A dynamic decision-making model to enhance the sustainability of construction waste management strategies

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Abstract

The construction industry creates a large quantity of waste, making effective construction waste (CW) management strategies crucial for environmental protection and resource utilization. However, determining the optimal strategies to maximize the benefits for all stakeholders is challenging and complex. This paper develops a decision-making model using system dynamics and multi-criteria decision analysis (MCDA). First, a system dynamics model is developed, incorporating the two main pillars of sustainability: environmental and economic perspectives. There are one causal-loop model and two stock-flow models developed to qualitatively and quantitatively evaluate the performance of the environmental and economic performance of CW management strategies. Based on the simulation results, an MCDA is applied to identify the optimal strategies considering these perspectives. The integration of dynamic simulation and MCDA effectively supports decision-making in CW management, providing a scientific foundation for reducing environmental impact and enhancing resource efficiency. This model offers a systematic and data-driven approach to developing CW management strategies, contributing to the advancement of sustainable construction practices. The research contributes an integrated decision-making framework that combines system dynamics and MCDA to optimize CW management strategies. It evaluates these strategies from both environmental and economic perspectives using causal-loop and stock-flow models, providing a comprehensive, data-driven approach. This framework supports informed decision-making for stakeholders, aiding in the development of sustainable practices that reduce environmental impact and enhance resource efficiency.

Keywords: construction waste (CW), system dynamics, sustainability, strategies, multi-criteria decision analysis (MCDA)

1. INTRODUCTION

The continuous expansion of urban areas generates substantial construction waste (CW), hindering sustainable city development, with most waste landfilled or illegally dumped and only a small portion recycled. CW is a serious issue in the construction industry, which can lead to serious environmental problems (Meshref et al., 2023). The construction industry is progressively acknowledging the importance of assessing sustainability that integrates up-to-date data and considers timing factors (Figueiredo et al., 2024). CW management involves society, economy, and environment, with each stage's diverse participants adding complexity through autonomy, nonlinearity, and evolving temporal and spatial structures (Ding et al., 2023).

Strategies related to CW are crucial for enhancing the efficiency of the construction sector (Hao et al., 2024; Kabirifar et al., 2020; Ramos et al., 2023). Various stakeholders, each with different priorities, are involved in the CW management process, with the government and contractors being the primary ones. Therefore, this paper employs a system dynamics approach combined with multi-criteria decision analysis MCDA to identify optimal CW management strategies. Optimizing CW management strategies is essential to minimize environmental degradation, enhance resource efficiency, and support sustainable urban development. Integrating system dynamics with MCDA provides a powerful approach to addressing complex challenges in sustainable resource management. System dynamics models dynamic interactions over time, while MCDA evaluates trade-offs across economic and environmental criteria. Although previous studies have explored these methods individually in construction and demolition waste management, their combined application to optimize recycling pathways remains limited. This paper addresses the lack of an integrated approach combining system dynamics and MCDA to identify optimal CW management strategies, which has not been adequately explored in previous studies.

2. METHODOLOGY

This paper adopts an integrated approach of system dynamics and MCDA to analyze the strategies of managing CW from the perspectives of the environment and economy. The system dynamics model develops two sub-models, including environment and economy. All these two sub-models can be integrated into one system using the MCDA approach through a comprehensive index for analyzing the comprehensive sustainability performance from all two perspectives.

2.1. System Dynamics Modeling

The system dynamics method utilizes feedback loops to embody systems thinking, enabling a deeper understanding of the interrelationships and dynamic behaviors within complex systems (Wang You, 2021). System dynamics modeling includes causal-loop models and stock-flow models (Golrizgashti et al., 2023). The causal-loop model reveals the interrelationships among elements through positive and negative feedback, while the stock-flow model enables quantitative analysis by simulating scenarios under various constraints (Zhao et al., 2024). The system dynamics approach allows for analyzing causal relationships among factors over time in a complex system (Ma et al., 2022).

This paper utilizes Vensim software to develop the causal-loop and stock-flow diagrams. This research develops two causal-loop models and two stock-flow models to qualitatively and quantitatively evaluate the performance of CW management strategies from environmental and economic aspects.

