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Life cycle assessment and management of carbon emission from reinforce concrete construction projects in Thailand

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Abstract

This study presented the comprehensive analysis and management to reduce carbon emissions in Thailand's reinforced concrete building construction projects using Structural Equation Modelling (SEM). Data were collected via questionnaires from experts certified by the Thailand Green Building Institute. The SEM analysis, which demonstrated good model fit, identified three main components: Material Manufacturing, Transportation, and Construction Processes. Structural work exhibited the highest factor loading, whilst electricity uses in construction showed the lowest. Notably, the study revealed the negative relationship between material manufacturing and transportation processes, challenging conventional assumptions. These findings provide crucial insights for designers and industry professionals in developing targeted strategies to reduce carbon emissions. The study's limitations include its focus on the Thai context and a specific set of variables. Future research should explore additional factors, such as renewable energy integration, and conduct longitudinal studies to refine our understanding of emission drivers in the construction sector.

Keywords: Structural equation modelling, Life cycle assessment, Carbon emissions, Reinforced concrete buildings, Thai construction industry

1. Introduction

Climate change is widely recognized as a critical global challenge, with the construction sector playing a significant role in greenhouse gas emissions due to its high energy consumption and reliance on carbon-intensive materials [1-6]. As a result, improving carbon management in construction has become an important research priority worldwide, thus presenting a significant potential for change [7, 8].

Within this global context, Thailand is considered one of the countries most vulnerable to climate change and is ranked 14th most at risk of extreme weather conditions. The country undergoes severe climate change effects, including drought and flood, classified as natural disasters [9, 10]. The Paris Agreement requires collective action to reduce the emission of GHG, especially from countries such as China and the USA, which together contribute 41%. It contributes to about 19% of the total global emissions [11]. This is important to avoid possible climate risks and reduce the scale of impacts that Thailand may experience.

The steady expansion of Thailand's construction industry has substantial implications for the country's economy, society, and environmental sustainability [10]. The sector generates greenhouse gas emissions across multiple lifecycle stages, including building construction, operation, maintenance, demolition, and recycling [12-14]. Notably, the production and construction phases alone account for approximately 40% of total emissions, underscoring the sector's critical role in national decarbonization efforts [5]. Despite this significance, systematic evidence on carbon emissions from Thailand's construction sector remains limited.

Although there are many studies on CO₂ emissions from different countries, there still needs to be systematic knowledge of emissions from Thailand's construction industry. This research aims to develop direct correlations between various factors influencing CO₂ emission from building construction projects. The findings are expected to provide helpful information and effective measures to reduce the carbon emissions of the construction industry. Previous literature mainly focuses on the global or regional level data, and the few studies that look at the factors affecting CO₂ emissions in Thailand are inconclusive. Thus, there is a need to conduct more extensive lifecycle assessments of construction projects in Thailand, from manufacturing construction materials to demolishing structures.

Moreover, specific solutions must be developed to decrease the negative environmental impact and consider the local traditions and economic situation. Further studies are necessary to understand the potential and risks of implementing advanced technologies like prefabricated assemblies and sustainable materials. Furthermore, research on the effectiveness of the current rules and regulations compared to international standards is needed to improve the policies and practices in the Thai construction industry.

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2. Research background

The Life Cycle Assessment (LCA) of carbon dioxide emissions emanating from building construction encompasses five principal stages: 1) product manufacturing; 2) transportation and construction; 3) usage, including maintenance, repair, and component replacement; 4) end-of-life processes, including demolition, deconstruction, transportation, processing, and waste disposal; and 5) reuse and recycling [12-14]. This investigation focuses predominantly on the factors influencing CO₂ emissions during the initial two stages: Firstly, product manufacturing, which includes procurement of raw materials, transportation of materials to manufacturing centers, and manufacturing of the material; and secondly, construction, which provides for transportation of material from manufacturing centers to construction sites and construction at the site. Table 1 below summarizes these factors and the literature related to them. The reference numbering presented in Table 1 reflects grouped citations from the systematic literature review, where multiple studies supporting the same emission factor are consolidated to improve readability and avoid redundancy. All references correspond directly to the sources listed in the reference section.

This research aims to identify and analyze specific factors that may influence CO₂ emissions during these critical stages and develop practical recommendations to reduce the carbon footprint of building construction projects in Thailand. Thus, it aims to explain the relationships between these factors to help advance appropriate construction practice in Thailand.

