INTEGRATED MANAGEMENT OF CONSTRUCTION WASTE USING BIM-BASED VISUAL MODELING

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Abstract. Rapid urbanization, especially in the Arab world, makes Construction and Demolition Debris (CDD) a major environmental and economic challenge. Inert debris like concrete and bricks forms 20-30% of regional solid waste, overloading landfills and wasting recoverable resources. This research developed a simulation model integrating mathematical analysis with Building Information Modeling (BIM) to manage CDD. It analyzes three treatment pathways: on-site reuse, recycling, and disposal. Using real project data from Syria, the model predicts specific debris quantities (e.g. concrete) and generates flow diagrams pinpointing waste generation timelines. Crucially, it forecasts the percentages for reuse, recycling, and disposal. The model core strength lies in its predictive analytics, allowing for the simulation of various "what-if" scenarios during the planning phase. Stakeholders can assess the environmental and financial outcomes of different material choices and waste management strategies before construction begins. This proactive planning is operationalized in two key phases: first, during the initial project design to set optimal waste diversion targets and logistics; and second, during the construction phase itself, where the model can be updated with real-time data to track progress and adjust plans. Furthermore, its application extends to pre-demolition audits for urban renewal projects, enabling the systematic recovery of valuable materials. By providing a clear economic and logistical framework for debris management, the model also aids in selecting contractors based on their waste management performance and facilitates compliance reporting for green building certifications, thereby embedding sustainability directly into the project's lifecycle and core decision-making processes.

Keywords: construction waste, building information modeling (BIM), construction waste management.

Introduction

Despite the benefits that can be achieved by using BIM and the wide range of recommendations and efforts for its adoption, BIM is often neglected for construction waste management [1]. Although many studies have contributed to supporting the use of BIM in construction waste management, none of these studies have provided clear instructions on how to use BIM in this field within a technical and legislative framework. Furthermore, this lack of clear instructions raises serious concerns about how to integrate construction waste management into BIM. Some studies have only provided a general framework by identifying factors to be considered during design [2-3].

Linking the project schedule with waste reduction plans can also reduce costs by 3.85% and time by 6.28% [4]. Building information modeling also enables obtaining all project-related information through quantity take-offs and cost schedules [5]. Therefore, studies have focused on modeling construction waste by understanding and tracking the methods and rates of its generation and working to display them clearly during project phases [6]. Hence, implementing comprehensive construction waste management strategies is crucial for achieving sustainability standards in the construction industry [7]. This challenge has led to a shift in research from focusing on traditional quantitative estimation towards developing integrated proactive tools that support circular economy principles. In this context, Building information modeling (BIM) has emerged as a digital cornerstone, defined as "a digital representation of physical and functional characteristics of a facility, forming a reliable knowledge source for decisions throughout its life cycle" [8].

Therefore, this study will focus on using the visual programming provided by Dynamo to predict waste treatment options for each construction material during the execution phase.

Research Objective. The research aims to create a flexible, BIM-based digital platform for managing construction waste and proactively predicting the three waste treatment options (Recycle, Reuse, Dispose), thereby enabling the utilization of construction waste, reducing waste transportation costs, and protecting the environment, thus supporting circular economy steps and achieving sustainability standards.

Research hypothesis. Proactive prediction of construction waste treatment options is an important step for sustainable planning in construction projects, as it can reduce costs and time, preserve the environment, and provide project management with prior visualization of the expected quantities of construction waste at various stages of the project.

Review of previous studies

A review of some research dealing with construction waste management in recent years was conducted. Each study was analyzed and compared with the current study, which relies on visual programming as a flexible option for early prediction of construction waste treatment steps. Table 1 shows a review of some studies.