2.2. Multi-criteria Decision Analysis (MCDA)

Multiple stakeholders participate in the CW management process, and the primary two stakeholders are the government and contractors (Kim et al., 2020). The government typically prioritizes the environmental performance of CW management processes, while contractors tend to focus more on economic performance. However, the priorities of these two stakeholders can contradict each other. Improving environmental performance, such as providing recycling subsidies, often incurs higher costs. In contrast, pollution-driven construction waste disposal methods, such as landfilling and illegal dumping, tend to be the cheapest options available. Therefore, the system dynamics model is developed for evaluating the environmental and economic performance is separate sub-models.

After developing the two sub-models, the MCDA approach should be employed to comprehensively evaluate these indicators by assigning weights to each aspect of environmental and economic performance in CW management. MCDA analysis is used to address problems involving the selection of the most satisfying options or the evaluation of solution quality (Więckowski et al., 2023). Environmental performance will be assessed based on carbon emissions from the CW management process, while economic performance will be evaluated using the total costs associated with CW management.

3. MODEL DEVELOPMENT

3.1. Causal-loop Model

The system dynamics model comprises two causal-loop diagrams and two stock-flow diagrams. The causal-loop models are utilized for a qualitative analysis of the environmental and economic performance of CW management. The causal-loop model depicted in Figure 1 integrates the environmental and economic subsystems, illustrating the interrelationships among elements that influence performance through positive and negative feedback loops.

