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BIM-Based Discrete Event Simulation for Embodied Carbon Assessment

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Abstract

The urgent need to reduce carbon emissions within the building and construction industry has underscored the importance of embodied carbon assessment. Building Information Modeling (BIM) and Discrete Event Simulation (DES) emerge as promising tools for enhancing this assessment process, offering detailed data extraction capabilities and dynamic simulation for energy consumption quantification. While previous research has explored the potential of BIM-DES integration, this paper addresses existing gaps by identifying and incorporating essential information requirements into BIM models for more effective DES-based embodied carbon assessment. This paper thus develops a BIM-based DES method for cradle-to-site embodied carbon assessment by (1) developing an integrated ontology to identify data requirements, (2) enriching BIM models with the necessary information for DES modeling based on the ontology, and (3) building the DES model based on the data extracted from the enriched BIM-related file and implementing scenario-based analysis. This integrated approach facilitates efficient and comprehensive analysis of cradle-to-site embodied carbon. The synergy between BIM and DES enables stakeholders to make informed decisions early in the project lifecycle, optimizing carbon reduction strategies through scenario-based analysis.

1 Introduction

With the increase in carbon emissions from the building and construction industry, there is an urgent trend of carbon reduction in the whole industry (UNEP, 2024). As one of the major parts of the life cycle carbon emissions of buildings and construction projects, the assessment of embodied carbon plays a pivotal role in understanding the environmental impact of building materials and processes (Huang et al., 2018). Embodied carbon refers to the sum of greenhouse gas emissions associated with the production, transportation, and disposal of construction materials throughout their life cycle (UNEP, 2023). From the Life Cycle Assessment (LCA) perspective of the carbon emission management of a project, cradle-to-site embodied carbon accounts for the majority of total embodied carbon for a building infrastructure, which refers to the emissions associated with the production and procurement of building materials, from raw material extraction (A1 – A3 stages), transportation to

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site (A4 stage), to on-site construction activities (A5 stage) (BSI, 2011). As the global construction industry increasingly focuses on reducing carbon emissions and mitigating climate change, accurate assessment and management of cradle-to-site embodied carbon have become imperative.

However, obtaining accurate and comprehensive data can be challenging for the cradle-to-site embodied carbon assessment, especially when considering the multitude of materials and construction activities involved in cradle-to-site stages (Sharrard et al., 2008). The emergence of Building Information Modeling (BIM) as a digital representation of physical and functional characteristics of buildings has paved the way for more sophisticated and data-driven approaches to different application fields in construction management, including embodied carbon assessment (Bryde et al., 2013). It can be used to extract material type information, quantities, and other data directly as inputs for embodied carbon quantification, especially streamlining the data collection for the product (A1 – A3 stages) embodied carbon assessment. Discrete Event Simulation (DES) is another potential tool that can support data collection and analysis for cradle-to-site embodied carbon assessment. It is a method for modeling and analyzing system behavior across time, enabling the simulation of construction processes, material flows, and resource usage to measure fuel consumption during construction (Robinson, 2005). Given the challenges of managing extensive data on early-stage construction activities and the inaccuracies stemming from the impracticality of empirical data in certain construction contexts, DES serves as a valuable tool for gathering precise information through simulated outcomes for process-driven embodied carbon assessment, particularly for stages A4 and A5.

Previous research has investigated the integration of BIM and DES for cradle-to-site embodied carbon assessment. Usually, BIM data extraction offers essential quantity details for DES model elements, enabling the simulation of energy consumption quantities crucial for cradle-to-site EC assessment (Wang et al., 2014; Dashti et al., 2021). For example, König et al. integrated BIM into the simulation input data creation process for construction scheduling management (König et al., 2012). This approach facilitated intelligent and efficient DES modeling by generating input data for construction simulation by using linked BIM data and reusable templates. However, the existing BIM-DES integration is not sufficient enough since common BIM models lack the necessary information required for DES modeling, such as detailed quantity-related data for different materials used in a single structural element, and on-site construction resource-related information. Therefore, this paper seeks to address the gap by exploring the integration of BIM with DES for embodied carbon assessment in construction projects. By identifying necessary information requirements for BIM-based DES for embodied carbon assessment, enriching the BIM model accordingly, and combining the rich information stored in BIM models with the dynamic simulation capabilities of DES, this approach offers a holistic and real-time analysis of cradle-to-site embodied carbon assessment. Through this integration, stakeholders can gain valuable insights into the environmental impact of design decisions, material selections, and construction processes based on scenario-based analysis, enabling them to optimize carbon reduction performance.

