Joint CSCE Construction Specialty & CRC Conference 2025
*Conférence conjointe spécialisée en construction de la SCGC et CRC-2025*

Montreal, Quebec
July 28-31, 2025 / *28-31 juillet 2025*

# Simulation-Based Multi-Objective Optimization for the Decarbonization of Bored Piles

Hegazy, Tayseir[1], Arab, Berlant[1], Essawy, Yasmeen A.S.[1]

[1] Dept. of Construction Engineering, The American University in Cairo, Cairo, Egypt

**ABSTRACT:** Decarbonization in the construction industry is crucial for mitigating its environmental impact. Piling, a key activity in many construction projects, is a significant contributor to carbon emissions, highlighting the need for sustainable practices. This research focuses on optimizing the sustainability of bored piling systems by simulating different construction scenarios. The study investigates the impact of various parameters, including the number of augers, concrete mixers, pumps, and other operational variables, on carbon emissions, cost, and time. Using simulation software, the model identifies optimal configurations that reduce CO2 emissions while maintaining project efficiency and cost-effectiveness. The incorporation of a user-defined importance factor further refines the analysis, enabling tailored solutions that align with specific project priorities. The findings provide actionable insights to promote environmentally responsible piling practices and support the broader goal of sustainable construction. By leveraging advanced simulation capabilities, this study demonstrates the potential for data-driven approaches to achieve meaningful decarbonization in construction.

## 1. INTRODUCTION

To combat climate change, many countries, including the U.S., aim to reduce greenhouse gas (GHG) emissions by 43% by 2030 and achieve net zero by 2050 (The Sustainable Development Goals Report 2023). Net zero refers to balancing emitted and removed emissions, extending beyond the energy sector to areas like waste, water use, and carbon emissions (Joustra & Yeh 2015). Achieving this requires rapid decarbonization through zero-carbon energy sources (wind, solar, hydropower) and carbon removal methods like reforestation and carbon capture (Cho R. 2022). The buildings and construction sector accounts for 37% of global GHG emissions, with operational emissions making up 27% of energy-related $CO_2$ emissions (UNEP 2023). Cement production alone contributes around 5% of global $CO_2$ emissions (Ma et al. 2016). Construction also impacts air, water, soil, and noise pollution due to demolition, land clearing, and equipment operations. Addressing these challenges requires sustainable practices and pollution prevention strategies. While achieving net zero by 2050 is technically feasible, it demands significant investments, an estimated $275 trillion between 2021 and 2050, primarily in power, transport, and buildings (Krishnan et al. 2022). Given this financial challenge, the construction sector must adopt cost-effective solutions to minimize emissions while maintaining economic feasibility. Piling is essential in construction, providing stability where soil cannot support loads. Among various methods, bored piling is widely used due to its strong load-bearing capacity and minimal settlement. Bored piles are drilled, filled with concrete, and often reinforced with steel cages (Fleming et al. 2008). The two common techniques are Continuous Flight Auger (CFA) and Rotary Bored Piling. CFA piling is cost-effective and efficient, reaching depths of 25m. It avoids open pile bores but is unsuitable for very soft soils. A hollow-stemmed auger drills while concrete is pumped in during extraction. However, risks like "over-flighting", excessive soil removal or insufficient concrete, can cause instability. These issues depend on factors such as rig settings, auger specifications, and concreting control. High-risk conditions may require cased CFA techniques (Federation of Piling Specialists 2014). Rotary bored piling is more versatile, working in soft soil and rock at depths of 60m with diameters up to 1.8m. It produces fewer vibrations but generates more spoil and requires additional labor. Using a hydraulic piling rig and Kelly bar, the bore is drilled, cleaned, and filled with concrete via tremie methods before casing extraction (Toprak et al. 2018; Fleming et al. 2008). Steel cages are installed using separate cranes or integrated piling machines for confined spaces (Zayed 2005). This research focuses on optimizing the sustainability of bored piling by evaluating scenarios that impact carbon emissions, cost, and duration. Through advanced simulations, it assesses variables like augers, concrete mixers, and pumps to identify optimal configurations. The goal is to enhance sustainable construction practices, reduce costs, and contribute to global decarbonization efforts.

