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Visualization of Carbon Footprint Across the Entire Lifecycle of Hospital Buildings Based on Building Information Modeling and Life Cycle Assessment

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Abstract. This study systematically investigates the application of integrated Building Information Modeling (BIM) and Life Cycle Assessment (LCA) technology for visualizing the carbon footprint throughout the entire lifecycle of hospital buildings. The research begins by analyzing the distinctive characteristics of hospital buildings as major energy consumers and carbon emitters, as well as the limitations of traditional carbon accounting methods, demonstrating the advantages of BIM-LCA integration in data aggregation, efficient accounting, and visual representation. It then delves into the implementation pathways, key technologies, and specific application scenarios for carbon footprint visualization across the four main stages of a hospital's lifecycle. In the design stage, parametric simulation and multi-scenario comparison enable proactive prediction and optimization of the carbon footprint. During the construction stage, dynamic management of construction process emissions is achieved through 4D carbon simulation and material management. For the operation and maintenance stage, a Building Information Modeling-Life Cycle Assessment- Internet of Thing (BIM-LCA-IoT) digital twin system is constructed to enable real-time monitoring and precise control of energy consumption and carbon emissions. In the demolition stage, a feasible technical pathway is proposed by leveraging the model for waste quantification and recycling scenario evaluation, supporting green demolition decisions. Finally, the paper summarizes current challenges, such as data standards and platform interoperability, and outlines future directions for the deep integration of technology and applications. This research provides a systematic technical framework and practical reference for achieving visible, manageable, and controllable carbon footprint management throughout the entire lifecycle of hospital buildings.

Keywords: LCA; carbon footprint visualization; whole life cycle; hospital buildings; digital twin.

1. Introduction

Climate change induced by global warming has become a significant issue of international concern, making the achievement of carbon neutrality an inevitable trend. The construction industry, as one of the three major high-energy-consuming sectors, has seen a continuously expanding market scale and increasing energy consumption in recent years. Reports indicate that the building sector is the largest emitter of greenhouse gases, accounting for approximately 37% of global emissions [1]. As the largest developing country, China's building sector contributes about 48% of the nation's carbon emissions [2]. Among building types, public buildings exhibit higher energy consumption intensity due to their large scale, stringent internal environmental requirements (e.g., constant temperature and humidity, high air exchange rates), and long operational hours. For instance, public building energy consumption is projected to account for 40.7% of the total building energy consumption by 2025. Hospital buildings, in particular, far exceed ordinary public buildings in energy demand, characterized by extremely high energy requirements and complex resource flows (medical equipment, pharmaceuticals, etc.). This grants hospital buildings significant emission reduction potential, making carbon footprint visualization research highly relevant [3].

Life Cycle Assessment (LCA) is an important and widely applied environmental management tool. LCA covers the entire life cycle of a building, including raw material extraction and processing, component manufacturing, use phase, and demolition [4, 5]. In recent years, it has been extensively applied in building energy analysis. Traditional building carbon emission calculation relies on collecting vast amounts of data through field measurements to create bills of quantities, which poses significant challenges for whole-lifecycle carbon accounting [6]. In contrast, Building Information Modeling (BIM), with its simulation and visualization capabilities, enables dynamic simulation and parametric design, providing an ideal data foundation for LCA analysis. The integration of BIM and LCA overcomes the data bottlenecks of traditional LCA analysis, achieves efficient and high-quality carbon accounting, and intuitively links abstract carbon emission data with building spaces, components, and systems, realizing carbon footprint visualization. Current research trends utilizing BIM-LCA in the construction industry are clear: assessment methods are shifting from static to dynamic, integrating time-sensitive parameters for real-time feedback on environmental impacts throughout the lifecycle; the scope is expanding from individual buildings to building stocks, adapting to urban sustainability planning needs; and the focus is broadening from single environmental indicators to multi-dimensional comprehensive assessments including economic and social aspects. Concurrently, the importance of demand-side management is highlighted, shifting the research focus from supply-side technological optimization to demand-side regulation. Strategies such as "avoiding," "shifting," and "improving" demand can yield significant cross-sectoral synergistic emission reduction effects. Circular economy principles are also being deeply integrated, enabling quantitative control from design and construction to demolition, promoting a transition towards a sustainable closed-loop in the construction industry. Based on these research characteristics, the objective of this paper is to summarize the research features and applications of BIM-LCA-based whole-lifecycle carbon footprint visualization, analyze its application in the specific context of hospital buildings, and propose a scientific, economical, and socially acceptable deep decarbonization pathway.