Table 1

Review of previous literature and comparison with the current study

No.	Researchers (Year)	Research Title	Methodology	Key Findings	Comparison with Current Research (Early Visual Programming)
[9]	Han et al. (2023)	The development of an integrated BIM-based visual demolition waste management planning system	A visual system integrating BIM with inventory analysis and multi-criteria decision-making algorithms (AHP-TOPSIS). Uses color coding	Improves planning and supports scenario analysis. Increased recycling rate compensates for emissions and costs	Convergence in goal with differences in timing and focus: Han's system is visual and supports decisions, but it is directed at the demolition phase and focuses on assessing existing components. The current research is directed at the conceptual design phase, focusing on the impact of initial design choices on future waste, making it more proactive
[10]	Saka et al. (2024)	Integrated BIM and machine learning system for circularity prediction of construction demolition waste	Integrating BIM with machine learning (XGBoost) to predict quantities of recyclable materials and those sent to landfills using data from thousands of projects	Very high predictive accuracy ($R^2 = 0.9977$). Supports pre-demolition auditing	Complementary: Saka's model is a powerful quantitative prediction tool for what will be generated. The current research is a qualitative planning tool that uses these predictions (or similar data) as inputs for visual programming. The current research provides the interface that translates complex numbers into visual action plans that can be discussed and modified by the design team
[11]	Aftab et al. (2024)	Building information modeling (BIM) application in construction waste quantification – Review	Systematic literature review of BIM applications in waste estimation	Confirms BIM capability to predict and reduce waste and points to the scarcity of research	Establishing the problem: Aftab's review identifies the research gap. The current research directly responds to this gap by presenting a practical model (visual programming) that enriches the research landscape and focuses on a specific applied aspect (early visual planning) not deeply explored in previous reviews

Table 1 (continued)

No.	Researchers (Year)	Research Title	Methodology	Key Findings	Comparison with Current Research (Early Visual Programming)
[12]	Awad et.al. (2024)	Construction and demolition waste generation prediction by using artificial neural networks and metaheuristic algorithms	Development of hybrid models (ANN with optimization algorithms) to predict waste generation using data from Gaza projects	AOA-ANN model superior in accuracy. Hybrid models provide accurate estimates with simple inputs	Difference in perspective: this research is purely quantitative and aims for statistical accuracy in predicting quantity. The current research is qualitative and planning-oriented, concerned with what to do with this quantity (treatment options). The outputs of this research could serve as valuable input for visual programming, providing initial figures for planning
[13]	Sakdirat et al. (2025)	BIM-driven digital twin for demolition waste management of existing residential buildings	A framework combining BIM and digital twin to simulate an actual demolition process and update data in real-time	Improves efficiency and sustainability. High recycling rates enhance financial returns	Integration in lifecycle: the digital twin model is ideal for the execution and demolition phase. The current research precedes and paves the way for it, as visual planning in the design phase sets the goals and scenarios that the digital twin will later manage. The current research aims to prevent waste, while Wang's focuses on intelligently managing it when it occurs
[14]	Saoud & Hindawi (2025)	A BIM-based approach to building deconstruction assessment	Development of measurable indicators for design for deconstruction (DfD) and their integration into the BIM environment via visual programming	A practical approach showing the impact of material and connection choices on the deconstructability score	Alliance in goal and integration in application: both researches operate in the early design phase. Saoud's research focuses on assessing the building's disassembly potential. The current research benefits from this assessment, as components with a high DfD score are primary candidates for "Reuse" options in visual programming. They can be integrated into a single framework
[15]	Bukovics et al. (2025)	A BIM-based automated framework for waste quantification and management in the deconstruction of historical buildings	An automated framework for automatically classifying waste into categories according to the waste management hierarchy using a material database	Manual selective deconstruction significantly increases the rate of high-value reuse compared to mechanical demolition	Integration in the hierarchy: Bukovics' framework applies the waste management hierarchy (avoid, reduce, reuse, recycle, dispose) to existing buildings. The current research applies the same principle but in the design phase, where the designer can avoid and reduce waste through visual options before it is created

Table 1 (continued)