## 2. KEY STUDIES AND RESRARCH GAP

Effective cost management is crucial for construction projects. A multiple linear regression model was developed to optimize pile construction costs, using data from 32 PVC-reinforced concrete piles in Bonny, Nigeria. Each 300 mm diameter, 5.4 m long pile was installed in silty sand using a boring method. Measurements included soil excavation, reinforcement weight, and concrete volume, forming the basis for cost calculations. The model, tested in SPSS, achieved high accuracy ($R^2 = 0.833$), identifying excavation volume, concrete usage, and reinforcement weight as key cost factors. Named "Oba’s optimization equation," the model provides a reliable tool for cost estimation, though further research should include additional variables (Oba, 2023). A separate study optimized pile group design for bridge foundations using a real genetic algorithm (RGA) to minimize total construction costs. RGA reduced computational time by a factor of 1,000 compared to exhaustive search methods, achieving near-optimal solutions within 48–61 minutes. Seven case studies validated the method, showing cost savings of 16–56%. Design variables included pile length, diameter, spacing, and cap thickness, while constraints considered land use, spacing limits, and bearing capacity (Hwang et al., 2011). While superstructure carbon emissions have been widely studied, substructure emissions remain underexplored. A recent study developed an optimization algorithm to reduce the environmental impact of bored and driven piles by adjusting concrete grade, steel-to-concrete ratio, and slenderness ratio. Applied to a monorail bridge in Egypt, the model reduced embodied carbon by 72.4%. The findings highlight the importance of integrating material selection and design parameters to lower environmental impact (Abushama et al., 2025). Despite progress in optimizing cost, time, and embodied carbon for bored piles, existing studies typically address these factors separately. This research introduces a multi-objective optimization approach that balances economic efficiency, timely execution, and sustainability. By integrating cost, time, and carbon footprint into a single framework, it offers a comprehensive solution for sustainable construction.

## 3. PROPOSED METHODOLGY

The proposed model framework begins with selecting an illustrative case study. The case study parameters and constraints are then identified for the base case calculations. The baseline objectives, including project duration, cost, and $CO_2$ emissions, are calculated using two different piling techniques: the Continuous Flight Auger (CFA) method and the Rotary Bucket method.

An optimization process is then conducted for each scenario by varying project parameters such as the number of equipment used and the pile selection sequence for each technique. This optimization is carried out in two stages:

1. **Stage 1: Local Optimization** –Each project objective (duration, cost, and $CO_2$ emissions) is optimized separately to identify the best set of parameters to produce the best possible outcome for each individual factor.
2. **Stage 2: Global Optimization** – A multi-objective optimization is performed, considering a user-defined importance factor. This factor assigns weights to each objective based on user preferences, ensuring a balanced trade-off among project duration, cost, and environmental impact.

### 3.1 Case Study

The case study consists of 61 piles of varying diameters and lengths as shown in Figure 1. Each pile undergoes a series of activities based on the selected piling technique. Depending on the simulated technique scenario, specific equipment is allocated accordingly.

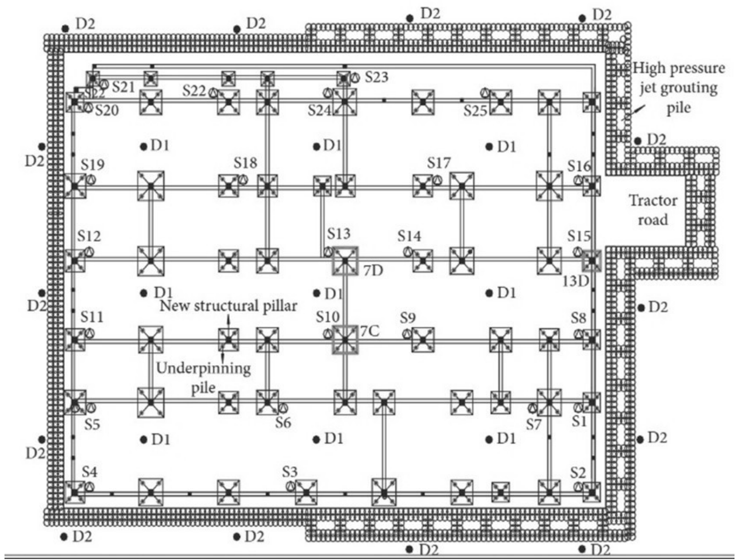


*Figure 1: Foundation Layout of the Case Study*

### 3.2 Scenario 1 – CFA Piles

The CFA piling method carries the risk of soil collapse (Over-Flighting), incorporated as a user-defined probability based on soil conditions, equipment, and labor quality (Fleming et al. 2008). Two execution options are considered: (1) a CFA machine handles drilling and concrete pouring, while a crane or excavator manages rebar cage activities, representing typical practice; (2) the CFA machine completes the entire process due to site constraints. Two sub-scenarios exist: (1) smooth execution or (2) Over-Flighting, requiring redrilling after hole cleaning, with outcomes controlled by a probability factor.