This paper aims to systematically review and evaluate the research progress, key technologies, and future challenges of applying BIM-LCA to the visualization, analysis, and management of the carbon footprint across the entire lifecycle of hospital buildings. It highlights the applicability of BIM-LCA for energy consumption visualization analysis in complex public buildings, providing a clear technical roadmap for researchers and practitioners, and offering theoretical support and methodological references for building the next generation of sustainable, low-carbon medical infrastructure.

2. Research Status of Hospital Energy Consumption Analysis

As major energy consumers within the public building sector, hospital buildings have an energy consumption intensity 1.6 to 2 times that of ordinary public buildings. This high energy consumption primarily stems from their 24/7 operational mode, stringent environmental requirements in special areas, and the high energy demand of large medical equipment. In this context, BIM-LCA offers a new research path for hospital energy management and carbon emission analysis.

2.1. Current Status of BIM-based Hospital Energy Consumption Research

BIM is a technological platform integrating 3D modeling and information management. Its implementation relies on various specialized modeling software, which form the foundation of BIM applications. Mainstream modeling tools such as Autodesk Revit, SketchUp, ArchiCAD, and Bentley are crucial not only for model creation but also for supporting the efficient operation of BIM. In the field of hospital buildings, Revit, due to its comprehensive medical component library and user-friendly interface, has become the most widely used BIM platform. Building Energy Modeling (BEM), as one of the most important and typical applications of BIM, collaborates with it to provide strong support for building energy consumption accounting. Numerous software tools can directly simulate building energy consumption, such as EnergyPlus, e (enhanced) QUick Energy Simulation Tool (eQUEST), Integrated Environmental Solutions - Virtual Environment (IES-VE), and Green Building Studio (GBS), enabling energy analysis of BIM models and predicting energy demands under different operating conditions.

In hospital building management, BIM technology is primarily applied in the following aspects: Firstly, optimizing building layout and equipment configuration through 3D visualization design helps avoid clashes and conflicts that are difficult to detect in traditional 2D drawings. Secondly, utilizing comprehensive Mechanical, Electrical, Plumbing (MEP) coordination optimizes the layout of various medical utility pipelines, improving space utilization. Finally, energy consumption simulation analysis predicts the energy performance of different design schemes, supporting decision-making. The practice in the Qilu Hospital Phase II project of Shandong University demonstrated that optimizing MEP layout through BIM technology saved material usage by streamlining arrangements and paths, consequently reducing carbon emissions associated with production, transportation, and construction processes. Calculations showed a reduction of approximately 7.3t of CO_2 in the material production stage and about 0.01t in the transportation stage [7]. However, BIM-based hospital energy analysis still has notable shortcomings: interoperability obstacles exist between different software platforms; the technology primarily focuses on energy analysis during the operational stage, often neglecting other stages; and the database for energy consumption characteristics of specialized medical equipment is insufficient.

2.2. Current Status of BIM-LCA-based Hospital Energy Consumption Research

BIM-LCA combines Building Information Modeling with Life Cycle Assessment to comprehensively quantify the energy consumption and environmental impact of hospital buildings throughout their entire lifecycle. This provides a more comprehensive and precise methodological support for hospital energy analysis. The integration of these two technologies occurs mainly at two levels: data-level integration and platform-level integration. At the data level, seamless transfer of model information to data analysis platforms is achieved by developing interfaces between BIM and LCA, as shown in Figure 1.

