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Carbon Footprint Assessment Model for Sustainable Construction Sites

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ABSTRACT: The construction industry plays a significant role in global carbon emissions, yet the focus of decarbonization efforts often centers on the operational phase of buildings and facilities. The construction phase, a critical contributor to overall emissions, has received comparatively less attention. This paper presents the development of a comprehensive model model for measuring and evaluating the carbon footprint of construction projects, addressing this gap. The proposed model leverages conversion factors from reputable standards, including the Greenhouse Gas (GHG) Protocol, to ensure accuracy and reliability. It evaluates both direct emissions, such as those produced by construction processes involving heavy machinery, and indirect emissions, such as the energy consumption of temporary site facilities and utility use. This dual-layer approach provides a holistic view of emissions during the construction stage. By integrating data from construction activities, the model identifies and quantifies the carbon emissions associated with various processes and operations. Construction managers can utilize the outputs of the model to pinpoint high-emission activities and develop targeted mitigation strategies. This allows for informed decision-making aimed at reducing the carbon footprint of construction projects. The implementation of the model not only promotes sustainable construction practices but also supports compliance with international standards and climate action goals. Through practical applications and case studies, this paper demonstrates the utility of the model in real-world scenarios, emphasizing its adaptability to different project types and scales.

1. INTRODUCTION

The construction industry plays a pivotal role in global development, yet it remains one of the largest contributors to carbon emissions. According to the United Nations Environment Programme (UNEP), the construction sector is responsible for approximately 39% of global energy-related carbon dioxide (CO_2) emissions, with a significant portion stemming from the use of heavy machinery, transportation, and temporary site facilities (Giesekam et al., 2016). While extensive research has been conducted on reducing operational carbon emissions in buildings through energy-efficient designs and renewable energy integration, the construction phase itself remains an overlooked area in decarbonization efforts (Kibert, 2016). Construction activities, including excavation, concreting, and steel fixing, rely heavily on fossil fuel-powered equipment, leading to substantial direct emissions. Additionally, indirect emissions arise from the energy consumption of site offices, lighting, and HVAC systems (Gupta & Jain, 2015). Despite these concerns, few standardized methodologies exist for accurately assessing and mitigating carbon emissions during the construction phase.

The need for a comprehensive, practical model to measure and analyze the carbon footprint of construction sites has become increasingly critical in the face of global climate action commitments. Existing carbon footprint assessment models (CFAMs) often focus on material-related emissions rather than on-site construction activities, leaving a crucial gap in real-time emissions monitoring (Foca et al., 2017). Moreover, while some models incorporate Lifecycle Assessment (LCA) and Building Information Modeling (BIM) for emissions tracking, they frequently lack real-time adaptability, making them ineffective for dynamic construction environments (Crawford & Stephan, 2013). Addressing these limitations requires a systematic, site-specific approach that quantifies emissions from both direct sources (fuel consumption in machinery) and indirect sources (electricity usage in temporary site facilities). Such an approach would enable construction, project managers, and the Environment, Health & Safety department (EHS) to make informed decisions on-site, helping reduce emissions without compromising operational efficiency.

Unlike other research focusing on operational or material embodied carbon, this model captures site-specific energy, equipment emission, and facility consumption. The model provides actionable insights for construction managers to gain a spectrum of emissions during the construction phase, an area overlooked in terms of identifying blindspots and understanding the associated impacts.

By focusing on high-emission activities, such as concreting and steel fixing, this model enables construction managers to create customized scenarios based on their unique site conditions, specifications, and operational practices. It allows them to select machinery, determine energy consumption at temporary facilities, to calculate the total emissions involved in the construction process. This flexibility empowers them to simulate different configurations, adjust variables like equipment choices, site energy sourcing, or construction methods, and estimate the total emissions for each scenario.

The model focuses specifically on quantifying GHG generated by equipment used during the construction phase. It relies on detailed, activity-based inputs such as fuel type, equipment specifications, and operating hours to provide accurate, phase-specific emission estimates.