2 Method

Figure 1 shows the overview of the proposed method of BIM-based DES for embodied carbon assessment. There are three modules in this method. Module 1 presents the integrated ontology development process to identify data requirements and mapping relationships in BIM-based DES for embodied carbon assessment, which involves the integration of two knowledge fields, embodied carbon assessment parameters and BIM elements in the Industry Foundation Classes (IFC) format. This ontology integrating embodied carbon assessment and BIM elements is developed in a commonly used knowledge management software called Protégé. Module 2 is then designed for IFC extension based on the data requirements identified in the integrated ontology in Module, which helps semantically enrich and prepare the IFC file ready for DES-based modeling and embodied carbon assessment. In Module 3 of BIM-based DES for embodied carbon assessment, the DES model is built based on the data directly extracted from the extended IFC file. This model is also used for scenario-based analysis to identify the embodied carbon reduction strategies.

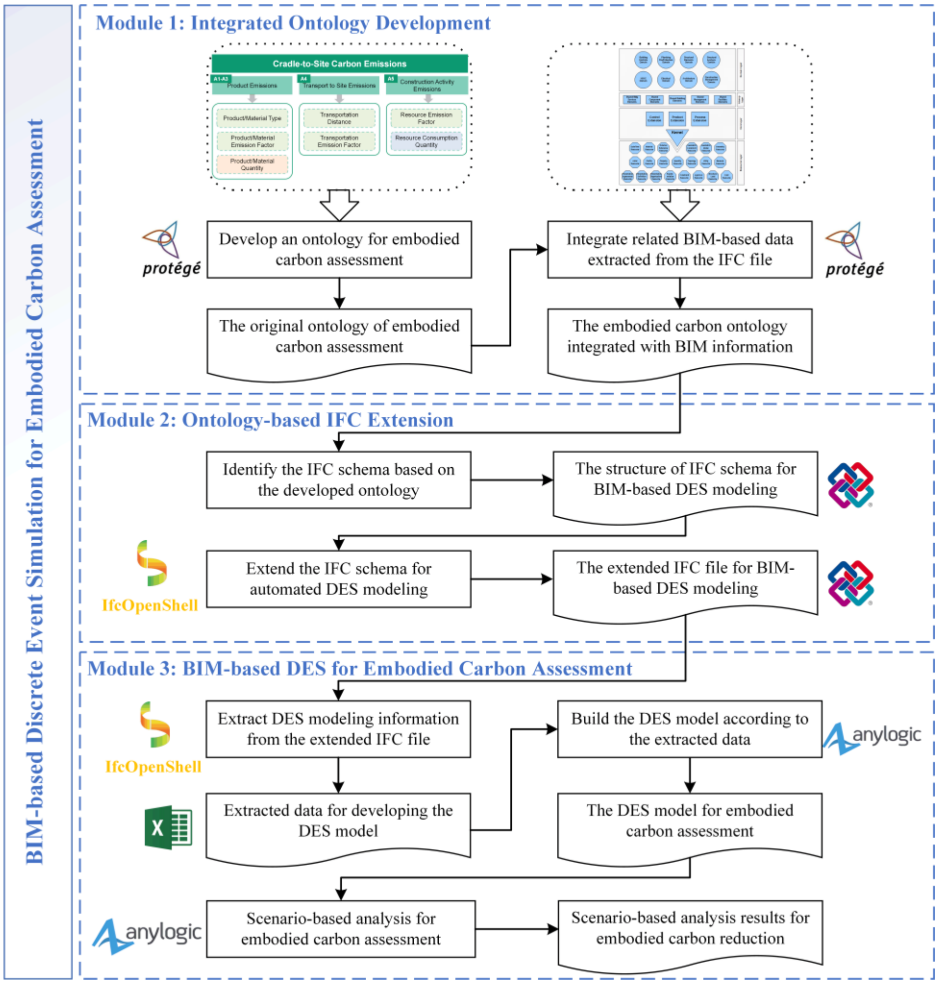
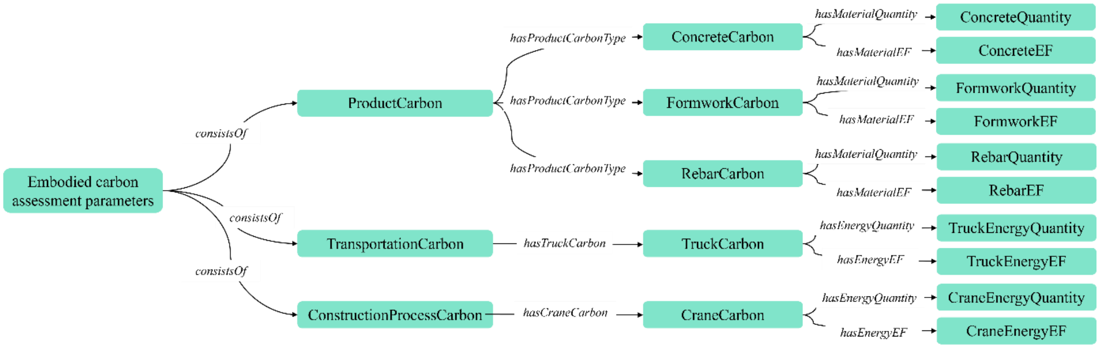