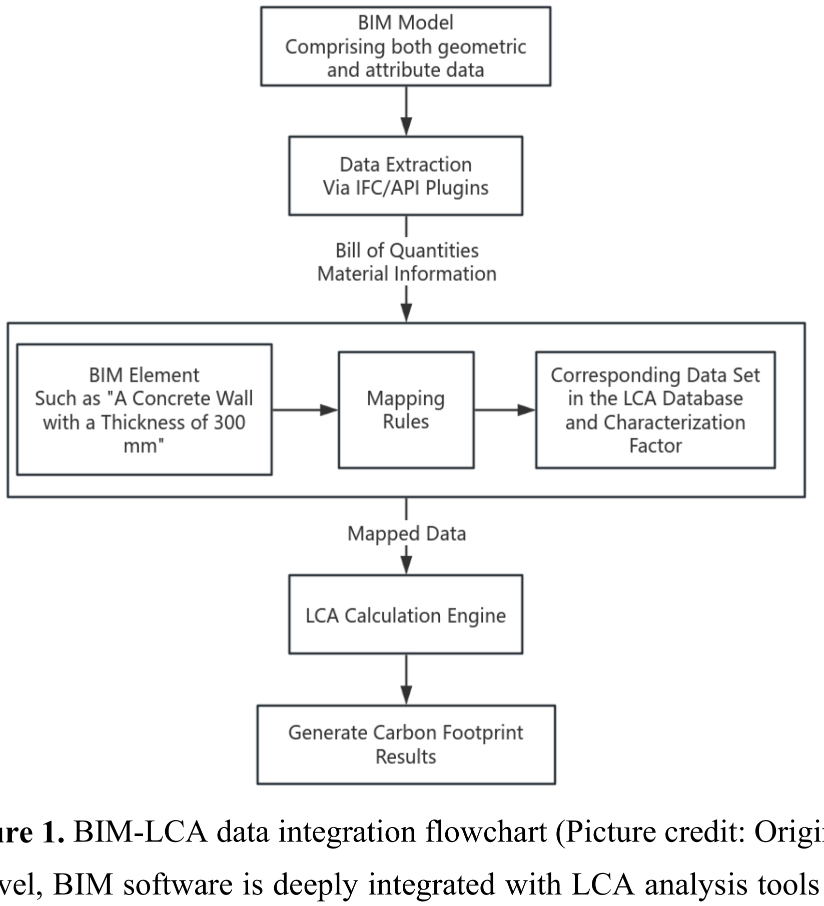

Figure 1. BIM-LCA data integration flowchart (Picture credit: Original)

At the platform level, BIM software is deeply integrated with LCA analysis tools to form a unified working environment. A study based on the Prospective Life Cycle Assessment (P-LCA) method for the Infection Building of the Mingguang City People's Hospital in Chuzhou constructed an energy consumption assessment model for the building's lifecycle. This included defining the study object and system boundaries (dividing the building lifecycle into construction, operation, maintenance, and demolition stages), creating a life cycle inventory (building quantity and energy consumption lists), conducting a life cycle energy assessment (calculation models for the four stages), and interpreting the results. This study identified the main characteristics of carbon emissions throughout the hospital's lifecycle, as shown in Figure 2 [8]. The application of LCA platforms in hospital building carbon accounting has also evolved significantly: from initial manual calculations to specialized carbon accounting software, and currently to integrated solutions with BIM platforms. This evolution has markedly improved the efficiency and accuracy of carbon accounting work, especially in complex systems like hospital buildings, where BIM-LCA can better handle large datasets and complex relationships. However, the application of BIM-LCA in hospital energy analysis still faces challenges: the complexity of hospital activities makes defining system boundaries difficult; dynamic carbon emission factor databases are incomplete; and there is a lack of specialized LCA databases for medical buildings.