### 3.3 Scenario 2 – Rotary Bored Piles

Examines the Rotary piling method, which operates without the risk of Over-Flighting. Similar to Scenario 1, two execution options are evaluated. The first option assigns drilling and concrete pouring to the Rotary piling machine while a separate crane or excavator handles the steel cage placement. The second option requires the Rotary piling machine to complete all tasks, including rebar cage installation, in cases where additional equipment is unavailable, or site conditions limit the presence of extra machinery. Unlike scenario 1, this scenario does not include any sub-scenarios involving potential delays.

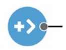
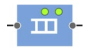
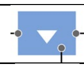
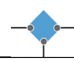
## 4. MODEL DEVELOPMENT

In modern project management, the use of software tools has become essential for efficiently managing complex tasks, optimizing resources, and ensuring timely project completion. The right tools not only streamline the planning and scheduling processes but also provide valuable insights into project performance through data analysis and visualization. For repetitive projects, where consistent coordination across multiple activities and units is crucial, specialized software tools enhance accuracy and flexibility. They allow for better decision-making, faster adjustments, and comprehensive tracking of project progress. In this research, the integration of advanced software tools plays a pivotal role in analysing, modelling, and optimizing the scheduling of repetitive construction projects.

### 4.1 Model Software

AnyLogic is a versatile simulation software that supports multi-method modeling, including agent-based, discrete-event, and system dynamics approaches. It is widely used for project optimization, enabling users to test scenarios, identify bottlenecks, and optimize strategies. AnyLogic was chosen for this study due to its ability to integrate multiple modeling paradigms, essential for capturing complex interactions in optimizing the decarbonization of bored piles. Its user-friendly interface and extensive library of pre-built components facilitated efficient model development. Table 1, summarizes the key blocks and elements used in this study's simulation model.

*Table 1: Description of Key AnyLogic Blocks Used in the Study*

| Block | Icon | Description |
|---|---|---|
| Source |  | Generated entities (e.g., customers, products) that entered the simulation model. |
| Queue |  | Held entities waiting for processing or resources. |
| Delay |  | Simulated a time delay for entities (e.g., processing or waiting time). |
| Service |  | Represented a process where entities were served or processed. |
| Seize |  | Allocated resources to entities (e.g., machines, staff). |
| Release |  | Freed resources after they were no longer needed by entities. |
| Select Output |  | Routed entities to different paths based on conditions (e.g., probability). |
| Resource Task End |  | Marked the end of a task for a resource, freeing it for the next task. |
| Parameter |  | Defined fixed inputs or settings for the model (remained constant during runtime). |
| Variable |  | Stored data or values that changed during the simulation. |
| Event |  | Triggered actions at specific times or under certain conditions. |

### 4.2 Model Activities

The CFA piling method involves a series of well-defined activities. First, the continuous flight auger is drilled into the ground to the required depth from 8 meters to 12.19 meters. During this process, the auger's helical flights transport the excavated soil to the surface, minimizing soil displacement. Once the target depth is reached, high-strength concrete is pumped through the hollow stem of the auger as it is gradually withdrawn. This ensures the formation of a stable and continuous pile. Reinforcement is then inserted into the freshly poured concrete to achieve the desired structural integrity. Table 2. Shows all the necessary activities for CFA application. It is important to note that the durations of all activities are stochastic, varying depending on site conditions, equipment performance, and other factors. The durations are function of L, where L is the pile length (Zayed 2005; Abu Kassim and Adnan, 2005).

