, Feniosky Peña-Mora, ; and Savarese, S. (2011), “Research in Visualization Techniques for Field Construction”, *Journal of Construction Engineering and Management*, American Society of Civil Engineers (ASCE), Vol. 137 No. 10, pp. 853–862, doi: 10.1061/(ASCE)CO.1943-7862.0000262.
Karlsson, I. (2024), “Achieving net-zero carbon emissions in construction supply chains Analysis of pathways towards decarbonization of buildings and transport infrastructure Achieving net-zero carbon emissions in construction supply chains-Analysis of pathways towards decarbonization of buildings and transport infrastructure”.
Kasul, R.A. and Motwani, J.G. (1997), “Successful implementation of TPS in a manufacturing setting: A case study”, *Industrial Management and Data Systems*, Emerald Group Publishing Ltd., Vol. 97 No. 7, pp. 274–279, doi: 10.1108/02635579710191707/FULL/PDF.
Kaudel, F.J. (1987), “A literature survey on distributed discrete event simulation”, *ACM SIGSIM Simulation Digest*, ACMPUB27New York, NY, USA, Vol. 18 No. 2, pp. 11–21, doi: 10.1145/29497.29499.
Kesidou, S. and Sovacool, B.K. (2019), “Supply chain integration for low-carbon buildings: A critical interdisciplinary review”, *Renewable and Sustainable Energy Reviews*, Pergamon, Vol. 113, p. 109274, doi: 10.1016/J.RSER.2019.109274.
Khodabandelu, A. and Park, J.W. (2021), “Agent-based modeling and simulation in construction”, *Automation in Construction*, Elsevier, Vol. 131, p. 103882, doi: 10.1016/J.AUTCON.2021.103882.
Khozema, A.A., Ahmad, M.I. and Yusup, Y. (2020), “Issues, impacts, and mitigations of carbon dioxide emissions in the building sector”, *Sustainability (Switzerland)*, MDPI AG, Vol. 12 No. 18, doi: 10.3390/SU12187427.
Komatsu Report. (2018), *Organization of Komatsu’s Annual Reports KOMATSU REPORT (Integrated Reporting) Annual Securities Report (Financial Conditions) CSR and Environmental Report (Social Activities and Environmental Performance) * KOMATSU REPORT, Annual Securities Report and CSR and Environmental Report, in Both Japanese*.
Koskela, L.J. (1992), “(3) (PDF) Application of the New Production Philosophy to Construction”, available at: https://www.researchgate.net/publication/243781224_Application_of_the_New_Production_Philosophy_to_Construction (accessed 5 January 2025).
Kowalski, J., Lendo-Siwicka, M., Wrzesiński, G. and Trach, R. (2023), “Verification of Performance Standards for Construction Equipment in Terms of CO2 Emissions”, *Sustainability 2023, Vol. 15, Page 15188*, Multidisciplinary Digital Publishing Institute, Vol. 15 No. 21, p. 15188, doi: 10.3390/SU152115188.
Krantz, J., Feng, K., Larsson, J. and Olofsson, T. (2019a), “‘Eco-Hauling’ principles to reduce carbon emissions and the costs of earthmoving - A case study”, *Journal of Cleaner Production*, Elsevier, Vol. 208, pp. 479–489, doi: 10.1016/J.JCLEPRO.2018.10.113.
Krantz, J., Feng, K., Larsson, J. and Olofsson, T. (2019b), “‘Eco-Hauling’ principles to reduce carbon emissions and the costs of earthmoving - A case study”, *Journal of*

Cleaner Production, Elsevier, Vol. 208, pp. 479–489, doi: 10.1016/J.JCLEPRO.2018.10.113.

Kwak, M., Kim, L., Sarvana, O., Kim, H.M., Finamore, P. and Hazewinkel, H. (2012a), "Life cycle assessment of complex heavy duty equipment", *ASME/ISCIE 2012 International Symposium on Flexible Automation, ISFA 2012*, American Society of Mechanical Engineers (ASME), pp. 625–635, doi: 10.1115/ISFA2012-7180.

Kwak, M., Kim, L., Sarvana, O., Kim, H.M., Finamore, P. and Hazewinkel, H. (2012b), "Life cycle assessment of complex heavy duty equipment", *ASME/ISCIE 2012 International Symposium on Flexible Automation, ISFA 2012*, American Society of Mechanical Engineers (ASME), pp. 625–635, doi: 10.1115/ISFA2012-7180.

Lahdenperä, P. (2012), "Making sense of the multi-party contractual arrangements of project partnering, project alliancing and integrated project delivery", *Construction Management and Economics*, Vol. 30 No. 1, pp. 57–79, doi: 10.1080/01446193.2011.648947/ASSET/04BDFEF1-5EB1-4071-AF5F-C9801AD4EC0F/ASSETS/IMAGES/RCME_A_648947_O_F0002G.GIF.

Lasvaux, S., Habert, G., Peuportier, B. and Chevalier, J. (2015), "Comparison of generic and product-specific Life Cycle Assessment databases: application to construction materials used in building LCA studies", *International Journal of Life Cycle Assessment*, Springer Verlag, Vol. 20 No. 11, pp. 1473–1490, doi: 10.1007/S11367-015-0938-Z.

Lee, J., Cho, H.J., Choi, B., Sung, J., Lee, S. and Shin, M. (2000), "Life cycle assessment of tractors", *International Journal of Life Cycle Assessment*, Vol. 5 No. 4, pp. 205–208, doi: 10.1007/BF02979361.

Leech, N.L., Dellinger, A.B., Brannagan, K.B. and Tanaka, H. (2009), "Evaluating Mixed Research Studies: A Mixed Methods Approach", *Http://Dx.Doi.Org/10.1177/1558689809345262*, SAGE PublicationsSage CA: Los Angeles, CA, Vol. 4 No. 1, pp. 17–31, doi: 10.1177/1558689809345262.

Lewis, P. and Hajji, A. (2012a), "Estimating the Economic, Energy, and Environmental Impact of Earthwork Activities", *Construction Research Congress 2012: Construction Challenges in a Flat World, Proceedings of the 2012 Construction Research Congress*, American Society of Civil Engineers, pp. 1770–1779, doi: 10.1061/9780784412329.178.

Lewis, P. and Hajji, A. (2012b), "Estimating the Economic, Energy, and Environmental Impact of Earthwork Activities", *Construction Research Congress 2012: Construction Challenges in a Flat World, Proceedings of the 2012 Construction Research Congress*, American Society of Civil Engineers, pp. 1770–1779, doi: 10.1061/9780784412329.178.

Lewis, P., Leming, M. and Rasdorf, W. (2011), "Impact of Engine Idling on Fuel Use and CO2 Emissions of Nonroad Diesel Construction Equipment", *Journal of Management in Engineering*, American Society of Civil Engineers, Vol. 28 No. 1, pp. 31–38, doi: 10.1061/(ASCE)ME.1943-5479.0000068.

Lewis, P. and Rasdorf, W. (2017), "Fuel Use and Pollutant Emissions Taxonomy for Heavy Duty Diesel Construction Equipment", *Journal of Management in Engineering*, American Society of Civil Engineers, Vol. 33 No. 2, p. 04016038, doi: 10.1061/(ASCE)ME.1943-5479.0000484.

Li, D., Huang, G., Zhu, S., Chen, L. and Wang, J. (2021), "How to peak carbon emissions of provincial construction industry? Scenario analysis of Jiangsu Province", *Renewable and Sustainable Energy Reviews*, Pergamon, Vol. 144, p. 110953, doi: 10.1016/J.RSER.2021.110953.

Li, H.X. and Lei, Z. (2010), "Discrete-event simulation (DES) of uncertainty-based time-cost trade-off analysis", *Proceedings - 2010 IEEE 17th International Conference on*

Industrial Engineering and Engineering Management, IE and EM2010, pp. 196–199, doi: 10.1109/ICIEEM.2010.5646648.

Li, X.J. and Zheng, Y. dan. (2020), "Using LCA to research carbon footprint for precast concrete piles during the building construction stage: A China study", *Journal of Cleaner Production*, Elsevier, Vol. 245, p. 118754, doi: 10.1016/J.JCLEPRO.2019.118754.

Light, A. (2004), "What is a Pragmatic Philosophy?"

Liker, J.K. (2003), "THE TOYOTA WAY, SECOND EDITION 14 MANAGEMENT PRINCIPLES FROM THE WORLD'S GREATEST MANUFACTURER".

Liker, J.K. and Morgan, J.M. (2006), "The Toyota Way in Services: The Case of Lean Product Development", *Https://Doi.Org/10.5465/Amp.2006.20591002*, Academy of Management Briarcliff Manor, NY 10510 , Vol. 20 No. 2, pp. 5–20, doi: 10.5465/AMP.2006.20591002.

Limsawasd, C. and Athigakunagorn, N. (2017), "An Application of Discrete-Event Simulation in Estimating Emissions from Equipment Operations in Flexible Pavement Construction Projects", *Engineering Journal*, Chulalongkorn University, Vol. 21 No. 7, pp. 197–211, doi: 10.4186/ej.2017.21.7.197.

Lindgren, M. (2005), "A Transient Fuel Consumption Model for Non-road Mobile Machinery", *Biosystems Engineering*, Academic Press, Vol. 91 No. 2, pp. 139–147, doi: 10.1016/J.BIOSYSTEMSENG.2005.03.011.

Liu, J. and Li, J. (2023), "Economic benefit analysis of the carbon potential of construction waste resource management based on a simulation of carbon trading policy", *Environmental Science and Pollution Research*, Springer Science and Business Media Deutschland GmbH, Vol. 30 No. 36, pp. 85986–86009, doi: 10.1007/S11356-023-28417-9/FIGURES/20.

Liu, J., Li, Y. and Wang, Z. (2023), "The potential for carbon reduction in construction waste sorting: A dynamic simulation", *Energy*, Pergamon, Vol. 275, p. 127477, doi: 10.1016/J.ENERGY.2023.127477.

Liu, J., Liu, Y. and Wang, X. (2020), "An environmental assessment model of construction and demolition waste based on system dynamics: a case study in Guangzhou", *Environmental Science and Pollution Research*, Springer Science and Business Media Deutschland GmbH, Vol. 27 No. 30, pp. 37237–37259, doi: 10.1007/S11356-019-07107-5/TABLES/5.

Liu, S., Li, Z., Teng, Y. and Dai, L. (2022), "A dynamic simulation study on the sustainability of prefabricated buildings", *Sustainable Cities and Society*, Elsevier, Vol. 77, p. 103551, doi: 10.1016/J.SCS.2021.103551.

Liu, Z., Li, P., Wang, F., Osmani, M. and Demian, P. (2022), "Building Information Modeling (BIM) Driven Carbon Emission Reduction Research: A 14-Year Bibliometric Analysis", *International Journal of Environmental Research and Public Health*, MDPI, Vol. 19 No. 19, doi: 10.3390/ijerph191912820.

Loizou, L., Barati, K., Shen, X. and Li, B. (2021), "Quantifying Advantages of Modular Construction: Waste Generation", *Buildings 2021, Vol. 11, Page 622*, Multidisciplinary Digital Publishing Institute, Vol. 11 No. 12, p. 622, doi: 10.3390/BUILDINGS11120622.

Lottaz, C., Smith, I.F.C., Robert-Nicoud, Y. and Faltings, B. V. (2000), "Constraint-based support for negotiation in collaborative design", *Artificial Intelligence in Engineering*, Elsevier Science Ltd, Vol. 14 No. 3, pp. 261–280, doi: 10.1016/S0954-1810(00)00020-0.

Lu, H., Matthews, J. and Iseley, T. (2020), "How does trenchless technology make pipeline construction greener? A comprehensive carbon footprint and energy consumption analysis", *Journal of Cleaner Production*, Elsevier Ltd, Vol. 261, doi: 10.1016/J.JCLEPRO.2020.121215.

Lu, W., Fung, A., Peng, Y., Liang, C. and Rowlinson, S. (2014), "Cost-benefit analysis of Building Information Modeling implementation in building projects through demystification of time-effort distribution curves", *Building and Environment*, Pergamon, Vol. 82, pp. 317–327, doi: 10.1016/J.BUILDENV.2014.08.030.