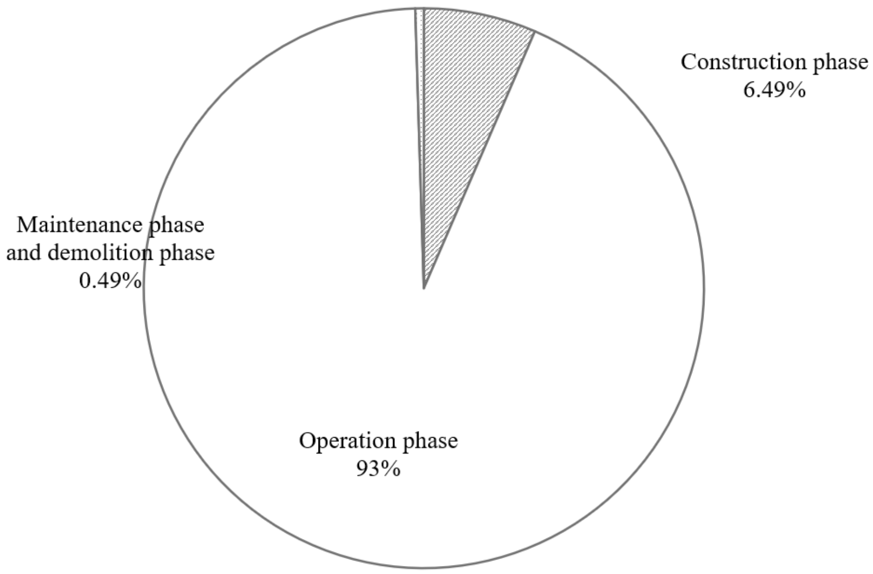

Figure 2. Energy consumption proportion by lifecycle stage for Mingguang City People's Hospital (Picture credit: Original)

3. Stage-specific Visualization Application Research

The exploration of visualization applications for hospital buildings runs through the entire building lifecycle, with different visualization methods employed at each stage according to specific objectives, as shown in Figure 3. Due to the complex functions, long operational hours, and high environmental control requirements of hospital buildings, their carbon footprint visualization applications also exhibit specific characteristics.