*Table 2: CFA Activities (Zayed 2005)*

| **Activity Name** | **Duration (min)** |
|---|---|
| Machine Setup & Axis Adjustment | Normal (0.04L,0.2L) |
| Drilling the Pile Hole | Normal (0.45L,1.35L) |
| Concrete or Grout Injection & Auger Withdrawal | 0.75 L |
| Cleaning the Auger | 0.155 L |
| Reinforcement Cage Placement | Triangular (0.7L,2.8L,1.1L) |

The cycle time for constructing a 12.19-meter, 0.36-meter CFA pile depends on the approach: using a separate crane for reinforcement shortens the cycle, while a single rig handling all tasks extends it. If over-flighting occurs, work halts until the pile is cleaned and redrilled. Rotary bored piling involves rig positioning, drilling, soil removal, stabilization, borehole inspection, reinforcement placement, and concrete pouring via tremie pipe. Efficiency varies: Option 1 uses a separate crane for reinforcement, while Option 2 relies on the rig for all tasks, increasing cycle time. Table 3 summarizes key activities with probabilistic time ranges.

*Table 3: Rotary Bored Piling Activities (Abu Kassim and Adnan, 2005)*

| Activity Name | Duration (min) |
|---|---|
| Machine Setup & Axis Adjustment | Normal (0.04L,0.2L) |
| Drilling the Pile Hole | Normal (0.4L,1.55L) |
| Steel Cage Installation | Triangular (0.6L,2.3L,1.2L) |
| Concrete Pouring | 0.62L |
| Clean the drilling rig and equipment after use | 0.155L |

## 4.3 Model Parameters

The accuracy and reliability of the optimization model depend on selecting appropriate input parameters. These parameters define the constraints, decision variables, and performance metrics that influence project outcomes.

### 4.3.1 Initial Parameters Setup

The scenarios will be optimized using the model parameters detailed in Table 4, To begin, these parameters are set to baseline values to develop the model and produce the initial outcomes. Following this, a Monte Carlo simulation will be employed to modify the parameters. This simulation will investigate a variety of potential values for each parameter, guided by user-defined ranges and increments, and will systematically evaluate different combinations to determine the most effective solution.

*Table 4: Initial Equipment Parameters in AnyLogic*

| Parameter (Unit) | Initial Value | Min | Max | Step |
|---|---|---|---|---|
| No. Augers (Count) | 3 | 1 | 10 | 1 |
| No. Cranes (Count) | 3 | 1 | 10 | 1 |

### 4.3.2 Parameters Related to Over-Flighting Phenomena

The over-flighting phenomenon in construction, especially during piling operations, is influenced by several critical factors. These factors impact the stability and efficiency of concrete flow, as well as the structural integrity of the piles. As discussed, over-flighting is affected by numerous elements, including auger withdrawal speed, concrete flow rate & pressure, soil type, concrete mix design, groundwater level, auger type & diameter, rig Power & sensors, operator skill level. Accordingly, these key factors will be integrated as parameters within the model to precisely simulate and analyze the over-flighting phenomena, The selected parameters influencing the probability of overflighting after drilling are: Type of Soil, Labor Experience, Equipment Conditions, and Pile Size.

- Type of Soil: Represents the degree of soil looseness and its impact on drilling stability.
- Equipment Conditions: Encompasses key operational factors such as rotation speed, withdrawal speed, and blade pitch, which affect drilling efficiency.
- Pile Size: Defines both the length and diameter of the pile, influencing structural integrity and drilling behavior.

Each parameter will be assigned a value between **0 and 1** by the user, reflecting its relative impact. The sum of these values will determine the overall probability, which will be fed into the selection output block to assess the likelihood of overflighting occurring post-drilling.

### 4.4 Model Implementation

The model follows sequential logic for processing activities. The **Source** block generates agents (piles), each assigned specific location coordinates to ensure accurate placement on the model map. These coordinates facilitate equipment movement between piles. Additionally, each pile carries its respective length parameter, which is used to calculate activity durations. Once generated, the piles are stored in a queue before progressing to the first activity, provided the required equipment is available. Equipment is managed within a **resource pool**, with a user-defined capacity for each type. In Figure 2, a **select output** block follows the drilling process, simulating the probability of over-flighting. If over-flighting occurs, the pile collapses, requiring the drilling process to be redone after cleaning the hole.