Macioszek, E. (2018), "First and Last Mile Delivery – Problems and Issues", *Advances in Intelligent Systems and Computing*, Springer, Cham, Vol. 631, pp. 147–154, doi: 10.1007/978-3-319-62316-0_12.

MacLeamy. (2004), "Collaboration, Integrated Information and the Project Lifecycle in Building Design, Construction and Operation".

Mangiaracina, R., Perego, A., Seghezzi, A. and Tumino, A. (2019), "Innovative solutions to increase last-mile delivery efficiency in B2C e-commerce: a literature review", *International Journal of Physical Distribution and Logistics Management*, Emerald Group Holdings Ltd., Vol. 49 No. 9, pp. 901–920, doi: 10.1108/IJPDLM-02-2019-0048/FULL/XML.

Marrero, M., Puerto, M., Rivero-Camacho, C., Freire-Guerrero, A. and Solís-Guzmán, J. (2017), "Assessing the economic impact and ecological footprint of construction and demolition waste during the urbanization of rural land", *Resources, Conservation and Recycling*, Elsevier B.V., Vol. 117, pp. 160–174, doi: 10.1016/j.resconrec.2016.10.020.

Matthews, R.B. and Macaulay, B. (2007), "A combined agent-based and biophysical modelling approach to address GHG mitigation policy issues".

Mawdesley, M.J., Askew, W.H. and Patterson, D.E. (2002), "A model for the automated generation of earthwork planning activities", *Construction Innovation2002;2: 249– 26*, Vol. 2.

Mazzetto, S. (2024), "Interdisciplinary Perspectives on Agent-Based Modeling in the Architecture, Engineering, and Construction Industry: A Comprehensive Review", *Buildings 2024, Vol. 14, Page 3480*, Multidisciplinary Digital Publishing Institute, Vol. 14 No. 11, p. 3480, doi: 10.3390/BUILDINGS14113480.

Meggers, F., Leibundgut, H., Kennedy, S., Qin, M., Schlaich, M., Sobek, W. and Shukuya, M. (2012), "Reduce CO 2 from buildings with technology to zero emissions", *Sustainable Cities and Society*, Vol. 2 No. 1, pp. 29–36, doi: 10.1016/j.scs.2011.10.001.

Moussavi Nadoushani, Z.S. and Akbarnezhad, A. (2017), "A Computational Framework for Estimating the Carbon Footprint of Construction", *Proceedings of the 31st International Symposium on Automation and Robotics in Construction and Mining (ISARC)*, International Association for Automation and Robotics in Construction (IAARC), doi: 10.22260/ISARC2014/0097.

Mukherjee, S.P. (2019), "A Guide to Research Methodology : An Overview of Research Problems, Tasks and Methods", *A Guide to Research Methodology*, CRC Press, doi: 10.1201/9780429289095.

Müller, D.B., Liu, G., Løvik, A.N., Modaresi, R., Pauliuk, S., Steinhoff, F.S. and Brattebø, H. (2013), "Carbon emissions of infrastructure development", *Environmental Science and Technology*, Vol. 47 No. 20, pp. 11739–11746, doi: 10.1021/ES402618M.

Mutuku, S. (2017), "Barriers and Opportunities to Environmental Leapfrogging in Developing Countries", *2017*.

Myhre, G. and Shindell, D. (2013), "Anthropogenic and Natural Radiative Forc-ing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I".

Nanayakkara, K., Wilkinson, S. and Halvitigala, D. (2021), "Influence of dynamic changes of workplace on organisational culture", *Journal of Management & Organization*, Cambridge University Press, Vol. 27 No. 6, pp. 1003–1020, doi: 10.1017/JMO.2021.69.

NASA. (2024), "Carbon Dioxide | Vital Signs – Climate Change: Vital Signs of the Planet", available at: https://climate.nasa.gov/vital-signs/carbon-dioxide/?intent=121 (accessed 1 January 2025).

Navon, R. and Berkovich, O. (2006), "An automated model for materials management and control", *Construction Management and Economics*, Vol. 24 No. 6, pp. 635–646, doi: 10.1080/01446190500435671.

Net 0. (2024), "Carbon Emissions in the Atmosphere and Emissions Abatement Methods - Net0", available at: https://net0.com/blog/emissions-abatement (accessed 1 January 2025).

Ng, D., Vail, G., Thomas, S. and Schmidt, N. (2010), "Applying the Lean principles of the Toyota Production System to reduce wait times in the emergency department", *Canadian Journal of Emergency Medicine*, Cambridge University Press, Vol. 12 No. 1, pp. 50–57, doi: 10.1017/S1481803500012021.

Nicholas, J. (2018), "Lean Production for Competitive Advantage : A Comprehensive Guide to Lean Methodologies and Management Practices, Second Edition", *Lean Production for Competitive Advantage*, Productivity Press, doi: 10.4324/9781351139083.

Nikakhtar, A., Abbasian Hosseini, A., Yew Wong, K. and Zavichi, A. (2015), *Application of Lean Construction Principles to Reduce Construction Process Waste Using Computer Simulation: A Case Study*, *Int. J. Services and Operations Management*, Vol. 20.

Nili, M.H., Taghaddos, H. and Zahraie, B. (2021), "Integrating discrete event simulation and genetic algorithm optimization for bridge maintenance planning", *Automation in Construction*, Elsevier, Vol. 122, p. 103513, doi: 10.1016/J.AUTCON.2020.103513.

Nilsson, F. and Darley, V. (2006), "On complex adaptive systems and agent-based modelling for improving decision-making in manufacturing and logistics settings Experiences from a packaging company", *International Journal of Operations & Production Management*, Emerald Group Publishing, Vol. 26 No. 12, pp. 144–3577, doi: 10.1108/01443570610710588.

Ogunbiyi, O., Oladapo, A. and Goulding, J. (2014a), "An empirical study of the impact of lean construction techniques on sustainable construction in the UK", *Construction Innovation*, Vol. 14 No. 1, pp. 88–107, doi: 10.1108/CI-08-2012-0045.

Ogunbiyi, O., Oladapo, A. and Goulding, J. (2014b), "An empirical study of the impact of lean construction techniques on sustainable construction in the UK", *Construction Innovation*, Emerald Group Publishing Limited, Vol. 14 No. 1, pp. 88–107, doi: 10.1108/CI-08-2012-0045/FULL/XML.

Ohno, T. (1988), "Toyota Production System: Beyond Large-Scale Production", *Toyota Production System: Beyond Large-Scale Production*, Taylor and Francis, pp. 1–143, doi: 10.4324/9780429273018/TOYOTA-PRODUCTION-SYSTEM-TAIICHI-OHNO/ACCESSIBILITY-INFORMATION.

Okwandu, A., Gil-Ozoudeh, I., Adeyemi, A.B., Chimaobi Ohakawa, T., Okwandu, A.C., Iwuanyanwu, O. and Ifechukwu, G.-O. (2024), "Advanced Building Information Modeling (BIM) for affordable housing projects: Enhancing design efficiency and cost management", doi: 10.57219/crrst.2024.2.1.0029.

Ortiz, O., Castells, F. and Sonnemann, G. (2009), "Sustainability in the construction industry: A review of recent developments based on LCA", *Construction and Building Materials*, Elsevier, Vol. 23 No. 1, pp. 28–39, doi: 10.1016/J.CONBUILDMAT.2007.11.012.

Overboom, M., Small, J., Naus, F. and De Haan, J. (2013), *Mark Overboom, James Small, Fons Naus, Job de Haan APPLYING LEAN PRINCIPLES TO ACHIEVE CONTINUOUS FLOW IN 3PLs OUTBOUND PROCESSES Introduction* *.

Pacheco-Torres, R., Jadraque, E., Roldán-Fontana, J. and Ordóñez, J. (2014), “Analysis of CO2 emissions in the construction phase of single-family detached houses”, *Sustainable Cities and Society*, Vol. 12, pp. 63–68, doi: 10.1016/j.scs.2014.01.003.

Pakdel, A., Ayatollahi, H. and Sattary, S. (2021), “Embodied energy and CO2 emissions of life cycle assessment (LCA) in the traditional and contemporary Iranian construction systems”, *Journal of Building Engineering*, Elsevier, Vol. 39, p. 102310, doi: 10.1016/J.JOBE.2021.102310.

Pampel, S.M., Jamson, S.L., Hibberd, D.L. and Barnard, Y. (2018), “Old habits die hard? The fragility of eco-driving mental models and why green driving behaviour is difficult to sustain”, *Transportation Research Part F: Traffic Psychology and Behaviour*, Pergamon, Vol. 57, pp. 139–150, doi: 10.1016/J.TRF.2018.01.005.

Pamukçu, H., Soyertaş Yapıcıoğlu, P. and İrfan Yeşilnacar, M. (2023), “Investigating the mitigation of greenhouse gas emissions from municipal solid waste management using ant colony algorithm, Monte Carlo simulation and LCA approach in terms of EU Green Deal”, *Waste Management Bulletin*, Elsevier, Vol. 1 No. 2, pp. 6–14, doi: 10.1016/J.WMB.2023.05.001.

Pandey, D., Agrawal, M. and Pandey, J.S. (2011), “Carbon footprint: Current methods of estimation”, *Environmental Monitoring and Assessment*, Springer, Vol. 178 No. 1–4, pp. 135–160, doi: 10.1007/S10661-010-1678-Y/METRICS.

Panwar, A., Jain, R. and Rathore, A.P.S. (2016), “Obstacles in lean implementation in developing countries - some cases from the process sector of India”, *International Journal of Lean Enterprise Research*, Inderscience Publishers, Vol. 2 No. 1, p. 26, doi: 10.1504/IJLER.2016.078228.

Partington, David. (2002), “Essential Skills for Management Research”, *Essential Skills for Management Research*, Sage, pp. 1–282.

Pasquire, C. (2012), “THE 8 TH FLOW-COMMON UNDERSTANDING”.

Patel, V. V, Karia, N. and Pandit, D. (2018), “Identifying value enhancing factors and applicability of visual management tools”, pp. 282–293, doi: 10.24928/2018/0239.

Peng, Z., Lu, W. and Webster, C. (2022), “If invisible carbon waste can be traded, why not visible construction waste? Establishing the construction waste trading ‘missing market’”, *Resources, Conservation and Recycling*, Elsevier, Vol. 187, p. 106607, doi: 10.1016/J.RESCONREC.2022.106607.

Pigato, M.A., Black, S.J., Dussaux, D., Mao, Z., Mckenna, M., Rafaty, R. and Touboul, S. (2020), “Technology Transfer and Innovation for Low-Carbon Development”.

Pinto, J.L.Q., Matias, J.C.O., Pimentel, C., Azevedo, S.G. and Govindan, K. (2018), “Lean Manufacturing and Kaizen”, *Management for Professionals*, Springer Nature, Vol. Part F628, pp. 5–24, doi: 10.1007/978-3-319-77016-1_2/FIGURES/3.

Pons, J.F. (2022), “The Big Room as a Visual Management concept in Last Planner® System”, available at: https://leanconstructionblog.com/The-Big-Room-as-a-Visual-Management-concept-in-Last-Planner-System.html (accessed 8 January 2025).

Prell, C. and Sun, L. (2015), “Unequal carbon exchanges: understanding pollution embodied in global trade”, *Environmental Sociology*, Routledge, Vol. 1 No. 4, pp. 256–267, doi: 10.1080/23251042.2015.1114208.

Que, S., Awuah-Offei, K. and Frimpong, S. (2016), “Optimising design parameters of continuous mining transport systems using discrete event simulation”, *International Journal of Mining, Reclamation and Environment*, Taylor and Francis Ltd., Vol. 30 No. 3, pp. 217–230, doi: 10.1080/17480930.2015.1037056/ASSET/0011357F-352F-4BB4-A368-EE76DBAB7E15/ASSETS/IMAGES/LARGE/NSME_A_1037056_F0010_OC.JPG.

Quéré, C., Andrew, R., Friedlingstein, P., Sitch, S., Hauck, J., Pongratz, J., Pickers, P., *et al.* (2018), “Global Carbon Budget 2018”, *Earth System Science Data*, Copernicus Publications, Vol. 10 No. 4, pp. 2141–2194, doi: 10.5194/ESSD-10-2141-2018.

Rahman, S.H.A., Endut, I.R., Faisol, N. and Paydar, S. (2014), "The Importance of Collaboration in Construction Industry from Contractors' Perspectives", *Procedia - Social and Behavioral Sciences*, Elsevier BV, Vol. 129, pp. 414–421, doi: 10.1016/J.SBSPRO.2014.03.695.

