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BIM-based Climate Action for Mitigation and Adaptation: Carbon-Neutral Buildings and Regional Carbon Footprint Management

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Abstract. This study addresses climate change by proposing a BIM-based framework for design decision-making that supports both mitigation and adaptation strategies in the built environment. In terms of mitigation, Building Information Modeling (BIM) enables a comprehensive assessment of operational and embodied carbon emissions throughout a building's lifecycle. For adaptation, integrating BIM with Geographic Information Systems (GIS) and the Internet of Things (IoT) facilitates the creation of digital twins to visualize and monitor regional carbon dynamics in real time. This research explores how BIM, when aligned with international carbon accounting standards and carbon trading platforms, can serve as a foundation for achieving net-zero carbon buildings and planning carbon-neutral urban zones. Through systematic analysis and integration of performance benchmarks, component libraries, and spatial data, the study demonstrates that BIM is not only a modeling tool but a strategic platform for climate-resilient architecture and policy formulation.

Keywords: Building Information Modeling, Carbon Footprint, Net Zero Carbon Buildings, Carbon Trading Platform
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1 MOTIVATION AND OBJECTIVES

As climate change accelerates the frequency and intensity of extreme weather events, there is an urgent global demand for proactive climate action. The United Nations' Sustainable Development Goal 13 emphasizes the necessity of both mitigation—reducing greenhouse gas emissions—and adaptation—enhancing resilience to climate impacts [8]. The construction industry plays a pivotal role, as buildings account for a substantial share of global carbon emissions. However, conventional planning and design methods fall short in addressing the full carbon lifecycle of buildings. This motivates the integration of digital technologies to enhance decision-making capabilities.

The purpose of this study is to develop a BIM-based design decision-making process that supports both mitigation and adaptation strategies. Specifically, it seeks to utilize BIM's capabilities in modeling, data integration, and lifecycle assessment to quantify and reduce operational and embodied carbon footprints. Additionally, by integrating Geographic Information Systems (GIS) and the Internet of Things (IoT), the study aims to visualize regional carbon emissions and support carbon-neutral urban zoning. The ultimate goal is to establish a systematic framework for achieving net-zero carbon buildings and enabling real-time, evidence-based planning and policy formulation that aligns with international standards and carbon trading mechanisms.

2 LITERATURE REVIEW

BIM serving as an information modeling and management tool for the entire lifecycle of a building, utilizes parameterized engines to organize and structure BIM component families within projects. It serves as the foundational platform for information exchange in various stages of the building lifecycle, including architectural planning, design, performance assessment, cost estimation, clash detection, construction scheduling, and post-completion operations. BIM is considered a core tool for collaboration, communication, and management among different stakeholders in the construction industry.[7]

Liu's (2022) bibliometric analysis on "Building Information Modeling (BIM) Driven Carbon Emission Reduction Research" reveals that existing BIM-related studies on carbon emissions largely concentrate on the design phase, particularly emphasizing energy-related carbon calculations and resource efficiency. However, the full potential of BIM across the entire building lifecycle—including construction, operation, maintenance, and end-of-life phases—remains underexplored. Liu identifies five key research directions gaining attention within the scope of sustainable architecture using BIM: building lifecycle assessment, the use of sustainable materials, energy efficiency in building design, and broader environmental protection strategies. These themes reflect the current focus areas where BIM is actively utilized to support carbon reduction goals. The study underscores a critical gap in applying BIM comprehensively throughout the building lifecycle. Expanding BIM's role beyond the design stage is essential for maximizing its impact on carbon emission mitigation, suggesting a promising area for future research in lifecycle-based sustainability assessments. [17]

Hsieh (2022) integrated BIM and GIS information to simulate the circularity and carbon emissions of architectural clusters [9]. Wang (2021) proposed the establishment of a platform for disclosing building material carbon footprints, emphasizing the integration of carbon disclosure with BIM systems to open up the feasibility of BIM [24]. On another note, since 2015, Professor Lin Xian-De, a prominent figure in green building, provided a comprehensive theoretical framework and detailed inventory operation mode for the disclosure of the carbon footprint throughout the entire lifecycle of buildings in his book on building carbon footprints. The objective is to leverage the three functions of building carbon footprint assessment: (1) carbon labeling, (2) hotspot diagnosis, and (3) carbon reduction actions [16]. However, the operational methods proposed in the book rely on tables, formulas, and manual or semi-automated calculations, limiting the "reliability" of the assessments. This is particularly evident as the "carbon coefficients" for various building materials and commodities are subject to annual updates and fluctuations, posing challenges and difficulties in the intricate manual calculation processes in carbon footprint assessment research. Therefore, it is more important to introduce BIM tools into the calculation of carbon emissions.

The goal of the United Nations Framework Convention on Climate Change is to reduce carbon emissions generated by economic activities, termed mitigation, and to alleviate the unavoidable impacts of climate change, referred to as adaptation. As depicted in Figure 1, mitigation measures encompass carbon trading programs, product and process standards, technology incentives and investments, carbon taxes, promotion of renewable energy, and standards for renewable energy portfolios. Adaptation strategies include modifications to building regulations, urban design, land planning, infrastructure investments, safety, and disaster prevention systems [13]. Building Information Modeling (BIM), serving as an information modeling and management tool for the entire lifecycle of a building, plays a crucial role in mitigation efforts. It can undertake the calculation of building energy consumption and carbon footprint, and adjust and optimize design goals, directions, and functional arrangements. BIM can also predict and assess carbon emission reduction amounts based on government or institution-defined standards. This facilitates decision-making regarding investments in clean energy mechanisms or participation in carbon trading, allowing for the offset and compensation of carbon emissions, thus effectively controlling global carbon emissions through market mechanisms [14]. In the context of adaptation planning, the integration of BIM with Geographic Information Systems (GIS) and the Internet of Things (IoT) is essential. From the perspective of urban carbon emission control, this integration allows for the real-time visualization (monitoring) of the carbon footprint dynamics of urban masses, facilities, transportation, and other urban systems. It enables the tracking of historical records, analysis, and review of the dynamic distribution of carbon sources and sinks in the region. The verification of the effectiveness of adaptation measures in achieving carbon neutrality can thus be substantiated through this comprehensive approach.

