

Simulation and Optimization of Carbon Footprint for Construction Earthworks

Hegazy, T. ¹; Abotaleb, I. ¹; Fakher, S. ¹; Ezeldin, A.S. ¹

¹ Dept. of Construction Engineering, The American University in Cairo (AUC), Cairo, Egypt

ABSTRACT: The construction industry's decarbonization has become a critical priority due to its significant contribution to global CO₂ emissions, which exacerbate climate change. Addressing high-emission activities such as earth-moving operations is essential. While numerous studies have sought to analyze and mitigate construction-related emissions, most rely on deterministic methods that lose accuracy as project complexity increases. This study introduces a unique simulation-driven computational approach that combines discrete event simulation and carbon footprint optimization. This combination provides much more accurate calculations and a better grasp of reality, particularly in complex, stochastic construction projects. The proposed model can optimize project outcomes based on CO₂ emissions, cost, or duration, while presenting trade-offs among these objectives. By leveraging advanced simulation software, this approach efficiently processes complex datasets to identify optimal scenarios tailored to specific priorities. The results demonstrate the model's capability to deliver actionable insights, enabling practitioners to select scenarios based on their objectives, whether prioritizing cost, duration, or emissions. This streamlined optimization framework highlights the effectiveness of simulation in addressing project complexities and supporting informed decision-making in construction project management.

Keywords: Decarbonization, Construction Management, Simulation, Earth-moving problems

1. INTRODUCTION

Greenhouse gases (GHGs) are atmospheric gases that trap heat, contributing to global warming and climate change. The primary GHGs include carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O), with CO₂ being the most significant due to its high concentration and long-term impact. GHG emissions have surged in the past decades, prompting global efforts toward net-zero targets through decarbonization. CO₂, the most abundant GHG, significantly contributes to climate change, leading to extreme weather and rising sea levels. The construction industry, a major emitter, accounts for 39% of global GHG emissions, 27% from operations and 17% from embodied carbon. Construction equipment, with high energy consumption, plays a key role in emissions. According to the Environmental Protection Agency (EPA), reducing diesel fuel consumption by 10% could lower industry emissions by 5% (Paneru, et al., 2024). This research contributes to the global effort to reduce greenhouse gas (GHG) emissions in the construction sector by targeting one of its most carbon-intensive components: earth-moving operations. These activities, typically performed during the early construction phase, involve extensive use of heavy machinery, fuel consumption, and inefficient logistics—factors that significantly contribute to up-front embodied carbon emissions. According to the Rocky Mountain Institute (RMI), a leading nonprofit focused on transforming global energy systems, a building's total embodied carbon is distributed across four main phases: 65–85% arises from the Product Phase (material extraction, transport, and manufacturing), 6–10% from the Construction Phase (material delivery and on-site activity), 8–15% from the Use and Maintenance Phase, and 3–15% from the End-of-Life Phase (Rocky Mountain Institute, 2023). Earth-moving falls within the Construction Phase, which, while representing a smaller portion of total emissions compared to material production, presents a crucial opportunity for early intervention. Since construction emissions are released before the building becomes operational, reducing them offers immediate and lasting climate benefits. This study introduces a simulation-driven optimization model that minimizes CO₂ emissions, fuel consumption, and process inefficiencies during earthworks. By enhancing scheduling, equipment allocation, and task sequencing, the model directly

contributes to reducing the project's embodied carbon footprint, supporting global decarbonization goals and offering a practical, scalable solution for sustainable construction practices.. While previous research has used deterministic and stochastic models to estimate emissions (Lim, et al., 2015) (González, et al., 2012) (Paneru, et al., 2024), most focused on deterministic methods due to their simplicity. Some models integrate economic factors, but they remain limited to micro-scale applications rather than project-level optimization. This paper introduces a simulation model using AnyLogic to optimize emissions, cost, and duration in complex construction projects. While previous research has used deterministic and stochastic models to estimate emissions, most focused on deterministic methods due to their simplicity. Some models integrate economic factors, but they remain limited to micro-scale applications rather than project-level optimization. Instead of predefined solutions, the model simulates different parameter variations based on existing project conditions to determine the most effective strategies for reducing emissions. By evaluating multiple scenarios, it identifies the optimal parameters that balance emissions, cost, and duration. Verified through an earthmoving case study, the model provides engineers with data-driven insights to minimize carbon emissions while maintaining project efficiency.

