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Quantifying environmental impact: carbon emissions analysis of cut and fill work in construction

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Abstract
The construction industry plays a pivotal role in global development, but it also significantly contributes to carbon emissions, necessitating urgent measures to mitigate its environmental impact. The main objective of this research is to analyse and estimate the carbon emissions resulting from cut and fill work in construction projects. This research conducted three comprehensive case studies focusing on heavy equipment excavation, material transport, material spreading, and compaction stages in the construction industry to analyse carbon emissions. The findings reveal that material transport emerges as a prominent source of CO_2 emissions within the construction life cycle. This underscores the urgent need for transformative measures to optimize transportation logistics and adopt eco-friendly alternatives, such as electric or hybrid vehicles, for material transport. Additionally, the study highlights the importance of integrating intermodal transportation options to maximize efficiency while minimizing emissions during material movement. The research emphasizes that mitigating carbon emissions in the construction industry requires a comprehensive approach encompassing technological advancements, logistical optimization, and the adoption of sustainable practices. By embracing the strategies highlighted in this study, construction projects can significantly contribute to the global fight against climate change and align with international efforts to achieve a more sustainable future. The insights provided by this research underscore the imperative for collaboration among stakeholders to drive meaningful change and foster a more sustainable and environmentally conscious construction industry.

Keywords:
Carbon emission;
Climate action;
Earthworks;
Global warming;
Greenhouse gasses;
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INTRODUCTION

Infrastructure development plays a crucial role in the progress and economic growth of a nation. As countries strive to improve their transportation systems, housing, and public facilities, the construction industry experiences significant expansion [1, 2, 3]. However, this rapid growth in infrastructure projects has brought about a concerning side effect: increased carbon emissions. The construction industry is a major contributor to greenhouse gas emissions, which leads to environmental degradation and contributes to global warming [4, 5, 6].

Global warming, driven primarily by the accumulation of greenhouse gases in the atmosphere, poses a serious threat to the planet. The World Meteorological Organization (WMO) has predicted a rise in global temperatures of approximately 1 to 1.5°C, leading to severe climate changes worldwide. These changes include rising sea levels due to the melting of polar ice caps, which could potentially submerge low-lying coastal areas and islands.

To address these issues, countries worldwide are taking measures to reduce their carbon emissions [7, 8, 9]. In Indonesia, the government has committed to achieving Net Zero Emission (NZE) by 2060 or possibly even earlier [10]. NZE is an ambitious goal where the total greenhouse gas emissions produced by a country are balanced by the amount of greenhouse gases absorbed or offset through various means, such as reforestation and carbon capture technologies. Additionally, the Nationally Determined Contributions (NDC) set specific emission reduction targets for Indonesia by 2030.

Among the various greenhouse gases found in the atmosphere, notable ones include water vapor, chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3). However, it is worth noting that contemporary environmental concerns primarily revolve around four main greenhouse gases: CO_2, SO_2, CH_4, and N_2O [11], as shown in Figure 1. While water vapor is indeed the most abundant naturally occurring greenhouse gas in the atmosphere, CO_2 stands out as the most prominently emitted greenhouse gas. Consequently, researchers have explored various methods and techniques for capturing and mitigating CO_2 emissions.

The construction industry across the world is responsible for more than 30% of the total extraction of natural resources, 25% of the total solid waste generation, 40% of the total global energy consumption, and 25% of the total greenhouse gas emission [12][13]. Building construction and operation sector alone accounts for 36% of global energy use and 39% of energy-related CO2 emissions every year. Actions and changes in the construction industry can have a significant and prompt impact on global climate change, energy consumption, economy as well as society [14].

Within the construction industry, various factors contribute to carbon emissions [15, 16, 17, 18].

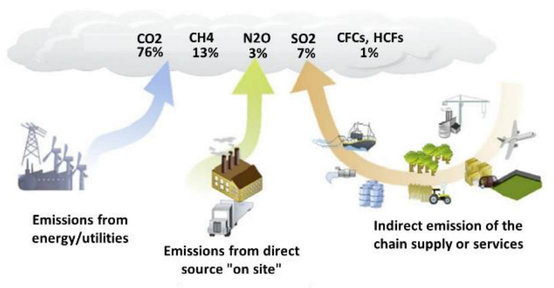

Figure 1. Greenhouse gasses and their sources

The entire life cycle of a construction project, from material extraction and transportation to building construction and maintenance, involves significant energy consumption and emissions [19][20]. Among the construction activities, "cut and fill work" stands out as a process that demands substantial energy and resources [21][22].