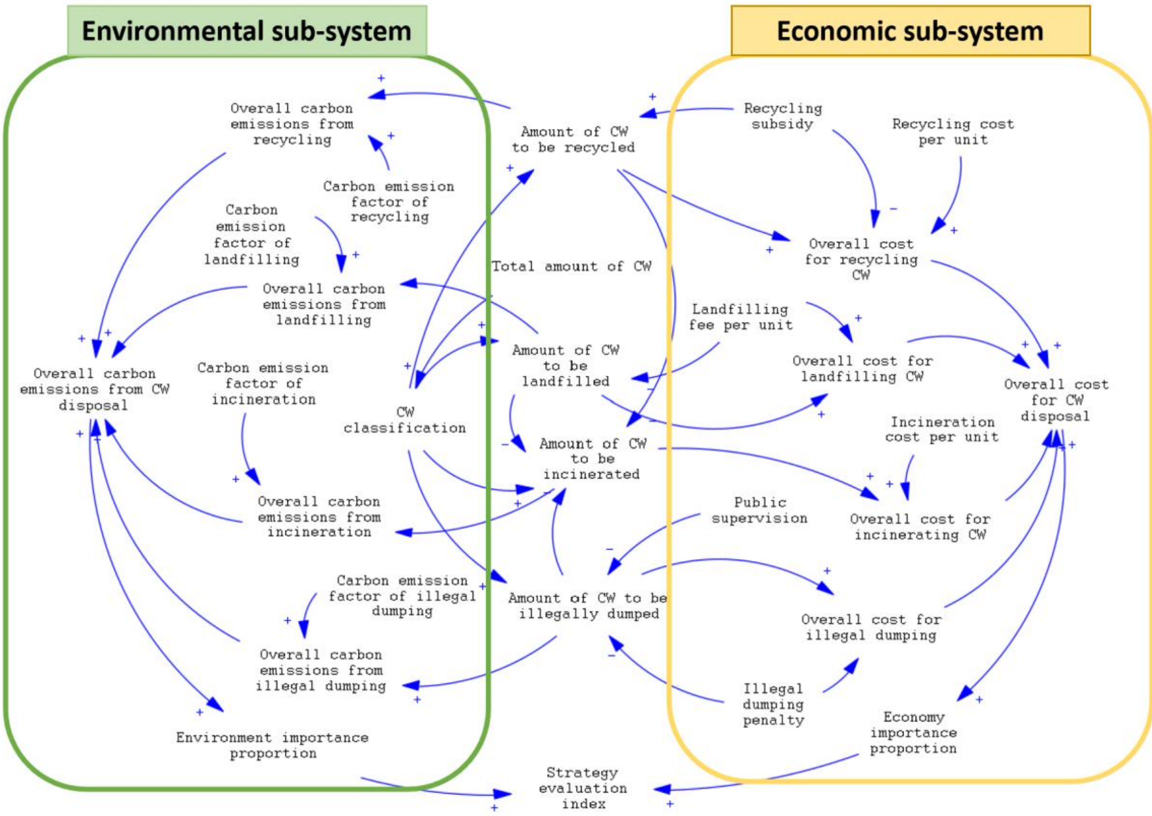

Figure 1. Integrated environmental and economic causal-loop model

3.2. Stock-flow Model

The stock-flow models are developed based on the integrated causal-loop model. The stock-flow models can be used to simulate potential carbon emissions and overall costs associated with CW management from 2010 to 2030 under various CW strategies. The model considers various construction waste (CW) disposal approaches, including landfilling, incineration, recycling, and illegal dumping. Each waste disposal methods have different environmental and economic performance. The environmental stock-flow model is presented in Figure 2.

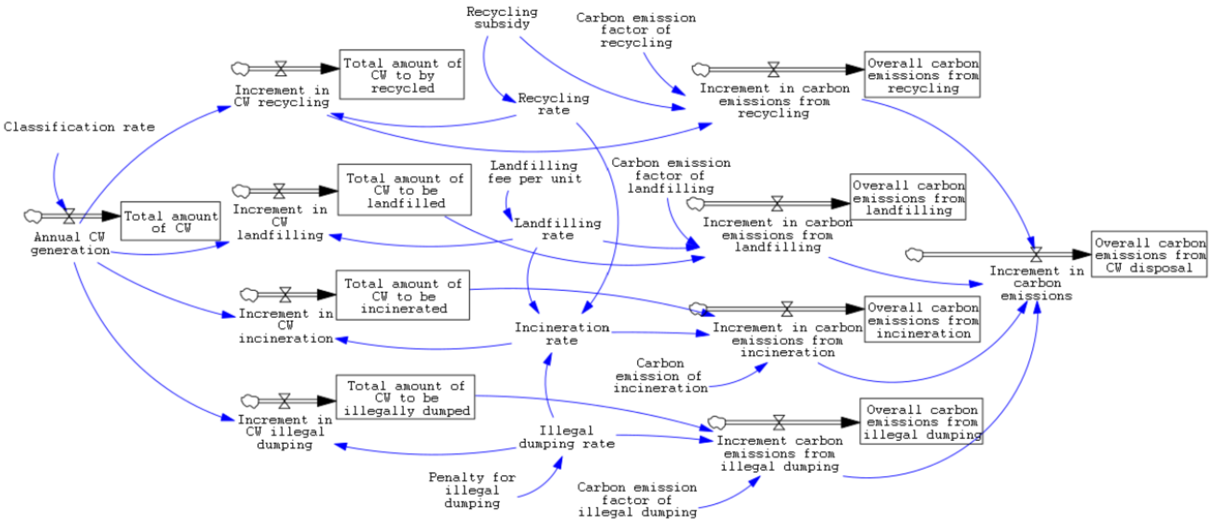

Figure 2. Environmental stock-flow model

The economic stock-flow model is presented in Figure 3. Different CW disposal approaches exhibit varying economic performances. For instance, illegal dumping is the cheapest waste disposal method but leads to the highest environmental pollution. In contrast, recycling is the most environmentally friendly option, though it incurs the highest costs.