This paper introduces a carbon footprint assessment model tailored for construction sites, integrating established greenhouse gas (GHG) accounting models with real-world data on fuel consumption and site energy use. The model leverages emission conversion factors from reputable standards such as the GHG Protocol (WRI & WBCSD, 2004) and national energy guidelines (Egyptian Code of Practice, 2017). By developing a structured methodology to evaluate construction-related emissions, this research aims to provide construction professionals with practical insights into emission hotspots and mitigation strategies. Through an in-depth assessment of construction equipment, site operations, and energy consumption patterns, the study contributes to the broader goal of sustainable construction practices and carbon reduction in the built environment.

2. LITERATURE REVIEW

Over the years, researchers in construction sustainability have adopted sustainable measures in assessing and reducing the carbon footprint. Despite the predominant focus on Mitigating carbon emissions during the operational phase of buildings, as well as the construction phase, which accounts for a significant share of emissions, has received relatively and comparatively less attention. This gap in the focus of decarbonization underscores the substance of developing comprehensive models that evaluate the carbon footprint (CF) during the construction phase.

2.1. Framework for Carbon Footprint Assessment in Construction

The Greenhouse Gas (GHG) Protocol is a commonly known model that assesses emissions and has been integrated into numerous carbon footprint models used across various industries, including the construction sector (WRI & WBCSD, 2004). It categorizes emissions into three scopes: Scope 1 (direct emissions), Scope 2 (indirect emissions from energy use), and Scope 3 (other indirect emissions). Scope 1 emissions are preliminary focused on fuel consumption by heavy machinery, vehicles, and onsite processes, while Scope 2 emissions arise from the energy consumed by temporary site facilities, lighting, and heating (Giesekam et al., 2016). Furthermore, although less commonly assessed, Scope 3 emissions co-exist with the production and transportation of materials used in construction.

2.2. Challenges in Implementing CFAMs in Construction

According to Gupta & Jain (2015), in recent years, compound carbon footprint assessment models (CFAMs) have been developed to measure the carbon footprint during construction along with the Lifecycle Assessment (LCA) and Building Information Modeling (BIM**)**. LCA is widely recognized for its ability to efficiently evaluate environmental impacts over a building's entire lifecycle from design to demolition. Similarly, BIM has been integrated with a carbon footprint to aid construction managers in identifying high-emission activities. However, these models often fall short of providing real-time actionable data during construction activities. This limitation hinders the dynamic decision-making process as the LCA and BIM typically rely on predefined scenarios and static data, which may not reflect the actual on-site conditions and performance (Crawford & Stephan, 2013). Consequently, while LCA offers valuable insights at a strategic level, it lacks the adaptability required for effective, real-time environmental management and optimization during the construction phase. Most models introduced to the market remain too complex for day-to-day use on construction sites or “focus primarily on material-related emissions, neglecting emissions from construction operations and energy use on-site” (Foca et al., 2017).

2.3. Research Gaps

Several models have been developed to assess the carbon footprint of construction activities including (LCA) tools, embodied carbon calculators, and Environmental Product Declarations (EPDs). Although these approaches provide valuable insights, they are limited to the embodied carbon of materials and provide a general estimate for building components rather than detailed, “activity-specific” emissions from construction activities (Cabeza et al., 2014; Dixit, 2017). Conventional LCA tools prioritize the design and material selection and are limited in capturing on-site emissions from construction operations (Pomponi & Moncaster, 2016). In contrast, the model proposed in this paper distinguishes itself by integrating real-time construction activity data, site-specific energy use, and machinery performance metrics. This enables a more dynamic and accurate assessment of both direct and indirect emissions during the construction phase, addressing limitations in previous methodologies that rely heavily on standardized emission factors without contextual, human adjustments (Giesekam et al., 2016).

Despite the advances in CFAMs, several challenges persist: data accuracy remains a major concern, particularly for large projects (Giesekam et al., 2016). Additionally, the complexity of some models, particularly LCA, deter widespread adoption in the construction industry (Foca et al., 2017). Addressing these challenges and improving the accessibility of CFAMs is essential to advocate sustainable practices during the construction phase. In contrast, LCA, or Product Carbon Accounting (PCA), offers a comprehensive evaluation of environmental impacts across all stages of a product's or building’s life cycle, from raw material extraction and manufacturing to construction, use, and end-of-life disposal. The developed model in this paper is designed to support emissions optimization during the active construction period.