Rao, A.S., Radanovic, M., Liu, Y., Hu, S., Fang, Y., Khoshelham, K., Palaniswami, M., *et al.* (2022), "Real-time monitoring of construction sites: Sensors, methods, and applications", *Automation in Construction*, Elsevier, Vol. 136, p. 104099, doi: 10.1016/J.AUTCON.2021.104099.

Reap, J., Roman, F., Duncan, S. and Bras, B. (2008), "A survey of unresolved problems in life cycle assessment. Part 2: Impact assessment and interpretation", *International Journal of Life Cycle Assessment*, Vol. 13 No. 5, pp. 374–388, doi: 10.1007/S11367-008-0009-9.

Reja, V.K., Sindhu Pradeep, M. and Varghese, K. (2024), "Digital Twins for Construction Project Management (DT-CPM): Applications and Future Research Directions", *Journal of The Institution of Engineers (India): Series A*, Springer, Vol. 105 No. 3, pp. 793–807, doi: 10.1007/S40030-024-00810-8/FIGURES/6.

Reyna, J.L. and Chester, M. V. (2015), "The Growth of Urban Building Stock: Unintended Lock-in and Embedded Environmental Effects", *Journal of Industrial Ecology*, Blackwell Publishing, Vol. 19 No. 4, pp. 524–537, doi: 10.1111/JIEC.12211.

RICS. (2024), "Whole life carbon assessment for the built environment RICS PROFESSIONAL STANDARD".

Rogelj, J., Den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., Schaeffer, R., *et al.* (2016), "Paris Agreement climate proposals need a boost to keep warming well below 2 °C", *Nature*, Nature, Vol. 534 No. 7609, pp. 631–639, doi: 10.1038/NATURE18307.

Romvall, K., Wiktorsson, M. and Bellgran, M. (2010), "(2) (PDF) Competitiveness by integrating the green perspective in production – A review presenting challenges for research and industry", available at: https://www.researchgate.net/publication/287199864_Competitiveness_by_integrating_the_green_perspective_in_production_-_A_review_presenting_challenges_for_research_and_industry (accessed 4 January 2025).

Roy, A., McCabe, B.Y., Saxe, S. and Posen, I.D. (2024), "Review of factors affecting earthworks greenhouse gas emissions and fuel use", *Renewable and Sustainable Energy Reviews*, Pergamon, Vol. 194, p. 114290, doi: 10.1016/J.RSER.2024.114290.

Rüdisüli, M., Bach, C., Bauer, C., Beloin-Saint-Pierre, D., Elber, U., Georges, G., Limpach, R., *et al.* (2022), "Prospective life-cycle assessment of greenhouse gas emissions of electricity-based mobility options", *Applied Energy*, Elsevier, Vol. 306, p. 118065, doi: 10.1016/J.APENERGY.2021.118065.

Rylander, D., Axelsson, J. and Wallin, P. (2014), "Energy savings by wireless control of speed, scheduling and travel times for hauling operation", *IEEE Intelligent Vehicles Symposium, Proceedings*, Institute of Electrical and Electronics Engineers Inc., pp. 1115–1120, doi: 10.1109/IVS.2014.6856451.

Sacks, A. (2010), "The interaction of lean and building information modeling in construction Title The interaction of lean and building information modeling in construction", doi: 10.1061/(ASCE)CO.1943-7862.0000203.

Sacks, R., Koskela, L., Dave, B.A. and Owen, R. (2010), "Interaction of Lean and Building Information Modeling in Construction", *Journal of Construction Engineering and Management*, American Society of Civil Engineers (ASCE), Vol. 136 No. 9, pp. 968–980, doi: 10.1061/(ASCE)CO.1943-7862.0000203.

Saghafi, M.D. and Hosseini Teshnizi, Z.S. (2011), "Recycling value of building materials in building assessment systems", *Energy and Buildings*, Elsevier, Vol. 43 No. 11, pp. 3181–3188, doi: 10.1016/J.ENBUILD.2011.08.016.

Sagoo, A., Simons, J., Skivington, J., Stamps, A., Ebbs, P. and Hesbrook, E. (2020), "How-to Guide to Best Practice Procurement Providing an Industry of Opportunity Constructing Excellence Midlands 1 How-to Guide to Best Practice Procurement Pre-Tender How-to Guide to Best Practice Procurement".

Sahlol, D.G., Elbeltagi, E., Elzoughiby, M. and Abd Elrahman, M. (2021), "Sustainable building materials assessment and selection using system dynamics", *Journal of Building Engineering*, Elsevier, Vol. 35, p. 101978, doi: 10.1016/J.JOBE.2020.101978.

Sandanayake, M., Zhang, G. and Setunge, S. (2016), "Environmental emissions at foundation construction stage of buildings – Two case studies", *Building and Environment*, Pergamon, Vol. 95, pp. 189–198, doi: 10.1016/J.BUILDENV.2015.09.002.

Santos, R., Costa, A.A., Silvestre, J.D. and Pyl, L. (2019), "Informetric analysis and review of literature on the role of BIM in sustainable construction", *Automation in Construction*, Elsevier, Vol. 103, pp. 221–234, doi: 10.1016/J.AUTCON.2019.02.022.

Sarhan, S. and Fox, A. (2013), "Barriers to Implementing Lean Construction in the UK Construction Industry", available at: https://www.researchgate.net/publication/263658667_Barriers_to_Implementing_Lean_Construction_in_the_UK_Construction_Industry (accessed 5 January 2025).

Seppänen, O., González, V.A. and Arroyo, P. (2015), "IGLC 23 Global Problems-Global Solutions Proceedings".

Seyedabadi, M.R., Karrabi, M. and Moghaddam, A.M. (2023), "The potential of CO2 emission reduction via replacing cement with recyclable wastes in the construction industry sector: the perspective of Iran's international commitments", *International Environmental Agreements: Politics, Law and Economics*, Springer Science and Business Media B.V., Vol. 23 No. 4, pp. 467–483, doi: 10.1007/S10784-023-09620-Y/FIGURES/5.

Shahnavaz, F. and Akhavian, R. (2021), "Automated Estimation of Construction Equipment Emission using Inertial Sensors and Machine Learning Models", *2021*.

Shelbourn, M., Bouchlaghem, N.M., Anumba, C. and Carrillo, P. (2007), "Planning and implementation of effective collaboration in construction projects", doi: 10.1108/14714170710780101.

Shi, Y. and Xu, J. (2021), "BIM-based information system for econo-enviro-friendly end-of-life disposal of construction and demolition waste", *Automation in Construction*, Elsevier, Vol. 125, p. 103611, doi: 10.1016/J.AUTCON.2021.103611.

Shibata, N., Sierra, F. and Hagras, A. (2023), "Integration of LCA and LCCA through BIM for optimized decision-making when switching from gas to electricity services in dwellings", *Energy and Buildings*, Elsevier, Vol. 288, p. 113000, doi: 10.1016/J.ENBUILD.2023.113000.

Shields, P.M., Peirce, S. and Dewey, J. (1998), "PRAGMATISM AS PHILOSOPHY OF SCIENCE: A TOOL FOR PUBLIC ADMINISTRATION All rights of reproduction in nny fornl reserved".

Siddiquei, A.N., Imam, H. and Asmi, F. (2022), "How and when temporal leadership facilitates the success of sustainable construction projects", doi: 10.1108/ECAM-10-2022-0965.

Singh, S., Dixit, S., Kumar, K. and Sharma ', K. (2018), "ScienceDirect An Introduction to Lean Construction/Visual Management tool in Construction Projects-review under

responsibility of WORLD CONFERENCE ON TRANSPORT RESEARCH SOCIETY".
Sivak, M. and Schoettle, B. (2012), "Eco-driving: Strategic, tactical, and operational decisions of the driver that influence vehicle fuel economy", *Transport Policy*, Pergamon, Vol. 22, pp. 96–99, doi: 10.1016/J.TRANPOL.2012.05.010.
Sizirici, B., Fseha, Y., Cho, C.S., Yildiz, I. and Byon, Y.J. (2021), "A Review of Carbon Footprint Reduction in Construction Industry, from Design to Operation", *Materials 2021, Vol. 14, Page 6094*, Multidisciplinary Digital Publishing Institute, Vol. 14 No. 20, p. 6094, doi: 10.3390/MA14206094.
Solís-Guzmán, J., Marrero, M. and Ramírez-De-Arellano, A. (2013), "Methodology for determining the ecological footprint of the construction of residential buildings in Andalusia (Spain)", *Ecological Indicators*, Vol. 25, pp. 239–249, doi: 10.1016/J.ECOLIND.2012.10.008.
Sotos, M.E. (2015), "GHG Protocol Scope 2 Guidance", 1 Winter.
Spišáková, M., Mandičák, T., Mésároš, P. and Špak, M. (2022), "Waste Management in a Sustainable Circular Economy as a Part of Design of Construction", *Applied Sciences 2022, Vol. 12, Page 4553*, Multidisciplinary Digital Publishing Institute, Vol. 12 No. 9, p. 4553, doi: 10.3390/APP12094553.
Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., *et al.* (2015), "Planetary boundaries: Guiding human development on a changing planet", *Science*, American Association for the Advancement of Science, Vol. 347 No. 6223, doi: 10.1126/SCIENCE.1259855/SUPPL_FILE/STEFFEN-SM.PDF.
Sterman, J.D. (2003), "SYSTEM DYNAMICS: SYSTEMS THINKING AND MODELING FOR A COMPLEX WORLD".
Suckiel, E.K. (1982), "The Pragmatic Philosophy of William James".
Sundar, R., Balaji, A.N. and Satheesh Kumar, R.M. (2014), "A Review on Lean Manufacturing Implementation Techniques", *Procedia Engineering*, No longer published by Elsevier, Vol. 97, pp. 1875–1885, doi: 10.1016/J.PROENG.2014.12.341.
Tak, A.N., Taghaddos, H., Mousaei, A., Bolourani, A. and Hermann, U. (2021), "BIM-based 4D mobile crane simulation and onsite operation management", *Automation in Construction*, Elsevier, Vol. 128, p. 103766, doi: 10.1016/J.AUTCON.2021.103766.
Tekin, M., Arslandere, M., Etlioğlu, M., Koyuncuoğlu, Ö. and Tekin, E. (2019), "An Application of SMED and Jidoka in Lean Production", *Proceedings of the International Symposium for Production Research 2018*, Springer, Cham, pp. 530–545, doi: 10.1007/978-3-319-92267-6_45.
Tezel, A., Koskela, L. and Tzortzopoulos, P. (2008), "Visual Management in Lean Construction".
Thomas, D.R. (2003), "A general inductive approach for qualitative data analysis".
Trinh, H.A., Truong, H.V.A., Do, T.C., Nguyen, M.H., Phan, V. Du and Ahn, K.K. (2022), "Optimization-based energy management strategies for hybrid construction machinery: A review", *Energy Reports*, Elsevier, Vol. 8, pp. 6035–6057, doi: 10.1016/J.EGYR.2022.04.050.
Truong, D.Q., Marco, J., Greenwood, D., Harper, L., Corrochano, D.G. and Yoon, J.I. (2018), "Challenges of micro/mild hybridisation for construction machinery and applicability in UK", *Renewable and Sustainable Energy Reviews*, Pergamon, Vol. 91, pp. 301–320, doi: 10.1016/J.RSER.2018.03.027.
Tu, R.;, Xu, J.;, Li, T.;, Chen, H., Yu, B., Gao, K., Xu, Y., *et al.* (2022a), "Effective and Acceptable Eco-Driving Guidance for Human-Driving Vehicles: A Review", *International Journal of Environmental Research and Public Health 2022, Vol. 19, Page 7310*, Multidisciplinary Digital Publishing Institute, Vol. 19 No. 12, p. 7310, doi: 10.3390/IJERPH19127310.

Tu, R.;, Xu, J.;, Li, T.;, Chen, H., Yu, B., Gao, K., Xu, Y., *et al.* (2022b), “Effective and Acceptable Eco-Driving Guidance for Human-Driving Vehicles: A Review”, *International Journal of Environmental Research and Public Health 2022, Vol. 19, Page 7310*, Multidisciplinary Digital Publishing Institute, Vol. 19 No. 12, p. 7310, doi: 10.3390/IJERPH19127310.