2. RESEARCH BACKGROUND AND GAPS

Carbon emissions estimation in construction has increasingly relied on computational methods, leveraging simulations and advanced analytical tools to process vast amounts of data. However, despite their growing application, existing methodologies exhibit critical limitations. Traditional deterministic models effectively quantify emissions but fail to accommodate the stochastic and dynamic nature of construction operations. Many studies (González, et al., 2012), (Lim, et al., 2015) and (Paneru, et al., 2024) have focused on specific emission contributors, such as construction equipment, while neglecting other major sources like material usage and labor-related emissions even when models incorporate multiple emission sources, they often make simplifying assumptions, such as uniform emissions over time, disregarding variations caused by idle time, equipment status, and operational uncertainties. (González, et al., 2012) explored the use of discrete-event simulation (DES) to estimate the environmental impact of road construction operations. They primarily focused on emissions from construction equipment, such as trucks and front loaders, and their impact on total carbon emissions. While their study demonstrated that optimizing equipment allocation could reduce emissions, it failed to consider idle time emissions. Additionally, their approach was limited to the planning phase and a single road construction case study, reducing its applicability to diverse construction projects. (Lim, et al., 2015) (Paneru, et al., 2024) developed a computational model that estimates carbon emissions in the construction phase using scheduled project data extracted from Primavera P6. Their study applied this method to a highway bridge project, demonstrating the model's effectiveness in calculating both daily and cumulative emissions. However they assumed constant emissions from laborers without accounting for variations in metabolism and work intensity, which could lead to inaccurate estimates. (Ahn, et al., 2010) specifically examined emissions from construction equipment, integrating DES with emissions factors for duty cycles to enhance emissions estimation accuracy. Their research presented a case study measuring emissions from earthmoving operations, highlighting the dominant role of equipment in overall emissions. However, their model is deterministic and does not account for the dynamic, stochastic nature of construction operations, limiting its accuracy in more complex projects. (YI, et al., 2016) introduced the Stochastic Carbon Emission Estimation (SCE2) tool to estimate emissions in microscale construction operations. Their model accounted for stochastic variations in equipment and labor emissions, improving accuracy compared to deterministic approaches. However, the tool was limited to operation-level assessments and did not extend to project-level integration. Additionally, the emissions database used in their modeling was outdated, and their method relied on extrapolated idle-time calculations rather than real measurements. (Paneru, et al., 2024) reviewed the existing carbon emissions modeling approaches in construction, identifying key challenges and opportunities. Their study highlighted the lack of comprehensive models that integrate cost, time, and emissions for large-scale projects. They emphasized the need for a more inclusive methodology capable of handling dynamic and interdependent construction operations. The complexity of construction projects makes it difficult to accurately estimate emissions while balancing cost and time constraints. Current models either focus on specific emission sources or lack a holistic approach to project-level integration. After a comprehensive review of existing literature on carbon emissions estimation in construction, several critical gaps have been summarized in the following points:

- 1- Deterministic Models Dominate, most existing approaches use deterministic models that fail to capture the stochastic and dynamic nature of real construction operations.

- 2- Oversimplified Assumptions Models often assume uniform emissions over time, disregarding variations due to idle time, equipment condition, labor metabolism, and task intensity.
- 3- Lack of Project-Level Integration Several tools operate only at the operation or task level, lacking integration into comprehensive, project-wide models.
- 4- Outdated or Incomplete Emission Data Some models rely on outdated databases or extrapolated values instead of real-time measurements, reducing their accuracy.
- 5- Limited Generalizability Case studies are often restricted to specific phases (e.g., planning) or isolated project types (e.g., road or bridge), limiting their applicability to diverse construction settings.
- 6- No Integration of Cost-Time-Emission Trade-offs There's a notable absence of holistic models that simultaneously optimize carbon emissions, cost, and time, hindering informed decision-making for project managers.

This research aims to bridge these gaps by introducing a simulation-driven optimization model that considers emissions, cost, and time, by incorporating real measurements based on the actual movement and operational state of equipment on site. The model is designed to function with minimal database requirements and includes a user-friendly interface that allows easy updating of each parameter. Additionally, all parameters have been clearly separated by the author to facilitate straightforward customization and future modifications.