Table 1 Systematic Review of Construction Processes and LCA of CO₂ Emissions

Scope of Study	Factors	Description	Reference
Material Manufacturing	M1: Concrete	CO ₂ emissions from concrete production in the material manufacturing phase	[15-36]
Material Manufacturing	M2: Steel and Rebar	CO ₂ emissions from steel reinforcement and structural steel production in the material manufacturing phase	[15-32, 34]
Transportation	T1: Fuel to transport labor	CO ₂ emissions from fuel use in vehicles for labor transportation	[23, 37]
	T2: Distant to transport labor	CO ₂ emissions from vehicle travel distances for labor transportation	[23, 37]
	T3: Fuel to transport material	CO ₂ emissions from fuel use in vehicles for material transportation	[18, 20, 22, 31, 32, 34, 38, 39]
	T4: Distant to transport material	CO ₂ emissions from vehicle travel distances for material transportation	[18, 20, 22, 31, 32, 34, 38, 39]
	T5: Fuel to transport waste material	CO ₂ emissions from fuel use in vehicles for waste or construction debris disposal	[16, 22, 31, 37]
	T6: Distant to transport waste material	CO ₂ emissions from vehicle travel distances for waste or construction debris disposal	[16, 22, 31, 37]
Construction	C1: Electricity	CO ₂ emissions from electricity use during construction	[16-18, 28, 31, 32, 34, 40, 41]
	C2: Structural work	CO ₂ emissions from structural work activities	[15, 18, 24, 26]
	C3: Architectural work	CO ₂ emissions from architectural construction activities	[15, 18, 24]

3. Research method

3.1 Identification of the factors

A systematic literature review and a robust quantitative analysis were conducted to identify the antecedents of CO₂ emissions in reinforced concrete construction projects. The variables were tested for Anti-image Correlation to narrow the list further, with any value below 0.5 being eliminated [42]. This process continued until all the remaining variables had Anti-image Correlation values of more than 0.5, resulting in 11 significant variables, as described in Table 1 below.

Exploratory Factor Analysis (EFA) was then performed to group these variables into different factors. The Kaiser-Meyer-Olkin (KMO) measure was computed to determine the sampling adequacy, and it was obtained at 0.805, above the recommended threshold of 0.5 [42, 43]. In addition, Bartlett's test of Sphericity was significant at $P = 0.001$ [42, 43], which also showed that the data was suitable for factor analysis. Principal Component Analysis (PCA) with varimax rotation was used in factor extraction. Three components emerged with Eigenvalues exceeding 1 [42, 43]: Manufacturing of materials, transport, and construction. Table 1 below presents detailed results of the study considering the research questions posed in this study.

3.2 Conceptual Framework and Hypotheses

Drawing upon an extensive review of pertinent literature, the following hypotheses were formulated:

H1: Transportation processes arising from Material Manufacturing processes contribute to generating CO₂ emissions.

H2: Material Manufacturing processes contribute to the rise in CO₂ emission during the Construction process.

H3: Transportation processes impact raising the level of CO₂ emissions within the Construction process.

These hypotheses make up the conceptual framework depicted in Figure 1 below.

Figure 1 Elucidates the hypothesized relationships between the three principal processes involved: material manufacturing, transportation, and construction. The asterisks represent the hypothesized influence links, as the directional arrows show.

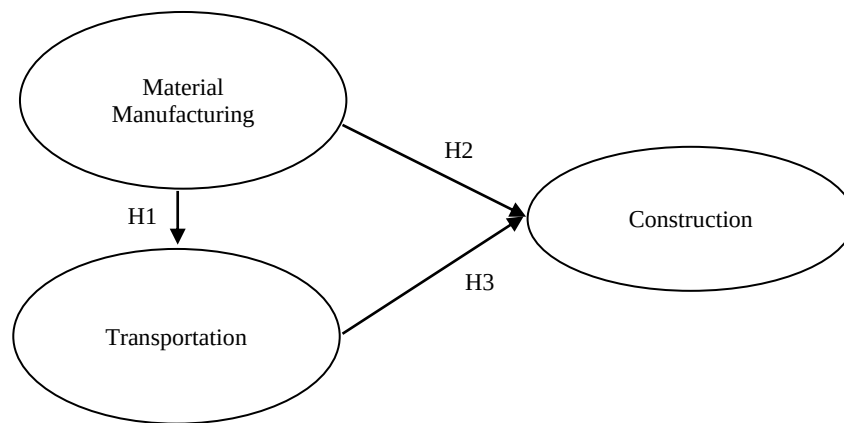


Figure 1 Conceptual Framework illustrating the hypothesized relationships among material manufacturing, transportation, and construction processes. Directional arrows indicate the proposed causal influences between latent variables.