UKGBC. (2023), *UKGBC Impact Report*.

Ullah, H., Zhang, H., Huang, B. and Gong, Y. (2024), “BIM-Based Digital Construction Strategies to Evaluate Carbon Emissions in Green Prefabricated Buildings”, doi: 10.3390/buildings14061689.

UN. (2015), *TRANSFORMING OUR WORLD: THE 2030 AGENDA FOR SUSTAINABLE DEVELOPMENT*.

UN Iran. (2021), “Iran tackles its cities’ carbon emissions | United Nations in Islamic Republic of Iran”, available at: https://iran.un.org/en/156437-iran-tackles-its-cities-carbon-emissions?utm_source=chatgpt.com (accessed 31 December 2024).

UNFCCC. (2016), “THE PARIS AGREEMENT”.

Uusitalo, P., Olivieri, H., Seppänen, O., Pikas, E. and Peltokorpi, A. (2017), “Review of Lean Design Management: Processes, Methods and Technologies”, *IGLC 2017 - Proceedings of the 25th Annual Conference of the International Group for Lean Construction*, The International Group for Lean Construction, pp. 571–578, doi: 10.24928/2017/0224.

Viana, D.D., Mota, B., Formoso, C.T., Echeveste, M., Peixoto, M. and Rodrigues, C.L. (2018), “Production Planning and Control”.

Vrijhoef, R. and Koskela, L. (2000), “The four roles of supply chain management in construction”, *European Journal of Purchasing & Supply Management*, Pergamon, Vol. 6 No. 3–4, pp. 169–178, doi: 10.1016/S0969-7012(00)00013-7.

Vrijhoef, R., Week, H. de R.-P.Q.R. and 2005, undefined. (2005), “Supply chain integration for achieving best value for construction clients: client-driven versus supplierdriven integration”, *Academia.EduR Vrijhoef, H de RidderProceedings QUT Research Week, 2005•academia.Edu*.

de Waal, A., Weaver, M., Day, T. and van der Heijden, B. (2019), “Silo-Busting: Overcoming the Greatest Threat to Organizational Performance”, *Sustainability 2019, Vol. 11, Page 6860*, Multidisciplinary Digital Publishing Institute, Vol. 11 No. 23, p. 6860, doi: 10.3390/SU11236860.

Wahab, A.N.A., Mukhtar, M. and Sulaiman, R. (2013), “A Conceptual Model of Lean Manufacturing Dimensions”, *Procedia Technology*, Elsevier, Vol. 11, pp. 1292–1298, doi: 10.1016/J.PROTCY.2013.12.327.

Wandahl, S. (2014), “Lean Construction with or without Lean – Challenges of Implementing Lean Construction”, available at: https://www.researchgate.net/publication/276417464_Lean_Construction_with_or_without_Lean_-_Challenges_of_Implementing_Lean_Construction (accessed 5 January 2025).

Wang, G., Luo, T., Luo, H., Liu, R., Liu, Y. and Liu, Z. (2024a), “A comprehensive review of building lifecycle carbon emissions and reduction approaches”, *City and Built Environment 2024 2:1*, Springer, Vol. 2 No. 1, pp. 1–28, doi: 10.1007/S44213-024-00036-1.

Wang, G., Luo, T., Luo, H., Liu, R., Liu, Y. and Liu, Z. (2024b), “A comprehensive review of building lifecycle carbon emissions and reduction approaches”, *City and Built Environment 2024 2:1*, Springer, Vol. 2 No. 1, pp. 1–28, doi: 10.1007/S44213-024-00036-1.

Wang, J., Li, Z. and Tam, V.W.Y. (2014), “Critical factors in effective construction waste minimization at the design stage: A Shenzhen case study, China”, *Resources,* *Conservation and Recycling*, Elsevier, Vol. 82, pp. 1–7, doi: 10.1016/J.RESCONREC.2013.11.003.

Wang, J., Yang, Z., Liu, S., Zhang, Q. and Han, Y. (2016), “A comprehensive overview of hybrid construction machinery”, *Advances in Mechanical Engineering*, Hindawi Limited, Vol. 8 No. 3, pp. 1–15, doi: 10.1177/1687814016636809/FORMAT/EPUB.

Wang, W., Hao, S., He, W. and Mohamed, M.A. (2022), “Carbon emission reduction decisions in construction supply chain based on differential game with government subsidies”, *Building and Environment*, Pergamon, Vol. 222, p. 109149, doi: 10.1016/J.BUILDENV.2022.109149.

Wang, Y. and Boggio-Marzet, A. (2018), “Evaluation of Eco-Driving Training for Fuel Efficiency and Emissions Reduction According to Road Type”, *Sustainability 2018, Vol. 10, Page 3891*, Multidisciplinary Digital Publishing Institute, Vol. 10 No. 11, p. 3891, doi: 10.3390/SU10113891.

Waris, M., Shahir Liew, M., Khamidi, M.F. and Idrus, A. (2014), “Criteria for the selection of sustainable onsite construction equipment”, *International Journal of Sustainable Built Environment*, Elsevier, Vol. 3 No. 1, pp. 96–110, doi: 10.1016/J.IJSBE.2014.06.002.

Wei, W., Xin-Gang, Z., Wenjie, L. and Shuran, H. (2023), “The sustainable development of a low-carbon system using a system dynamics model: A case study of China”, *Journal of Renewable and Sustainable Energy*, American Institute of Physics Inc., Vol. 15 No. 1, doi: 10.1063/5.0130437.

Wei, X., Ye, M., Yuan, L., Bi, W. and Lu, W. (2022), “Analyzing the Freight Characteristics and Carbon Emission of Construction Waste Hauling Trucks: Big Data Analytics of Hong Kong”, *International Journal of Environmental Research and Public Health 2022, Vol. 19, Page 2318*, Multidisciplinary Digital Publishing Institute, Vol. 19 No. 4, p. 2318, doi: 10.3390/IJERPH19042318.

Werner-Lewandowska, K. and Grzelczak, A. (2021), “Arabian Journal of Business and Management Review”, doi: 10.4172/2223-5833.1000216.

Wiedmann Thomas and Minx Jan. (2008), *(2) (PDF) A Definition of Carbon Footprint*.

Van Wijngaarden, W.A., Happer, W. and Co, O. (2020), “Dependence of Earth’s Thermal Radiation on Five Most Abundant Greenhouse Gases The atmospheric temperatures and concentrations of Earth’s five most important, green-house gases”.

Winther, M. and Dore, C. (2017), *EMEP/EEA Air Pollutant Emission Inventory*.

Womack, J., Jones, D.T. and Roos, D. (1991), “The machine that changed the world : the story of lean production”.

Womack, J.P. and Jones, D.T. (1996), “Lean Thinking—Banish Waste and Create Wealth in your Corporation”, *Journal of the Operational Research Society*, Springer Science and Business Media LLC, Vol. 48 No. 11, pp. 1148–1148, doi: 10.1038/sj.jors.2600967.

Womack, J.P., Jones, D.T. and Roos, D. (2007), “The Machine That Changed the World: The Story of Lean Production-- Toyota’s Secret Weapon in the Global Car Wars That Is Now Revolutionizing World Industry”, p. 352.

WorldGBC. (2019), *Bringing Embodied Carbon Upfront*.

Xu, J., Zhang, Q., Teng, Y. and Pan, W. (2023), “Integrating IoT and BIM for tracking and visualising embodied carbon of prefabricated buildings”, *Building and Environment*, Pergamon, Vol. 242, p. 110492, doi: 10.1016/J.BUILDENV.2023.110492.

Xu, N., Li, X., Liu, Q. and Zhao, D. (2021), “An overview of eco-driving theory, capability evaluation, and training applications”, *Sensors*, MDPI, Vol. 21 No. 19, doi: 10.3390/s21196547.

Xue, Q., Wang, Z. and Chen, Q. (2022), “Multi-objective optimization of building design for life cycle cost and CO2 emissions: A case study of a low-energy residential building in a severe cold climate", *Building Simulation*, Tsinghua University, Vol. 15 No. 1, pp. 83–98, doi: 10.1007/S12273-021-0796-5/METRICS.

Yan, H., Shen, Q., Fan, L.C.H., Wang, Y. and Zhang, L. (2010), "Greenhouse gas emissions in building construction: A case study of One Peking in Hong Kong", *Building and Environment*, Vol. 45 No. 4, pp. 949–955, doi: 10.1016/j.buildenv.2009.09.014.

Yang, X.T., Huang, K., Zhang, Z., Zhang, Z.A. and Lin, F. (2021), "Eco-Driving System for Connected Automated Vehicles: Multi-Objective Trajectory Optimization", *IEEE Transactions on Intelligent Transportation Systems*, Institute of Electrical and Electronics Engineers Inc., Vol. 22 No. 12, pp. 7837–7849, doi: 10.1109/TITS.2020.3010726.

Younes, A., Elbeltagi, E., Diab, A., Tarsi, G., Saeed, F. and Sangiorgi, C. (2023), "Incorporating coarse and fine recycled aggregates into concrete mixes: mechanical characterization and environmental impact", *Journal of Material Cycles and Waste Management*, Springer, Vol. 26 No. 1, pp. 654–668, doi: 10.1007/S10163-023-01834-1/FIGURES/12.

Yu-Jing, W. (2012), "Application of system dynamics in construction project planning and control", *Proceedings of the 2012 2nd International Conference on Business Computing and Global Informatization, BCGIN 2012*, pp. 51–54, doi: 10.1109/BCGIN.2012.20.

Zamani, V., Yavari, E. and Taghaddos, H. (2024), "A science mapping lens on discrete event simulation applications in construction engineering and management", *Automation in Construction*, Elsevier, Vol. 166, p. 105625, doi: 10.1016/J.AUTCON.2024.105625.

Zhang, H. (2015), "Discrete-Event Simulation for Estimating Emissions from Construction Processes", *Journal of Management in Engineering*, American Society of Civil Engineers (ASCE), Vol. 31 No. 2, p. 04014034, doi: 10.1061/(ASCE)ME.1943-5479.0000236/ASSET/BAB3A205-813A-4A65-9C53-820AFE542F83/ASSETS/IMAGES/LARGE/FIGURE4.JPG.

Zhang, W., Wang, J., Du, S., Ma, H., Zhao, W. and Li, H. (2019), "Energy Management Strategies for Hybrid Construction Machinery: Evolution, Classification, Comparison and Future Trends", *Energies 2019, Vol. 12, Page 2024*, Multidisciplinary Digital Publishing Institute, Vol. 12 No. 10, p. 2024, doi: 10.3390/EN12102024.

Zhang, Y., Jiang, X., Cui, C. and Skitmore, M. (2022), "BIM-based approach for the integrated assessment of life cycle carbon emission intensity and life cycle costs", *Building and Environment*, Pergamon, Vol. 226, p. 109691, doi: 10.1016/J.BUILDENV.2022.109691.

Zsofia, R. (2024), "Analyzing the Big Room concept through a case study".

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Developing a Model for Reducing Carbon Emissions of Construction Heavy Machinery through ECO-hauling and Collaboration

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Abstract. Incorporating Eco-hauling and the Big Room approach emerges as a viable strategy for curbing carbon emissions in the construction phase. Eco-hauling optimises heavy vehicle operations to reduce emissions and costs through strategic, tactical, and operational measures, emphasising fuel efficiency and sustainable practices. On the other hand, the Big Room approach, rooted in lean management principles, promotes collaborative decision-making, transparent communication, and shared goals among project stakeholders in the construction phase. Thus, synthesising Eco-hauling with the Big Room approach provides a collaborative environment that enables streamlining processes, anticipating constraints, resolving bottlenecks, and reducing idle and operation time, leading to lower emissions and environmental sustainability. A hauling operation within a road project was analysed via a case study method to explore the synthesise result. Discrete event simulation (DES) and AnyLogic software were employed to evaluate different scenarios, taking into account variables such as the number of dumper trucks, payload capacity, and speed. The primary objective was to assess the carbon emissions for each scenario. From an initial set of 30 scenarios, expanded to over 400, Stat-Ease software identified two scenarios with the lowest CO2 output, focusing on minimising the operation total time in one case and without considering the operation total time in the other. The outcomes contribute critical insights into sustainable logistics practices, offering pragmatic pathways for enhancing hauling operations and addressing environmental concerns in construction projects.