3. RESEARCH METHODOLOGY

The proposed model provides a series of functions that enable calculating the carbon emissions from construction equipment and site facilities by considering direct (equipment operation) and indirect emissions (site facilities' electricity consumption). The assessment includes various types and brands of construction equipment such as light machinery (e.g., generators, plate compactors, concrete saws) and heavy machinery (e.g., trucks, wheel loaders, concrete mixers, pumps), along with site facilities like HVAC systems, water pumps, lighting, and electrical appliances.

Along with the fuel and energy consumption data per brand collected from manufacturer specifications and try emission databases, performance handbooks, and international and local codes, the carbon emissions are calculated using standard emission factors for various fuels (diesel, petrol, electricity). For electricity consumption, the Egyptian Code of Practices (ECP 302) is referenced to calculate the total electrical consumption on-site, considering HVAC systems, electrical outlets, water pumps, elevators, and electrical devices used during the construction phase. Likewise, guidelines and emission factors from the U.S.

Department of Energy (DOE). & Intergovernmental Panel on Climate Change (IPCC) have been applied to estimate the total site lighting required. The perceived value is further multiplied by the relevant emission factor to compute the CO_2 emissions associated with site facilities. The total emissions for each piece of equipment used in the user's scenario are computed by totting the direct and indirect emissions.

To evaluate the effectiveness of the proposed CFAM, the developed model has been tested on a construction project of a residential building. This project is selected to initiate a representation of different scales and ensure a comprehensive assessment of the software's performance. The residential project consists of a 3-story mid-rise building with a total built-up area of 1,200 m². This project involves typical residential construction activities, including excavation and concrete works. The case study is ideal for evaluating the model's ability to quantify and analyze carbon emissions at different construction stages.

4. MODEL DEVELOPMENT

The proposed model has 3 main modules, 1) inputs, 2) calculations, and 3) outputs. The inputs are broken down into inputs that are inputted by users (mainly site operations data), and those that are already obtained and saved in the back-end database by the researchers. The model then utilizes those inputs and processes the calculations to output the results related to the carbon footprint of the construction site. Users can then make changes in the construction plan and reflect those changes as new inputs; which then are translated as new emissions. With this, users can try multiple construction strategies until they reach the one with the lowest carbon footprint, by selecting alternative models and equipment brands from the database. Figure 1 shows a summarized visual representation of the developed model.

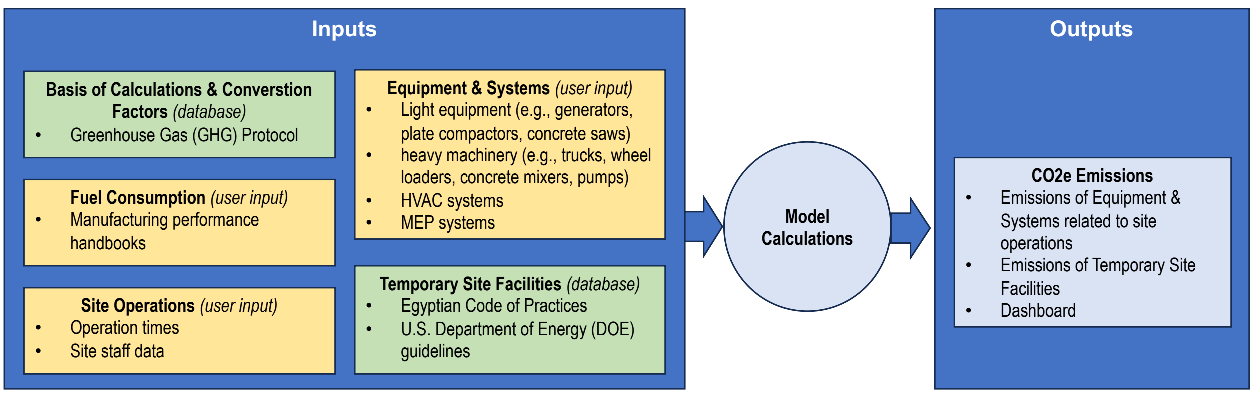

Figure 1: Modules of the Developed Model

The model is built on an activity-based carbon estimation model tailored for construction activities, organized into three main sections: Light Equipment, Heavy Equipment, and Site Facilities. Each section features a user-friendly interface that allows users to select equipment type, brand, and model from a preloaded database via dropdown menus. Once selected, users input the quantity, daily operation time, and total duration of use for each piece of equipment.