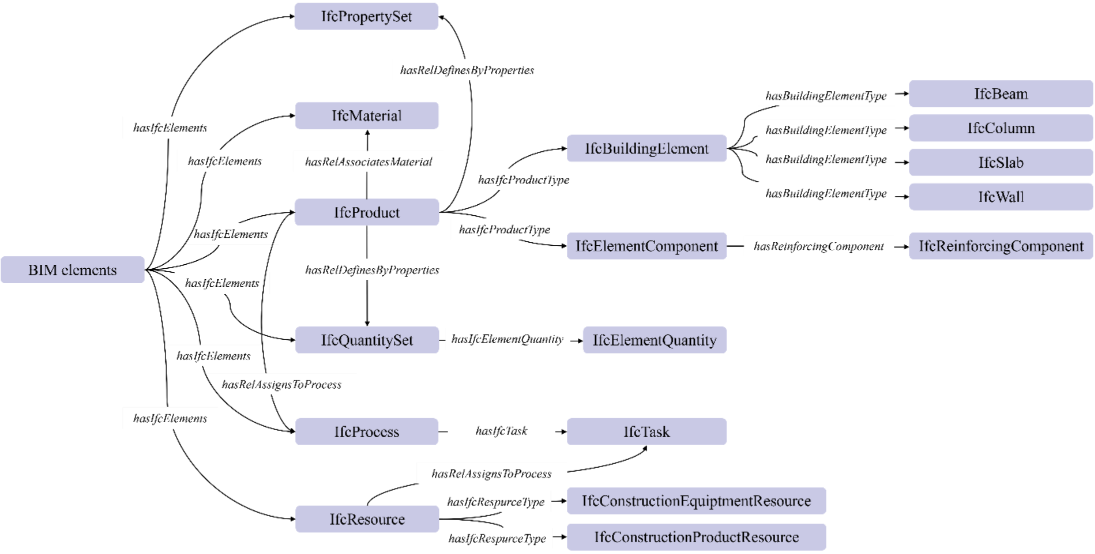
Figure 1: Method overview

2.1 Integrated Ontology Development

This section presents the ontology integration of two domains: (1) cradle-to-site EC assessment parameters to identify basic parameters for embodied carbon quantification from A1 to A5 stages, and (2) BIM elements for embodied carbon assessment to identify how BIM could store and provide such parameters required in EC assessment. Accordingly, two sub-ontologies are first developed (as shown in Figure 2) as components of the integrated ontology with class hierarchies, object property hierarchies, and data property hierarchies. In the sub-ontology for cradle-to-site embodied carbon assessment in Figure 2(a), three main cradle-to-site embodied carbon emission sources are set as individual classes in the second hierarchy, which are product carbon (A1 – A3 stages), transportation carbon (A4 stage), and construction process carbon (A5 stage). For product carbon, three main materials, concrete, formwork, and rebar, are considered in this study, and each material is equipped with its quantity and emission factor for EC assessment. Similarly, trucks and cranes are considered in this sub-ontology for transportation carbon and construction process carbon, respectively. Figure 2(b) describes all BIM elements in the format of IFC entities that are related to parameters required in cradle-to-site embodied carbon assessment, which further directs to how IFC entities can store and provide data for BIM-based DES for embodied carbon assessment. In Figure 2(b), IFC entities as classes at the second hierarchy are shown in the ontology, including IfcMaterial, IfcProduct, IfcResource, IfcProcess, IfcPropertySet, and IfcQuantitySet that can provide the necessary information in embodied carbon assessment.