Keywords: Big Room approach, Carbon emissions, Eco-hauling, Heavy Machinery, Sustainability

1 Introduction

The construction industry has substantial and irreversible environmental effects by generating carbon and excessively using natural resources. Therefore, a fundamental shift towards sustainable construction is essential [1]. Subsequently, embodied carbon emitted during building construction has largely been overlooked historically but contributes around 11% of all global carbon emissions [2]. Meggers et al. [3]argued that carbon emissions are the foremost reason for transforming the construction sector into a more sustainable one. Besides, [4] asserted that construction machinery is a major emission source in air pollutant inventories during the construction phase. Hence, the construction phase is a notable environmental factor [5].

Employing Eco-Hauling principles can significantly reduce earthmoving machinery emissions and costs while enhancing overall sustainability and competitiveness[6]. Similarly, The Big Room approach within construction projects involves various stakeholders, including contractors, engineers, fleet managers, environmental specialists, and project managers, working together to optimize operations, minimize environmental impact, and achieve project goals. As De Groot [7] stated, a collaborative environment facilitates the achievement of enriching sustainable objectives.

Therefore, this research aims to illuminate pathways for the evolution of the built environment towards greater environmental consciousness and sustainability by leveraging the synthesise of Eco-hauling and the Big Room approach as a lean management tool.

Integrating these approaches fosters collaboration and enhances stakeholders' communication to eliminate constraints and blockages, ensuring a continuous flow in hauling routes. Eco-hauling diminishes the number of brakes and queues at service locations like loading and dumping points, while collaborative planning eliminates bottlenecks. Such a combination can streamline operations, promote transparency, and drive collective problem-solving efforts to pursue net-zero goals in construction projects.

2 Literature Review

Construction phase emissions as an element of embodied carbon possess various resources mainly caused by energy consumption in two aspects: transportation of material and construction equipment [8]. Case in point, Marrero et al. [9]evaluated the carbon footprint of five construction projects, and on average, in all projects, the machinery had the highest impact on carbon emissions by 52%. In agreement with Marrero et al. [9], [8] assessed six different residential and industrial projects, and the results confirmed the significant effect of machinery by 73%. These findings highlight that controlling and managing construction machinery operations is critical in reducing carbon emissions in the construction phase.

As a practical strategy, Krantz et al. [6] defined Eco-hauling as an extension of the Eco-Driving concept that aims to reduce carbon emissions in earthmoving operations. It considers environmentally conscious practices at strategic, tactical, and operational levels and encompasses strategies to minimise carbon emissions during earthmoving operations within construction projects. These strategies, ranging from eco-routing systems and selecting an energy-optimal vehicle to focusing on decisions like limiting the vehicle load and eco-driving styles, underscore a holistic approach to mitigating environmental impact. Indeed, Eco-hauling employs Discrete Event Simulation (DES) to model equipment activities and identify strategies for efficient resource utilisation, emission reduction, and cost reduction [10]. In terms of the role of collaboration in diminishing carbon footprint in construction projects, Benjaafar et al. [11]stated that firms could effectively reduce their carbon emissions without significantly increasing costs by making only operational adjustments and enhancing collaboration among project members. Accordingly, several stakeholders can collaborate to solve obstacles to achieve notable cuts in construction carbon emissions.

In order to conquer challenges, three essential key collaboration factors have been suggested: sharing information and data, strong leadership, and incentive mechanisms that encourage stakeholders to consider their carbon footprint throughout the asset's lifetime [12]. Considering these facts, the qualities of the Big Room approach offer a collaborative project delivery strategy that emphasises integrated planning, coordination, and communication among stakeholders to streamline construction processes [13]

Eventually, synthesising eco-hauling and the Big Room approach will optimise machinery activities and stakeholder collaboration, effectively curbing carbon emissions in construction projects. Krantz et al. [6]underline the significance of site information and detailed planning on reducing carbon footprint, aligning with [14] proposal to integrate eco-hauling with collaborative planning to reduce carbon emissions. Eco-hauling focuses on refining earthmoving and driving procedures, while collaborative planning elevates workflow and collaboration among diverse stakeholders. Combining these strategies emerges as a reasonable approach for construction practitioners to minimise carbon emissions and costs efficiently.

Although previous research has explored the eco-friendly hauling approach [15] [16] and collaborative strategies individually [17] [18] for curbing carbon emissions, there is limited understanding of how they can be effectively integrated to achieve greater environmental sustainability [14]. Hence, this study aims to address this gap by investigating how the combined impact of Eco-Hauling and stakeholder collaboration can create more effective solutions for reducing carbon emissions in construction projects.

3 Method

Case studies have widely been used to examine earthmoving activities through DES and other simulation methodologies [19] [20] [21]. The case study approach comprehensively demonstrates Eco-hauling's ability to curb CO2 within a real-life project [6]. The research methodology is depicted in Figure 1.

Fig. 1. Research framework

3.1 Case Study Characteristics

The case study examines a hauling operation in a road construction project in Iran involving two sub-contractors: Soil Hauling (Orange route) and Asphalt Laying (Yellow route), both under the same main contractor. Their routes intersect at two points (Blockage 1 and Blockage 2). The task involves hauling 900 tonnes of soil over a 6620-meter loop (3310 meters each way). Dump trucks are loaded by an excavator, travel to the dumping area, unload, and return, facing possible stoppages at the blockage points caused by the asphalt contractor's trucks. This loop continues until the task is completed (see Fig. 2 and 3).

Fig. 2. Hauling project site

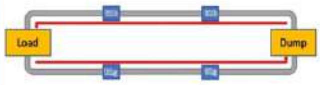

Fig. 3. Hauling task schematic illustration

3.2 Data Collection and Modelling Validation

The core data for this case study consisted of project details conducted through contractor interviews to ensure a thorough understanding of the project. Additional information regarding equipment fuel consumption and construction methods was sourced from scientific literature [22], [6], as well as estimates and assumptions provided by the contractor. Besides, the data collection for both the existing and Eco-hauling scenarios involved structured observations to gather numerical data. However, the data collection for the synthesis of the Eco-hauling and Big Room scenario was done through modelling using AnyLogic software. Also, a sample scenario of Eco-hauling was modelled to validate modelling data. The results demonstrated an average accuracy of 90% between real-life data and the data simulated by the model, suggesting a solid alignment between the observed behaviours in the site and the predictions made by the simulation model. This indicates a reliable representation of the scenarios within the software.

Material Quantities. To estimate the quantity of soil (Earth (Sand, Clay, Silt) with a density of 1.5 Tonnes/M3) that needed to be loaded onto each dumper truck, the loader bucket capacity, which amounted to 3 tonnes or two cubic meters, was considered. To ensure accuracy, data on the load amount in the excavator bucket was collected by measuring the dimensions of the soil in the bucket at ten different time points. The contractor also provided data on the material composition and estimated density.

Diesel Consumption and CO2 Emission Calculation. The contractor had a Komatsu WA470 excavator for loading and a fleet of five Mercedes-Benz 2624 trucks for soil transport. Drawing on 15 years of experience with this truck model, the contractor estimated fuel consumption to be 25 litres per hour during idling and non-idling activities, calculated by starting with a full tank and measuring the remaining diesel at the end of the operation. Also, based on Abbasian-Hosseini et al. [23], CO2 emissions in idling and non-idling are the same. Moreover, to calculate the difference in fuel use between a loaded and an empty dumper truck, it was assumed that the trucks were full half the time and empty the other half [6]. Thus, again, the contractor's estimate of 25 litres per hour was relied upon for both conditions. Finally, for calculating the effect of each brake, the findings of Rylander et al. [22] were considered; they found that each stop per km of driving on a quarry track added about 10% to the fuel used to bring the vehicle speed back to normal. Diesel consumption and CO2 emissions are then computed, considering 2.62 kg CO2 per litre of diesel combusted [24].

3.3 Discrete Event Simulation (DES), AnyLogic and Parameters

DES models discrete events and system state changes over time, aiding in understanding processes and resource utilisation. It resembles a virtual lab, simulating events step by step to study interactions and optimise real-life processes, especially in construction operations [25]. AnyLogic is simulation software that employs the DES method to model and analyse complicated systems, such as hauling operations. It involves system setup, event modelling, and data analysis. Also, inputs like number of trucks, payload, speed, and number of deliveries are crucial. AnyLogic calculates outputs such as brakes, operation time, and idle time, which influence diesel consumption.

3.4 Modelling

To study scenarios realistically, it is crucial to consider the dynamic conditions under which the hauling task is conducted. Dumper trucks interact not only with each other but also with blockages and the excavator loading them. Additionally, the hauling operation is influenced by factors such as queues and the frequency of drivers applying the brakes. Hence, to capture these complex dynamics and interactions across various scenarios, a Discrete Event Simulation (DES) model was developed in AnyLogic software (see Fig. 4).

Events Duration Estimation. The time required for the excavator to load one dumper truck depends on various factors, such as the bucket capacity, soil type, and the excavator's productivity. Based on structured observation, Figure 5 shows the average time it took the excavator to load a dumper truck and the unloading time of a dumper truck. Furthermore, the probability that dumper trucks face blockages 1 and 2 are 60% and 40% of the time, respectively, with a duration expressed as a triangular distribution.

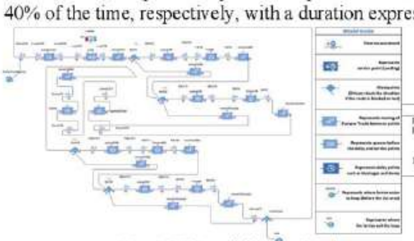

Fig. 4. DES model in AnyLogic

Parameter	Value
Probability of blockage at the Blockage 1	60%
Probability of blockage at the Blockage 2	40%
Time of stoppage at Blockage 1	Triangular (1, 2, 4)
Time of stoppage at Blockage 2	Triangular (1, 2, 3)
Loading a dumper truck by the excavator	Triangular (4, 6, 8)
Unloading time of a dumper truck	Triangular (3, 4, 5)

Fig. 5. Timing parameters

3.5 Hauling Scenarios

The existing scenario. In this scenario, the contractor conducted hauling operations without any specific strategy.

The Eco-hauling Scenario. Checkpoints ahead of bottlenecks and service points were included in the Eco-hauling scenario. To proactively address potential obstacles in this setup, dumper trucks passed checkpoints 300 meters before blockage 1, blockage 2, and loading/dumping points. At these checkpoints, drivers assessed the passage status and promptly adjusted the dumper truck's speed if the obstruction was detected. Conversely, if the passage remained unobstructed, the dumper truck maintained its speed uninterrupted. This proactive measure enabled smoother navigation of the hauling route, reducing brake frequency and enhancing operational efficiency.

The Synthesised Eco-hauling and Big Room Approach. In this scenario, alongside implementing checkpoints, the Big Room approach facilitated a shared space where contractors, project managers, fleet managers, and other practitioners could communicate transparently and make collective decisions on an online group chat. The conclusion drawn from this collaborative effort was that the contractors can operate in two distinct time blocks within a 24-hour day. For instance, the hauling contractor may work from 5 am to 4 pm, while the asphalt-laying contractor operates from 4 pm to 5 am. This strategic scheduling promoted collaboration, eliminated blockages and ensured a seamless project workflow.

3.6 Scenarios Application into the Model

Each scenario consists of four key elements: the number of dumper trucks, the payload capacity per dumper truck (Tonnes), the dumper truck speed (Km/h) and the number of deliveries. These elements form the basis for assessing the outcomes across the various scenarios. Three main scenarios were appointed to validate modelling and compare the strategies. Incipiently, 30 scenarios were simulated and assessed, comprising 15 instances of Eco-hauling and 15 scenarios involving Eco-hauling integration with the Big Room approach (Without bottlenecks).

The inputs considered were the number of dumper trucks (ranging from 1 to 5), payload capacity (between 8 and 12 Tonnes), and speed for the outbound trip (from 14 to 26 km/h, with a limitation due to drivers' feedback indicating an inability to exceed 26 km/h when trucks are loaded). In addition, all return trips are considered at 30 km/h to maintain consistency (see Fig. 6).