This process applies to the following equipment: generators, concrete vibrators, plate compactors, concrete saws, concrete mixer trucks, wheel loaders, concrete pump trucks, roller compactors, and transport vehicles, which are further categorized by vehicle type. Based on these inputs, the backend performs automated CO_2 emissions calculations using built-in emission factors and performance data specific to each user input selected model and category.

For site facilities, the software is designed to align with real-life user scenarios. For example, in the case of HVAC systems, users simply input the total duration of use, horsepower, and quantity. Similarly, for water pumps, electrical outlets, appliances, and lighting systems, the platform provides tailored input fields to reflect actual operational usage. For direct emission, the user inputs the operation time per hour and the total duration of usage in days, which is then combined with the liters per hour (l/hr) consumption rate to estimate the total fuel consumption. Subsequently, the carbon emissions are then calculated using standard emission factors for various fuels (diesel, petrol, electricity). For indirect emissions, this study utilized the Egyptian Code of Practices (ECP) and U.S. Department of Energy (DOE) guidelines to determine the total electricity consumption required for the construction site. The total electricity consumption is then multiplied by the relevant emission factor for electricity to estimate the associated CO_2 emissions.

Each variables are defined in Table 1.

Table 1: Nomenclature and Units

Variables	Units	Description
TE	kg CO2	Total CO_2 emission
FC	l/hr	fuel consumption rates in
OT	hr	Operation time
D	Days	Total Duration
EF	kg/l	CO_2 Emissions Factor
P	HP	Total Horsepower
NbS	Number of sockets	Number of Sockets
Nbd	Number of electrical devices up to 10 Amp	Number of electrical devices up to 10 Amp
NbD	Number of Electrical Devices exceeding 10 Amp	Number of Electrical Devices exceeding 10 Amp
T	Lux	Total lumens required for the site
A	m^2	Site Area
L	Lux	Lighting intensity
NLF	Number of Light Fixtures	Number of Light Fixtures
P	Power	Power rating of each fixture

4.1. Light & Heavy Equipment

Carbon emissions from light equipment, including generators, plate compactors, and concrete saws, concrete vibrators & power towels are perceived from fuel consumption rates, operating time per hour, total duration in days, and CO_2 emission factors kg/l. Heavy equipment, including trucks, wheel loaders, concrete mixers, vehicles, and concrete pumps, typically exhibits high fuel consumption, making it a substantial source of carbon emissions. The guidelines for Eq.1 are forth by the EPA (2024): throughout the user's selection of the brand, model, and load percentage, the total CO_2 emission is calculated using Eq.1.
[1] $TE = FC \times OT \times D \times EF$

4.2. Site Facilities

Site facilities such as HVAC systems, lighting, and water pumps contribute indirectly to construction site emissions through electricity consumption.

4.2.1. HVAC Systems

The Guide to the Application of the Egyptian Code for the Foundations of Design and Implementation Conditions for Electrical Connections and Installation in Buildings, Volume One: Design Works (ECP 302) outlines the methodology for calculating the total electrical consumption of HVAC systems during the design phase. To estimate the total CO_2 emissions kg CO_2 for an HVAC system, the system's total electrical power consumption can be calculated using its total horsepower (P). By multiplying this value by the associated CO_2 emission factor (EF), the total emissions can be derived. This approach is based on calculations outlined in Eq. 2.

[2] $TE = (P / (220 \times 0.85 \times 0.8)) \times EF$

4.2.2. Electrical Outlets

Following the Guide to the Application of the Egyptian Code for the Foundations of Design and Implementation Conditions for Electrical Connections and Installation in Buildings, Volume One: Design Works (ECP 302), the methodology of calculating the total CO_2 emissions (TE) in kgCO2 for electrical consumption of electrical outlets is perceived by the product of the total number of sockets (NbS) and the standard assumption based on typical electrical load usage per socket, 0.5 kW per socket, as perceived with Eq.3.

[3] TE =NbS × 0.5 × EF

4.2.3. Water Pumps

The following equation follows standard electrical engineering principles to determine the actual power requirement of water pumps, ensuring proper system design and efficiency optimization per the Egyptian Code (ECP 302), as perceived with Eq.4.