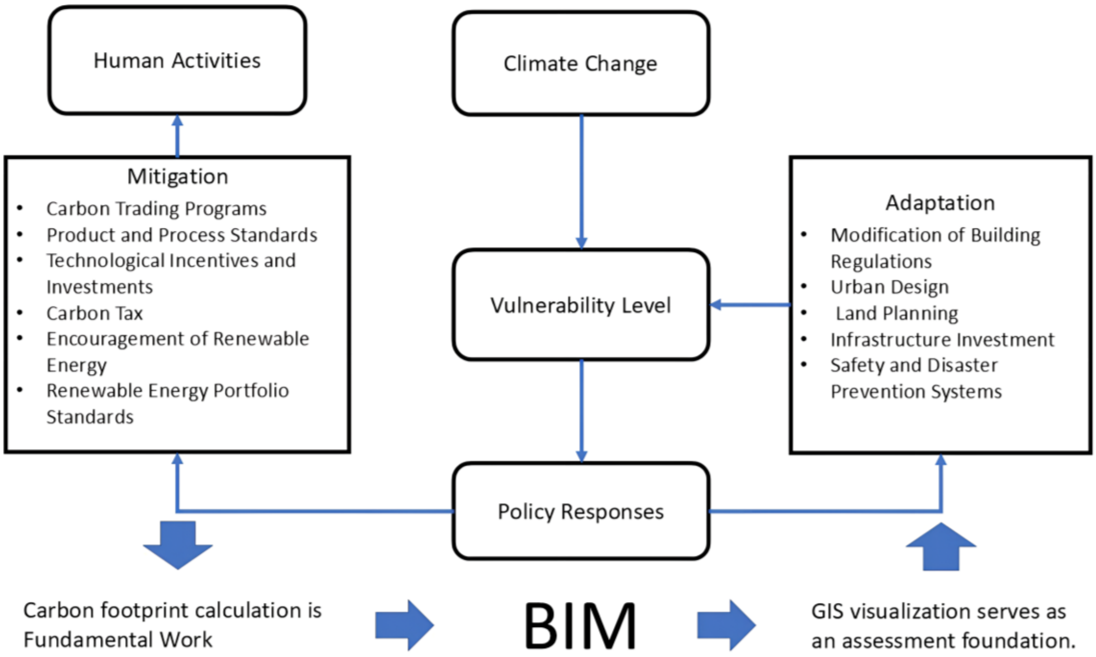


Figure 1: Mitigation and Adaptation Measures in Climate Policies, Adapted from [13].

The concept of net-zero carbon (carbon-neutral) buildings lacks a universally defined framework but can be derived from the closely related concept of net-zero energy buildings. Net-zero energy buildings are defined as structures that exhibit high energy efficiency and locally generate sufficient energy equivalent to their annual energy demand. The fundamental elements include (1) building systems, (2) energy networks, and (3) weighting systems. To achieve a clear balance calculation for net-zero goals, it is essential to delineate the boundaries of building systems with on-site renewable energy. Within this boundary, when the Renewable Energy Power system generates excess power, the building system channels surplus energy, comprising electricity, natural gas, on-site renewable energy, and power from the grid, back into the grid. Furthermore, different weighting systems are selected based on various design objectives. For instance, building owners may prioritize a balance of energy costs over energy equilibrium, leading them to select weighting systems that convert energy into cost [4],[2] (Figure 2, left). Similarly, net-zero carbon (carbon-neutral) buildings can be defined as structures that demonstrate high-efficiency carbon reduction and possess on-site carbon sinks equivalent to their annual carbon emissions. The fundamental elements include (1) building systems, (2) transaction networks, and (3) carbon trading platforms. To achieve a clear balance calculation for net-zero goals, it is crucial to delineate the boundaries of building systems with on-site carbon sources and sinks. Within this boundary, if the total carbon emissions exceed the designated emission rights, the building needs to purchase carbon credits from the carbon trading market. Conversely, any surplus reduction in emissions can be sold in the carbon trading market (Figure 2, right). This framework provides a structured approach for achieving net-zero carbon building goals by accounting for both emissions and offsets through carbon trading mechanisms.

Through the conversion of carbon coefficients, also known as weighting systems, "carbon emissions" can be considered a common unit for building energy consumption, materials, and supplies. Therefore, net-zero energy buildings are considered family members of net-zero carbon buildings [25]. The diagram titled "Definitions: Net Zero Carbon Buildings", published by the World Green Building Council, illustrates a step-by-step pathway toward achieving carbon neutrality across the entire building lifecycle. It is structured around the concept of Whole Life Carbon, which consists of two major components:

(1) Operational Carbon: Emissions generated during the building's use phase, including electricity, heating, cooling, water usage, and equipment operation.

(2) Embodied Carbon: Emissions associated with the manufacturing, transportation, construction, and maintenance of building materials.

The central flow of the diagram visualizes the progressive reduction of operational carbon, starting from a high-emission baseline and moving through several stages:

(1) Energy efficiency measures

(2) Partial on-site renewable energy

(3) 100% on-site renewable energy

(4) More than 100% on-site (energy-positive)

(5) Partial or full off-site renewable energy

Each stage corresponds to a performance classification visualized through progressively darker shades of blue:

- Lighter blue: Energy Efficient / Nearly Net Zero / Zero Energy
- Darkest blue: Net Zero Operational Carbon

Through the conversion of carbon coefficients—also referred to as weighting systems—carbon emissions can be standardized as a common metric across building energy use, materials, and resource inputs. This makes it possible to compare performance consistently across various systems. Therefore, net-zero energy buildings, which achieve carbon neutrality strictly during the operational phase (without external offsets), are considered part of the net-zero carbon building family.