3.3 Population and sample

The study population consists of 829 professionals who are certified by the Thai Green Building Institute. Out of this population, 330 certified experts filled out the questionnaire, which formed the basis of data collection and analysis. This sample size is in line with the recommendations made by Hair et al. [42], who opined that in factor analysis, the sample size should be more than 250 whenever the number of variables exceeds 30 [42].

3.4 Questionnaire design

This research uses a quantitative research method to answer the research hypotheses. The primary instrument is a self-developed questionnaire that is developed considering the conceptual framework, theoretical frameworks, and related studies in line with the research objectives. The questionnaire identifies three independent variable groups: materials manufacturing, transportation and the construction process. It is structured in two parts: It is structured in two parts:

Demographic and Professional Information: Gender, Age, Education level, Occupation, Position, Experience, and Type of Professional Certification of the Respondents Part 1.

Factors affecting CO₂ emission in reinforced concrete building construction in Thailand: Part 2. This section utilizes a five-point Likert scale: This section utilizes a five-point Likert scale:

Part 2: Factors influencing CO₂ emissions in reinforced concrete building construction in Thailand. This section utilizes a five-point Likert scale:

- 5 - No discernible impact on carbon emissions
- 4 - Minimal impact on carbon emissions
- 3 - Moderate impact on carbon emissions
- 2 - Significant impact on carbon emissions
- 1 - Profound impact on carbon emissions

3.5 Validity and reliability test

The validity and reliability of the questionnaire were rigorously tested in two phases:

- 1) Content Validity: Five construction and environmental industry experts with more than 20 years of experience reviewed the questionnaire to ensure its validity. To determine content validity, the index of objective congruence (IOC) was used, and the IOC obtained must be 0.60 to be considered acceptable [42, 43]. These findings showed that all the questions had an IOC value higher than 0.60, which shows that the content validity was quite high.
- 2) Reliability: After the content validity assessment, the questionnaire was pilot-tested on 30 respondents who are involved in construction projects. The results gave Cronbach's alpha value of 0.904, indicating that the questionnaire has a high internal consistency and reliability of the questionnaire [42, 43].

3.6 Data collection

Data collection was facilitated through the deployment of electronic questionnaires [44]. Of the total population, 330 experts completed the survey, and the response rate was 39 percent. 8%. Table 2 presents the demographic and professional information of the respondents to give a clear picture of the study participants.

This methodological approach helps to obtain reliable and valid data and, therefore, obtain a representative sample of experts that will be used for further analysis and inference.

However, it is important to note that a substantial proportion of respondents were professors and lecturers (55.5%), reflecting the strong representation of academic professionals within the Thai Green Building Institute certification network. These individuals are actively engaged in research, professional training, and industry collaboration, and therefore possess extensive knowledge of sustainable construction practices and carbon management. Their expertise provides informed evaluations of emission drivers across construction phases, which strengthens the analytical reliability of the SEM results.

Nevertheless, this distribution may limit the full representation of practitioner perspectives, particularly those of contractors and field engineers. Accordingly, the findings should be interpreted with appropriate caution when generalizing to the broader construction

industry. Future studies are encouraged to incorporate a more balanced mix of academic and industry respondents to enhance external validity.

Table 2 Percentage of samples classified by the general information (n = 330)

Characteristic	Information	N	Percentage
Education	Master's degree	260	78.8
	Doctorate degree	70	21.2
Occupation	Government employee	20	6.1
	State enterprise employees	5	1.5
	Private employee	122	37.0
	Professor	183	55.5
Position	Project Director	13	4.8
	Project Manager	35	10.6
	Project Engineer	21	6.4
	Project Architect	50	15.2
	Lecturer	197	59.7
	Other	11	3.3

4. Results

To understand the interdependency of the factors that influence carbon emissions in Thailand's reinforced concrete building construction projects, Structural Equation Modelling (SEM) was implemented. This complex statistical method was adopted because it tests the various hypothesized correlations between the various latent variables, each represented by several indicators (Kline, 2015). The model fit indices used in the analysis of the SEM included Chi-Square (χ^2), Relative Chi-Square (χ^2/df), p-value, Goodness of Fit Index (GFI), Normal Fit Index (NFI), Tucker-Lewis Index (TLI), Comparative Fit Index (CFI), Root Mean Square Residual (RMR), and Root Mean Square Error of Approximation (RMSEA). According to Schumacker, E., & Lomax, G. (2016), Hair, J. F., et al. (2019), the criteria for a good fit are as follows: The cut-off criteria for the current analysis were $\chi^2/df < 2.00$, p-value > 0.05 , GFI > 0.90 , NFI > 0.90 , TLI > 0.90 , CFI > 0.90 , RMR < 0.08 , and RMSEA < 0.05 [42, 45].