Cut and fill work, also known as earthwork, is a fundamental construction process that involves the excavation of soil or rock (cut) from one location and the placement of the excavated material in another area (fill) [23]. This technique is commonly employed to level uneven terrains, create building foundations, construct roadways, and develop infrastructure projects. To achieve specific construction requirements, such as desired elevation and ground stability, cut and fill work often relies on heavy machinery and equipment [24, 25, 26, 27, 28]. The operation of these machinery and the associated fuel consumption contribute significantly to the carbon footprint of construction projects.

This research aims to analyse and estimate the carbon emissions resulting from cut and fill work in construction projects. By quantifying the environmental impact of this particular construction process, the study seeks to provide valuable insights into how cut and fill activities contribute to the overall carbon emissions of the construction industry. Furthermore, the research aims to assist the government in developing appropriate strategies and measures to reduce carbon emissions associated with cut and fill work, aligning with the commitment to achieve Net Zero Emission (NZE) by 2060.

Understanding the carbon emission in cut and fill work is crucial for promoting sustainable construction practices. By identifying the carbon-intensive aspects of this process, construction stakeholders, including policymakers, developers, and contractors, can make informed decisions to minimize their environmental impact. Implementing sustainable practices in cut and fill work can contribute significantly to the national efforts to combat climate change and achieve emission reduction targets.

METHODS

The methodology employed in this research is the case study approach, wherein the emissions of CO_2 resulting from excavation and embankment activities in a road construction project are quantified. Figure 2 presents the stepwise procedure to calculate carbon emissions in cut and fill works.

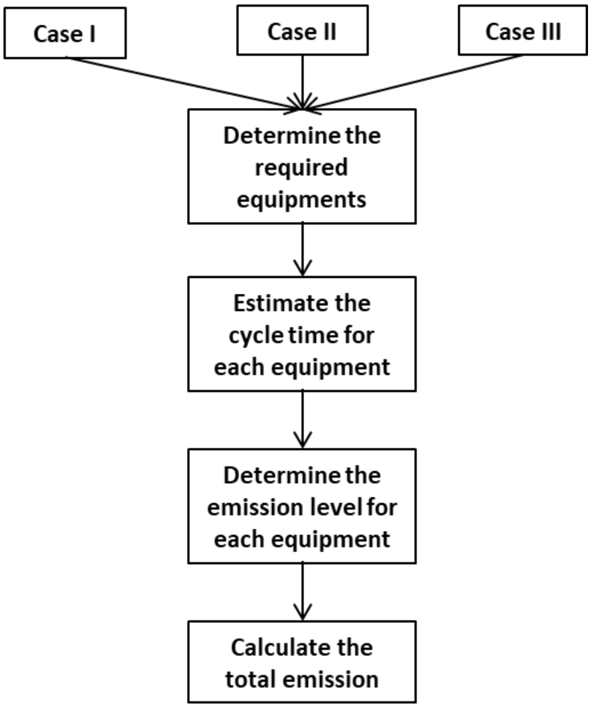

Figure 2. Procedure of carbon emissions calculation

The focus of this research is primarily on the emissions associated with fuel consumption. This methodology considers the fuel consumption of heavy equipment, a significant contributor to carbon emissions in the construction industry. While there may be other factors contributing to CO_2 emissions in construction, such as material extraction and transportation, this study narrows its scope to the emissions derived from the operation of construction equipment, which is predominantly influenced by fuel consumption. This targeted approach provides a specific and detailed analysis of the emissions directly linked to the cut and fill work in construction projects.

The calculation of emissions involves determining the coefficients of heavy equipment or cycle time by utilizing the Analysis of Work Unit Price (AHSP) method [26]. Subsequently, these coefficients are used to estimate the CO_2 emissions.