However, if the achievement of operational neutrality involves external renewable energy sourcing or carbon offset mechanisms, the building is classified as a net-zero operational carbon building. While operational neutrality is a major milestone, it does not represent full lifecycle decarbonization.

As emphasized in the right section of the diagram, embodied carbon must also be addressed. This includes actions such as:

- Reducing embodied carbon through material selection and construction efficiency
- Compensating for residual emissions through verified carbon offsets

Only by addressing both operational and embodied emissions can a building be classified as a net-zero whole-life carbon building, the most comprehensive and rigorous standard. This final classification is represented by the green label in the diagram. (Figure 3).

Achieving net-zero is a progressive continuum, not a single target. From energy-efficient design and renewable integration to full lifecycle carbon compensation, it provides a structured framework for building strategy, policy development, and sustainability assessment. It highlights how Building Information Modeling (BIM) and lifecycle carbon accounting must align to meet the demands of future-ready, climate-resilient architecture.

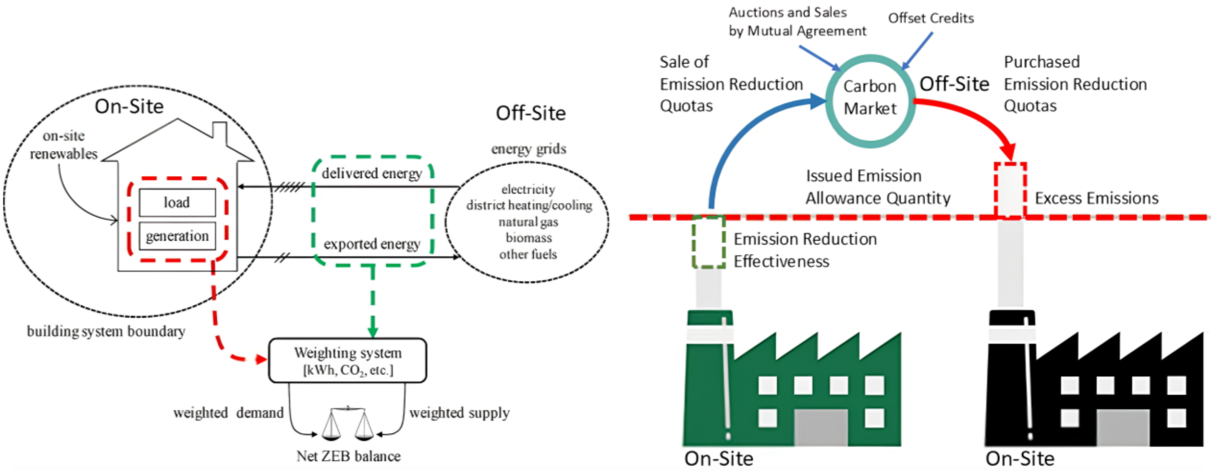


Figure 2: Key Elements of Net Zero Energy Building (Left)[4] vs. Net Zero Carbon Building (Right).

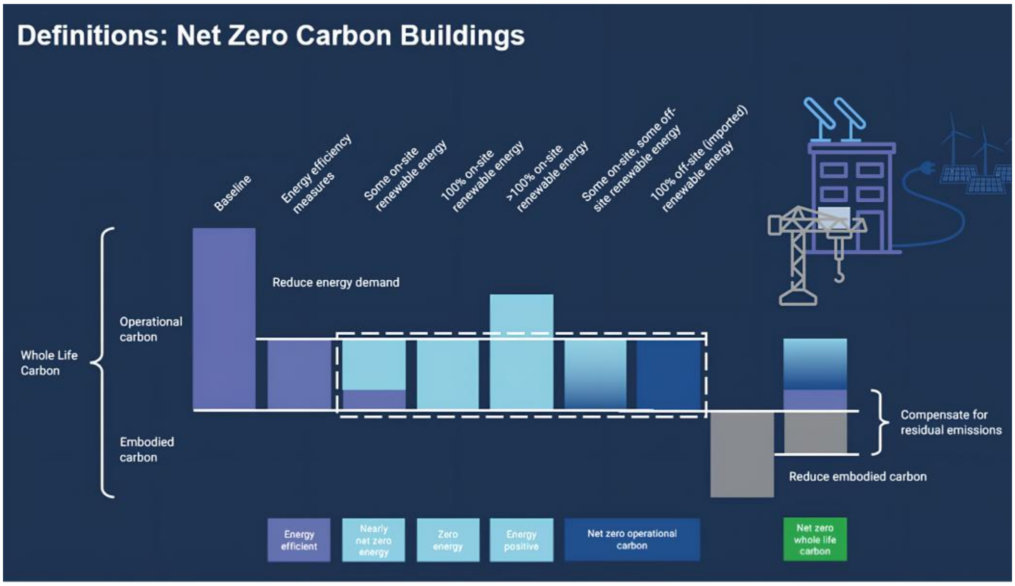


Figure 3: Net Zero Carbon Building Family [25].

3 THEORY AND METHODOLOGY

In response to climate change, this study proposes an integrated BIM-based design decision-making methodology that addresses both mitigation and adaptation in climate action. Unlike conventional BIM applications that primarily focus on either operational or embodied carbon emissions in isolation, this approach integrates both within a comprehensive whole-life carbon footprint assessment. It quantifies operational carbon during the usage phase and embodied carbon from materials and construction, enabling more precise and holistic net-zero carbon strategies.

At its core, the methodology employs a BIM component library embedded with carbon footprint data, facilitating automated, transparent carbon calculations within the modeling environment. This overcomes limitations of current practices, where such data often relies on external tools or manual input. The system further interfaces with government-defined carbon benchmarks to support performance optimization, energy efficiency certification, and tax classification. Moreover, it is aligned with international greenhouse gas accounting standards and connects with carbon trading platforms, allowing for participation in carbon markets—an area not yet common in existing BIM workflows.