(a) Sub-ontology for cradle-to-site embodied carbon assessment



(b) Sub-ontology for BIM elements related to embodied carbon assessment

Figure 2: Sub-ontologies in related domains

Based on the two sub-ontologies above, the integrated ontology is designed with content and mapping representations between the two sub-ontologies. As shown in Figure 3, the integrated ontology keeps all classes and internal relationships in two sub-ontologies as components. Apart from these existing components, classes in the second hierarchy from two sub-ontologies are connected with external relationships, which helps to identify mapping relationships among different domains. Three classes (product carbon, transportation carbon, and construction process carbon) from the sub-ontology that indicate three main cradle-to-site embodied carbon emission sources are connected to classes in sub-ontology of BIM elements based on how IFC entities can provide parameter data for different emission sources in embodied carbon assessment. To summarize, this integrated ontology identifies clear and structured data requirements from two domains for BIM-based DES for embodied carbon assessment and establishes mapping relationships between two domains to ensure data availability during BIM extraction, which is helpful to improve DES modeling efficiency based on direct BIM extractions.

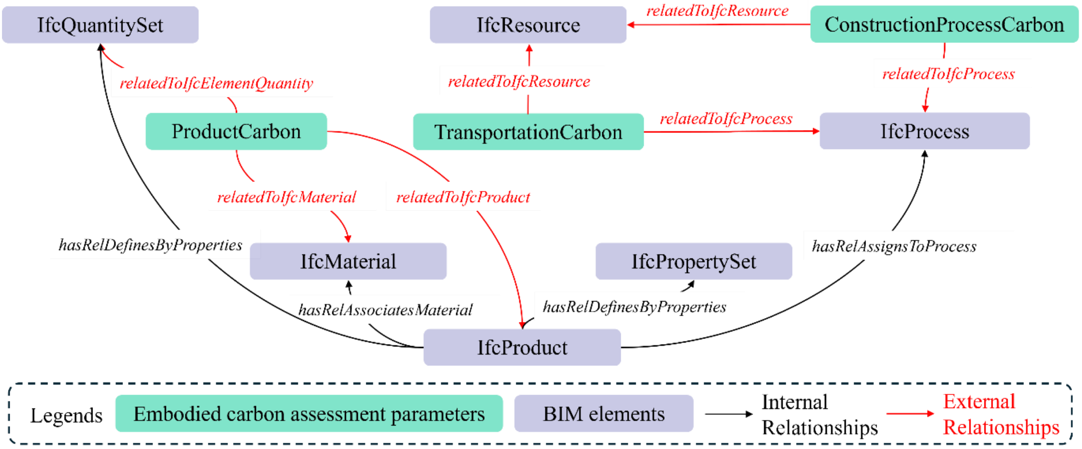


Figure 3: Integrated ontology

2.2 Ontology-based IFC extension

Although the IFC schema incorporates numerous classes referred to as "entities" to describe building information, the information identified in BIM-based DES for cradle-to-site embodied carbon assessment in the integrated ontology is beyond the current scope of the IFC schema, especially for (1) detailed quantity-related data for different material used in a single structural element, and (2) on-site construction resource-related information. To enable the IFC file to provide the necessary information required for DES modeling for embodied carbon assessment, the IFC file exported from the BIM model is semantically enriched based on the integrated ontology. The enriched IFC property sets with properties are proposed in Table. 1. For the enrichment of detailed quantity-related data, parameters of different ratios deciding the material quantities are incorporated into a new property set, designated as "Mset_ModelingSourceCommon", which is attached to the IfcBuildingElement entities (including IfcBeam, IfcColumn, IfcWall, and IfcSlab) to provide quantity information in DES modeling. For the enrichment of on-site construction resource-related information, the enriched property sets "Mset_ModelingResourceCommon" and "Mset_ModelingResourceIndicators" are added to IfcConstructionEquipmentResource to store basic equipment parameters (such as number and loading capacities) and emission-related indicators of equipment operations, respectively. The initial IFC schema is then further extended by IfcOpenshell to incorporate all these mentioned property sets with properties to realize BIM-based DES modeling for cradle-to-site embodied carbon assessment.