4.1 Model development and refinement

The first SEM analysis with 11 variables showed that the model has a poor fit with the empirical data (Table 1). This misalignment is not surprising in such systems as construction industry where many factors and actors work in a system and their behavior is not always easy to predict. The first SEM analysis performed with 11 variables produced the model presented in Figure 2.

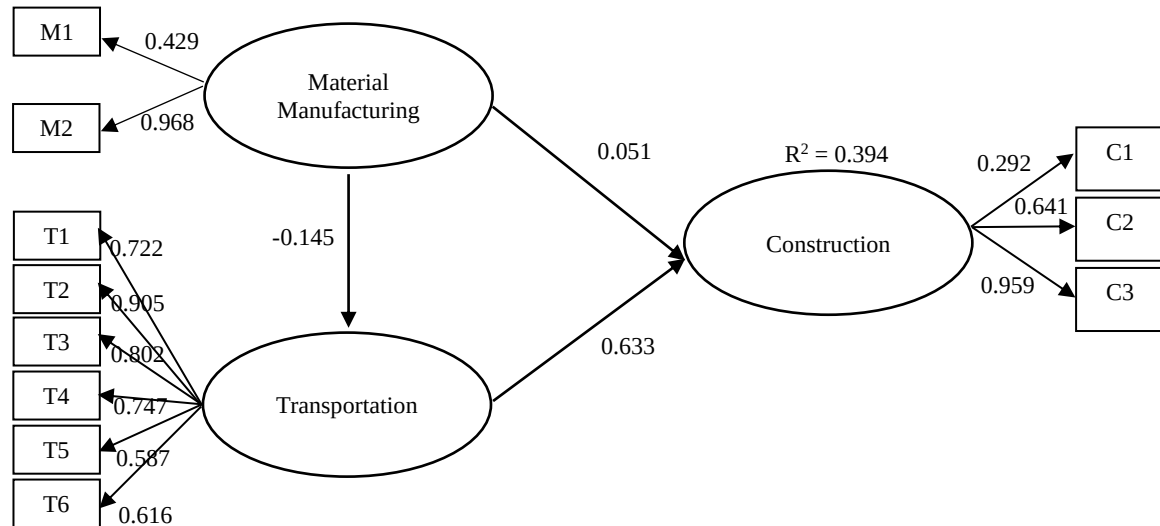


Figure 2 Initial structural equation model showing standardized path coefficients among latent constructs. Arrows represent causal relationships, while rectangles denote observed variables used as measurement indicators.

As can be observed from Figure 2, the preliminary SEM analysis indicates a Relative Chi-Square (χ^2/df) of 7.273 (> 2.00), a p-value of 0.00 (< 0.05), and GFI of 0.862 (< 0.90), NFI of 0.814 (< 0.90), TLI of 0.777 (< 0.90), CFI of 0.834 (< 0.90), RMR of 0.138 (> 0.08), and RMSEA of 0.056 (> 0.05). These results suggest that the initial SEM is not an adequate fit to the empirical data.

To increase the model fit, we used the Model Modification Indices (MI) to guide an iterative process of model refinement. This process eliminated five variables: X40, X21, X22, X29, and X30 from the initial model. It was possible to remove these variables since they were either irrelevant or less influential in the construction process in Thailand. The revised SEM analysis is presented in Figure 3 below.

4.2 SEM Analysis results

The last analysis of SEM was Factor Loading Standardised (Beta), Factor Loading Unstandardised (b), Standard Error (SE), Critical Ratio (CR), and p-value (P). The results are shown in Table 3 below.