Externally, the methodology expands BIM's role from individual buildings to the regional scale. By integrating BIM with GIS and IoT technologies, a 3D GIS-based digital twin is constructed to monitor and visualize carbon emissions in real time across urban systems. This enables carbon intensity classification, regional neutrality assessments, and evidence-based zoning or infrastructure planning. (Figure 4)

Ultimately, this research positions BIM not only as a digital modeling tool but as a strategic platform for climate-resilient design, lifecycle carbon governance, and policy compliance—significantly advancing current BIM applications in climate-responsive architecture and urban development.

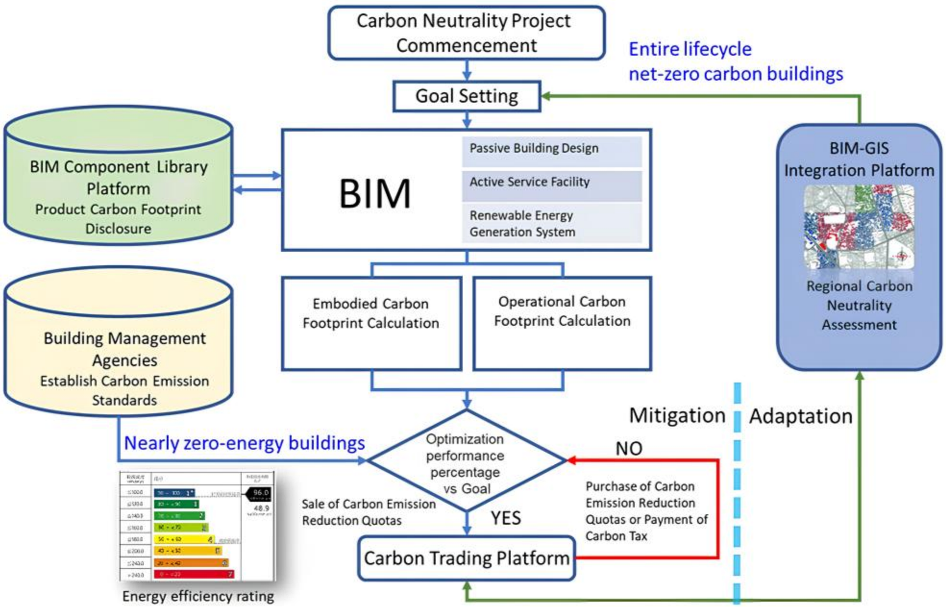


Figure 4: Integrated Design Process for Mitigation and Adaptation Based on BIM.

3.1 BIM-Based Whole-Life Carbon Footprint Calculation: Quantifying Operational and Embodied Carbon Through BIM-Integrated Lifecycle Assessment

Currently, there are two definitions regarding the scope of building whole-life carbon footprint calculations. One is from "cradle to grave," and the other is from "cradle to cradle." According to the Environmental Protection Administration's Product Carbon Footprint Information Network [5], the calculation of the carbon footprint of a building, defined under Product Category Rules (PCR), spans a 60-year lifecycle from construction to disposal. It includes four stages:

1. Production Stage: Involves raw material extraction, transportation to the factory, and raw material manufacturing.
2. Construction Stage: Encompasses the transportation of building materials to the construction site and the assembly of building materials.
3. Use Stage: Includes daily operation, maintenance, repairs, and replacements.
4. End-of-life Stage: Involves demolition work, waste transportation, and disposal.

The other definition, "cradle to cradle," goes beyond the building lifecycle stages mentioned above. According to ISO 21930:2017 [12], it includes stages such as reuse, recovery, and recycling—commonly known as the 3Rs. However, these additional stages, falling outside the defined boundaries, are considered optional in the benefit assessment (Figure 5). Following the definition of the entire lifecycle for building carbon footprint calculations, ISO 14067, in compliance with international standards for life cycle assessment, has established principles and standards for the quantification of product carbon footprints [10].

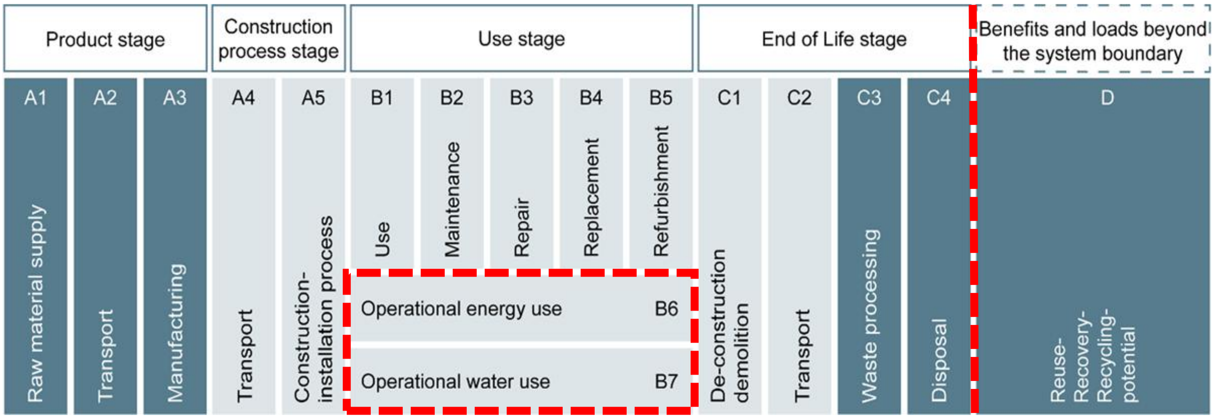


Figure 5: Life cycle stages for building products, based on ISO 21930:2017 [12].

The carbon footprint emitted by buildings can be categorized into two types: operational carbon footprint and embodied carbon footprint. BIM tools are currently capable of addressing the operational carbon footprint, specifically in terms of electricity and fuel consumption. For the embodied carbon footprint, which pertains to the building materials, the emission factor method is applied for conversion, enabling predictions. The details are outlined as follows:

1. Operational Carbon Footprint:

The operational carbon footprint, also known as operational carbon, refers to the carbon emissions generated from the consumption of resources during the operational phase of a building, including electricity, natural gas, water, etc. (Figure 5, B6, B7, highlighted by the thick red dashed line). This can be calculated based on the consumption of building resources.