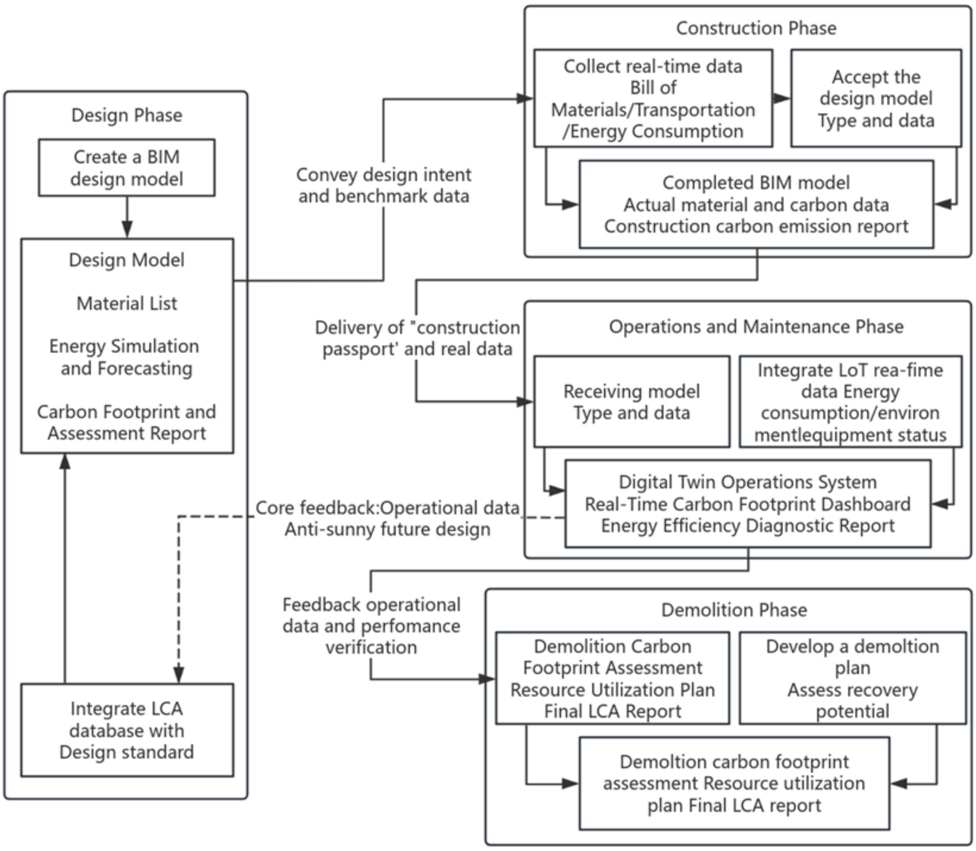

Figure 3. Data flow for whole-lifecycle carbon footprint visualization of hospital buildings (Picture credit: Original)

3.1. Design Stage

While the design stage does not generate actual carbon emissions, it is crucial for predicting the carbon emissions of the entire construction project and formulating corresponding reduction strategies. BIM-LCA technology provides solutions for assessing scheme feasibility, cost, schedule optimization, material selection, and comparing the environmental benefits of different technical routes, offering decision support to designers regarding "how to build" and "why to choose." By constructing parametric BIM models and integrating LCA databases, designers can evaluate the carbon emission performance of different schemes in real time. Specifically, the carbon emissions determined during the design stage mainly include embodied carbon and operational carbon. Research indicates that the error range of BIM-LCA technology in green hospital building design can be controlled within approximately 15%, providing reliable basis for design decisions [9]. The case study of Maluan Bay Hospital verified that proposing energy consumption optimization measures during the design stage is key to achieving the project's ultimate green rating goals, facilitating the sustainable development of green hospitals [10].

Furthermore, BIM-LCA-based carbon footprint visualization can employ methods such as 3D model color rendering, Sankey diagrams for carbon flow, and environmental performance dashboards, allowing designers to compare carbon emissions of different schemes and select the optimal one. However, visualization in the design stage of hospital buildings has specific challenges: on one hand, the specific environmental requirements of hospital functional units set higher standards for energy system design; on the other hand, the complexity of hospital workflows necessitates considering differences in energy demand between functional zones, preventing the application of a unified design standard. Currently, the Fever Outpatient Building of the Sixth People's Hospital in Taizhou, Jiangsu Province, China, applied BIM-LCA technology during the design stage, innovatively adopting a "passive design priority + active energy optimization" strategy, significantly reducing energy consumption, with an estimated annual carbon reduction of about 100 tons.

3.2. Construction Stage

Carbon footprint visualization in the construction stage primarily focuses on material selection, process optimization, and waste management. By extracting material quantity information from the model and combining it with carbon emission factors from LCA databases, detailed carbon footprint inventories can be generated, providing a basis for optimizing procurement and construction plans, as shown in Figure 4. The particularity of the hospital construction stage lies in: specialized medical facilities requiring specific materials and construction techniques, which significantly impact carbon emissions; high requirements for phased construction, as hospitals often require expansion or renovation without disrupting normal operations, increasing the complexity of construction organization.