[4] TE = (NbP × HP × 0.746) / (0.85 × 0.88) × EF

The product of the number of pumps (NbP), horsepower per pump (HP), and 0.746 (which converts HP to kW) is divided by 0.85 (power factor) and 0.88 (motor efficiency) to determine the total electrical consumption of the water pumps. This value can then be multiplied by the CO_2 Emission Factor (EF**)** (kg/l) to estimate the total CO_2 emissions perceived from the use of water pumps.

4.2.4. Electrical Devices

According to the ECP code, electrical power consumption for devices is categorized by current rating. Electrical devices up to 10 Amp are perceived from the following formula Eq.5.

[5] TE =1.87 × Nbd × EF

Assuming that the average power consumption of Computers, Printers, Servers, and Appliances is 1.87 kW, the resulting power consumption is multiplied by the average power consumption by the total number of devices (NbD) and the CO_2 Emission Factor (kg/l) to perceive the total CO_2 emissions. Similarly, for electrical devices exceeding 10 amps, the power calculation is further adjusted by multiplying with a 0.5 factor as observed in Eq.6.

[6] TE = 1.87 × NbD × 0.5 × EF

The resulting power consumption is multiplied by the CO_2 Emission Factor (kg/l) to perceive the total CO_2 emissions.

4.2.5. Site Lighting

To assess the total CO_2 emissions associated with lighting on a construction site, the equations provide a systematic approach based on key parameters such as site area, illumination levels, operation hours, and emission factor of electricity to ensure precise calculations as perceived in perceived with Eq.7.

[7] T = A × L

Where A represents the site area and L denotes the required lighting intensity in lux. Based on Eq. 10, the number of light fixtures is calculated using the following equation: P refers to the power rating of each fixture and its efficacy, which is about 80%, as seen in equation Eq.8.

[8] NLF = T_l / (P × Efficacy)

Furthermore, the Total CO_2 emission is obtained using Ep. 9, multiplying the power, several light fixtures, daily operating duration, the total duration and the CO_2 emission factor.

[9] TE = (P × NLF × OT × D) × EF / 1000

To ensure standardization, a lighting scheme is adopted based on guidelines from the U.S. Department of Energy (DOE) and the Intergovernmental Panel on Climate Change (IPCC) to ensure international best practices for sustainable lighting categorization. The scheme in constriction sites is designed to meet the specific needs of various tasks. Heavy lighting (500 lux) is used for high-visibility activities such as concreting or when the area is completely dark, requiring bright illumination for safety and accuracy. While, moderate lighting (200 lux) is appropriate for general work on-site, offering sufficient visibility without the need for intense lighting, and finally low lighting (50 lux), on the other hand, is typically used for security or minimal lighting, for safety and surveillance without excessive brightness (Department of Energy, n.d.)

5. CASE STUDY

The selected project for the case study is a residential project consisting of a 3-story mid-rise building with a total built-up area of 1,200 m². This project involves typical residential construction activities, including excavation and concrete works. It shall be noted that the model can be easily scaled to larger projects. The analysis of the total CO_2 emissions for light, heavy, and site facilities has been successfully calculated for the period of the concreting activities; which was about 3 months.

In the scope of the light equipment, the main equipment used were the Generator, Plate Compactors, and Concrete Vibrator. Table 2 shows the model selected, quantity, duration of use, and the resulting CO_2 emissions. The calculations revealed that for this project, the Airman SDG100S generator contributes the highest emissions, with 14,400 kg CO_2 over 90 days, accounting for the majority of the total light equipment emissions. The Plate Compactors (TKP-90 Brava) and Concrete Vibrators (Allen Engineering EF-500) also contribute emissions yet on a a smaller scale, with emissions of 130.5 kg CO_2 over 10 days and 312 kg CO_2 over 6 days, respectively. In total and for the duration of the concreting and steel fixing stages, light equipment contributes to a total of 14,842.5 kg CO_2, as perceived in Table 2.