BIM tools already can predict electricity and fuel usage, while the application module for water usage is still under development. Firstly, an energy analysis is performed during the design phase. As shown in Figure 6, three measures significantly impact overall energy consumption: (1) passive building design, (2) active service equipment and facilities, and (3) renewable energy generation systems [2]. The planning and design, as well as modeling, are carried out using the Revit tool platform. The energy simulation package Insight, integrated with the Revit platform, is employed for simulating and calculating energy consumption. The software's built-in graphical parameter panel allows for the customization of different building parameters, such as window-to-wall ratio, window material, skylight ratio, roof type, HVAC system type, and wall surface area, among other key factors affecting energy consumption (Figure 7). Finally, the results of the simulation are obtained through the Insight online query service, providing insights into energy consumption (Figure 8).

In the second step, the relevant values for energy consumption, such as electricity and natural gas, obtained from the building energy simulation results, are multiplied by the government's announced carbon emission factors for electricity and natural gas (Table 1). This yields the carbon footprint of electricity and fuel usage during the operational phase.

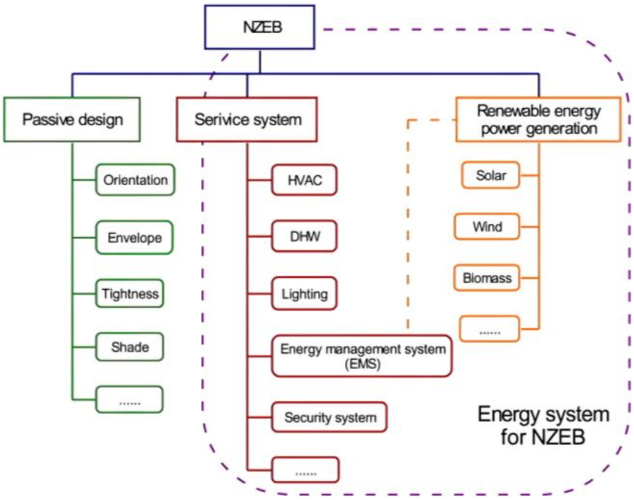


Figure 6: Three Measures for Overall Energy Consumption Calculation [4].

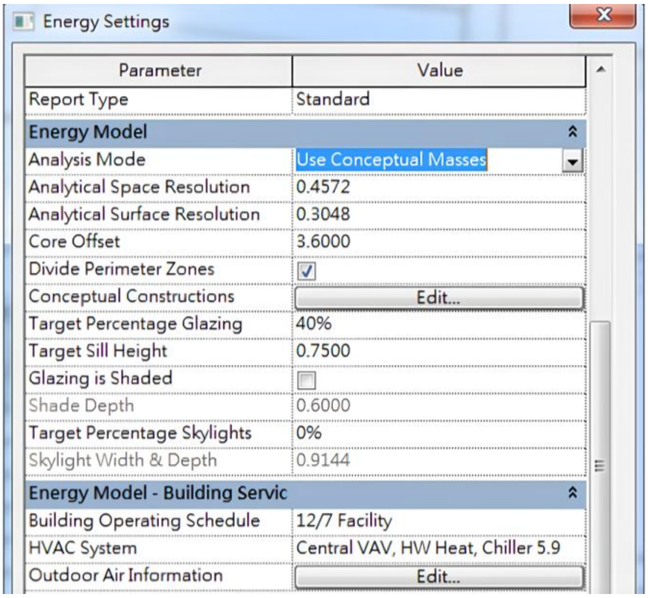


Figure 7: Parameter Settings Influencing Energy Consumption [2].

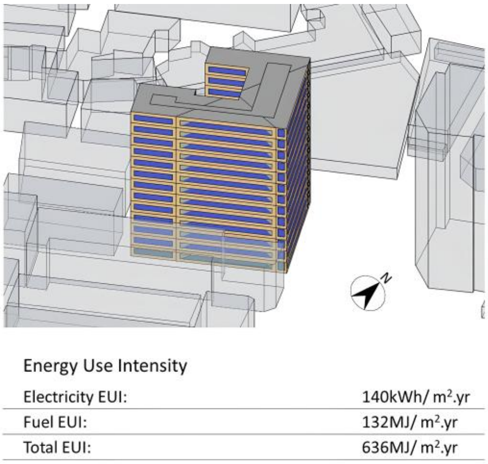


Figure 8: Example of Energy Consumption Calculation Results [2].

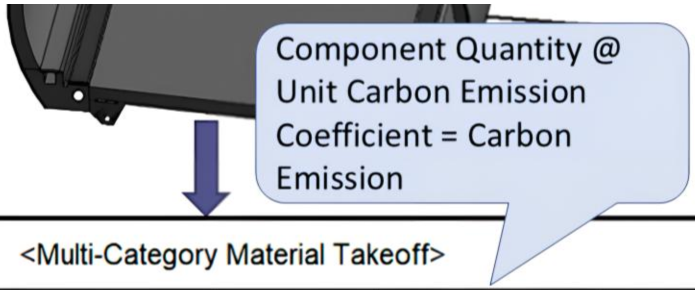
Coefficient Name	Carbon Footprint Value (kgCO2e)	Declared Unit	Government Department/Company Name (Optional Disclosure)	Announcement Year
Natural Gas (Used in Fixed Sources, 2021)	2.63	Cubic Meter (m3)	Environmental Protection Administration	2023
Automotive Gasoline (Used in Mobile Sources, 2021)	2.92	Liter (L)	Environmental Protection Administration	2023
Automotive Gasoline (Used in Fixed Sources, 2021)	2.88	Liter (L)	Environmental Protection Administration	2023
Diesel (Not Burned, 2021)	0.673	Liter (L)	Environmental Protection Administration	2023
Unused Fuel Oil (Residual Oil/Heavy Oil Not Burned, 2021)	0.764	Liter (L)	Environmental Protection Administration	2023
Fuel Oil Usage (Residual Oil/Heavy Oil Usage, 2021)	3.88	Liter (L)	Environmental Protection Administration	2023
Electricity Indirect Carbon Footprint (2021)	0.0973	kWh	Environmental Protection Administration	2023
Electricity Carbon Footprint (2021)	0.606	kWh	Environmental Protection Administration	2023

Table 1: Carbon Footprint Emission Coefficients (Extract) [6].