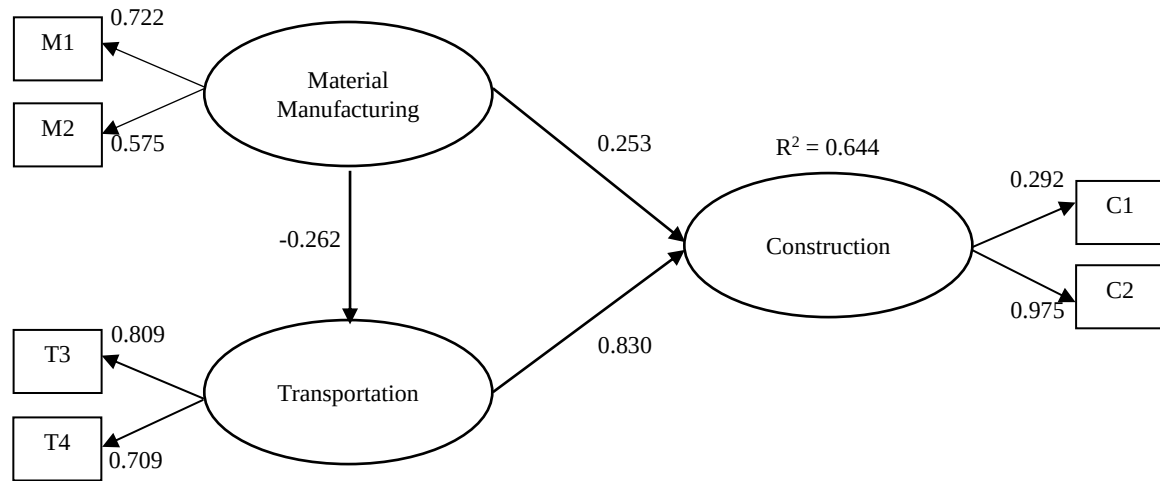


Figure 3 Final structural equation model after modification, presenting standardized regression weights and the strength of relationships among material manufacturing, transportation, and construction factors.

The SEM analysis, as presented in Figure 3 with the modifications, gave a Relative Chi-Square (χ^2/df) of 1.985 (< 2.00), a p-value of 0.064 (> 0.05), and GFI of 0.988 (> 0.90), NFI of 0.972 (> 0.90), TLI of 0.964 (> 0.90), CFI of 0.986 (> 0.90), RMR of 0.055 (< 0.08), and RMSEA of 0.018 (< 0.05). These statistics show that the new SEM has a good fit with the empirical data. The goodness-of-fit indices before and after model modification are presented in Table 3 below.

Table 3 Fit indices for the SEM analysis

Index	Criterion	Initial Structural Model		Final Structural Model	
		Statistic	Result of Consideration	Statistic	Result of Consideration
Relative Chi-Square	< 2.00	7.273	Unqualified	1.985	Qualified
p-value	> 0.05	0.000	Unqualified	0.064	Qualified
GFI	> 0.90	0.862	Unqualified	0.988	Qualified
NFI	> 0.90	0.814	Unqualified	0.972	Qualified
TLI	> 0.90	0.777	Unqualified	0.964	Qualified
CFI	> 0.90	0.834	Unqualified	0.986	Qualified
RMSEA	< 0.08	0.138	Unqualified	0.055	Qualified
RMR	< 0.05	0.056	Qualified	0.018	Qualified

After that, the SEM analysis was used to analyze the Factor Loading Standardize (Beta) Factor Loading Unstandardized (b) Standard Error (SE) Critical Ratio (CR) p-value (P). The results of the SEM analysis are shown in Table 4 below.

The Factor Loading Standardize (Beta) is shown in Table 4, which varies between -0.262 and 0.975. The highest component weight is C2, which is Structural work, and the factor loading value is 0.975. The smallest factor loading value is C1 (Electricity use), and the element weight value is 0.292.

From the hypothesis test results, it was found that the statistical significance accepts hypothesis H1, but the relationship between Material Manufacturing (M) and Transportation (T) is equal to -0.262, which is negative. This means that if M increases, T will decrease, or if M decreases, T will increase, and so on, which does not conform to the hypothesis of H1. The statistical significance supports the hypotheses H2 and H3. Thus, it can be stated that Material Manufacturing leads to the augmentation of the CO₂ emission in the Construction process. In contrast, Transportation leads to the augmentation of CO₂ emission in the Construction process.