Table 2: Light Equipment Total Emissions

Equipment	Model	Total Duration (in days)	Quantity of Equipment	Total CO_2 Emissions per day (kg CO_2)	Total CO_2 Emissions per Total Duration (kg CO_2)
Generator	Airman SDG100S	90	1	431.5	14,400.0
Plate Compactors	TKP-90 Brava Plate Compactor	10	2	13.1	130.5
Concrete Vibrator	Allen Engineering EF-500	6	2	52	312
Total CO_2 Emissions for Light Equipment (kg CO_2)					14,842.50

When it comes to heavy equipment, the site utilized trucks, wheel loaders, concrete mixers, concrete pumps, and passenger vehicles. As demonstrated in Table 3, the analysis of the total CO_2 emissions for heavy equipment shows a considerable environmental impact. In total, heavy equipment contributes 109,542 kg of CO_2 over the specified durations, underlining a substantial carbon footprint.

Table 3: Heavy Equipment Total Emissions

Equipment	Model	Total Duration (in days)	Operation Time per day (Hours)	Quantity of Equipment	Total CO_2 Emissions per day (kg CO_2)	Total CO_2 Emissions per Total Duration (kg CO_2)
Trucks	Mercedes Bens Actros Tripper 4049	10	3	10	2,505.6	25,056.0
Trucks	Renault Trucks D-Series	10	8	3	1,440.72	14,407.2
Trucks	Mercedes Bens Actros Tripper 4049	10	4	2	626.4	6,264.0
Wheel Loader	Yammar V4-3	10	8	3	1879.2	18,792.0
Concrete Mixer Truck	Mercedes-Benz Arocs 8x4 Concrete Mixer	9	8	5	3340.8	30,067.2
Concrete Pumps	Hamac	6	5	2	652.5	3,915.0
Roller Compactors	Caterpillar CB10	10	8	2	501.12	5011.2
Vehicles		30	5	3	201	6030.0

Total CO_2 Emissions for Heavy Equipment (kg CO_2)	109,542.80

Figure 2 illustrates the total CO_2 emissions (in Kg CO_2) for different types of heavy equipment. It is perceived that Trucks have the highest emissions, exceeding 35,000 Kg CO_2, followed by Concrete Mixer trucks and Wheel loaders with emissions above 15,000 Kg CO_2. Among the listed items, trucks are the most significant contributors to CO_2 emissions.

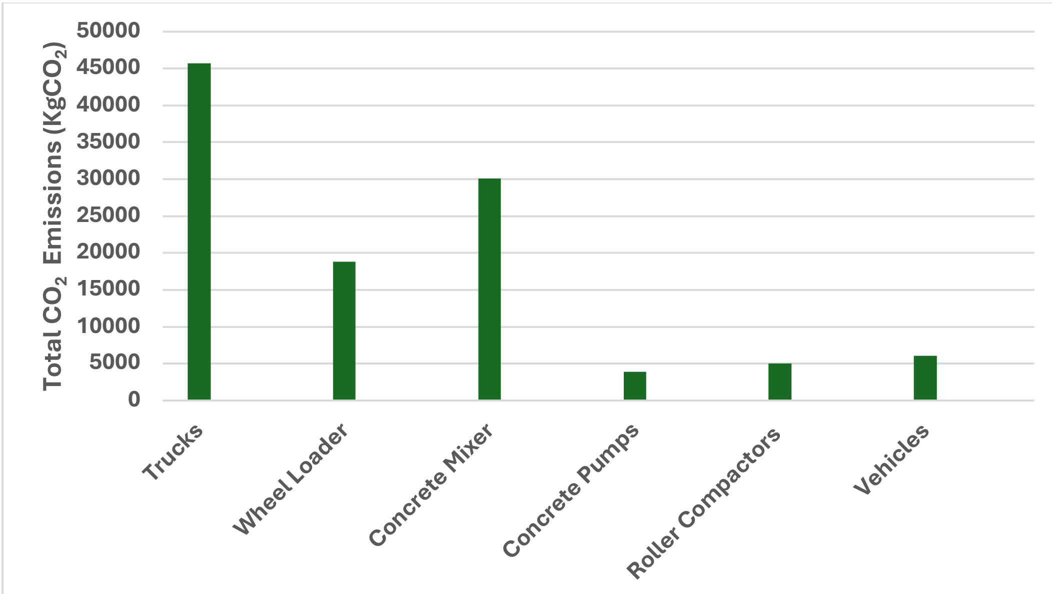

Figure 2: CO_2 Emissions from Heavy Equipment

Concerning site facilities, it is perceived that the total CO_2 emissions for all site facilities amount to 8,515.04 kg CO_2. The HVAC system is the dominant source of emissions, whereas lighting and water pumps contribute comparatively less.