3. PROPOSED METHODOLOGY

This research will investigate a case study of an earthmoving cycle within a construction project. The earthmoving process will be simulated using a simulation software to efficiently calculate performance data. Initially, different scenarios will be analyzed in the simulation with baseline parameters provided by the user, focusing on key project objectives duration, cost, and CO₂ emissions. Each scenario will then be optimized to identify the best fleet parameters for each objective. Additionally, a sensitivity analysis will be performed to evaluate the effect of the parameter on the project's objectives. Figure 1, illustrates the steps followed in this research. The methodology of this research begins with an illustrative case study focusing on an earthmoving problem within a construction project. The second step involves building a simulation model for each possible scenario (route), incorporating all relevant parameters such as the number of trucks and loaders, truck size, and loader bucket size. Once the simulation models are constructed, a base case is run using the initial parameter values to evaluate the performance across three key objectives: time, cost, and CO₂ emissions. The final step involves optimizing each objective separately by alternating the decision parameters to determine the best-performing configuration for each route and each objective individually.

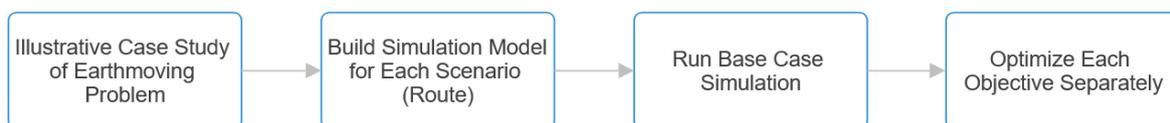


Figure 1 Proposed Methodology Steps followed in Research

3.1 Objective Functions and Decision Parameters

The study evaluates and optimizes an earthmoving cycle based on three independent performance objectives. Each objective is optimized separately to determine the optimal fleet configuration for the specific goal. The following presents the objective functions and decision parameters considered in this research.

3.1.1 Objective Functions

1. Minimize CO₂ Emissions

$$\min CO_2(x)$$

Where CO₂(x) is the total carbon emissions generated during the earthmoving operation under scenario x.

2. Minimize Cost

$$\min Cost(x)$$

Where Cost(x) is the total project cost associated with fleet operation and activity duration.

3. Minimize Duration

$$\min Duration(x)$$

Where Duration(x) refers to the total time required to complete the earthmoving cycle.

3.1.2 Decision Parameters

Each scenario is defined by a unique combination of the following decision parameters:

T_n : Number of trucks

L_n : Number of loaders

T_s : Truck size (m^3 per load)

B_s : Loader bucket size (m^3 per scoop)

These parameters are defined within a feasible range and varied during the optimization process

Table 1

4. CASE STUDY

In this simulated case study, a total of 500,000 cubic meters of soil must be transported from a construction site to a designated dump site. The operation involves two types of equipment—loaders and dump trucks—along with support vehicles. Additionally, three alternative routes are considered to evaluate the most efficient transportation strategy. The objective is to optimize logistics, minimizing total operation time and costs. This scenario is purely hypothetical and designed for analytical and simulation purposes rather than representing a real-world project.

4.1 Equipment:

- Loaders: 3 units (Capacity: 6 cubic meters per load)
- Dump Trucks: 10 units (Capacity: 20 cubic meters per load)

4.2 Route Scenarios:

1. ROUTE A - BRIDGE ROUTE:

- Distance: 5 kilometers.
- Constraints:
 - A single-lane bridge that only allows one truck at a time in each direction.
 - The bridge has a weight limit of 30 tons, which limits the truck load capacity.
 - A toll booth at the end of the bridge charges a fee per crossing.
 - Toll Cost: \$50 per crossing.

2. Route B - Toll Road:

- Distance: 7 kilometers.
- Constraints:
 - A toll road with a fee that varies depending on the time of day:
 - Off-Peak Hours (8:00 PM - 6:00 AM): \$30 per crossing.
 - Peak Hours (6:00 AM - 8:00 PM): \$70 per crossing.
 - Road maintenance scheduled from 12:00 PM to 2:00 PM daily, reducing available lanes to one, causing delays.

3. Route C - Narrow Road:

- Distance: 4 kilometers.
- Constraints:
 - A narrow road that only allows one truck per direction at a time.
 - Steep inclines and sharp turns, which reduce the speed of the trucks by 50%.
 - No toll cost for this route, but potential delays due to the road conditions.