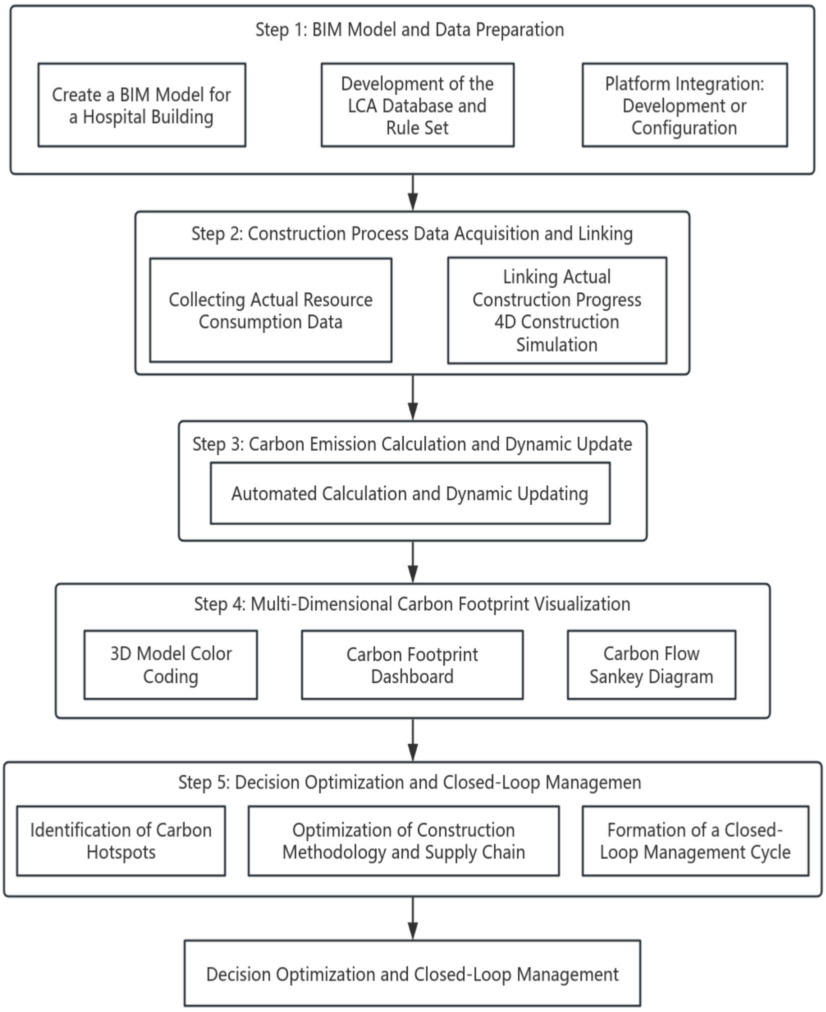

Figure 4. Carbon footprint visualization flowchart for the construction stage (Picture credit: Original)

3.3. Operation and Maintenance Stage

The operation and maintenance (O&M) stage is the primary source of carbon emissions for hospital buildings, accounting for over 90% of the total lifecycle emissions [8]. Therefore, the carbon footprint visualization application in this stage is most critical and mature. Constructing a Building Information Modeling- Internet of Thing (BIM-IoT) digital twin system based on LCA methodology, which integrates the BIM operational model with Building Automation Systems (BAS), smart meters, and sensor data to acquire real-time energy consumption data, enables real-time visual monitoring of hospital energy consumption and carbon emissions, as shown in Figure 5. This system can not only accurately monitor the consumption of water, electricity, gas, and other utilities in various zones but also reveal usage patterns and trends through data analysis, evaluate equipment efficiency, and promote energy-saving optimization while ensuring efficient operation. Simultaneously, the system supports: calculation of energy consumption indicators and year-on-year/period-on-period analysis; exploration of the relationship between equipment operation and energy consumption; implementation of sub-metering and energy efficiency evaluation for key energy-consuming equipment like lighting and Heating, Ventilation, and Air Conditioning (HVAC) and identification of high-consumption areas and equipment through energy Key Performance Indicators (KPIs) and rankings, providing a basis for formulating energy-saving strategies [11]. Special applications of carbon emission visualization in hospital O&M management include: precise temperature and humidity control in operating rooms, management of medical equipment standby functions, and optimization of ventilation for infection prevention. For example, Shulan (Jinan) Hospital utilizes a BIM-IoT system to monitor ward temperature and humidity in real-time and automatically adjust the HVAC system, achieving precise control in operating rooms.