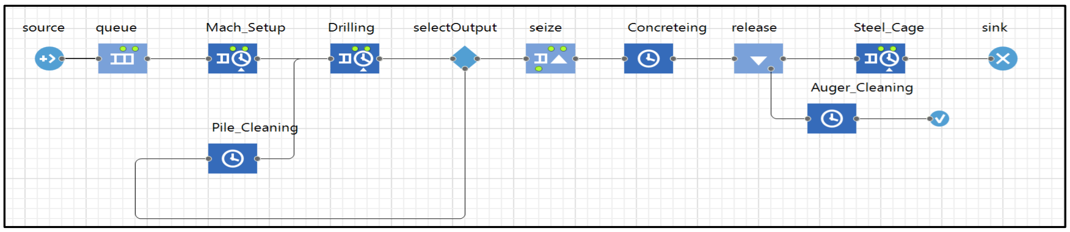


*Figure 2: Activities Representation of CFA technique*

In Figure 3, no over-flighting probability is considered, meaning there is no **select output** block. As a result, the agent (pile) moves directly to the next activity without any potential delays.

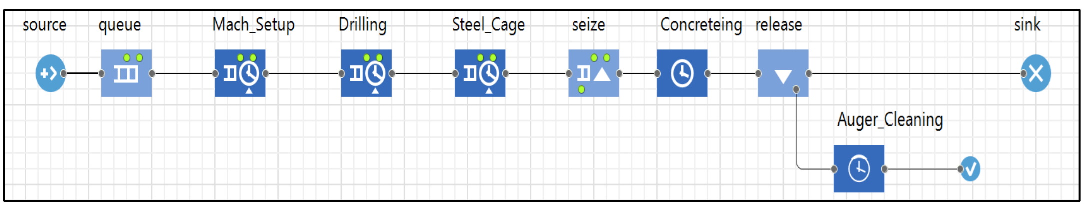


*Figure 3 Activities Representation of Rotary Bucket technique*

Regarding objective calculations, specific parameters and variables within the model determine the outcomes.

- **Project Duration**: Calculated as the time from when the first agent (pile) is injected until the last pile completes its final activity.
- **Project Cost**: Determined by tracking the number of active equipment at any given moment and multiplying it by their respective hourly costs. This approach is particularly useful when equipment is shared across different sites, allowing the model to differentiate between actual working hours on-site and idle time.
- **$CO_2$ Emissions**: First, the model identifies the horsepower of each piece of equipment. A user-defined parameter specifies the amount of fuel burned per horsepower per hour, providing the total fuel consumption per hour. Another parameter defines the amount of $CO_2$ emitted per liter of fuel for each equipment type, ultimately calculating the total $CO_2$ emissions.

## 5. CALCULATIONS AND RESULTS

Both scenarios were modeled using actual pile coordinates, enabling equipment to navigate predefined routes. Carbon emissions were divided into idle and working states, with LHM (liters burned per horsepower) defined for both. Emission factors were sourced from the GHG Protocol Mobile Combustion-Fuel Use Table which provides standardized emission factors for non-road mobile sources such as diesel-powered construction equipment, including augers and cranes (GHG Protocol, 2024). Total emissions were calculated for Augers and Cranes in both states. The model dynamically tracks piling and updates emissions, using default values of 300 HP for Augers, 150 HP for Cranes, 0.0008325 L/HP/min, and an emission factor of 2.7 kg $CO_2e$/L, all adjustable to project-specific equipment.

### 5.1 Scenario 1 – Results

In this trial, Scenario 1 for CFA piles was analyzed using AnyLogic simulation software to evaluate performance under real-world conditions. The results are presented sequentially, starting with the base case outcomes derived from the parameters in Table 4. Next, an optimization process is conducted, targeting three critical objectives: $CO_2$ emissions, project duration, and cost. The optimization begins by refining each objective individually before integrating trade-offs to achieve a well-balanced solution. This approach ensures a comprehensive assessment of efficiency, sustainability, and cost-effectiveness. A summary of the optimized results is provided in Table 5.

*Table 5: Base Case Results and Optimization Results for Scenario 1*

| **Objective** | **Initial Parameter Value** | | ***Base Case Results*** | **Optimization Parameter Value** | | **Optimization Result** | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | **CO2 Emissions** | **Project Cost** | **Project Duration** |
| Project CO2 Emissions | #Augers (count) | 3 | 37,825 kilograms | #Augers (count) | 1 | **31,775 kilograms** | 33,312$ | 3,989 minutes |
| | #Cranes (count) | 3 | | #Cranes (count) | 5 | | | |
| | OverFlight (%) | 50 | | OverFlight (%) | 50 | | | |
| Project Duration | #Trucks (count) | 3 | 1,659 minutes | #Augers (count) | 10 | 59,599 kilograms | 62,275$ | **972 minutes** |
| | #Loaders (count) | 3 | | #Cranes (count) | 6 | | | |
| | OverFlight (%) | 50 | | OverFlight (%) | 50 | | | |
| Project Cost | #Trucks (count) | 3 | 39,600$ | #Augers (count) | 1 | 31,775 kilograms | **33,312$** | 3,989 minutes |
| | #Loaders (count) | 3 | | #Cranes (count) | 5 | | | |
| | OverFlight (%) | 50 | | OverFlight (%) | 50 | | | |