4.3 Operating Constraints:

- **Loading Time:** Each loader takes 5 minutes to fully load one dump truck.
- **Unloading Time:** Each dump truck takes 2 minutes to unload at the dump site.
- **Refueling:** Trucks need to refuel after every 6 trips. Refueling takes 7 minutes.
- **Maintenance:** Each truck requires maintenance after every 10 trips, taking 2 hours per maintenance session.

5. MODEL PARAMETERS

The model parameters, listed in Table 1, will be used to optimize the scenarios. Initially, these parameters are assigned baseline values to construct the model and generate the initial results. Subsequently, the parameters will be adjusted through a Monte Carlo simulation. This simulation will explore a range of possible values for each parameter, based on the user-defined range and increment, systematically testing various combinations to identify the optimal solution.

Table 1: Parameters Ranges Used in the Model

Parameter (Unit)	Initial Value	Min	Max	Step
Trucks Tn (Count)	4	2	20	1
Loaders Ln (Count)	2	2	10	1
Truck Size Ts (M3)	10	4	20	2
Bucket Size Bs (M3)	2	2	6	1

It is essential to incorporate the locations of the site, dump, gas station, maintenance station, and all roads and bridges into the model as GIS points. The complexity of the problem arises from the large number of parameter combinations (7,695 solutions), each evaluated across three distinct route scenarios. For every scenario, the model simultaneously monitors three key objectives—project duration, total cost, and CO₂ emissions—while incorporating spatial data through a GIS-based framework. This multi-dimensional evaluation significantly increases the computational and analytical load, making traditional optimization methods insufficient and highlighting the need for simulation-based approaches to handle the complexity effectively. The trucks will follow the actual routes based on the GIS map. Table 2 provides the GIS points for all stations, including the longitude and latitude of each location.

Table 2: Longitude and Latitude of all Site Locations Used in the Model

Point	Point Coordinates	
	Longitude	Latitude
Site location	31.48827	30.06587
Dump	31.43777	30.08204
Gas Station	31.5212	30.07085
Maintenance Station	31.453	30.03721
Garage	31.5125	30.05132

6. MODEL ANALYSIS

Each scenario of the three route options was modeled in the software. All site points listed in Table 2 were incorporated into the GIS map of the model using their actual coordinates, enabling the trucks to navigate between these points based on the GIS map routes. The carbon emissions of the equipment were calculated by separating them into two components: idle emissions and working emissions. A user-defined factor, LHM (liters burned per horsepower), for both idle and working states, was provided. Additionally, the emission factor for each liter burned was sourced from the GHG Protocol tables. The total project emissions are calculated by summing the following: truck emissions in the idle state, truck emissions in the working state, loader emissions in the idle state, and loader emissions in the working state. The simulation model tracks the earthmoving process and calculates emissions dynamically, accounting for each truck's state within the proposed route scenario. The factors used were 300 horsepower for trucks, 150 horsepower for loaders, 0.0008325 liters burned per horsepower per minute, and an emission factor of 2.7. These factors can be easily adjusted by the user to match the specifications of the equipment used in each project.

6.1 Route A Scenario

In this trial, the Route A scenario was analyzed using the AnyLogic simulation software. The results are presented as follows: first, the base case results, based on the parameters outlined in Table 1, are provided. Next, optimization is carried out targeting three objectives: CO2 emissions, project duration, and project cost. Initially, optimization focuses on a single objective.

6.1.1 Route A Scenario – Base Case Modeling Results

Running the model with the initial parameter values from Table 1 resulted in a total project duration of 3,514 minutes, CO2 emissions of 21,843 kilograms, and a total project cost of \$81,700. The model also provides detailed calculations for these figures. As illustrated in Figure 2, the trucks produced 21,843 kg of CO2, while the loaders emitted 2,959 kg. The associated costs were \$35,400 for the trucks, \$41,300 for the loaders, \$100 for toll entries, and \$5,000 for toll costs.