Table 4 SEM Analysis Results

Variable	Beta	b	SE	CR	p	Hypothesis
Transportation <--- Material Manufacturing	-0.262	0.000	0.257	-2.984	0.003	Reject
Construction <--- Material Manufacturing	0.253	-	0.202	3.585	***	Accept
Construction <--- Transportation	0.830	-	0.073	11.064	***	Accept
MM1 <--- Material Manufacturing	0.722	1.112	0.323	3.439	***	
MM2 <--- Material Manufacturing	0.575	1.000	-	-		
T3 <--- Transportation	0.809	1.000	-	-		
T4 <--- Transportation	0.709	0.834	0.073	11.460	***	
C1 <--- Construction	0.292	0.287	0.077	3.736	***	
C2 <--- Construction	0.975	1.000	-	-		

*** p < 0.001

4.3 Hypothesis testing results

- H1:** It was revealed that Material Manufacturing (M) has a significant but negative impact on Transportation (T) ($\beta = -0.262$, $p = 0.003$). This counter-intuitive negative correlation implies that while the manufacturing of materials rises, transportation

emissions fall, or the other way around. This result does not support the hypothesis developed at the beginning of this study and needs further exploration.

2. **H2:** The hypothesis was formulated for Material Manufacturing and Construction was supported. The positive and significant coefficient ($\beta = 0.253$, $p < 0.001$) suggests that material manufacturing processes are a factor that leads to higher CO₂ emissions in the construction process.
3. **H3:** The hypothesis concerning the relationship between Transportation and Construction was also accepted. The significant and positive correlation coefficient ($\beta = 0.830$, $p < 0.001$) indicates that transportation processes play a huge role in enhancing CO₂ emission in the construction process.

These findings are useful in understanding the factors influencing carbon emissions in Thailand's reinforced concrete building construction projects and forming a solid platform for analysis and interpretation.

4.4 Key findings

1. **Material Manufacturing and Transportation:** However, the results indicated an unexpected negative relationship where the results were ($\beta = -0.262$, $p = 0.003$). This counterintuitive result implies that with the growth of material manufacturing activities, transportation emissions are not growing. This could potentially point to increased supply chain efficiency or the use of more localized production processes as manufacturing is ramped up, a trend that has not been observed in the Thai construction literature before. One possible explanation is that large construction projects with substantial material demand often rely on nearby suppliers, such as local ready-mixed concrete plants and regional steel distributors, to reduce delivery time and control logistics costs. As a result, although material manufacturing activities increase, transportation distances may decrease, leading to lower transport-related emissions. Another interpretation is the growing maturity of construction supply chains in Thailand, where contractors increasingly optimize procurement strategies by sourcing materials from geographically proximate production hubs. This operational adjustment may create an emission trade-off in which carbon intensity shifts toward the manufacturing phase rather than the transportation phase, instead of both increasing simultaneously. From a managerial perspective, this finding highlights the importance of evaluating carbon emissions using a systems-based approach. Strategies that focus solely on reducing transportation distances may unintentionally encourage the use of carbon-intensive materials, while prioritizing low-carbon materials without considering sourcing proximity may not produce the expected environmental benefits. Therefore, integrated decision-making across material selection, supplier location, and logistics planning is essential for achieving meaningful emission reductions in reinforced concrete construction projects.
2. **Material Manufacturing and Construction:** It was possible to verify a positive relationship ($\beta = 0.253$, $p < 0.001$), thus corroborating the hypothesis that a higher material production generates more significant emissions in the construction phase. This is in line with earlier works that established a strong correlation between construction materials and carbon emissions.
3. **Transportation and Construction:** Logistics has the highest coefficient of determination in the model ($\beta = 0.830$, $p < 0.001$), thus pointing to the importance of the factor in explaining overall carbon emissions. This strong result supports recent research highlighting the importance of efficient supply chain management in sustainable construction.
4. **Factor Loadings within Construction Process:** As shown in the factor loadings, structural work (C2) had the highest factor loading of 0.975, and electricity use (C1) had the lowest factor loading of 0.292. This implies that direct energy consumption on-site may have a relatively lower impact on emissions than other construction activities. This result contradicts some of the existing literature, and thus requires further research.

These results present a more complex view of the determinants of carbon emissions in Thailand's construction sector and can inform more specific strategies for change and policy suggestions. The other interesting findings of this study include the negative relationship between material manufacturing and transportation, and this discovery creates new research directions for the changing nature of sustainable construction practices in developing economies.

5. Discussion

This research's results help explain that the manufacturing and transportation of materials are the main factors influencing CO₂ emissions during construction in Thailand's reinforced concrete buildings (Figure 4). These results support and expand the current research on the environmental effects of construction phases [24, 39]. The findings presented in this study provide a better understanding of the multiple factors within the Thai construction context and are, therefore, a significant theoretical and practical contribution to the field.