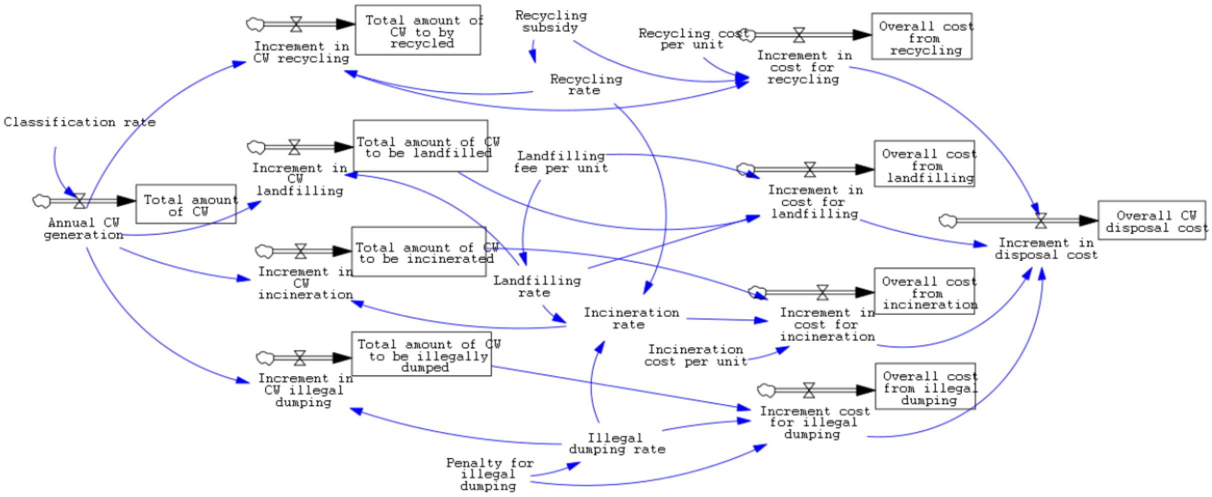

Figure 3. Economic stock-flow model

3.3. Model Validation and Integration

The system dynamics model's validation involves several steps: validity testing, dimensional consistency testing, sensitivity testing, and extreme condition testing. The validity test is performed through comparing the simulated value with historical value to ensure that the error between the two remains within a reasonable range. If the comparison value lies within the acceptable range, it suggests that the simulation results are reliable and effectively represent the real-world conditions. This ensures that the simulation based on the model is accurate and reflects the real situation effectively. The dimension consistency test can be conducted using the function in the Vensim software. The sensitivity test and extreme condition test are adopted to ensure that the model remains feasible under extreme conditions and is sensitive enough to reflect slight changes in strategies. By inputting extreme data into the model and varying the values within a specific range, these tests can be conducted effectively.

After developing the system dynamics model, various scenarios under different CW management strategies from 2010 to 2030 can be simulated. The total carbon emissions and overall costs associated with managing CW will be determined through these simulations. This data can then be utilized in the MCDA to calculate a comprehensive evaluation index, helping to identify the CW management strategy that maximizes both environmental and economic performance to the utmost.

4. DISCUSSION

This research develops a system dynamics model that includes an integrated causal-loop model and two stock-flow models. The causal-loop model combines environmental and economic performance into a cohesive framework, revealing the interrelationships among elements that influence the economic and environmental outcomes of CW management strategies through positive and negative feedback loops. The stock-flow models quantitatively evaluate economic and environmental performance across various scenarios from 2010 to 2030.

Key strategies evaluated include unit landfilling fees, penalties for illegal dumping, and recycling subsidies. Each strategy has distinct impacts on economic and environmental outcomes. For instance, higher unit landfilling fees discourage landfilling and promote recycling, thereby improving environmental performance but potentially increasing short-term economic costs for contractors. Penalties for illegal dumping create a deterrent effect, leading to reduced illegal disposal activities, while recycling subsidies incentivize contractors to adopt sustainable practices, reducing environmental impacts and fostering a circular economy.

The simulation results reveal that different combinations of these strategies can yield varying performance outcomes. For example, scenarios with increased recycling subsidies paired with moderate landfilling fees achieve substantial environmental benefits but may require careful economic adjustments to support implementation. Conversely, scenarios prioritizing economic performance may compromise environmental gains, underscoring the need for a balanced approach.

5. CONCLUSION

This study contributes to CW management research by integrating economic and environmental considerations into a system dynamics model, providing insights into the interrelationships and trade-offs between these dimensions. By examining the impact of strategies such as landfilling fees, illegal dumping penalties, and recycling subsidies, the model enables stakeholders to identify optimal strategies tailored to specific objectives.

The findings emphasize the need for a holistic evaluation framework using MCDA to balance economic and environmental outcomes. By simulating scenarios from 2010 to 2030, this research highlights the importance of long-term planning and adaptive strategies to achieve sustainable CW management. Ultimately, this study offers valuable guidance for policymakers, contractors, and other stakeholders in formulating strategies that promote both environmental sustainability and economic efficiency.

6. ACKNOWLEDGMENTS

The data will be made available on request.

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