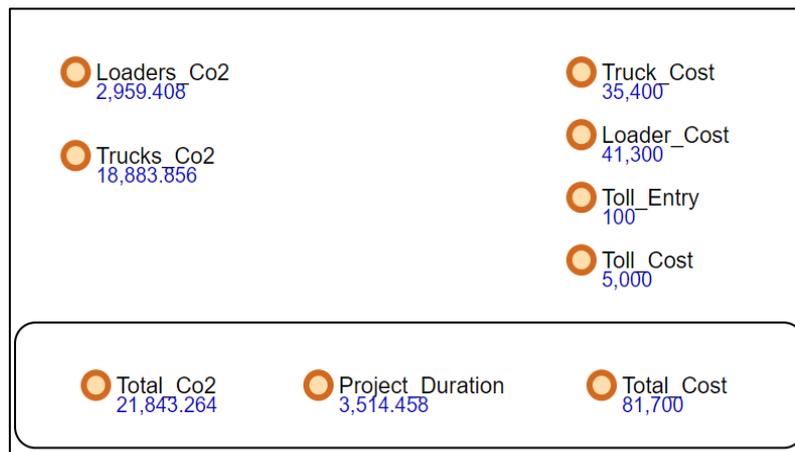


Figure 2 Route A Scenario Base Case Results

6.1.2 Route A Scenario – Optimization Results

Several trials were conducted to optimize the results for the Route A scenario. The optimization process involved using a Monte Carlo simulation to identify the optimal set of parameters that would enhance the desired objectives. The initial parameter values and optimization ranges were those provided in Table 1. The results of the optimization are presented in Table 3. The findings showed substantial improvements in the project's three objectives: duration, cost, and CO2 emissions. Each objective had its own optimal scenario, determined by a unique set of parameters. The model works by adjusting the parameters and testing all potential solutions within the input range specified in Table 1. The table also presents the corresponding values of the other project objectives, namely cost and duration, associated with the set of parameters that optimize the CO2 emissions objective.

Table 3: Route A Scenario Optimization Results in Project Objectives

Objective	Initial Parameter Value	Base Case Results	Optimization Parameter Value	Optimization Result		
				CO2 Emissions	Project Cost	Project Duration
Project CO2 Emissions	#Trucks (count)	4	#Trucks (count)	10,143 kilograms	28,900\$	1,413 Minutes
	#Loaders (count)	2	#Loaders (count)			
	Truck Size (m3)	10	Truck Size (m3)			

Bucket Size (m3)	2	Bucket Size (m3)	4		
------------------	---	------------------	---	--	--

Multiple trials were conducted to optimize the results for the Route A scenario. The optimization process involved a Monte Carlo simulation to determine the optimal set of parameters that enhance the targeted objective. The initial parameter values and optimization ranges were specified in Table 1. Findings revealed significant improvements across the project's first objective: CO2 emissions. Each objective had an optimal scenario corresponding to a distinct set of parameters. Figure 2 illustrates the various parameter trials, depicting the CO2 objective results for each trial until the model achieved the best possible outcome. The horizontal axis in Figure 3 represents the iteration number, while the vertical axis corresponds to the objective value. It is evident that the model effectively leverages optimization algorithms—namely Genetic Algorithm and OptQuest—to minimize the objective value. Results demonstrated the effectiveness of the optimization process in improving project performance across multiple objectives. CO2 emissions were significantly reduced from 21,843 kilograms in the base case to 10,143 kilograms as shown Figure 3, showcasing the model's capability to enhance environmental sustainability. Additionally, the optimized parameters achieved a project cost of \$28,900 and a reduced duration of 1,413 minutes. The process was repeated, this time focusing on the other project objectives: cost and duration, results highlighted significant improvements in the project's three objectives: duration, cost, and CO2 emissions, achieved through separate optimization processes for each.

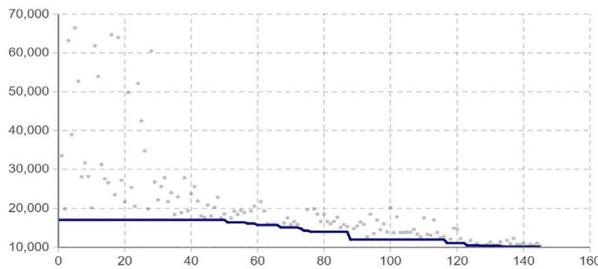


Figure 3: CO2 Emissions Optimization Results

Each objective was optimized using a distinct set of parameters, as the model systematically adjusted and tested possible solutions within the input range provided in Table 1. Table 4 presents the results of these local optimizations, detailing the parameter combinations—the number of trucks, loaders, truck size, and bucket size—that optimize each objective individually. Notably, optimizing one objective, like minimizing CO2 emissions (5 trucks, 1 loader, a truck size of 20, and a bucket size of 4), often negatively impacts the other two objectives. This trade-off underscores the need for a three-objective optimization to balance emissions, cost, and duration for the best overall outcome. These findings demonstrate the model's value in enhancing the efficiency and sustainability of construction projects by systematically identifying optimal solutions tailored to specific project goals.