To comprehensively assess the impact of varying volume scenarios of cut and fill works, three distinct case studies have been designed, each with specific volume parameters:

1. Case Study I: volume of cut works equals volume of fill
   In this scenario, the volume of earthwork cut operations is equal to the volume of earthwork fill operations, with both set at 2000 m³. The focus here is to analyse the carbon emissions when the excavation and embankment processes are in balance, with no net movement of materials. Data collection will include detailed records of heavy equipment usage, transportation distances, fuel consumption, and emissions at each stage of the construction process.
2. Case Study II: volume of cut works less than volume of fill
   This case study investigates the carbon emissions when the volume of cut works is greater than the volume of fill works, with 2000 m³ of excavation and 1000 m³ of embankment. In this scenario, 1000 m³ of surplus material will need to be transported and dumped in a designated dumping area (2 km). Data collection will involve tracking the transportation of materials from external sources, emissions during transport, and the subsequent handling and compaction processes.
3. Case Study III: volume of cut works greater than volume of fill
   In this scenario, the volume of cut works is less than the volume of fill works, with 1000 m³ of excavation and 2000 m³ of embankment. To meet the embankment requirements, 1000 m³ of material will need to be sourced from a nearby quarry (2 km). The case study examines the emissions associated with material extraction, transportation from the quarry, and handling at the construction site.

The following heavy equipment is employed in this study.

- Excavator (133 HP) for cut works: The excavator with a power rating of 133 HP is employed for excavation operations.
- Dump Truck (254 HP, 10-ton capacity) for material transportation: Material transport is facilitated by dump trucks with a power rating of 254 HP, each having a capacity of 10 tons.
- Motor Grader (135 HP) for material spreading: Material spreading is achieved using a motor grader with a power rating of 135 HP.
- Tandem Roller (74 HP) and Water Tank (135 HP) for material compaction: Compaction of the embankment is carried out with a tandem roller and a water tank, each with specific power ratings of 74 HP and 135 HP, respectively.

It is understood that cycle time plays an important role in carbon emission calculation. Cycle time represents the time required for a specific equipment to complete one unit of work, measured in hours per cubic meter (hr/m³). The cycle times for each equipment utilized in the construction process are calculated based on AHSP [26] as shown in Table 1.

Table 1. Equipment cycle time

Equipment	Cycle time (hr/m^3)
Excavator	0.0071
Dump truck	0.0303
Motor grader	0.0039
Tandem roller	0.0027
Water tanker	0.0070

RESULTS AND DISCUSSION

Carbon Emission Analysis

To quantify carbon emissions accurately, a systematic approach is employed, which involves the calculation of emissions for each piece of heavy equipment used in the construction process. Emissions are determined by multiplying the emission level ($KgCO_2$/hour) by the activity or cycle time, as previously detailed.

The emission level ($KgCO_2$/hour) for each tool is derived from a combination of factors, primarily based on the specifications provided by the tool manufacturer, which are further informed by direct observations in the field. A comprehensive set of specifications for each tool is obtained, considering factors such as tool type and model.

The specific calculation of the emission level ($KgCO_2$/hr) is as follows:

- Horsepower (hp): The horsepower rating of each tool is considered in the calculation. This value is a fundamental indicator of the tool's power and energy consumption.
- Fuel Consumption for Diesel Engines: The fuel consumption level for diesel engines is factored into the emission calculation. A standard fuel consumption rate of 0.04 gallons per horsepower-hour (gal/HP.hr) is used to quantify fuel usage during tool operation [29].
- Emission Factor for Diesel: The emission factor for diesel engines 10.15 $kgCO_2$/gal, as provided by the EPA [29], is incorporated into the calculation.

The calculation of carbon emissions level is based on (1).

$$E_f = EC \times F \times E_c \times C \quad (1)$$

where E_f is carbon emission level (in $kgCO_2/m^3$); EC is engine capacity (in HP); F is fuel consumption (in gal/HP.hr); E_c is carbon factor (in $kgCO_2$/gal); and C is cycle time of the equipment (hr/m^3). The total amount of carbon emissions, E_{tot} is determined using (2).

$$E_{tot} = \Sigma E_f \times V \quad (2)$$

where V is the volume of work (m^3).

Additionally, it is imperative to explore and analyse existing research efforts aimed at addressing the environmental impact of construction activities. This includes a detailed examination of methodologies employed in previous studies. This approach stands out for its comprehensive consideration of equipment specifications, direct field observations, and the incorporation of standard emission factors. The use of manufacturer-provided specifications and observed field data ensures a robust foundation for emission calculations, enhancing the reliability and accuracy of our results. This method not only aligns with established industry practices but also offers a nuanced understanding of emissions specific to the context of cut and fill work in construction.