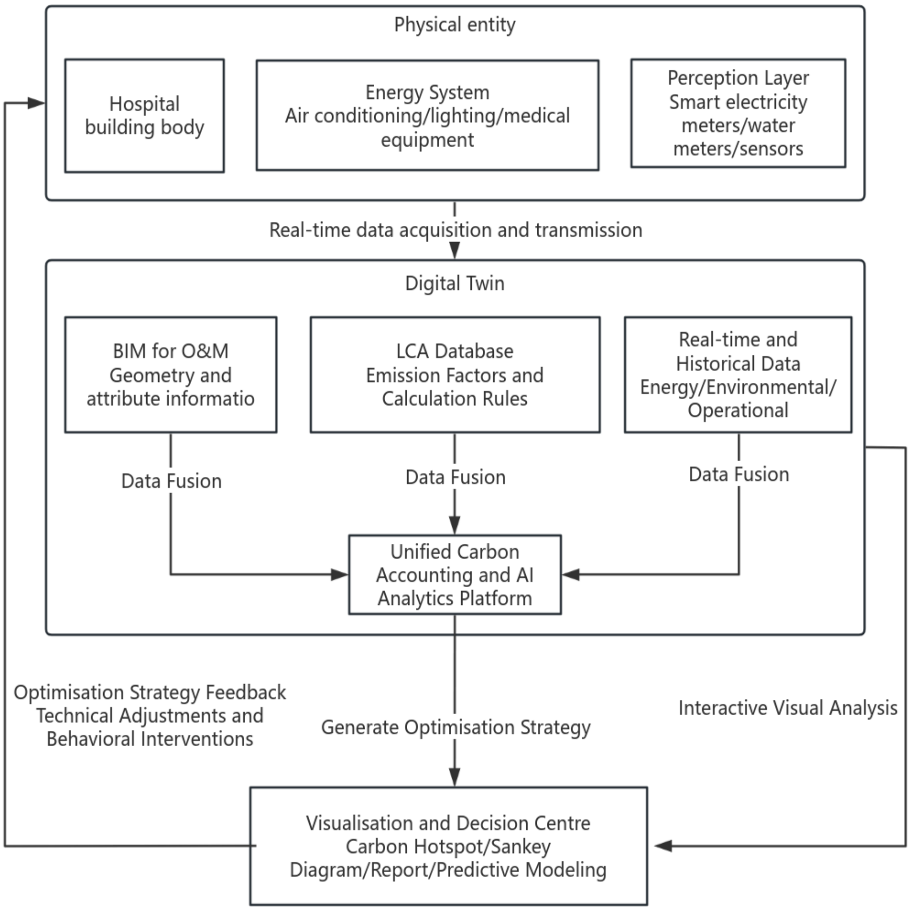

Figure 5. BIM-LCA-IoT framework diagram (Picture credit: Original)

3.4. Demolition Stage

The demolition stage is the final phase of the hospital building lifecycle. Carbon footprint management here focuses primarily on assessing emissions from waste treatment processes and optimizing resource recovery and reuse plans. The BIM model can be used to accurately estimate the quantities of various types of waste generated during demolition, and combined with the LCA database to evaluate the carbon emission impacts of different treatment methods. Thes pecialnessof the hospital demolition stage includes: medical waste requires particularly careful handling, and components potentially containing hazardous substances need special treatment procedures; the high possibility of functional changes often leads to partial demolition and partial renovation, requiring more refined demolition planning due to this complexity.