Table 4: Route A Scenario - Project Objectives Optimization Results

Objective	Initial Parameter Value	Base Case Results	Optimization Parameter Value	Optimization Result			
				CO2 Emissions	Project Cost	Project Duration	
Project Duration	#Trucks (count)	4	#Trucks (count)	16,837 kilograms	49,300\$	756 minutes	
	#Loaders (count)	2	#Loaders (count)				3
	Truck Size (m3)	10	Truck Size (m3)				20
	Bucket Size (m3)	2	Bucket Size (m3)				3
		3,514 minutes					

Project Cost	#Trucks (count)	4	81,700\$	#Trucks (count)	5	10,143 kilograms	28,900\$	1,413 minutes
	#Loaders (count)	2		#Loaders (count)	1			
	Truck Size (m3)	10		Truck Size (m3)	20			
	Bucket Size (m3)	2		Bucket Size (m3)	4			

6.2 Route B Scenario

The procedure applied in Scenario A is repeated here to determine the optimal solution for each of the three project objectives individually. Route B, a 7-kilometer toll road, has variable fees based on the time of day: \$30 per crossing during off-peak hours (8:00 PM - 6:00 AM) and \$70 during peak hours (6:00 AM - 8:00 PM). Daily maintenance is conducted from 12:00 PM to 2:00 PM, reducing the road to a single lane and potentially causing delays. The extracted model results are summarized in Table 5.

Table 5: Route B Scenario - Project Objectives Optimization Results

Objective	Initial Parameter Value	Base Case Results	Optimization Parameter Value	Optimization Result			
				CO2 Emissions	Project Cost	Project Duration	
Project CO2 Emissions	#Trucks (count)	4	#Trucks (count)	11,589 kilograms	36,300\$	939 minutes	
	#Loaders (count)	2	#Loaders (count)				2
	Truck Size (m3)	10	Truck Size (m3)				20
	Bucket Size (m3)	2	Bucket Size (m3)				3
Project Duration	#Trucks (count)	4	#Trucks (count)	12,718 kilograms	43,000\$	555 minutes	
	#Loaders (count)	2	#Loaders (count)				4
	Truck Size (m3)	10	Truck Size (m3)				20
	Bucket Size (m3)	2	Bucket Size (m3)				4
Project Cost	#Trucks (count)	4	#Trucks (count)	11,589 kilograms	36,300\$	939 minutes	
	#Loaders (count)	2	#Loaders (count)				2
	Truck Size (m3)	10	Truck Size (m3)				20
	Bucket Size (m3)	2	Bucket Size (m3)				3

The results of optimizing each project objective—CO2 emissions, project duration, and project cost—highlight significant improvements compared to the base case. CO2 emissions were reduced by 47.4%, from 22,420 kilograms to 11,589 kilograms, by increasing the number of trucks to 9, and utilizing larger truck and bucket sizes (20 m³ and 3 m³). Project duration was minimized by 84.6%, from 3,601 minutes to 555 minutes, through the use of 17 trucks, 4 loaders, and larger truck and bucket sizes (20 m³ and 4 m³), but this led to higher CO2 emissions (12,718 kilograms) and cost (\$43,000). Cost optimization reduced the project cost by 57.9%, from \$86,300 to \$36,300, with 9 trucks, 2 loaders, and slightly larger

truck and bucket sizes (20 m³ and 3 m³), though duration increased to 939 minutes, and CO2 emissions slightly decreased to 11,589 kilograms. These results underscore the trade-offs between the three objectives, showing that optimizing one often impacts the others, highlighting the need for a balanced, multi-objective optimization approach to achieve a globally optimal solution.