Case Study I

In Case 1, where the volume of cut works equalled the volume of fill works (1000 m^3), there were two primary construction stages: cut and fill. Cut operations were executed using an excavator, while fill operations involved the utilization of a motor grader, tandem roller, and water tanker for compaction. This scenario, characterized by a net zero movement of materials, allowed for a simplified analysis of emissions pertaining to excavation and embankment activities. Table 2 presents carbon emissions for each piece of equipment for Case Study I.

Case Study II

In Case 2, the volume of cut works exceeded the volume of fill works (Cut: 2000 m^3, Fill: 1000 m^3), necessitating the introduction of a third stage: material transportation. Similar to Case 1, cut and fill operations employed an excavator, motor grader, tandem roller, and water tanker. However, the surplus material generated during excavation required transportation to an appropriate disposal area, thus introducing dump trucks into the construction process. This multifaceted scenario allowed for the examination of emissions associated with excavation, embankment, and material transport activities. Table 3 presents carbon emissions for each equipment for Case Study II.

Table 2. Carbon emission calculation for Case Study I

Equipment	Emission level ($kgCO_2/m^3$)	Total emission ($kgCO_2$)
Cut works		
Excavator	0.38	383.61
Fill works		
Motor grader	0.21	213.39
Tandem roller	0.08	80.86
Water tanker	0.39	385.21

Table 3. Carbon emission calculation for Case Study II

Equipment	Emission level ($kgCO_2/m^3$)	Total emission ($kgCO_2$)
Cut works		
Excavator	0.38	383.61
Fill works		
Motor grader	0.21	426.79
Tandem roller	0.08	161.72
Water tanker	0.39	770.42
Material transportation		
Dump truck	3.13	3127.14

Case Study III

In Case 3, the volume of fill works exceeded the volume of cut works (Cut: 1000 m³, Fill: 2000 m³), mirroring the circumstances of Case 2. The construction stages and equipment mirrored those of Case 2, with the inclusion of material transportation to meet embankment requirements. This scenario provided a parallel exploration of emissions associated with excavation, embankment, and material transport activities, emphasizing the variability in construction scenarios and their environmental implications. Table 4 presents carbon emissions for each equipment for Case Study III.

Discussion

The analysis of carbon emissions in the construction industry across three distinct cases, each representing varying scenarios of cut and fill works, yields valuable insights into the environmental impact of construction activities. The findings emphasize the significance of material transportation in influencing the overall carbon footprint of construction projects.

In Case I, where the volume of cut works equalled the volume of fill works (both set at 2000 m³), it's noteworthy that the total emission for cut works was 767 $kgCO_2$ (36%), whereas the total emission for fill works was 1358 $kgCO_2$ (64%) as shown in Figure 3. This disparity in emissions despite similar volumes requires further examination.

Table 4. Carbon emission calculation for Case study III

Equipment	Emission level ($kgCO_2/m^3$)	Total emission ($kgCO_2$)
Cut works		
Excavator	0.38	767.23
Fill works		
Motor grader	0.21	213.39
Tandem roller	0.08	80.86
Water tanker	0.39	385.21
Material transportation		
Dump truck	3.13	3127.14

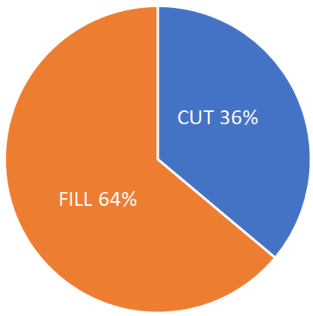

Figure 3. CO_2 emission percentage for Case I

One plausible explanation for the higher emissions from fill works could be attributed to the specific equipment and processes involved in the fill operations. The machinery used for fill works, including the motor grader, tandem roller, and water tanker, collectively emitted 1358 $kgCO_2$. These equipment units may have characteristics that result in higher emissions per unit of work completed compared to the excavator used for cut works.

Moreover, the nature of the tasks performed during fill works, such as material spreading and compaction, may require extended operating times or higher energy consumption, contributing to increased emissions. It's possible that these tasks involve more frequent starts and stops, leading to inefficiencies that drive up emissions.