After developing an optimization model for each individual project objective (local optimization), a global weighted optimization process was implemented. This approach allows users to prioritize project duration, cost, and $CO_2$ emissions based on specific project needs. Three global weighted scenarios were evaluated, as outlined in Table 6, each reflecting a different priority distribution among the three objectives.

- Global Weighted Scenario 1 prioritizes shorter project duration (70% weight), resulting in higher $CO_2$ emissions (35,086 kg) and cost ($36,754), but achieving the shortest duration (1,180 minutes) through the use of additional augers and cranes.
- Global Weighted Scenario 2 shifts focus to cost efficiency (75% weight), reducing total cost to $31,587 and $CO_2$ emissions to 30,131 kg, though extending project duration to 1,925 minutes.
- Global Weighted Scenario 3 prioritizes emissions reduction (75% weight), resulting in the same cost and emissions as Scenario 2, with no further improvement in duration.

These scenarios highlight trade-offs: minimizing duration increases cost and emissions, while prioritizing cost or emissions extends project timelines. Notably, Scenarios 2 and 3 yield similar outcomes, suggesting that prioritizing emissions under the given constraints does not reduce duration further than cost optimization alone.

*Table 6: Weighted Optimization Results for Scenario 1*

| Scenario | Weighted Objectives | Optimization Parameter Value | | Optimization Result | | |
|---|---|---|---|---|---|---|
| | | | | CO2 Emissions | Project Cost | Project Duration |
| **1** | Project Duration = 70 %<br>Total Cost = 20 %<br>Co2 Emissions = 10 % | #Augers (count) | 4 | 35,086 kilograms | 36,754$ | 1,180 minutes |
| | | #Cranes (count) | 2 | | | |
| | | OverFlight (%) | 50 | | | |
| **2** | Project Duration = 15 %<br>Total Cost = 75 %<br>Co2 Emissions = 10 % | #Augers (count) | 2 | 30,131 kilograms | 31,587$ | 1,925 minutes |
| | | #Cranes (count) | 1 | | | |
| | | OverFlight (%) | 50 | | | |
| **3** | Project Duration = 10 %<br>Total Cost = 15 %<br>Co2 Emissions = 75 % | #Augers (count) | 2 | 30,131 kilograms | 31,587$ | 1,925 minutes |
| | | #Cranes (count) | 1 | | | |
| | | OverFlight (%) | 50 | | | |

## 5.2 Scenario 2 – Results

In this trial, Scenario 2 for rotary bored piles was analyzed using AnyLogic simulation software, yielding the same results as Scenario 1. Table 7 presents the local optimization results, where each objective is optimized individually, while The table compares base case results with optimization results for Scenario 2 across project CO2 emissions, duration, and cost, revealing significant trade-offs. Reducing emissions from 23,542 to 17,998 kilograms was achieved by lowering the number of augers and cranes, which also reduced project cost to $19,033 but nearly doubled the project duration to 1,460 minutes. Conversely, optimizing for speed reduced the project duration from 731 to 523 minutes by increasing the number of augers and cranes, but this led to a sharp rise in emissions (37,967 kilograms) and cost ($40,095). The findings highlight the competing priorities in project management, where minimizing CO2 emissions can extend project timelines, while reducing duration significantly inflates costs and carbon footprint.
Table 8 displays the weighted optimization results based on user-defined importance factors.