2. Embodied Carbon Footprint:

This includes the entire life cycle from cradle to grave, deducting the portion related to energy consumption during the building use phase. It encompasses aspects such as materials themselves, manufacturing, transportation, assembly, maintenance, repair, and replacement. The embodied carbon footprint needs to be calculated through complex assessments involving material consumption, transportation costs, machinery, and labor.

Currently, using BIM's material takeoff sheets, the embodied carbon footprint for the material part can be obtained. The primary source of carbon emissions in buildings is the construction materials. Through BIM-based quantity surveying software, the building's precise material quantities such as walls, columns, beams, slabs, doors, windows, railings, and reinforcements are separated, and various data sources are indexed to calculate carbon emissions. Analysis reports are then presented based on floor levels, the percentage of carbon emissions for each material, and other relevant information. The carbon emissions during the construction phase mainly come from machinery and labor. The detailed breakdown of construction activities and the machinery and labor quantities used during the construction phase are separated using the detailed breakdown service. Various data sources are indexed to calculate carbon emissions. Therefore, if a carbon footprint database for building materials and components is established through the BIM component library platform, and the carbon footprint of materials is calculated using BIM's material takeoff sheets, it is a reliable and scientific method (Figure 9).



<Multi-Category Material Takeoff>

A	B	C	D	E
Family	Material: Name	Material: Volume	CO2 emission[kg per m^3]	CO2 emission(kg)
drainage way	ready-mixed concrete 25-210-12	19.95 m^3	400	7978.07
cement treated base	cement	11.25 m^3	3308	37226.64
Common ditch cover	ready-mixed concrete25-210-12	0.60 m^3	400	240.00
Ditch cover	stainless steel	0.68 m^3	7560	5103.00
concrete lining	Ready-mixed concrete25-240-15	62.61 m^3	420	26298.03
Drainage pipe filling	rubble	7.74 m^3	11	85.15
drainpipe	PVC pipe	0.18 m^3	1619	294.99
rock bolt	carbon steel	0.63 m^3	5846	3684.49
shotcrete	general concrete(ready-mixed concrete)	11.45 m^3	346	3960.21
steel pipe	steel pipe(carbon steel)	0.05 m^3	5846	266.29
waterproofing sheet	PVC waterproofing sheet(PVC)	0.31 m^3	1619	501.46
concrete slab(30cm)	general concrete(ready-mixed concrete	22.50 m^3	346	7784.96

Figure 9: Calculation of Embodied Carbon Footprint of Building Materials Using BIM Material Details Table [20].

3.2 BIM Component Library Platform: BIM Objects for Automated Carbon Assessment

BIM elements that disclose carbon footprints form the basis for calculating the embodied carbon footprint of building materials. The government should introduce legislation to ensure the disclosure and registration of the product carbon footprints of BIM components through the Climate Change Response Act. Taking Taiwan as an example, the establishment of Taiwan's BIM component library began with the display platform subsidized by the Architecture and Building Research Institute, Ministry of the Interior, and implemented by the Taiwan Architecture & Building Center in 2017 [21]. However, its primary purpose was to offer white-label BIM components for government public projects during the design and contracting phases, providing only geometric information and classification codes, without detailed non-geometric information on materials, components, or even carbon emission coefficients.

In 2021, the Architects Association of Taiwan took the lead in establishing the BIM Knowledge Resource Platform [22], focusing on providing BIM components needed at different stages of the building life cycle. This platform emphasizes the accuracy of information in BIM component registrations, clearly indicating codes based on different classification standards (OmniClass coding, MasterFormat coding, PCCES coding), applicable LOD (Level of Development) stages, manufacturers, product models, product functionality, and energy efficiency ratings (Figure 10). However, as of now, BIM components still do not include registrations for product carbon footprints. In the future, the Climate Change Response Act should make it mandatory for certain products to apply for carbon footprint labels in order to fully meet the conditions for using BIM to calculate the embodied carbon footprint of buildings.

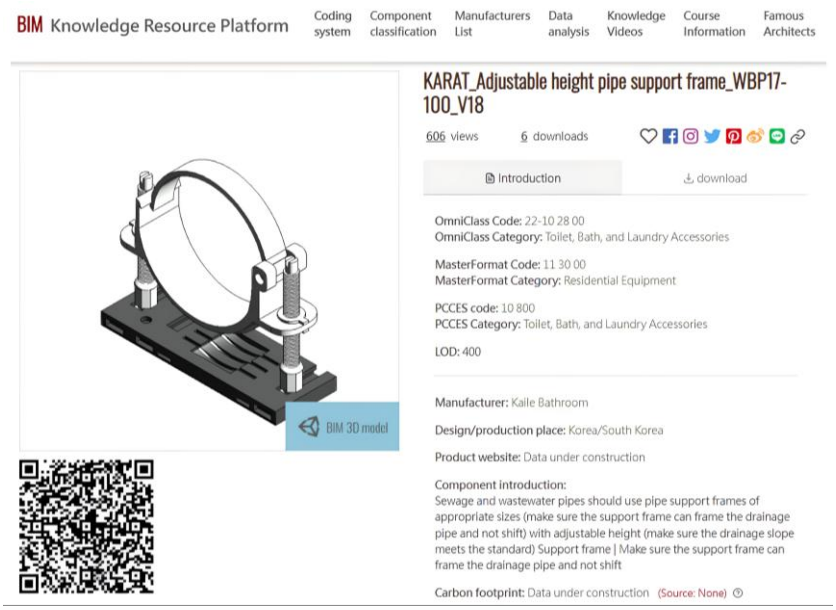


Figure 10: Component Examples in BIM Knowledge Platform [22].