Table 1. Extended property sets for DES-based modeling

Property set	Property	Description
Mset_ModelingSourceIndicators	M_ConcreteRatio	The ratio of actual concrete use to element quantity in structural elements
	M_RebarRatio	The ratio of actual rebar use to element quantity in structural elements
	M_FormworkRatio	The ratio of actual formwork use to element quantity in structural elements
Mset_ModelingResourceCommon	M_ResourceNumber	The number of construction equipment on-site
	M_ResourceCapacity4Concrete	The capacity for concrete (m^3)
	M_ResourceCapacity4Rebar	The capacity for rebar (kg)
	M_ResourceCapacity4Formwork	The capacity for formwork (m^2)
Mset_ModelingResourceIndicators	M_ResourceBusyEF	The EF of equipment during operation
	M_ResourceBusyEFUnit	The EF unit of equipment during operation
	M_ResourceIdleEF	The EF of equipment during idling
	M_ResourceIdleEFUnit	The EF unit of equipment during idling

2.3 BIM-based DES for Embodied Carbon Assessment

The last module in this method is developing the corresponding DES model based on the data extracted from the BIM-related files to implement embodied carbon assessment under different scenarios. The whole process is shown in Figure 4. After semantic enrichment in the IFC file based on the developed integrated ontology, all data related to DES modeling for embodied carbon assessment is extracted from the enriched IFC file via IfcOpenShell. The DES modeling-related data is then stored in an Excel file as the output of the developed extraction tool, providing data sources for building the corresponding DES model. AnyLogic is used as the DES modeling tool in this study. Based on the data in Excel, the corresponding DES model is then developed for simulation and scenario-based embodied carbon assessment to implement carbon reduction strategies. The detailed scenarios considered and final simulation results in this study are introduced in Section 3.

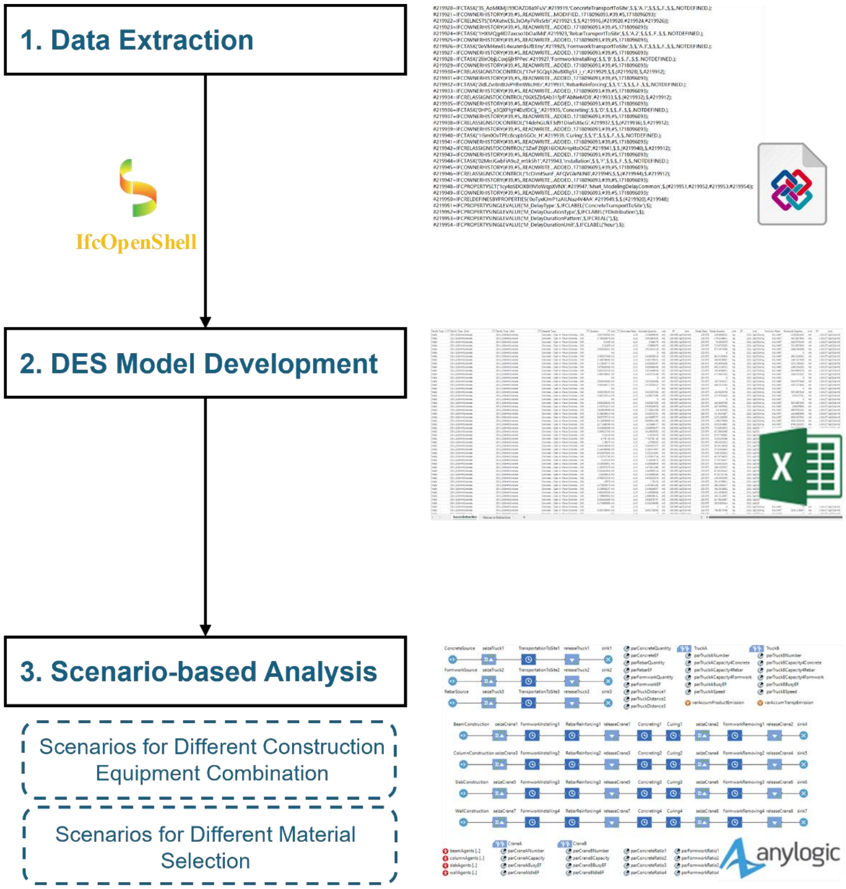
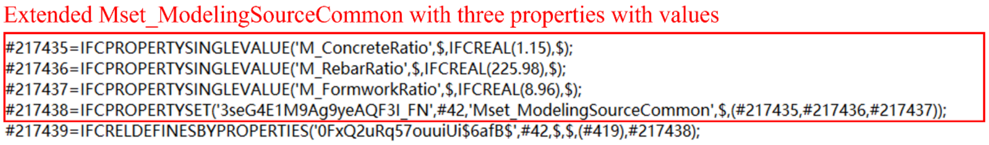