Model	Deliveries	Speed	Payloads	No of Trucks	Eco-hauling					Eco-hauling and Big Room				
					Total Time	Idle Time	Brakes	Diesel	CO2	Total Time	Idle Time	Brakes	Diesel	CO2
1	100	23	9	4	779	557	625	1320.1	3458.8	667	104	334	1107.7	2902.1
2	90	20	10	3	890	481	536	1139.5	2985.4	749	46	279	938.5	2458.3
3	82	23	11	4	652	486	518	1104.8	2894.6	552	30	260	914.1	2394.8
4	82	23	11	2	1228	376	435	1037.8	2719.2	1048	18	189	876.7	2297.1
5	113	20	8	3	1193	563	581	1511.6	3960.4	1000	33	347	1279.6	3352.7
6	82	17	11	2	1359	390	343	1144.5	2998.8	1188	5	108	975.1	2554.7
7	90	20	10	3	957	472	469	1212.7	3177.2	815	33	234	1020.8	2674.6
8	90	20	10	1	2778	400	358	1170.1	3065.6	2401	12	180	1008.7	2637.6
9	100	17	9	2	1067	488	526	1407.2	3686.9	1421	4	205	1188.8	3114.8
10	90	14	10	3	1101	498	561	1195.9	3057.3	946	40	376	1184.7	3103.8
11	90	20	10	5	624	679	594	1320.8	3460.5	572	408	351	1179.0	3088.9
12	100	23	9	2	1507	472	505	1273.6	3337.0	1275	13	205	1067.2	2796.0
13	82	17	11	4	706	640	431	1188.4	3113.7	614	84	259	1017.4	2665.6
14	75	20	12	3	808	404	395	1023.8	2682.4	683	28	232	854.4	2238.4
15	100	17	9	4	831	533	526	1436.7	3764.3	739	88	333	1222.6	3216.4

Note: Total time should be multiplied by the number of dumper trucks, but idle time is cumulative.

Fig. 6. Outcomes of 30 origin scenarios

4 Findings

4.1 Processing Initial Result

Comparing outputs from three scenarios with identical inputs sheds light on the impact of Eco-Hauling and collaborative strategies on carbon emissions reduction (see Fig 7). As evident in the table below, adopting an Eco-Hauling and Big Room approach has led to enhancements in sustainability across various aspects. Notably, the Eco-Hauling scenario exhibits a nearly 1.9 % reduction in CO2 emissions compared to the existing scenario. In comparison, the synthesise of the Eco-Hauling and Big Room scenario demonstrates an impressive 11.8 % decrease in CO2 emissions compared to the existing scenario.

Strategies	Inputs				Outputs				
	No of Deliveries	Speed KM/h	Payload Tonnes	No of Trucks	Total Time Mins	Idle Time Mins	No of Brakes	Diesel Litres	CO2 Kg CO2
Existing	90	20	10	5	635	708	649	1345.6	3525.5
Eco-hauling	90	20	10	5	624	679	594	1320.8	3460.5
Eco-Hauling & Big Room	90	20	10	5	572	408	351	1203.9	3154.2

Fig. 7. Assessing the Impact of Each Strategy on Carbon Emission

4.2 Identifying the most optimised scenarios in terms of CO2 emissions

The early 30 scenarios underwent further expansion and analysis utilising Stat-Ease software, which generated more than 400 scenarios. Next, Stat-Ease analysed these scenarios and generated a set of diagrams that provided a comprehensive understanding of the impact of each input, such as payload, speed and number of trucks, on carbon emissions factors (see Fig. 8). Following this evaluation, Stat-Ease optimisation tools were employed to pinpoint three scenarios with different importance regarding CO2 emissions and time (see Fig 9).

One scenario prioritised minimising overall operation time, while another focused solely on reducing carbon emissions. In another, time and carbon share the same importance. This approach enables a nuanced exploration of the trade-offs between minimising environmental impact and operational efficiency, offering valuable insights for decision-making in pursuing sustainable hauling practices.

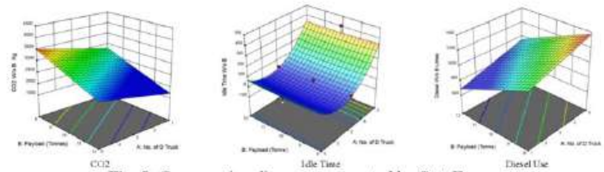

Fig. 8. Comparative diagrams generated by Stat-Ease

Importance Weightings	Inputs				Outputs				
	No of Deliveries	Speed KM/h	Payload Tonnes	No of Trucks	Total Time Mins	Idle Time Mins	No of Brakes	Diesel Litres	CO2 Kg CO2
Time 50% Carbon 50%	75	24	12	4	494	35	159	828.8	2171.5
Time 0% Carbon 100%	75	26	12	1	1816	0	150	761.9	1996.2
Time 100% Carbon 0%	75	26	12	5	460	362	294	968.5	2537.5

Fig. 9. The most sustainable Scenarios suggested by Stat-Ease

5 Discussion

In the analysis of models and scenario outcomes, it was observed that increasing speed leads to reduced CO2 emissions due to decreased total operation time (see Fig. 6). Additionally, increasing the payload of each truck resulted in reduced CO2 emissions, attributed to the reduction in the number of deliveries and subsequent decrease in total time. While this study indicated that total time has the most significant impact on CO2 emissions in most cases, it's essential to note that scenarios with low total time may still have high idle time, leading to increased CO2 emissions. For instance, a scenario with 5 dumper trucks with 624 minutes total time may seem faster and with a lower carbon than the scenario with 4 dumper trucks with 704 minutes. However, the scenario with 5 dumper trucks demonstrated higher CO2 emissions due to higher idle time (see Fig. 6). Therefore, the significance of the idle time of dumper trucks should not be underestimated. Besides, though the number of brakes appears to have a minimal impact on carbon emissions, it's worth saying that an increase in the number of trucks tends to raise the number of brakes, while an increase in payloads reduces the number of brakes. Interestingly, speed changes do not seem to impact the number of brakes significantly.

6 Conclusion

Incorporating Eco-Hauling and the Big Room approach is a promising strategy for achieving net zero in the built environment. This synthesise optimises logistic operations and fosters collaboration among stakeholders, paving the way for the evolution of the built environment towards greater environmental consciousness. Through a case study analysis employing Discrete Event Simulation (DES) and AnyLogic software, it was demonstrated that synthesising these approaches can significantly decrease CO2 emissions. Furthermore, the study identified optimised scenarios with minimal CO2 emissions, highlighting the importance of factors such as idle time, total operating time and payload capacity in achieving sustainable hauling practices.

In fact, this research provides a practical opportunity for construction stakeholders to identify and select the most effective modelled scenarios before initiating operations in a collaborative environment. Stakeholders can evaluate different scenarios, anticipate potential challenges, and make informed decisions that align with sustainability goals. Overall, by proposing a pioneering strategy, this research contributes to efficiency and reduces carbon emissions in construction projects, encouraging practitioners to transcend conventional boundaries and advance towards an enhanced sustainable future. Future studies could explore these methods' scalability across different construction sectors and locations, which would be helpful for broader applicability.

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References

1. I. S. Vasilca, M. Nen, O. Chivu, V. Radu, C. P. Simion, and N. Marinescu, 'The management of environmental resources in the construction sector: An empirical model', *Energies (Basel)*, vol. 14, no. 9, May 2021, doi: 10.3390/en14092489.
2. WorldGBC, 'Bringing embodied carbon upfront', 2019. Accessed: Jun. 29, 2022. [Online]. Available: www.worldgbc.org/embodied-carbon
3. F. Meggers *et al.*, 'Reduce CO 2 from buildings with technology to zero emissions', *Sustain Cities Soc*, vol. 2, no. 1, pp. 29–36, 2012, doi: 10.1016/j.scs.2011.10.001.
4. D. I. Lee, J. Park, M. Shin, J. Lee, and S. Park, 'Characteristics of Real-World Gaseous Emissions from Construction Machinery', *Energies 2022, Vol. 15, Page 9543*, vol. 15, no. 24, p. 9543, Dec. 2022, doi: 10.3390/EN15249543.
5. R. Pacheco-Torres, E. Jadraque, J. Roldán-Fontana, and J. Ordóñez, 'Analysis of CO2 emissions in the construction phase of single-family detached houses', *Sustain Cities Soc*, vol. 12, pp. 63–68, Jul. 2014, doi: 10.1016/j.scs.2014.01.003.
6. J. Krantz, K. Feng, J. Larsson, and T. Olofsson, '"Eco-Hauling" principles to reduce carbon emissions and the costs of earthmoving - A case study', *J Clean Prod*, vol. 208, pp. 479–489, Jan. 2019, doi: 10.1016/J.JCLEPRO.2018.10.113.
7. R. De Groot, 'Function-analysis and valuation as a tool to assess land use conflicts in planning for sustainable, multi-functional landscapes', *Landsc Urban Plan*, vol. 75, no. 3–4, pp. 175–186, Mar. 2006, doi: 10.1016/J.LANDURBPLAN.2005.02.016.
8. X. J. Li and Y. dan Zheng, 'Using LCA to research carbon footprint for precast concrete piles during the building construction stage: A China study', *J Clean Prod*, vol. 245, Feb. 2020, doi: 10.1016/J.JCLEPRO.2019.118754.
9. M. Marrero, M. Puerto, C. Rivero-Camacho, A. Freire-Guerrero, and J. Solís-Guzmán, 'Assessing the economic impact and ecological footprint of construction and demolition waste during the urbanization of rural land', *Resour Conserv Recycl*, vol. 117, pp. 160–174, Feb. 2017, doi: 10.1016/j.resconrec.2016.10.020.
10. Kailun Feng, 'ENVIRONMENTALLY FRIENDLY CONSTRUCTION PROCESSES UNDER UNCERTAINTY: ASSESSMENT, OPTIMISATION AND ROBUST DECISION-MAKING', *Division of Industrialized and Sustainable Construction Department of Civil, Environmental and Natural Resources Engineering Luleå University of Technology*, 2020, Accessed: Apr. 04, 2024. [Online]. Available: www.ltu.se/shb

11. S. Benjaafar, Y. Li, and M. Daskin, 'Carbon footprint and the management of supply chains: Insights from simple models', *IEEE Transactions on Automation Science and Engineering*, vol. 10, no. 1, pp. 99–116, 2013, doi: 10.1109/TASE.2012.2203304.
12. D. Jackson and F. Ascui, 'Achieving infrastructure emission reductions through supply chain collaboration: challenges and opportunities', 2019.
13. B. A. Temel, H. B. Başağa, M. U. Temel, G. K. Yılmaz, and M. M. Nasery, 'Big Room concept in project management and control', *Journal of Construction Engineering, Management & Innovation*, vol. 2, no. 4, pp. 204–214, Dec. 2019, doi: 10.31462/JCEMI.2019.04204214.
14. S. Arogundade, M. Dulaimi, and S. Ajayi, 'The Role of Contractors in Reducing Carbon during Construction-A Preliminary Study', 2021.
15. H. S. H. Jassim, J. Krantz, W. Lu, and T. Olofsson, 'A model to reduce earthmoving impacts', *Journal of Civil Engineering and Management*, vol. 26, no. 6, pp. 490–512, Jun. 2020, doi: 10.3846/JCEM.2020.12641.
16. H. Almujibah, *SUSTAINABLE DEVELOPMENT OF FREIGHT TRANSPORT USING A FASTER AND MORE ECO-FRIENDLY MODE*. 2015. doi: 10.2495/CR220181.
17. K.-H. Lee, 'Integrating carbon footprint into supply chain management: the case of Hyundai Motor Company (HMC) in the automobile industry', 2011, doi: 10.1016/j.jclepro.2011.03.010.
18. C. Jira and M. W. Toffel, 'Engaging Supply Chains in Climate Change', 2013, doi: 10.1287/msom.1120.0420.
19. P. V. Rekapalli and J. C. Martinez, 'Discrete-Event Simulation-Based Virtual Reality Environments for Construction Operations: Technology Introduction', *J Constr Eng Manag*, vol. 137, no. 3, pp. 214–224, Aug. 2010, doi: 10.1061/(ASCE)CO.1943-7862.0000270.
20. F. Vahdatikhaki and A. Hammad, 'Framework for near real-time simulation of earthmoving projects using location tracking technologies', *Autom Constr*, vol. 42, pp. 50–67, Jun. 2014, doi: 10.1016/J.AUTCON.2014.02.018.
21. O. Alshboul, A. Shehadeh, O. Tatari, G. Almasabha, and E. Saleh, 'Multiobjective and multivariable optimization for earthmoving equipment Optimization for earthmoving equipment 21', *Journal of Facilities Management*, vol. 22, no. 1, pp. 21–48, 2024, doi: 10.1108/JFM-10-2021-0129.
22. D. Rylander, J. Axelsson, and P. Wallin, 'Energy savings by wireless control of speed, scheduling and travel times for hauling operation', *IEEE Intelligent Vehicles Symposium, Proceedings*, pp. 1115–1120, 2014, doi: 10.1109/IVS.2014.6856451.
23. S. A. Abbasian-Hosseini, M. L. Leming, and M. Liu, 'Effects of Idle Time Restrictions on Excess Pollution from Construction Equipment', *Journal of Management in Engineering*, vol. 32, no. 2, p. 04015046, Mar. 2016, doi: 10.1061/(ASCE)ME.1943-5479.0000408/ASSET/445137D8-8991-47AA-A139-EEC5D247AF1C/ASSETS/IMAGES/LARGE/FIGURE4.JPG.
24. C. Ji, T. Hong, and H. S. Park, 'Comparative analysis of decision-making methods for integrating cost and CO 2 emission-focus on building structural design', *Energy Build*, vol. 72, pp. 186–194, 2014, doi: 10.1016/j.enbuild.2013.12.045.
25. S. Abbasi, Katayoon Taghizade, E. Noorzai, and M. Asce, 'BIM-Based Combination of Takt Time and Discrete Event Simulation for Implementing Just in Time in Construction Scheduling under Constraints', *J Constr Eng Manag*, vol. 146, no. 12, Dec. 2020, doi: 10.1061/(ASCE)CO.1943-7862.0001940.