Table 4: Site Facilities Total Emissions

Site Facilities	Total Duration (Days)	Quantity of Equipment	Total CO_2 Emissions per Total Duration (kg CO_2)
HVAC System	90	2	4,685.4
Electrical Outlets	90	10	1,174.5
Water Pump	90	1	470.34
Electrical Appliances	90	4	1,317.8
Heavy Lighting	15	1	255
Moderate Lighting	90	1	612
Total CO_2 Emissions for Site Facilities (kg CO_2)			8,515.04

The pie chart illustrated in Figure 3 underlines the proportion of CO_2 emissions from different sources.it is identified that Heavy equipment is the largest contributor, accounting for 89% of total emissions. Light equipment follows, contributing 7%, while site facilities have the smallest share at 4%. This indicates that heavy equipment plays the most significant role in CO_2 emissions, whereas site facilities have a minimal impact in comparison. It shall be noted that these calculations and analysis are executed in the earthwork and concreting activities only in this case study. Also, it shall be noted that the resulting numbers are relevant only to the case study and are not to be generalized to other projects.

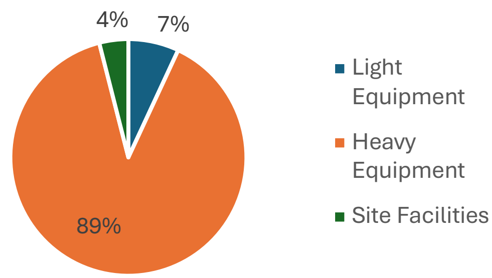

Figure 3: Breakdown of CO_2 Emissions by Light, Heavy and Site Facilities

6. CONCLUSIONS AND RECOMMANDATION

The construction industry remains one of the largest contributors to global carbon emissions, yet emissions from active construction sites have been largely overlooked in decarbonization efforts. While existing research has extensively focused on reducing operational emissions in buildings, there remains a critical gap in assessing and mitigating emissions generated during the construction phase. This study has developed a carbon footprint assessment model (CFAM) specifically tailored for construction sites, addressing both direct emissions from fuel consumption in heavy machinery and indirect emissions from temporary site facilities such as HVAC systems, lighting, and electrical appliances. By leveraging established models such as the Greenhouse Gas (GHG) Protocol and integrating real-time data on fuel and energy consumption, the model provides a more practical and actionable approach to reducing carbon emissions in construction projects.

The results of this study highlight the key emission hotspots within the construction phase, with heavy equipment accounting for the largest share of emissions, followed by light equipment and site facilities. By identifying high-emission activities, this model enables construction managers and industry professionals to make informed decisions regarding equipment selection, operational strategies, and carbon reduction initiatives. Additionally, the incorporation of standardized emission factors and real-time monitoring capabilities enhances the model's applicability across different project types and scales. The findings of this research contribute to the broader goal of sustainable construction practices, aligning with global climate action commitments and carbon reduction targets.

Furthermore, the model has successfully integrated real-time data input by users, enabling continuous tracking of emissions throughout the construction lifecycle. This capability allows construction, project managers and the environment, health and safety offices to make informed decisions in equipment selection, optimize processes, and reduce environmental impact. Equally, this model supports scenario analysis, providing a tool for identifying the most effective strategies for minimizing emissions, such as choosing alternative energy-efficient machinery. Tailored to the unique requirements of each construction project, this model shall empower managers to adapt and refine their approach to sustainability, ultimately driving more informed decision-making and greater environmental responsibility on the job site.

Despite its strengths, this study also recognizes several challenges in implementing carbon footprint assessment models on construction sites, including data availability, variability in site conditions, and the need for improved integration with digital construction tools such as Building Information Modeling (BIM) and Internet of Things (IoT) solutions. Future research should focus on expanding the scope of CFAMs to incorporate a wider range of construction activities, improving real-time emissions tracking, and exploring automated data collection techniques to enhance model accuracy and usability. By bridging the gap between theoretical carbon assessments and practical implementation, the construction industry can take significant steps toward reducing its environmental impact, fostering innovation in low-carbon construction technologies, and achieving a more sustainable built environment.

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