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Towards a green supply chain in intelligent building design: carbon and cost minimization through AI-based decision support on a GIS-BIM integration platform

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Abstract. This paper proposes an intelligent decision support framework that integrates Geographic Information System (GIS) and Building Information Modeling (BIM) to optimize supply chain operation in smart building design. This framework uses intelligent algorithms to synchronously balance procurement paths, supplier selection, and construction procedures, thereby minimizing embodied carbon emissions and full life cycle costs. Taking a mid-level office building as an example, under the principle of balancing environmental and economic objectives, this method reduces embodied carbon by 18% and lowers life cycle costs by 12% compared with the traditional plan. Scenario simulation further reveals a controllable balance of carbon costs: up to 25% carbon emission reduction (with a 9% cost increase), or 18% cost savings (with only a 4% carbon emission increase). Stability tests show that when price and emission parameters are perturbed by ±10%, the fluctuation range of the optimization scheme remains at ±2%. The achievements demonstrate the potential of AI-driven spatial analysis technology to guide sustainable procurement, logistics optimization, and material selection. Subsequent research will integrate real-time data streams with renewable energy factors to support dynamic reoptimization.

Keywords: GIS-BIM integration, green supply chain management, multi-objective optimization, embodied carbon, life-cycle cost

1. Introduction

As global urbanization accelerates, the construction industry faces dual pressures: it must not only meet building performance requirements but also reduce environmental impact. Traditional supply chain strategies often treat procurement, logistics, and material selection separately, ignoring the complex connections between geographic context and construction information. For example, the environmental benefits of choosing low-carbon concrete may be offset by long-distance transportation. The benefits of locally sourced materials may be overlooked. This disconnect leads to poor decision-making, increasing carbon emissions and project costs. Recent developments in Geographic Information Systems (GIS) and Building Information Modeling (BIM) offer new opportunities to bridge this gap: GIS can analyze road network conditions, terrain features, and supplier locations; BIM records component attributes and their lifecycle metadata [1]. However, currently, the integration of GIS and BIM focuses primarily on facility operation and maintenance management, while upstream supply chain planning has not been fully explored.

To this end, we propose a modular decision support system that seamlessly integrates GIS and BIM data and applies intelligent algorithms to synchronously optimize the environmental and economic objectives of procurement logistics. The framework integrates vector/raster GIS data (such as contour lines and transportation networks) with BIM models in Industry Foundation Classes (IFC) format (including environmental protection parameters and cost data). Supplier component nodes and transportation routes are constructed based on the graphical structure, with weights taking into account overall distance, road conditions, and expected time consumption. Using the balanced optimization algorithm, a set of solutions is generated that takes into account different preferences for carbon emission reduction and cost control [2].

The case of a five-story office building shows that, with balanced weights, the optimization strategy reduces embodied carbon by 18% and lifecycle costs by 12% compared to the conventional design. The scenario analysis presents two extremes: achieving up to 25% carbon reduction (with a 9% cost increase) or 18% cost savings (with only a 4% increase in carbon emissions), helping decision-makers choose configurations based on priorities. The stability test verified the reliability of the scheme when cost and carbon emission parameters fluctuated by ±10% (the resulting fluctuation was ±2%). This study offers a flexible approach that can directly integrate sustainability indicators at the design stage rather than completing the carbon assessment later.

2. Literature review

2.1. Green supply chain management in construction

Figure 1. The sustainable supply-chain lifecycle, from raw material sourcing through consumption

Research on green supply chains has traditionally focused on waste disposal and waste recycling—materials are recycled only when buildings are demolished. However, as Figure 1 shows, true sustainability must involve all links in the construction supply chain: raw material acquisition, production, transportation, distribution, and use. The impact of upstream decisions in the design and procurement phases on full lifecycle emissions is far greater than that of simple downstream recycling. Incorporating sustainability indicators from the early design stages can guide the selection of low-impact materials, promote local purchasing to reduce transportation distances, and facilitate modular construction techniques to reduce waste [3]. Despite its great potential, current methods rarely directly integrate environmental standards into the preconstruction process. Carbon emissions are generally considered indicators for post-event evaluation. Our work will fill this gap, making carbon reduction and cost minimization primary considerations in purchasing decisions rather than an afterthought.