The present work reveals that concrete, steel, and reinforcements are the primary carbon emission sources in manufacturing materials. This finding supports the recent study by Wang et al. [46] and Liwthaisong et al. [47]. For instance, cement making, which is an input in concrete production, contributes to about 90% of the total CO₂ emissions in concrete production. This figure only proves the urgent call for new and more sustainable cement substitutes and better cement manufacturing methods to decrease the overall emissions in the construction industry. Further research should be conducted about the new materials and technologies that could be used in the production process to make the industry more sustainable. [16, 28, 47-52]

Distance and fuel type are the two factors that influence the amount of CO₂ emissions during transportation. This is in line with the studies Li et al. [28], who also pointed out the possibility of emissions cuts via efficient logistics management and the use of electric vehicles. As for the second comparison, the transition to battery electric vehicles would lead to indirect carbon emissions during electricity generation. However, our analysis shows that the total emissions would still be lower than emissions from fossil fuels, which aligns with Wang et al. [46]. Nevertheless, the practical application of such changes in the Thai context may have particular difficulties, such as infrastructure and cost, which require further research.

The construction process is the primary source of CO₂ emissions, mainly due to electricity consumption and construction work. This result is in line with the research conducted by Zhang et al. [18] and Wang et al. [46], which emphasized the need to adopt sustainable construction practices and materials. From our findings, it is possible to conclude that enhancing energy efficiency on construction sites and investigating other possibilities for constructing structures can lead to considerable decreases in carbon emissions. Future research could be directed toward exploring and validating new low-emission construction practices appropriate to the Thai climate and building culture.

The enhancement of the fit of our SEM model after the modification supports the assertion that variable selection and model adjustment are critical to SEM analysis. This methodological insight is helpful for the construction research field and shows the usefulness of refining the model in iterations. Furthermore, the non-acceptance of some hypotheses suggests a dependency between the construction phases, which this research has yet to fully explain and should be studied in future research. This finding supports the need to adopt a life cycle thinking approach in managing carbon emissions in the construction industry.

However, it is essential to note that this study has its limitations. The emphasis on the Thai construction industry may reduce the transferability of our results to other settings.

Additionally, the respondent profile was predominantly academic, which may introduce perspective bias toward strategic and policy-level interpretations rather than operational construction challenges. While academic experts often collaborate closely with industry and contribute to professional standards, future research should seek broader participation from contractors, project managers, and on-site practitioners to improve the generalizability of the findings.

Beyond sampling considerations, the structural model developed in this study does not explicitly incorporate several emerging variables that may influence carbon emissions in contemporary construction projects. Factors such as renewable energy adoption, low-carbon materials, construction automation, and digital technologies (e.g., Building Information Modeling and smart logistics systems) have demonstrated growing potential to reshape emission patterns across the project lifecycle. Their exclusion was primarily intended to preserve model parsimony and maintain statistical stability; however, integrating these variables in future research could generate a more comprehensive representation of carbon mitigation mechanisms.

Furthermore, infrastructure conditions within Thailand present additional contextual constraints. While decarbonization strategies such as electrified transportation fleets, advanced supply chain optimization, and technology-driven construction practices are widely promoted in global sustainability discourse, their large-scale deployment in Thailand remains uneven due to technological readiness, investment capacity, and regional infrastructure disparities. These structural challenges may limit the immediate applicability of certain low-carbon interventions and should therefore be considered when interpreting the study's practical implications.

Accordingly, the findings should be interpreted as context-sensitive rather than universally generalizable, particularly when compared with construction environments supported by more mature low-carbon infrastructure systems.

Future research could build on this study by conducting similar investigations across different countries, especially in the Southeast Asia region, to reveal regional trends and contextual factors that influence carbon emissions in construction.

Therefore, this research adds to the existing literature on carbon emissions in construction and provides more detailed information about Thailand. The results reveal the relationships between different phases of construction projects and their effects on carbon footprint. These results can be used for policy and practice to decrease the carbon impact of construction projects in Thailand and perhaps in other developing nations with similar construction profiles. As the world struggles to find solutions to the effects of climate change, research like this is helpful in formulating a better-built environment.

Future work could focus on the identification and empirical studies of other low-emission construction practices that are suitable for the Thai climate and construction traditions.