*Table 7: Base Case Results and Optimization Results for Scenario 2*

| Objective | Initial Parameter Value | | ***Base Case Results*** | Optimization Parameter Value | | Optimization Result | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | CO2 Emissions | Project Cost | Project Duration |
| Project CO2 Emissions | #Augers (count) | 3 | 23,542 kilograms | #Augers (count) | 1 | **17,998 kilograms** | 19,033$ | 1,460 minutes |
| | #Cranes (count) | 3 | | #Cranes (count) | 2 | | | |
| | OverFlight (%) | 50 | | OverFlight (%) | 50 | | | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Project Duration | #Trucks (count) | 3 | 731 minutes | #Augers (count) | 7 | 37,967 kilograms | 40,095$ | **523 minutes** |
| | #Loaders (count) | 3 | | #Cranes (count) | 8 | | | |
| | OverFlight (%) | 50 | | OverFlight (%) | 50 | | | |
| Project Cost | #Trucks (count) | 3 | 24,820$ | #Augers (count) | 1 | 17,998 kilograms | **19,033$** | 1,460 minutes |
| | #Loaders (count) | 3 | | #Cranes (count) | 2 | | | |
| | OverFlight (%) | 50 | | OverFlight (%) | 50 | | | |

The table compares base case results with optimization results for Scenario 2 across project CO2 emissions, duration, and cost, revealing significant trade-offs. Reducing emissions from 23,542 to 17,998 kilograms was achieved by lowering the number of augers and cranes, which also reduced project cost to $19,033 but nearly doubled the project duration to 1,460 minutes. Conversely, optimizing for speed reduced the project duration from 731 to 523 minutes by increasing the number of augers and cranes, but this led to a sharp rise in emissions (37,967 kilograms) and cost ($40,095). The findings highlight the competing priorities in project management, where minimizing CO2 emissions can extend project timelines, while reducing duration significantly inflates costs and carbon footprint.

Table 8: Weighted Optimization Results for Scenario 2

| Scenario | Weighted Objectives | Optimization Parameter Value | | Optimization Result | | |
|---|---|---|---|---|---|---|
| | | | | CO2 Emissions | Project Cost | Project Duration |
| **1** | Project Duration = 70 %<br>Total Cost = 20 %<br>Co2 Emissions = 10 % | #Augers (count) | 3 | 20,818 kilograms | 22,041$ | 546 minutes |
| | | #Cranes (count) | 10 | | | |
| | | OverFlight (%) | 50 | | | |
| **2** | Project Duration = 15 %<br>Total Cost = 75 %<br>Co2 Emissions = 10 % | #Augers (count) | 2 | 18,847 kilograms | 19,945$ | 755 minutes |
| | | #Cranes (count) | 7 | | | |
| | | OverFlight (%) | 50 | | | |
| **3** | Project Duration = 10 %<br>Total Cost = 15 %<br>Co2 Emissions = 75 % | #Augers (count) | 1 | 17,998 kilograms | 19,033$ | 1,460 minutes |
| | | #Cranes (count) | 2 | | | |
| | | OverFlight (%) | 50 | | | |

## 6. CONCLUSION AND RECOMMENDATIONS

This study demonstrates the effectiveness of simulation-based multi-objective optimization in reducing the carbon footprint of bored piling operations while maintaining efficiency in cost and time. By integrating discrete-event simulation with optimization techniques, the model identifies the optimal configurations for equipment usage, pile sequencing, and execution strategies. The results highlight the impact of operational parameters—such as the number of augers, and cranes—on project sustainability. Additionally, the study incorporates user-defined importance factors to provide flexible, project-specific trade-offs among $CO_2$ emissions, cost, and duration. The findings emphasize that sustainable piling practices can be achieved through data-driven decision-making, balancing environmental responsibility with construction efficiency. By addressing challenges like over-flighting in CFA piles and equipment availability constraints in rotary bored piling, the model provides valuable insights for industry professionals seeking to enhance sustainability in foundation engineering. Future research could expand on this approach by integrating real-world project data, refining optimization algorithms, and exploring additional sustainability metrics beyond carbon emissions. The results shows that the best scenario for cost is **Rotary Bored Piles – Scenario 2** , as it minimizes expenses by optimizing resource allocation and avoiding risks associated with over-flighting. Similarly, the best scenario for duration is also Rotary Bored Piles, despite CFA piles generally being faster. This outcome is influenced by the high probability of over-flighting assumed in this research, which increases delays in CFA execution. Additionally, the best scenario for $CO_2$ emissions is also Rotary Bored Piles, due to its more controlled execution and reduced idle time. However, these findings are not universally applicable to every project. The best scenario depends on various factors, including the specific equipment used, project specifications, and operational constraints. Each project will have a unique execution map and different parameters, leading to varying probabilities and results. The novel approach introduced in this research allows for scenario adjustments tailored to any project, ensuring that outcomes and decisions reflect the real constraints and conditions of each case. This research recommends incorporating additional $CO_2$ and cost sources, such as labor and concrete mixers, into the analysis. This would enhance result accuracy and provide a more realistic assessment, ultimately improving the decision-making process.

