A Knowledge-Based Data-Driven Algorithm for Sustainable Supply Chain Optimization in Modular Integrated Construction

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Abstract

Modular Integrated Construction (MiC) enhances efficiency through off-site prefabrication, yet its logistics-related carbon footprint remains underexplored. This study introduces a data-driven framework that integrates multi-agent simulation (MAS) with deep learning to evaluate and optimize CO_2 emissions, cost, and schedule performance across the MiC supply chain. The MAS framework, developed in AnyLogic, models suppliers, an MiC factory, transport fleets, and construction sites as autonomous agents interacting over a GIS-based logistics network for Paris region to capture decentralized decision-making and emergent logistics behavior. Using 23,328 simulated scenarios, we trained an artificial neural network (ANN) that accurately predict project outcomes and identify optimal fleet allocation strategies. Using straight-through estimator (STE)-based surrogate gradient optimization for discrete variables applied to the ANN, we derive an optimal sustainable strategy that reduced total cost to approximately €1.95 million and improved project duration to about 82.7 days, with minimal impact on total CO_2 emissions (~3.78 Mt CO_2e). These results demonstrate the framework's capability as a knowledge-based, data-driven decision-support tool for sustainable, cost-efficient, and adaptive MiC logistics planning.