Figure 4: Process map of Module 3

3 Results

To validate the workability of the proposed method of BIM-based DES for embodied carbon assessment, the ground floor of a 2-story building with a reinforced concrete structure located in Hong Kong is used for the validation. The IFC file of the case study extracted from the BIM model is semantically enriched based on the data requirements from the developed integrated ontology. Figure 5 shows the example of the extended property set “Mset_ModelingSourceCommon” with three properties with values in the IFC schema. In the next step, all data related to DES modeling stored in the enriched IFC file is extracted via IfcOpenShell and stored in the Excel file (as shown in Figure 4) to support the data sources for the DES model development. After manually building the DES model based on the Excel data, the simulation result of embodied carbon in this case study is generated, which is presented in Figure 6 with three parts following the LCA stages.



```
#217435=IFCPROPERTYSINGLEVALUE('M_ConcreteRatio',$,IFCREAL(1.15),$);
#217436=IFCPROPERTYSINGLEVALUE('M_RebarRatio',$,IFCREAL(225.98),$);
#217437=IFCPROPERTYSINGLEVALUE('M_FormworkRatio',$,IFCREAL(8.96),$);
#217438=IFCPROPERTYSET('3seG4E1M9Ag9yeAQF3I_FN',#42,'Mset_ModelingSourceCommon',$,(#217435,#217436,#217437));
#217439=IFCRELDEFINESBYPROPERTIES('0FxQ2uRq57ouuiUi$6afB$',#42,$,$,(#419),#217438);
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Figure 5: Example of extended IFC schema

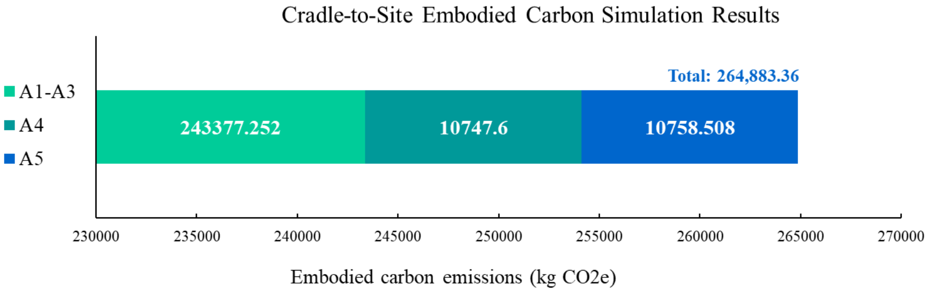

Figure 6: DES result of embodied carbon quantification (in the base scenario)

Figure 6 shows the cradle-to-site embodied carbon results of the base scenario with initial settings for both construction material types and on-site construction equipment use. To better assess how construction materials and construction equipment influence total embodied carbon emissions, this study implements a scenario-based analysis regarding different materials and equipment use in the case study. Figures 7 and 8 present the embodied carbon emission results under different scenarios. As shown in Figure 7, utilizing materials can greatly affect the total embodied carbon, especially the use of concrete with high-ground granulated blast slag (GGBS) proportions and highly recycled rebar. At the same time, emissions from material transportation should be considered together before final material selections. In Figure 8, different combinations of on-site construction equipment have slight effects on the total cradle-to-site embodied carbon but can still reduce 10% to 30% embodied carbon emissions at corresponding stages compared to the base scenario.