To address this issue, further investigation is necessary to identify the specific factors contributing to the higher emissions in fill works. This may involve examining the equipment specifications, fuel consumption rates, and operational practices associated with fill activities. Once these factors are identified, strategies can be developed to optimize the equipment or processes to reduce emissions during fill works.

Case II, featuring a surplus of cut works (383.61 $kgCO_2$) compared to fill works (1358.92 $kgCO_2$) and the introduction of material transportation (3127.14 $kgCO_2$) as presented in Figure 4, underscores the considerable impact of material movement on emissions. While cut and fill operations still contribute to emissions, the dominant factor here is the transportation of surplus material to a disposal area. The emissions generated during transportation substantially outweigh those from excavation and embankment. This case serves as a clear illustration of the environmental consequences of importing materials to the construction site, making evident the need for sustainable transportation practices and efficient material utilization.

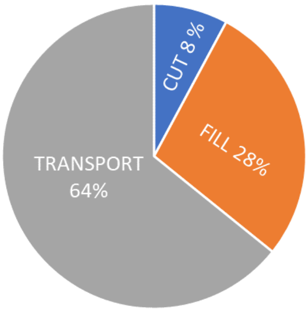

Figure 4. CO_2 emission percentage for Case II

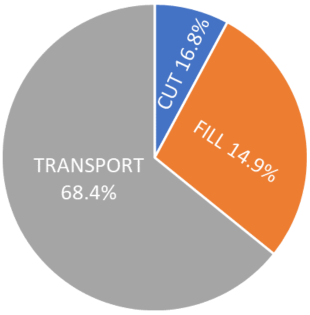

Figure 5. CO_2 emission percentage for Case III

To address this issue and mitigate the dominance of material transportation emissions, construction projects should prioritize strategies aimed at reducing surplus material generation. These may include more precise excavation planning, improved material utilization, and recycling or repurposing of surplus material on-site or in other projects. Additionally, optimizing transportation routes, employing fuel-efficient vehicles, and exploring sustainable disposal methods can contribute to emission reduction.

In Case III, mirroring the material transportation dynamics of Case II, but with a surplus of fill works (679.46 kgCO_2), similar trends are observed. Material transportation continues to be the primary contributor to emissions (3127.14 kgCO_2), overshadowing emissions from excavation (767.23 kgCO_2) and embankment (679.46 kgCO_2) as presented in Figure 5. Once again, this scenario highlights the paramount role of transportation, whether for importation (Case II) or exportation (Case III) of materials, in shaping the carbon emissions profile of construction projects.

The analysis reveals that among the various heavy equipment used in cut and fill work, the dump truck stands out as the primary contributor to CO_2 emissions. The elevated CO_2 emissions from dump trucks can be attributed to several key factors. Firstly, dump trucks typically have higher engine capacities, resulting in increased fuel consumption during their operation. Moreover, their function in transporting large volumes of materials over considerable distances necessitates frequent and prolonged use, further amplifying their carbon footprint.

These findings underscore the importance of optimizing material transportation in construction activities to mitigate carbon emissions. Strategies such as efficient routing, use of eco-friendly transport modes, and reducing surplus material movement can significantly reduce the carbon footprint of construction projects.

Furthermore, the results highlight the potential for sustainability initiatives in the construction industry, emphasizing the need for environmentally conscious decision-making and resource management throughout the project lifecycle [30][31].

CONCLUSION

The conducted studies have provided valuable insights into the carbon emissions associated with various stages of the construction process. Each case study shed light on specific aspects of construction activities, allowing for a comprehensive understanding of the environmental impact and opportunities for mitigation. The findings underscore the pivotal role of material transportation in shaping the carbon footprint of construction projects and emphasize the need for sustainable practices within the industry.

This study highlights the pressing need for sustainable practices within the construction industry. Optimizing material transportation, efficient routing, the use of environmentally friendly transport modes, and reducing surplus material movement are crucial steps in reducing the carbon footprint of construction projects. These measures not only contribute to environmental stewardship but also align with broader global efforts to combat climate change.

In conclusion, this study underscores the intricate interplay between excavation, embankment, and material transportation in determining carbon emissions in construction. By acknowledging the environmental implications of material movement and embracing sustainable practices, construction stakeholders can play an active role in addressing climate challenges and fostering a culture of eco-conscious decision-making and resource management throughout the construction project lifecycle. The construction industry has the potential to be an agent of positive change in mitigating its environmental impact and promoting a sustainable future.

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