6.3 Route C Scenario

The procedure used in Scenario A and B is replicated in this scenario to determine the optimal solution for each of the three projects individually. Route C is a 4-kilometer narrow road that accommodates only one truck per direction at a time, featuring steep inclines and sharp turns that reduce truck speeds by 50%. While there is no toll fee, the road conditions may cause delays. Operationally, loading takes 5 minutes and unloading takes 2 minutes per truck, with refueling needed every 6 trips, taking 7 minutes. Moreover, each truck requires maintenance after 10 trips, which lasts for 2 hours. The results from the model are presented in Table 6.

Table 6: Route C Scenario - Project Objectives Optimization Results

Objective	Initial Parameter Value	Base Case Results	Optimization Parameter Value	Optimization Result			
				CO2 Emissions	Project Cost	Project Duration	
Project CO2 Emissions	#Trucks (count)	4	#Trucks (count)	10,966 kilograms	28,600\$	1,531 minutes	
	#Loaders (count)	2	#Loaders (count)				1
	Truck Size (m3)	10	Truck Size (m3)				20
	Bucket Size (m3)	2	Bucket Size (m3)				3
Project Duration	#Trucks (count)	4	#Trucks (count)	23,158 kilograms	65,700\$	1,076 minutes	
	#Loaders (count)	2	#Loaders (count)				4
	Truck Size (m3)	10	Truck Size (m3)				20
	Bucket Size (m3)	2	Bucket Size (m3)				4
Project Cost	#Trucks (count)	4	#Trucks (count)	10,966 kilograms	28,600\$	1,531 minutes	
	#Loaders (count)	2	#Loaders (count)				1
	Truck Size (m3)	10	Truck Size (m3)				20
	Bucket Size (m3)	2	Bucket Size (m3)				3

The optimization results show a significant improvement in CO2 emissions, project duration, and cost. CO2 emissions are reduced by 53%, from 23,375 kg in the base case to 10,966 kg in the optimized scenario, primarily due to the addition of a truck and adjustments to other parameters like truck and bucket size. Project duration is drastically shortened from 3,709 minutes to 1,076 minutes, indicating that the optimized equipment configuration (more trucks, larger sizes) leads to greater efficiency in completing tasks. Additionally, the project cost drops from \$80,600 to \$28,600, likely due to better equipment utilization and fewer trucks and loaders needed. Overall, optimization enhances sustainability by reducing emissions, accelerating project completion, and lowers costs, demonstrating the effectiveness of the adjusted parameters.

It's notable in all scenarios that the scenario that provides the lowest project cost also results in the lowest CO2 emissions, which suggests that the optimization has successfully aligned cost efficiency

with environmental sustainability. By reducing the number of trucks and optimizing the equipment configuration (such as increasing truck and bucket sizes), the project not only cuts costs but also minimizes fuel consumption and operational inefficiencies, leading to fewer emissions. This outcome highlights the potential for achieving both financial and environmental benefits simultaneously, proving that sustainability can be integrated into cost-saving strategies, rather than being seen as a trade-off.

7. SENSITIVITY ANALYSIS

The optimization results consistently show a preference for larger truck sizes (20 m³) in all scenarios. To better understand how this parameter influences project outcomes, a sensitivity analysis will be performed for Route C as a case study. This analysis will explore how variations in truck size impact the three main project objectives. Conducting a sensitivity analysis is crucial as it offers valuable insights into how changes in key parameters affect project performance. By understanding these impacts, project planners can make more informed decisions, optimize resource allocation, and identify which parameters significantly influence costs, duration, or environmental impact. Sensitivity analysis is particularly useful in optimization processes, ensuring that the chosen parameters deliver reliable and robust results under various conditions. The truck size sensitivity analysis reveals clear trends across all three project objectives—CO₂ emissions, total cost, and project duration—as truck size increases.

1. **Total CO₂ Emissions:** There is a noticeable reduction in CO₂ emissions as truck size increases. Initially, emissions drop sharply, but the rate of reduction slows down as truck size reaches 20 m³. This indicates that larger trucks reduce the number of trips required, leading to lower emissions due to fewer operations as shown in Figure 4.
2. **Total Cost:** Total project cost also decreases significantly with larger truck sizes. The most substantial cost savings occur when transitioning from smaller trucks to moderately larger ones. As truck size increases further, the rate of cost reduction slows, suggesting diminishing returns in savings beyond a certain truck capacity.
3. **Total Project Duration:** Project duration consistently decreases with larger truck sizes, although the reduction levels off as truck size approaches 20 m³. This decline in duration is likely due to fewer loading and unloading cycles, which speeds up task completion.