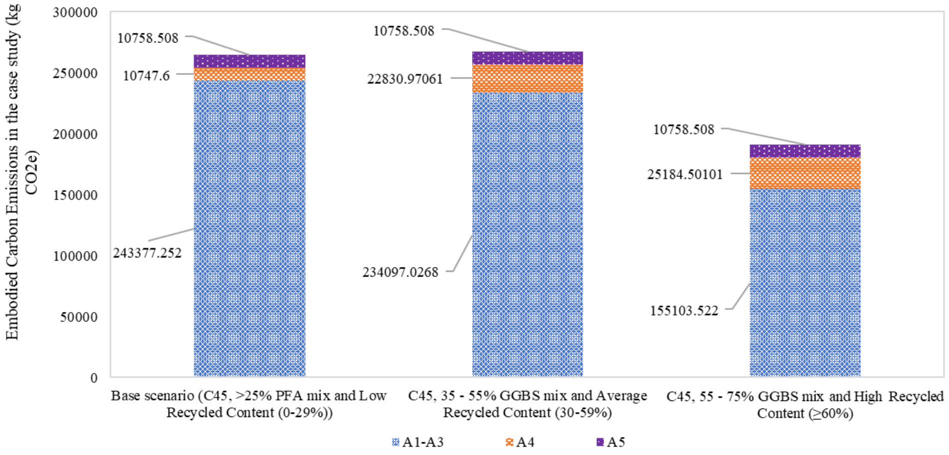

Figure 7: Embodied carbon emissions in the case study with different materials

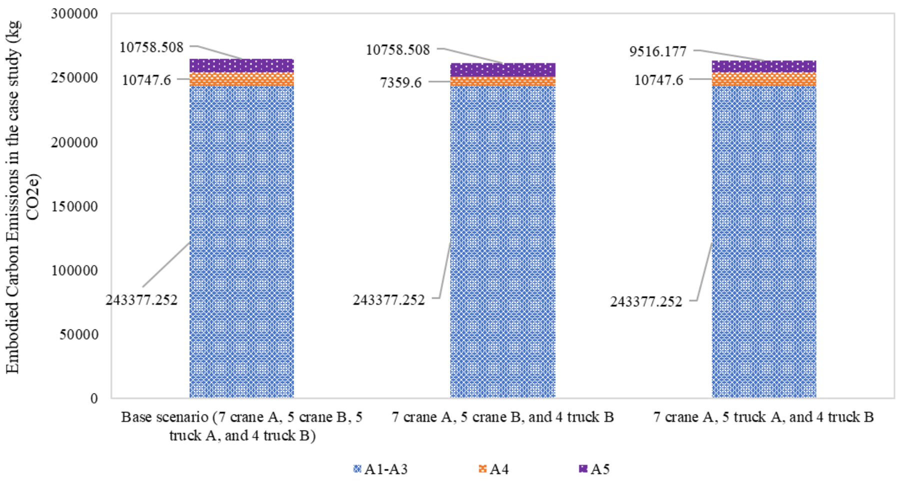

Figure 8: Embodied carbon emissions in the case study with different construction equipment quantities

4 Discussion

The integration of BIM with DES for embodied carbon assessment in this paper presents a significant advancement in sustainable construction practices. By addressing the challenges associated with data collection for cradle-to-site embodied carbon assessment, this integrated approach offers a more holistic understanding of the environmental impact of construction materials and activities. The combination of BIM's detailed material and quantity information extraction capabilities with DES's dynamic simulation abilities allows for real-time analysis of energy consumption and carbon emissions throughout the project lifecycle. Compared with previous studies, the BIM-DES integration in this study improves the data richness of the single data source, the BIM model, by enriching the necessary data via the IFC file, which helps enhance the efficiency of BIM-based DES modeling for embodied carbon assessment. This integration also streamlines the assessment process, enabling stakeholders to identify carbon hotspots, optimize material selection, and enhance construction processes for improved environmental performance.

5 Conclusions

This paper proposes and develops BIM-based DES for cradle-to-site embodied carbon assessment, which mainly includes three parts: integrated ontology development, ontology-based IFC extension, and BIM-based DES for embodied carbon assessment. The integration of BIM and DES holds great promise for advancing embodied carbon assessment in construction projects. By bridging the gap between detailed data extraction and dynamic simulation, this integrated approach provides stakeholders with valuable insights into the environmental impact of their decisions. Through scenario-based analysis and optimized carbon reduction strategies, construction industry professionals can make informed choices that minimize carbon emissions and contribute to more sustainable building practices. Moving forward, further research and implementation of BIM-DES integration are essential for improving the efficiency of DES modeling by realizing automated DES modeling based on BIM data.

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