## REFERENCES


Abu Kassim, K.A., & Adnan, A.B. (2005). Productivity and Cost Comparison of Bored Piling Using Casing versus Bentonite Slurry. Journal of the Institution of Engineers, Malaysia, 66(3), 33–40

Abushama, K., Hawkins, W., Pelecanos, L., and Ibell, T. 2025. Optimizing the Embodied Carbon of Concrete, Timber, and Steel Piles with a Case Study. In Lecture Notes in Civil Engineering, pp. 899–911. https://doi.org/10.1007/978-3-031-69626-8_76

Cho, R. 2022. What is Decarbonization, and How Do We Make It Happen? Columbia Climate School. Retrieved from https://news.climate.columbia.edu

Edeoja, J.A. and Edeoja, A.O. 2015. Carbon Emission Management in the Construction Industry – Case Studies of Nigerian Construction Industry. American Journal of Engineering Research (AJER), 4(7): 112–122. https://www.ajer.org

Federation of Piling Specialists. 2014. CFA Piling: Preventing Ground and Rig Instability Through Over-Flighting. Federation of Piling Specialists. https://www.fps.org.uk

Fleming, K., Weltman, A., Randolph, M., and Elson, K. 2008. Piling Engineering (3rd ed.). Routledge. https://doi.org/10.4324/9780203937648

GHG Protocol. 2024. Calculation Tools and Guidance – Mobile Combustion: Fuel Use (v2.0). World Resources Institute. https://ghgprotocol.org/calculation-tools-and-guidance#sector_specific_tools_id

Hwang, J.H., Da Lyu, Y., and Chung, M.C. 2011. Optimizing Pile Group Design Using a Real Genetic Approach. The Twenty-first International Offshore and Polar Engineering Conference, pp. 491–499. https://onepetro.org/ISOPEIOPEC/proceedings/ISOPE11/All-ISOPE11/ISOPE-I-11-056/12500

Hu, H., Ji, X., and Liang, H. 2019. Study on Construction Schedule Optimization of Bored Pile Based on Genetic Algorithm. IOP Conference Series Earth and Environmental Science, 300(2): 022020. https://doi.org/10.1088/1755-1315/300/2/022020

Joustra, C.M. and Yeh, D.H. 2015. Framework for Net-Zero and Net-Positive Building Water Cycle Management. Building Research & Information, 43(1): 121–132. https://doi.org/10.1080/09613218.2015.961002

Krishnan, M., Samandari, H., Woetzel, J., Smit, S., Pacthod, D., Pinner, D., Nauclér, T., Tai, H., Farr, A., Wu, W., and Imperato, D. 2022. The Net-Zero Transition: What It Would Cost, What It Could Bring. McKinsey & Company. https://www.mckinsey.com

Ma, F., Sha, A., Yang, P., and Huang, Y. 2016. The Greenhouse Gas Emission from Portland Cement Concrete Pavement Construction in China. International Journal of Environmental Research and Public Health, 13(7): 632. https://doi.org/10.3390/ijerph13070632

Oba, K.M. 2023. A Cost Optimization Model for the Construction of Bored Piles. International Journal of Structural and Construction Engineering, 17(11).

Spence, D.B. 2016. Paradoxes of Decarbonization. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.2802231

The Sustainable Development Goals Report 2023: Special Edition. 2023. In The Sustainable Development Goals Report. https://doi.org/10.18356/9789210024914

Toprak, B., Sevim, O., Totic, E., and Kalkan, I. 2018. The Functions of Pile Types and Piles Used in Construction. International Journal of Advances in Mechanical and Civil Engineering, 5(2): 34–36.

United Nations Environment Programme. 2023. Building Materials and the Climate: Constructing a New Future. https://doi.org/10.59117/20.500.11822/43293

Zayed, T.M. 2005. Productivity and Cost Assessment for Continuous Flight Auger Piles. Journal of Construction Engineering and Management, 131(6): 677–688. https://doi.org/10.1061/(ASCE)0733-9364(2005)131:6(677)