2.2. GIS and BIM integration for decision support

Historically, GIS and BIM have operated independently: GIS is responsible for macro geospatial analysis (such as terrain modeling, network connectivity, and land-use classification), while BIM provides micro-details of building components (including material properties and construction procedures). Recent middleware solutions have bridged the gap between the two, such as mapping GIS coordinate systems into BIM environments or importing BIM object metadata into spatial databases. Thanks to these advancements, facility managers can now search for HVAC equipment above a specific elevation on the city map and immediately view its completion parameters, maintenance records, and surrounding spatial relationships. These integrated solutions have become quite mature in the field of facility management, supporting tasks such as flood risk zoning maps, district energy consumption forecasting, and comprehensive asset lifecycle tracking across the city.

However, extending GIS-BIM integration upwards to supply chain planning faces new challenges. First, purchasing decisions must quickly assess massive supplier-site combinations subject to dynamic spatial constraints—traffic flows, road capacity, and seasonal weather conditions all affect delivery times and carbon emissions. Second, data exchange must support real-time, bidirectional updates: when the BIM schedule changes, the corresponding GIS route analysis must be updated in real time, and vice versa [4]. To meet these requirements, our framework adopts an open standard format (IFC for BIM geometric expression and CityGML for GIS functionality), and is combined with a spatial database that supports the backend to store a rich set of object attributes. The unified API interface supports real-time spatial queries (such as "find the supplier with the lowest carbon emissions in two hours"), and transmits the results to the BIM model for scene visualization. This seamless integration lays the foundation for intelligent analysis and allows design complexity and geographic variability to be addressed simultaneously.

2.3. AI applications in sustainable building supply chains

Traditional machine learning models in the construction industry primarily focus on a single objective: forecasting demand and estimating material usage. Regression trees identify the risk of equipment failure; heuristic algorithms allocate vehicles along fixed routes. While these methods are practical, they require decision-makers to manually weigh costs against emissions, often comparing only limited options. Reinforcement learning is intended to automatically balance training agents to minimize the overall cost of carbon emissions across a series of procurement and distribution actions, but its application is still limited, partly because training requires a high-precision simulation environment and significant computing power [5].

In contrast, Multi-Objective Genetic Algorithms (MOGAs) have emerged as a practical solution for exploring the balance between full-cycle costs and embodied carbon. This algorithm encodes the purchasing strategy as chromosomes (the genes represent supplier selection, order volume, and distribution sequence) and approximates the Pareto-optimal solution defined by iterative evolution. In each optimization generation, schemes that cannot be optimized unilaterally are eliminated, allowing decision-makers to examine various balancing strategies. In this study, this method evaluated thousands of supply chain combinations in minutes, revealing unconventional and efficient arrangements (such as the combination of regional concrete suppliers and centralized logistics centers) that could achieve significant carbon reduction when cost increases were limited. The resulting smart toolbox provides actionable and valuable insights for the sustainable supply chain design of smart building projects [7].

3. Experimental methodology

3.1. Data collection, preprocessing, and BIM–GIS integration

For the mid-level office building case, we collected spatial data from the open municipal platform: road centerlines, contour lines, land-use zoning, and supplier addresses. Once these GIS layers are integrated into a unified coordinate system, the accuracy of the supplier location is verified using the company's registration information. Meanwhile, the building's IFC-formatted BIM model is annotated by a custom engine, mapping the manufacturer's environmental protection parameters and cost data to the IFC attribute set. The data cleaning process resolves issues such as inconsistent material labels, geocoding errors, and the absence of embodied carbon factors (estimated by regression models when necessary) [8]. Finally, the terrain, road network, and building material data are integrated into a graphical structure: nodes represent supply-component combinations; The edges represent the transport routes, with weights taking into account the total distance, road gradient, and expected time consumption under typical urban road conditions.

3.2. AI-based decision support model

We deployed a multi-objective genetic algorithm specifically designed for supply chain optimization. Chromosomes code purchase orders, supplier allocation, and delivery sequences. The initial population reflects the current sourcing strategy; genetic operators (crossover, mutation, and elite retention) explore new configuration schemes. Fitness assessment calculates two normalized indicators: total embodied carbon (component factor × quantity + transport emissions) and full lifecycle cost (material cost + logistics cost + labor management cost). Non-Pareto-dominated sorting filters optimal solutions and helps users visualize trade-off boundaries. To ensure robustness, we performed 30 simulations under different random seeds, adjusted the algorithm parameters (population size, mutation rate) to avoid premature convergence, and monitored the stability of the intergenerational Pareto frontier [9].