ARCOM Doctoral Workshop

DEVELOPING A MODEL FOR REDUCING CARBON EMISSIONS OF CONSTRUCTION HEAVY VEHICLES THROUGH ECO-HAUING AND COLLABORATION

Incorporating Eco-hauling and the Big Room approach emerges as a viable strategy for curbing carbon emissions in the construction phase. Eco-hauling optimises heavy vehicle operations to reduce emissions and costs through strategic, tactical, and operational measures, emphasising fuel efficiency and sustainable practices. On the other hand, the Big Room approach, rooted in lean management principles, promotes collaborative decision-making, transparent communication, and shared goals among project stakeholders in the construction phase. Thus, synthesising Eco-hauling with the Big Room approach provides a collaborative environment that enables streamlining processes, anticipating constraints, resolving bottlenecks, and reducing idle and operation time, leading to lower emissions and environmental sustainability. A hauling operation within a road project was analysed via a case study method to explore the synthesise result. Discrete event simulation (DES) and AnyLogic software were employed to evaluate different scenarios, taking into account variables such as the number of dumper trucks, payload capacity, and speed. The primary objective was to assess the carbon emissions for each scenario. From an initial set of 30 scenarios, expanded to over 400, Stat-Ease software identified two scenarios with the lowest CO2 output, focusing on minimising the operation total time in one case and without considering the operation total time in the other. The outcomes contribute critical insights into sustainable logistics practices, offering pragmatic pathways for enhancing hauling operations and addressing environmental concerns in construction projects.

Keywords: Big Room approach, carbon emissions, Eco-hauling, heavy vehicles, sustainability.

INTRODUCTION

The construction industry has substantial and irreversible environmental effects by generating carbon and excessively using natural resources. Therefore, a fundamental shift towards sustainable construction is essential (Vasilca et al., 2021). Subsequently, embodied carbon emitted during building construction has largely been overlooked historically but contributes around 11% of all global carbon emissions (WorldGBC, 2019). Meggers et al. (2012) argued that carbon emissions are the foremost reason for transforming the construction sector into a more sustainable one. Besides, Lee et al. (2022) asserted that construction machinery is a major emission source in air pollutant inventories during the construction phase. Hence, the construction phase is a notable environmental factor (Pacheco-Torres et al., 2014).

Employing Eco-Hauling principles can significantly reduce earthmoving machinery emissions and costs while enhancing overall sustainability and competitiveness(Krantz et al., 2019). Similarly, The Big Room approach within construction projects involves various stakeholders, including contractors, engineers, fleet managers, environmental specialists, and project managers, working together to optimize operations, minimize environmental impact, and achieve project goals. As De Groot (2006) stated, a collaborative environment facilitates the achievement of enriching sustainable objectives.

Therefore, this research aims to illuminate pathways for the evolution of the built environment towards greater environmental consciousness and sustainability by leveraging the synthesise of Eco-hauling and the Big Room approach as a lean management tool.

Integrating these approaches fosters collaboration and enhances stakeholders' communication to eliminate constraints and blockages, ensuring a continuous flow in hauling routes. In fact, Eco-hauling diminishes the number of brakes and queues at service locations like loading and dumping points, while collaborative planning eliminates bottlenecks. Such a combination can streamline operations, promote transparency, and drive collective problem-solving efforts to pursue net-zero goals in construction projects.

LITERATURE REVIEW

Construction phase emissions as an element of embodied carbon possess various resources mainly caused by energy consumption in two aspects: transportation of material and construction equipment (Li & Zheng, 2020). Case in point, Marrero et al. (2017) evaluated the carbon footprint of five construction projects, and on average, in all projects, the machinery had the highest impact on carbon emissions by 52%. In agreement with Marrero et al. (2017), Li & Zheng (2020) assessed six different residential and industrial projects, and the results confirmed the significant effect of machinery by 73%. These findings highlight that controlling and managing construction machinery operations is critical in reducing carbon emissions in the construction phase.

As a practical strategy, Krantz et al. (2019) defined Eco-hauling as an extension of the Eco-Driving concept that aims to reduce carbon emissions in earthmoving operations. It considers environmentally conscious practices at strategic, tactical, and operational levels and encompasses strategies to minimise carbon emissions during earthmoving operations within construction projects. These strategies, ranging from eco-routing systems and selecting an energy-optimal vehicle to focusing on decisions like limiting the vehicle load and eco-driving styles, underscore a holistic approach to mitigating environmental impact. Indeed, Eco-hauling employs Discrete Event Simulation (DES) to model equipment activities and identify strategies for efficient resource utilisation, emission reduction, and cost reduction (Kailun Feng, 2020). In terms of the role of collaboration in diminishing carbon footprint in construction projects, Benjaafar et al. (2013) stated that firms could effectively reduce their carbon emissions without significantly increasing costs by making only operational adjustments and enhancing collaboration among project members. Accordingly, several stakeholders can collaborate to solve obstacles to achieve notable cuts in construction carbon emissions.

In order to conquer challenges, three essential key collaboration factors have been suggested: sharing information and data, strong leadership, and incentive mechanisms that encourage stakeholders to consider their carbon footprint throughout the asset's lifetime (Jackson & Ascui, 2019). Considering these facts, the qualities of the Big Room approach offer a collaborative project delivery strategy that emphasises integrated planning, coordination, and communication among stakeholders to streamline construction processes (Temel et al., 2019).

Eventually, synthesising eco-hauling and the Big Room approach will optimise machinery activities and stakeholder collaboration, effectively curbing carbon emissions in construction projects. Krantz et al. (2019) underline the significance of site information and detailed planning on reducing carbon footprint, aligning with (Arogundade et al., 2021) proposal to integrate eco-hauling with collaborative planning to reduce carbon emissions. Eco-hauling focuses on refining earthmoving and driving procedures, while collaborative planning elevates workflow and collaboration among diverse stakeholders. Combining these strategies emerges as a reasonable approach for construction practitioners to minimise carbon emissions and costs efficiently.

Although previous research has explored eco-friendly hauling approach (Jassim et al., 2020) (Almujibah, 2015) and collaborative strategies individually (K.-H. Lee, 2011) (Jira & Toffel, 2013) for curbing carbon emissions, there is limited understanding of how they can be effectively integrated to achieve greater environmental sustainability (Arogundade et al., 2021). This gap underscores the need for research examining how collaboration among stakeholders can enhance the implementation of eco-friendly hauling practices and reduce carbon emissions during construction.

METHOD

Discrete Event Simulation (DES), Anylogic and Parameters

DES models discrete events and system state changes over time, aiding in understanding processes and resource utilisation. It resembles a virtual lab, simulating events step by step to study interactions and optimise real-life processes, especially in construction operations (Abbasi et al., 2020). AnyLogic is simulation software that employs the DES method to model and analyse complicated systems, such as hauling operations. It involves system setup, event modelling, and data analysis. Also, inputs like number of trucks, payload, speed, and number of deliveries are crucial. AnyLogic calculates outputs such as brakes, operation time, and idle time, which influence diesel consumption. Diesel consumption and CO_2 emissions are then computed, considering 2.62 kg CO_2 per litre of diesel combusted (Ji et al., 2014).

Case Study Characteristics

The selected case study examines a hauling operation within a road construction project in Iran. Two sub-contractors, namely Soil Hauling (Gray route) and Asphalt Laying (White route), were concurrently operating under the same main contractor, each assigned to distinct routes. These routes intersected at two points: Blockage 1 and Blockage 2 (Figure 1). The task involved hauling 900 tonnes of soil from the loading point to the dump point, with each loop spanning a length of 6620 meters, consisting of 3310 meters for the outbound trip and 3310 meters for the return trip.

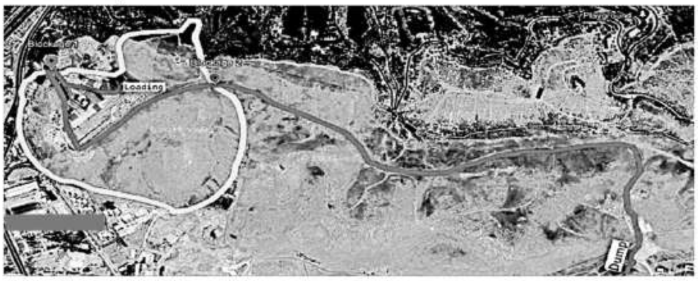

Figure 1: Image showing the hauling project site

Scenarios Elements

Each scenario consists of four key elements: the number of dumper trucks, the payload capacity per dumper truck (Tonnes), the dumper truck speed (Km/h) and the number of deliveries. These elements form the basis for assessing the outcomes across the various scenarios (Figure 2). Moreover, the loader bucket capacity, which amounted to 3 tonnes or two cubic meters, was considered to determine the payload capacity of each dumper truck.

Hauling Scenarios

Three main scenarios were appointed to validate modelling and compare the strategies.

The existing scenario
In this scenario the contractor conducted hauling operations without any specific strategy.

The Eco-hauling scenario
Checkpoints ahead of bottlenecks and service points were included in the Eco-hauling scenario. To proactively address potential obstacles in this setup, dumper trucks passed checkpoints 300 meters before blockage 1, blockage 2, and loading/dumping points. At these checkpoints, drivers assessed the passage status and promptly adjusted the dumper truck's speed if the obstruction was detected. Conversely, if the passage remained unobstructed, the dumper truck

maintained its speed uninterrupted. This proactive measure enabled smoother navigation of the hauling route, reducing brake frequency and enhancing operational efficiency.

The synthesised Eco-hauling and Big Room approach

In this scenario, alongside implementing checkpoints, the Big Room approach facilitated a shared space where contractors, project managers, fleet managers, and other practitioners could communicate transparently and make collective decisions on an online group chat. The conclusion drawn from this collaborative effort was that the contractors can operate in two distinct time blocks within a 24-hour day. For instance, the hauling contractor may work from 5 am to 4 pm, while the asphalt-laying contractor operates from 4 pm to 5 am. This strategic scheduling promoted collaboration, eliminated blockages and ensured a seamless project workflow.

Data Collection and Modelling Validation

The data collection for both the existing and Eco-hauling scenarios involved structured observations to gather numerical data. However, the data collection for the synthesis of the Eco-hauling and Big room scenario was done through modelling using AnyLogic software. Also, a sample scenario of Eco-hauling was modelled to validate modelling data. The results demonstrated an average accuracy of 90% between real-life data and the data simulated by the model, suggesting a solid alignment between the observed behaviours in the site and the predictions made by the simulation model. This indicates a reliable representation of the scenarios within the software.