3.3 Establishment of Carbon Emission Standards by Building Management Authorities: Defining Baseline Metrics for Building Carbon Performance and Compliance

To achieve nearly zero-carbon buildings, government agencies must establish benchmarks, allowing businesses to align with these benchmarks and set clear carbon reduction performance objectives. As mentioned above, Building Information Modeling (BIM) tools have been instrumental in facilitating the "simulation estimation" of energy consumption, including electricity and natural gas, necessary for the operational carbon footprint of buildings. By querying carbon footprint emission coefficients of energy resources from government open data platforms and multiplying them by the simulated energy consumption, one can obtain the carbon emission values per unit floor area of a building (unit: kgCO2e/m2.year).

On the other hand, organizations can conduct statistical and computational analyses based on the actual energy and resource usage within their facilities, using this information to establish a benchmark for "carbon emissions." For instance, referring to the Energy Use Intensity (EUI) approach, Table 2 presents the benchmark values for electricity consumption per unit area announced by the Ministry of Economic Affairs and the Ministry of Education in 2020 [18]. The published EUI, which represents the annual electricity consumption per unit area (Formula 1), has become a basis for institutions to assess their energy efficiency performance. However, considering the diverse energy sources involved in building operations, such as electricity, natural gas, and water usage, the government must integrate data from energy and resource supply agencies, compile and analyze operational data, and formulate "average annual unit area carbon emission benchmarks" for various types of buildings.

Table 2: Electricity Efficiency Management Plans for Government Agencies and Schools Benchmark Values (Extract) [18].

No.	Category	Business Category	Group	EUI Benchmark
1-1	Government Offices	Central Government Agencies	Group 1	124
1-2			Group 2	112
1-3			Group 3	92
1-4			Group 4	76
1-5			Group 5	64
1-6			Group 6	52
1-7		Local Government Agencies	Group 1	101
1-8			Group 2	84
1-9			Group 3	54
1-10			Group 4	45
1-11			Group 5	38
1-12			Group 6	28
1-13		Business Organization Government Agencies	Group 1	144
1-14			Group 2	123

$$EUI = \frac{Annual\ electricity\ consumptionn}{Total\ floor\ area\ of\ building} \quad \text{(Unit: kWh/ m2 .year) [2]} \tag{1}$$

3.4 Optimization Performance Percentage: Assessing Design Improvements through Carbon Reduction Benchmarking

In alignment with the principles of LEED certification, the assessment and rating of a building's carbon footprint are conducted through the optimization of performance percentage. This percentage, denoted as "Optimization Performance Percentage" (Formula 2), is computed by discerning the variance between the "Baseline Value" and the "Design Value" associated with optimization strategies. Chen (2019) has introduced a grading and scoring system (Table 3) based on this percentage [2]. These assessments serve various purposes, such as establishing and comparing carbon reduction goals, determining building performance grades, obtaining energy efficiency certifications, tax categorization, incentives for reductions, and participation in carbon credit acquisition or trading.

$$Optimize\ performance\ percentage = \frac{Baseline\ value - optimized\ design\ value}{Baseline\ value} X100\% \ \text{[2]} \tag{2}$$

Table 3: LEED Performance Optimization Percentage and Credit Point Correlation [2]

New Construction	Major Renovation	Points
6%	4%	1
8%	6%	2
10%	8%	3
12%	10%	4
14%	12%	5
16%	14%	6

3.5 Carbon Trading Platform: Linking BIM-Based Carbon Metrics to Regulatory and Voluntary Carbon Markets

The regulation of carbon emissions involves two main approaches: first, government-set thresholds with the imposition of carbon taxes or fees, and second, market-driven trading and offsetting based on carbon credits. According to Taiwan's Climate Change Administration, Ministry of Environment, the billing basis for carbon fees will be the total annual carbon emissions in 2024, with payment starting in 2025. The primary targets for carbon fee collection are manufacturing industries with annual emissions exceeding 25,000 metric tons [26]. The carbon market is categorized into (1) the regulated market, where emissions are controlled based on total quantity, and companies are allocated specific emission quotas within legal limits. If a company exceeds its quota, it can purchase carbon credits from enterprises with unused quotas through the trading market. Conversely, companies with surplus quotas can sell them in the carbon market. (2) The voluntary market focuses on voluntary participation in emission reduction activities, involving the buying and selling of carbon credits to offset the buyer's carbon emissions [3]. On August 7, 2023, the Taiwan Carbon Solution Exchange was established in Kaohsiung, operating within the framework of the voluntary carbon market. It provides domestic and international carbon trading services for voluntary reduction project quotas and incremental offset quotas [22]. In addition to government taxation and market trading as two carbon emission control methods, Taiwan's Environmental Protection Administration is actively formulating a dual-pronged strategy. As illustrated in Figure 14, enterprises can either pay taxes to the government or opt for voluntary offsetting by purchasing reduction quotas or offsetting carbon emissions through the carbon trading exchange [14] (Figure 11).

3.6 3D GIS Information Integration Platform: Visualizing Urban Carbon Emissions with BIM-GIS Digital Twins

As mentioned in the motivations and objectives, concerning "adaptation," there is a need for a review and planning regarding building regulations, urban design, land planning, infrastructure investment, safety, and disaster prevention systems. Therefore, tools that provide visualization for decision-making are essential. GIS can integrate BIM and AIoT, utilizing digital twin geospatial information systems to visualize urban volumes, equipment, facilities, material transport, and traffic carbon emissions, and analyze carbon emission density data. [19]

Therefore, in the design and planning of low-carbon cities, visual analysis can be employed to consider regional carbon neutrality. This involves contemplating the overall planning and development of carbon emission and carbon sink areas, investing in infrastructure to adapt to climate change, and imposing restrictions on the development or altering land use regulations in certain areas to "mitigate" and "adapt" to climate change. As illustrated in Figure 12, based on the digital twin geospatial information system, a visual assessment can be conducted to classify the "carbon emissions" intensity of different systems within the city.