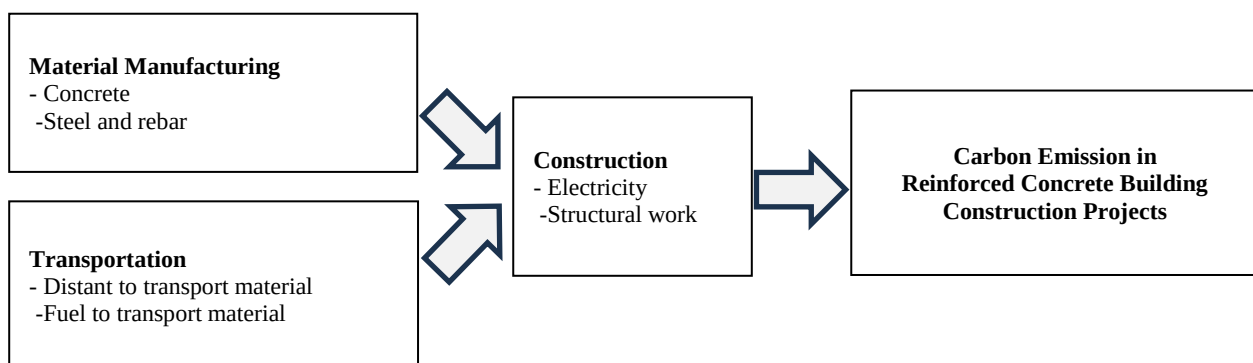


Figure 4 Causal model summarizing the key emission drivers identified in reinforced concrete building construction projects in Thailand. Arrows indicate the direction of influence between major construction phases.

6. Conclusion

The present research aims at identifying CO₂ emissions in the construction sector of Thailand and helps in fulfilling the key research questions and objectives, and significantly contributes to the understanding of the carbon footprint in the developing countries. Using structural equation modeling, material manufacturing, transportation, and construction activities significantly affect carbon emissions in reinforced concrete building projects. Remarkably, an inverted U-shape relationship between material manufacturing and transportation processes were identified, which was not previously theorized and thus extends the existing knowledge by suggesting that supply chain configuration and sourcing proximity may significantly influence the distribution of carbon emissions across construction phases.

The fact that construction emissions are dominated by transportation shows that logistics optimization, which has not been considered a significant factor before, is crucial. This is because, through our analysis of the construction process, we have identified structural work as the major source of emissions and, therefore, a clear area of focus for improvement through the use of new methods and materials.

Despite the shortcomings in data collection and variable selection, this research offers a reference model for approaching the problem of CO₂ emissions in the construction sector. The findings' implications are relevant to policymakers and industry professionals as a guide to sustainable practices and policies.

Further research should be directed toward using new technologies, assessing policy effects, and long-term research to improve the understanding of emission factors. Such an approach is crucial for the advancement of a sustainable construction industry and the effective implementation of climate change initiatives at the international level.

Future research should focus on integrating advanced technologies, evaluating policy impacts, and conducting longitudinal studies to refine our understanding of emission drivers. This comprehensive approach is essential for progressing towards a sustainable construction sector and contributing meaningfully to global climate change mitigation strategies.

6.1 Policy implications

The results of this study are very relevant to policymakers in the construction industry. These findings can be used by policymakers to formulate policies that require low-carbon materials and energy-efficient construction. Promoting the use of electric vehicles for material transportation and establishing sustainable construction guidelines can also help reduce CO₂ emissions. Other long-term policies that could work for the industry include those that encourage research and development in low-carbon cement and steel production.

6.2 Practical applications

The study is particularly significant to industry professionals as it reveals that sustainability should be integrated into construction projects at all levels. Material manufacturers should ensure that they use low-carbon processes in the production of the materials, while construction firms should ensure that they use efficient transport and energy-saving technologies. Implementing these practices can significantly reduce the carbon footprint of construction projects in line with international sustainable development goals.

1. The data was collected mostly from Thai experts, and as such, the findings may not be generalizable to other countries.
2. The study focused on a specific subset of variables influencing CO₂ emissions. Future research should explore additional variables, such as the impact of renewable energy sources and technological advancements.
3. Expanding the datasets and conducting more longitudinal research could help fine-tune the model and improve the model's potential for use in the construction industry, which would help create a more sustainable construction industry.
4. Future research should also centre on the application of superior technologies and the assessment of the effects of policies in order to improve emission reduction initiatives.

Therefore, this approach is crucial in moving towards the development of a sustainable construction industry in Thailand and possibly in other developing nations with similar construction practices.

7. Acknowledgments

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