Modelling

Incipiently, 30 scenarios were simulated and assessed, comprising 15 instances of Eco-hauling and 15 scenarios involving Eco-hauling integration with the Big Room approach (Without bottlenecks). The inputs considered were the number of dumper trucks (ranging from 1 to 5), payload capacity (between 8 and 12 Tonnes), and speed (from 14 to 26 km/h, with a limitation due to driver feedback indicating an inability to exceed 26 km/h when trucks are loaded) (Figure 2).

900 Tonnes soil					Eco-hauling					Eco-hauling and Big room approach (Without bottlenecks)				
Model NO	Deliveries	Speed Km/H	Payload Tonnes	No of Trucks	No of Brakes	Total Time	Idle Time	CO2 Kg CO2	Fuel Use Litres	No of Brakes	Total Time Mins	Idle Time Mins	CO2 Kg CO2	Fuel Use Litres
1	100	23	9	4	623	779	557	4066.82	1552.22	314	667	104	3054.89	1165.99
2	90	26	10	3	556	896	481	3510.48	1339.88	279	749	46	2528.78	965.18
3	82	23	11	4	518	652	486	3425.12	1307.30	260	552	99	2542.32	970.35
4	82	23	11	2	415	1228	376	3129.66	1194.53	169	1048	16	2321.10	885.92
5	113	20	8	3	581	1193	563	4574.96	1746.17	347	1020	33	3408.34	1300.90
6	82	17	11	2	343	1359	390	3424.35	1307.01	169	1166	5	2566.72	979.67
7	90	20	10	3	469	957	472	3692.45	1409.33	274	815	33	2730.28	1042.09
8	90	20	10	1	359	2778	400	3502.24	1336.73	180	2401	11	2649.61	1011.30
9	100	17	9	2	516	1667	488	4219.67	1610.56	205	1421	4	3123.68	1193.01
10	90	14	10	3	561	1101	498	4200.87	1603.39	276	946	40	3167.13	1208.83
11	90	20	10	5	594	624	679	4201.71	1603.71	351	572	408	3599.75	1373.95
12	100	23	9	2	509	1507	472	3852.23	1470.32	205	1275	13	2816.74	1075.09
13	82	17	11	4	431	704	440	3593.99	1371.75	259	614	84	2796.58	1067.40
14	75	20	12	3	395	808	404	3123.45	1192.16	232	683	28	2288.67	873.54
15	100	17	9	4	526	851	533	4346.13	1658.83	313	739	86	3349.55	1278.46

Note: Total time should be multiplied by the number of dumper trucks, but idle time is cumulative.

Figure 2: Outcomes of 30 origin scenarios

FINDINGS

Comparing outputs from three scenarios with identical inputs sheds light on the impact of Eco-hauling and collaborative strategies on carbon emissions reduction (Table 1). As evident in the table below, adopting an Eco-hauling and Big Room approach has led to enhancements in sustainability across various aspects. Notably, the Eco-hauling scenario exhibits a nearly 2.3% reduction in CO2 emissions compared to the existing scenario. In comparison, the synthesise of the Eco-hauling and Big Room scenario demonstrates an impressive 19.5% decrease in CO2 emissions compared to the existing scenario.

Table 1: Assessing the Impact of Each Scenario on Carbon Emission

Scenarios	Inputs	Outputs

900 tonnes of soil hauling	No of Deliveries	Speed KM/h	Payload Tonnes	No of Trucks	No of Brakes	Total Time Mins	Idle Time Mins	CO2 Kg CO2	Fuel Use Liters
Existing	90	20	10	5	649	635	708	4298.55	1640.67
Eco-hauling	90	20	10	5	594	624	679	4201.71	1603.71
Eco-h & Big R	90	20	10	5	351	572	408	3599.75	1373.95

Identifying the most optimised scenarios in terms of CO_2 emissions

The early 30 scenarios underwent further expansion and analysis utilising Stat-Ease software, which generated more than 400 scenarios. Next, Stat-Ease analysed these scenarios and generated a set of diagrams that provided a comprehensive understanding of the impact of each input, such as payload, speed and number of trucks, on carbon emissions factors (Figure 3). Following this evaluation, Stat-Ease optimisation tools were employed to pinpoint two scenarios with the lowest CO_2 emissions (Table 2). One scenario prioritised minimising the overall operation time, while the other disregarded the total time. This approach enables a nuanced exploration of the trade-offs between minimising environmental impact and operational efficiency, offering valuable insights for decision making in pursuing sustainable hauling practices.

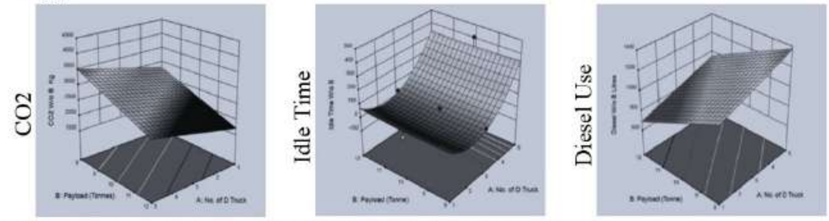

Figure 3: Comparative diagrams generated by Stat-Ease

Table 2: Assessing the Impact of Each Scenario on Carbon Emission

Lowest Carbon Scenarios	No of D	Speed KM/h	Payload Tonnes	No of Trucks	No of Brakes	Total time Mins	Idle Time Mins	CO2 Kg CO2	Fuel Use Liters
With considering total time	82	25	11	4	213	533	0	2346.97	895.79
Without considering total time	75	19	12	1	150	2040	0	2,240.75	855.25

Discussion

In the analysis of models and scenario outcomes, it was observed that increasing speed leads to reduced CO_2 emissions due to decreased total operation time (Figure 2). Additionally, increasing the payload of each truck resulted in reduced CO_2 emissions, attributed to the reduction in the number of deliveries and subsequent decrease in total time. While this study indicated that total time has the most significant impact on CO_2 emissions in most cases, it's essential to note that scenarios with low total time may still have high idle time, leading to increased CO_2 emissions. For instance, a scenario with 5 dumper trucks with 624 minutes total time may seem faster and with a lower carbon than the scenario with 4 dumper trucks with 704 minutes. However, the scenario with 5 dumper trucks demonstrated higher CO_2 emissions due to higher idle time (Figure 2). Therefore, the significance of the idle time of dumper trucks should not be underestimated. Besides, though the number of brakes appears to have a minimal impact on carbon emissions, it's worth saying that an increase in the number of trucks tends to raise the number of brakes, while an increase in payloads reduces the number of brakes. Interestingly, speed changes do not seem to impact the number of brakes significantly.

Conclusion

Incorporating Eco-hauling and the Big Room approach is a promising strategy for achieving net zero in the built environment. This synthesise optimises logistic operations and fosters collaboration among stakeholders, paving the way for the evolution of the built environment towards greater environmental consciousness. Through a case study analysis employing Discrete Event Simulation (DES) and AnyLogic software, it was demonstrated that synthesising these approaches can significantly decrease CO_2 emissions. Furthermore, the study identified optimised scenarios with minimal CO_2 emissions, highlighting the importance of factors such as idle time, total operating time and payload capacity in achieving sustainable hauling practices. Overall, by proposing a cutting-edge strategy, this research contributes to efficiency and reduces carbon emissions in construction projects, encouraging practitioners to transcend conventional boundaries and advance towards an enhanced sustainable future. Future studies could explore these methods' scalability across different construction sectors and locations, which would be helpful for broader applicability.

REFERENCES

Abbasi, S., Katayoon Taghizade., Noorzai, E., & Asce, M. (2020). BIM-Based Combination of Takt Time and Discrete Event Simulation for Implementing Just in Time in Construction Scheduling under Constraints. *Journal of Construction Engineering and Management, 146*(12). https://doi.org/10.1061/(ASCE)CO.1943-7862.0001940

Almujibah, H. (2015). *Sustainable Development of Freight Transport Using a Faster and More Eco-friendly Mode*. https://doi.org/10.2495/CR220181

Arogundade, S., Dulaimi, M., & Ajayi, S. (2021). *The Role of Contractors in Reducing Carbon during Construction-A Preliminary Study*.

Benjaafar, S., Li, Y., & Daskin, M. (2013). Carbon footprint and the management of supply chains: Insights from simple models. *IEEE Transactions on Automation Science and Engineering, 10*(1), 99–116. https://doi.org/10.1109/TASE.2012.2203304

De Groot, R. (2006). Function-analysis and valuation as a tool to assess land use conflicts in planning for sustainable, multi-functional landscapes. *Landscape and Urban Planning, 75*(3–4), 175–186. https://doi.org/10.1016/J.Landurbplan.2005.02.016

Jackson, D., & Ascui, F. (2019). *Achieving infrastructure emission reductions through supply chain collaboration: challenges and opportunities*.

Jassim, H. S. H., Krantz, J., Lu, W., & Olofsson, T. (2020). A model to reduce earthmoving impacts. *Journal of Civil Engineering and Management, 26*(6), 490–512. https://doi.org/10.3846/JCEM.2020.12641

Ji, C., Hong, T., & Park, H. S. (2014). Comparative analysis of decision-making methods for integrating cost and CO 2 emission-focus on building structural design. *Energy and Buildings, 72*, 186–194. https://doi.org/10.1016/j.enbuild.2013.12.045

Jira, C., & Toffel, M. W. (2013). *Engaging Supply Chains in Climate Change*. https://doi.org/10.1287/msom.1120.0420

Kailun Feng. (2020). Environmentally Friendly Construction Process Under Uncertainty: Assessment, Optimisation and Robust Decision-making. *Division of Industrialized and Sustainable Construction Department of Civil, Environmental and Natural Resources Engineering Luleå University of Technology*. www.ltu.se/shb

Krantz, J., Feng, K., Larsson, J., & Olofsson, T. (2019). 'Eco-Hauling' principles to reduce carbon emissions and the costs of earthmoving - A case study. *Journal of Cleaner Production, 208*, 479–489. https://doi.org/10.1016/J.JCLEPRO.2018.10.113

Lee, D. I., Park, J., Shin, M., Lee, J., & Park, S. (2022). Characteristics of Real-World Gaseous Emissions from Construction Machinery. *Energies 2022, Vol. 15, Page 9543, 15*(24), 9543. https://doi.org/10.3390/EN15249543

Lee, K.-H. (2011). *Integrating carbon footprint into supply chain management: the case of Hyundai Motor Company (HMC) in the automobile industry*. https://doi.org/10.1016/j.jclepro.2011.03.010

Li, X. J., & Zheng, Y. dan. (2020). Using LCA to research carbon footprint for precast concrete piles during the building construction stage: A China study. *Journal of Cleaner Production, 245*. https://doi.org/10.1016/J.JCLEPRO.2019.118754

Marrero, M., Puerto, M., Rivero-Camacho, C., Freire-Guerrero, A., & Solís-Guzmán, J. (2017). Assessing the economic impact and ecological footprint of construction and demolition waste during the urbanization of rural land. *Resources, Conservation and Recycling, 117*, 160–174. https://doi.org/10.1016/j.resconrec.2016.10.020

Meggers, F., Leibundgut, H., Kennedy, S., Qin, M., Schlaich, M., Sobek, W., & Shukuya, M. (2012). Reduce CO 2 from buildings with technology to zero emissions. *Sustainable Cities and Society, 2*(1), 29–36. https://doi.org/10.1016/j.scs.2011.10.001

Pacheco-Torres, R., Jadraque, E., Roldán-Fontana, J., & Ordóñez, J. (2014). Analysis of CO2 emissions in the construction phase of single-family detached houses. *Sustainable Cities and Society, 12*, 63–68. https://doi.org/10.1016/j.scs.2014.01.003

Temel, B. A., Başağa, H. B., Temel, M. U., Yılmaz, G. K., & Nasery, M. M. (2019). Big Room concept in project management and control. *Journal of Construction Engineering, Management & Innovation, 2*(4), 204–214. https://doi.org/10.31462/JCEMI.2019.04204214

Vasilca, I. S., Nen, M., Chivu, O., Radu, V., Simion, C. P., & Marinescu, N. (2021). The management of environmental resources in the construction sector: An empirical model. *Energies*, *14*(9). https://doi.org/10.3390/en14092489
WorldGBC. (2019). *Bringing embodied carbon upfront*. www.worldgbc.org/embodied-carbon