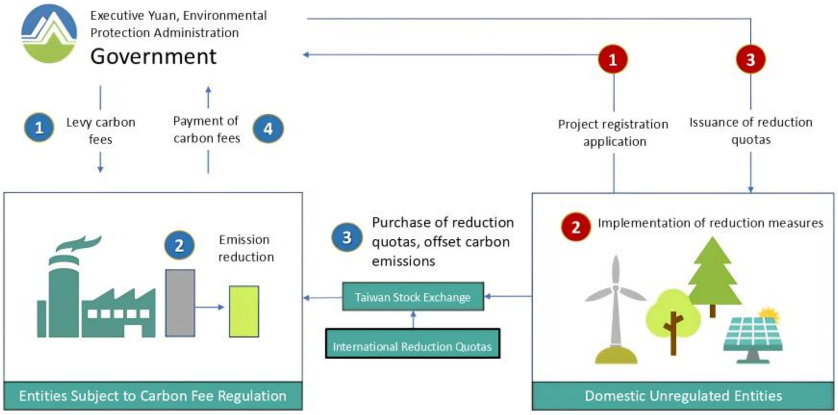


Figure 11: Control Through Government Carbon Levy and Offset Carbon Trading [14].

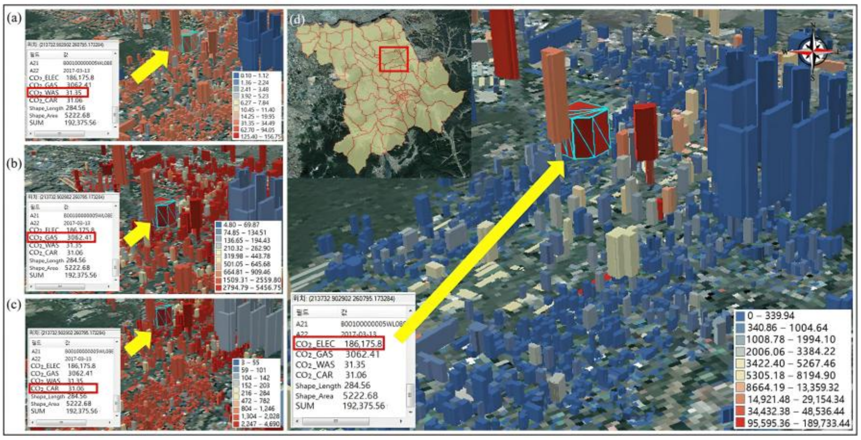


Figure 12: Visualization of Carbon Emission Intensity in Various Urban Systems through GIS-enabled Digital Twin Systems: (a) Household Waste Emission; (b) Urban Gas; (c) Vehicles; and (d) Electricity [19].

3.7 Regional Carbon Neutrality Assessment: Implementing Carbon Balance Evaluation at the Urban and District Scale

Using PAS 2060 Carbon Neutrality as a design blueprint [1], ISO 14068 standards ensure the accuracy, verifiability, and consistency of carbon neutrality commitments [11]. PAS 2060 promotes carbon accounting through four main steps: (1) accounting, (2) reduction, (3) offsetting, and (4) documentation and verification [1]. A net-zero carbon emission (carbon-neutral) building is defined as one that demonstrates highly efficient carbon reduction and has sufficient carbon sinks locally to offset its annual carbon emissions. The key elements include (1) building systems, (2) trading networks, and (3) carbon trading platforms.

In the foreseeable future, the Government can consider the practices of regulated markets. Following the principle of total quantity control, companies will be allocated predetermined emission quotas within legal carbon emission limits. Companies can choose to pay taxes to the government or opt for voluntary offsetting, which involves purchasing reduction quotas to offset excess carbon emissions. The total quantity control is based on the actual needs of regional development. Regional carbon neutrality, within the delineated boundaries, means that the carbon emissions from buildings within the region are controlled under legal thresholds. Buildings in the region demonstrate highly efficient carbon reduction and have sufficient local carbon sinks to meet their annual carbon emission requirements.

4 CONCLUSION AND RECOMMENDATIONS

Following international greenhouse gas ISO standards and the principles of carbon trading platforms, this study underscores the pivotal role of Building Information Modeling (BIM) in achieving carbon neutrality through mitigation and adaptation strategies. BIM serves as a robust platform enabling accurate calculation and management of operational and embodied carbon footprints throughout a building's lifecycle, thus supporting informed sustainable design decisions.

In terms of mitigation, BIM technology effectively facilitates lifecycle carbon assessments, empowering stakeholders to accurately measure and manage operational and embodied carbon footprints. To maximize the benefits of BIM, it is recommended that governmental and institutional bodies establish clear benchmarks for carbon emissions per unit area, explicitly including both operational and embodied carbon emissions. Additionally, legislative frameworks mandating comprehensive product carbon footprint disclosures should be implemented, ensuring greater reliability and consistency in BIM-based carbon accounting.

Regarding adaptation, integrating BIM with Geographic Information Systems (GIS) and Artificial Intelligence of Things (AIoT) significantly enhances urban climate resilience. The creation of digital twin geographic information systems facilitates real-time monitoring and analysis of urban carbon dynamics, offering valuable insights for urban planning and infrastructure development aimed at carbon neutrality.

Achieving net-zero carbon buildings requires systematic progression through enhanced energy efficiency standards, nearly zero-energy buildings, net-zero energy buildings, and finally, comprehensive net-zero whole-life carbon buildings. To accelerate this transition, further investment in BIM platform enhancements, standardized carbon footprint labeling for BIM components, and expanded regulatory support through carbon trading mechanisms are necessary.

Future research should concentrate on improving BIM methodologies, enhancing the integration of BIM with broader digital technologies such as AIoT and GIS, and developing robust regulatory frameworks to support effective carbon footprint management across the building lifecycle. BIM's comprehensive integration within climate action strategies ultimately holds significant promise for advancing global sustainability goals.

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