To achieve precise management and visualization of the carbon footprint during the hospital demolition stage, the following systematic technical pathway can be adopted: First, develop specialized carbon footprint calculation plugins based on mature BIM platforms like Revit. These plugins can automatically extract material quantities from the model and provide parameter interfaces for demolition techniques, transport distances, and treatment methods, enabling one-click generation of carbon emission reports and visual charts for immediate decision support. Second, it is essential to collaborate within the industry to build specialized LCA databases for hospital buildings, focusing on incorporating carbon emission and recycling factors for special materials like radiation-proof lead plates, specific clean room panels, and large medical equipment, significantly improving calculation accuracy. Furthermore, explore data integration with smart city waste management platforms, connecting waste information extracted from the BIM model with government regulatory systems to obtain real-time data on transport routes and final disposal, forming a closed-loop management of the carbon footprint from calculation to verification. Finally, promote the upgrade of BIM models to digital twins, integrating technologies like drone scanning and IoT sensors to dynamically update the model status and carbon data during the demolition process, achieving real-time visualization and precise control throughout the operation, providing forward-looking solutions for future green demolition of hospitals.

4. Conclusion

This study systematically explored the theoretical methods, key technological pathways, and practical applications of achieving carbon footprint visualization throughout the entire lifecycle of hospital buildings based on BIM-LCA technology. The research demonstrates that the deep integration of BIM and LCA can effectively overcome the bottlenecks of fragmented data, rough calculations, and abstract representation inherent in traditional building carbon management. It provides a whole-process, multi-dimensional, and visual means for carbon footprint management of functionally complex and energy-intensive buildings like hospitals.

In the design stage, BIM-LCA significantly improves the accuracy of carbon prediction through parametric simulation and multi-scheme comparison, with errors controllable within 15%, providing a reliable basis for low-carbon design decisions. During the construction stage, based on automatic quantity extraction and dynamic linkage with carbon emission factors, it enables refined management and dynamic visualization of the carbon footprint of materials and construction processes. In the operation and maintenance stage, integrating BIM with IoT and Building Automation Systems to construct a digital twin operational platform allows for real-time monitoring, diagnosis, and optimization of energy consumption and carbon emissions. This stage, accounting for over 90% of the lifecycle carbon emissions, is key to carbon control. In the demolition stage, utilizing the BIM model for waste quantification and disposal simulation supports decision-making for green demolition and resource reuse.

However, current research and applications still face numerous challenges, such as the lack of specialized LCA databases for medical buildings, data interoperability issues between BIM and LCA software, and the immaturity of mechanisms for continuous carbon data transfer across stages, which hinder the widespread application and deep empowerment of this technological system.

In the future, research on BIM-LCA-based carbon footprint visualization for hospital buildings will continue to deepen and develop in the following aspects:

First, at the level of technology integration, efforts should promote the deep integration of BIM-LCA with cutting-edge technologies like Digital Twins, Artificial Intelligence (AI), and Big Data. This will lead to the development of intelligent carbon management platforms with self-learning and self-optimizing capabilities, advancing from "visualization" to "predictability and controllability." Second, regarding data standards and database construction, there is an urgent need to establish specialized LCA databases tailored to the characteristics of medical buildings, covering special medical materials, equipment, and energy types. Unified data exchange and carbon accounting standards should be formulated to facilitate seamless cross-platform, whole-chain data integration. The establishment of these databases will also significantly improve the accuracy of carbon accounting for hospital buildings. Third, in renovation and expansion projects, BIM-LCA technology will play a more central role. Facing the strict requirement of "construction without suspending hospital operations," future approaches could use laser scanning and reverse modeling technologies to quickly obtain accurate BIM models of existing buildings. Integrating historical operational data would help build an integrated digital baseline encompassing the "as-is," "design," and "construction" states. Based on this, LCA can be used to simulate the carbon impact of different renovation options, thereby selecting the carbon-optimal design and construction organization plan while ensuring uninterrupted medical functions.

In summary, BIM-LCA technology provides powerful support for achieving visible, manageable, and controllable carbon footprint management throughout the entire lifecycle of hospital buildings. Continuous innovation in technology, data, and mechanisms in the future will strongly promote the construction and development of green, low-carbon, and smart hospitals.

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