Overall, the results emphasize that increasing truck size can reduce CO₂ emissions, costs, and project duration, with the greatest impact occurring when moving from smaller to moderately larger trucks. However, beyond a certain point, the benefits plateau, suggesting that excessively large trucks may not provide proportionally greater advantages. This insight is valuable for making cost-effective and environmentally sustainable decisions in project planning.

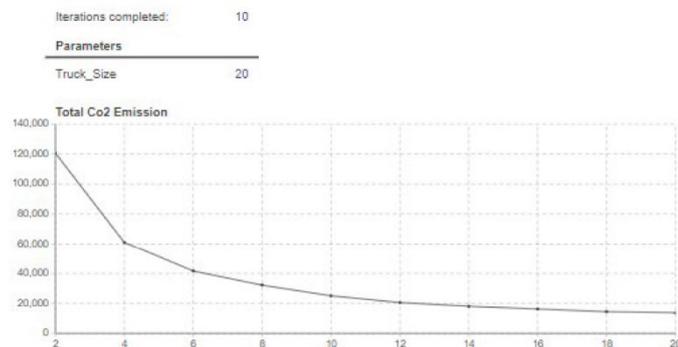


Figure 4: CO₂ Emissions vs Truck Size Sensitivity Analysis

8. CONCLUSION

This study presents a comprehensive approach to optimizing a project with three objectives: project duration, total cost, and CO₂ emissions. By utilizing simulation software, the study systematically adjusted variable parameters and observed how the model responded to these changes across various scenarios. The use of simulation was essential in navigating the complexity of optimization, as it not only enabled dynamic adjustments but also provided a clear visualization of the trade-offs between the objectives. In the first phase of the study, the focus was on performing local optimization for each route scenario. This method aims to optimize one objective at a time—project duration, total cost, or CO₂ emissions—resulting in clear improvements in the targeted objective but with significant trade-offs for the others. For instance, when minimizing project duration, local optimization achieved the fastest completion time but led to higher project costs and increased CO₂ emissions. Similarly, minimizing total cost successfully reduced expenses but resulted in longer project duration. These results highlighted the challenge of local optimization, where improving one objective often negatively impacted the others, illustrating the inherent trade-offs in multi-objective optimization. The study proves valuable in the decision-making process for construction projects. Simulating such intricate projects, like the one

presented in this case study, involves challenging procedures to analyze, monitor, and calculate project parameters, especially when dealing with hypothetical project data. This research provides an effective technique to address these challenges. Additionally, it not only calculates project parameters and objectives but also optimizes them, offering a comprehensive solution.

9. REFERENCES

Ahn, C., Lee, S., Peña-Mora, F., and Abourizk, S. 2010. Enhanced estimation of air emissions from construction operations based on discrete-event simulation. Proceedings of the International Conference on Computing in Civil and Building Engineering, Nottingham, U.K., December 2010.

AnyLogic. n.d. Optimization experiment. AnyLogic Help, AnyLogic. <https://anylogic.help/anylogic/experiments/optimization.html>.

González, V. and Echaveguren, T. 2012. Exploring the environmental modeling of road construction operations using discrete-event simulation. *Automation in Construction*, 24: 100–110.

Lim, T.-K., Lee, J.-H., Lee, S., and Lee, D.-E. 2015. Integrated carbon emission estimation method for construction operation and project scheduling. *KSCE Journal of Civil Engineering*, 20(4): 1211–1220.

Paneru, S., Zhang, L., and Yu, W. 2024. A review of carbon emissions modeling in construction: Challenges and opportunities. *Sustainable Construction and Engineering*, 12(1): 45–62.

Paneru, S., Zhang, L., Yu, W., and Li, H. 2024. Evaluating the decarbonization potential of industrialized construction: A review of the current state, opportunities, and challenges. *Journal of Construction Engineering and Management*, 150(9).

Rocky Mountain Institute. 2023. Embodied carbon 101: Building materials. RMI. <https://rmi.org/embodied-carbon-101/>.

Yi, C.-Y., Gwak, H.-S., and Lee, D.-E. 2016. Stochastic carbon emission estimation method for construction operation. *Journal of Construction Engineering and Management*, 23(1): 137–149.