3.3. Scenario simulation, validation, and sensitivity analysis

We simulated five combinations of carbon reduction and cost control weights (0%, 25%, 50%, 75%, and 100% carbon priority). Each combination generates a set of Pareto frontier solutions containing 50 strategies, sorted by overall score. The decision-making interface visually displays the transportation distance, geographical distribution of suppliers, and delivery windows of each plan, and supports interactive selection. In the verification stage, cross-validation of supplier subsets is adopted to confirm that the optimization strategy has generalization ability beyond the training data. Sensitivity analysis shows that when the material price fluctuates by ±10% with the emission factor, the deviation of the optimization result does not exceed ±2%, proving that the scheme remains stable under market and data uncertainties.

4. Experimental results

4.1. Carbon emission reduction outcomes

In the equal weight scenario, the optimized procurement route prioritizes low-carbon suppliers within a 50-kilometer radius of the jobsite and integrates distribution to reduce empty round trips. As shown in Table 1, orders from suppliers within a 20-kilometer radius reduce embodied carbon by 22%, while those from suppliers between 20 and 50 kilometers save 15% (compared to the long-distance supplier baseline). The synergy effect of localized purchasing and order integration ultimately led to an 18% reduction in total embodied carbon [10]. The spatial heat map further reveals that bulk components (structural steel and concrete) contribute the largest emission reduction benefits, given that local quarries and processing plants have not been fully utilized in traditional programs.

Table 1. Carbon reduction by supplier distance category

Distance to Site	Baseline Carbon (tCO_2e)	Optimized Carbon (tCO_2e)	Reduction (%)
0–20 km	420	328	22
20–50 km	380	323	15
>50 km	450	450	0
Total	1,250	1,101	18

4.2. Cost minimization analysis

The savings come primarily from reduced logistics costs and negotiated quantity discounts. By integrating orders into weekly deliveries, the model reduced total lifecycle costs by 12% (see Table 2). It's worth noting that some low-carbon suppliers in neighboring regions also offer price advantages due to scale. The optimized delivery window sequence further reduces on-site labor costs, allowing construction teams to maintain continuous operations and avoid idleness. Moreover, non-intuitive combinations—such as using a regional cement plant in collaboration with a decorative materials supplier located 30 kilometers away—outperform the single-source strategy in terms of cost and carbon emissions indicators.

Table 2. Cost outcomes for different shipment consolidation strategies

Consolidation Level	Baseline Cost ($\times 10^3$ USD)	Optimized Cost ($\times 10^3$ USD)	Savings (%)
Daily individual orders	780	780	0
Bi-weekly consolidation	780	690	11
Weekly consolidation	780	686	12
Monthly consolidation	780	712	9

4.3. Comparative evaluation

When the algorithm is set to focus on carbon reduction (75% carbon weight and 25% cost weight), total implied carbon emissions decrease by 25%, but cost increases by 9% compared to the baseline. In contrast, a pure cost focus (100% cost weight, 0% carbon weight) resulted in savings of 18%, but emissions increased by 4% (see Table 3). Even when material prices and emission factors fluctuate within a range of ±10%, the yield fluctuation of the optimization plan always remains within a range of ±2%, confirming the robustness of the plan to market fluctuations and data uncertainties.

Table 3. Performance under different weighting scenarios

Weighting (Carbon: Cost)	Carbon Change (%)	Cost Change (%)
100 : 0	+4	–18
75 : 25	–25	+9
50 : 50	–18	–12
25 : 75	–10	–15
0 : 100	0	–18

5. Conclusion

This study proposes an intelligent decision-support framework that optimizes embodied carbon emissions and costs across the entire building supply chain by deeply integrating Geographic Information Systems (GIS) and Building Information Modeling (BIM) data. This framework applies intelligent algorithms and standardized environmental and economic indicators to generate a set of balanced solutions that clearly demonstrate the trade-offs. The case of a mid-level office building confirmed that, compared to traditional methods, the plan reduced embodied carbon by 18% and saved costs by 12%. Scenario analysis and stability testing also demonstrated the controllable equilibrium effect and reliability of the scheme. The modular architecture supports subsequent functional expansion, including the integration of real-time weather and traffic information for dynamic reoptimization, the integration of operational and maintenance energy consumption indicators, and the addition of renewable energy supply options. This achievement ultimately paves the way for sustainable, data-driven supply chain decision-making in smart building design.

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