No.	Researchers (Year)	Research Title	Methodology	Key Findings	Comparison with Current Research (Early Visual Programming)
[16]	Samal et al. (2025)	Estimation, classification, and prediction of construction and demolition waste using machine learning: A critical review	Systematic critical review of literature on using machine learning in CDW management	Deep learning achieves high classification accuracy. Machine learning is a promising tool for transforming practices	Identifying supporting tools: Samal's review confirms the power of AI. The current research could benefit from these tools (especially in material classification and quantity estimation) to make visual programming smarter and more accurate in automatically suggesting appropriate treatment options
[17]	Karanafti et al. (2024)	Integrating BIMs in construction and demolition waste management for circularity enhancement – A review	Analytical review of studies integrating BIM in CDW management to enhance the circular economy	BIM is effective in reducing CDW and increasing recycling. The challenge lies in data collection for existing buildings	General framing and specialization: Karanafti's review provides a comprehensive overview of BIM's role in the circular economy. The current research delves into a specific branch of this framework, namely the visual planning mechanism, offering a tangible applied contribution to one of the general recommendations typically emerging from such reviews

The comparison column shows that the current research (visual programming) is not separate from previous literature but rather a complementary and developmental link within it the following.

- Integration with Quantitative Tools: The current research fills the gap between accurate predictive tools (like AI) and the end-user, transforming their digital outputs into understandable and modifiable visual plans.
- Proactivity in the Lifecycle: While much research focuses on the demolition or end-of-life phase, the current research shifts focus to the leftmost stage of the lifecycle (early design phase), where the cost of change is low and the impact of waste prevention is greatest.
- Enhancing Collaboration and Decision-making: Visual programming aims to make waste management data a visible and available part of the design decision-making process, enhancing collaborative work among designers, project managers, and sustainability specialists.

In summary, this approach represents a bridge between advanced technical research and the daily practical needs in design offices, thereby increasing the practical feasibility of applying circular economy principles.

Materials and methods

This approach is based on integrated resource management theories, circular economy principles, and process simulation models, which combine to form an integrated methodological framework through which an environmental challenge can be transformed into an economic opportunity. This study aims to present an integrated mathematical model that can leverage the immense potential of BIM technology in predicting construction waste management and contribute to achieving sustainable development goals by reducing waste, rationalizing consumption, and maximizing the use of available resources.

An integrated mathematical model was prepared that contributes to construction waste management, also taking into account the diversity of materials, waste generation rates, and waste treatment rates (Recycle-Reuse-Disposal).

After preparing tools for quantitative and temporal modeling of waste, in addition to waste reduction tools based on visual programming (BIM & Dynamo), a tool based on visual programming was prepared to predict waste treatment options (Reuse, Recycle, Dispose), relying on a mathematical model developed to suit the case study.

1. Main Variables of the Mathematical Model

- Q_i: Total quantity of material *i* used in the project (m^3, m^2, ton, etc.).
- F_i: Waste factor for material *i* as a percentage, %.
- $R_{u,i}$: Proportion of waste reusable for material *i*.
- $R_{c,i}$: Proportion of waste recyclable for material *i*.
- D_i: Proportion of waste to be disposed of for material *i*.

2. Basic Equations

A. Total waste quantity for material *i*:

$$W_i = F_i \times Q_i \,, \tag{1}$$

where W_i – quantity of waste generated from material *i*.

B. Distribution of waste by type:

1. quantity of reused waste

$$W_{u,i} = R_{u,i} \times W_i \,; \tag{2}$$

2. quantity of recyclable waste

$$W_{c,i} = R_{c,i} \times W_i \,; \tag{3}$$

3. quantity of waste to be disposed of

$$W_{d,i} = D_i \times W_i \,. \tag{4}$$

C. Comprehensive model for all materials. To calculate the total waste in the project:

$$W_{total} = \sum_{i=1}^{n} W_i = \sum_{i=1}^{n} \left(W_u + W_c + W_d\right)_i \,. \tag{5}$$

3. Linking the Model to the Project Schedule

To link waste to time using Phases in Revit:

$$W(t) = \sum_{i=1}^{n} F_i \times Q_i(t), \tag{6}$$

where $Q_i(t)$ – quantity of material *i* used at time *t*.

This equation allows us to obtain the quantity of waste at any time during the project for any construction material.

The equations rely on survey data to determine waste factors (F_i), such as 6.387% for concrete, 7.31% for wall ceramics. $R_{u,i}$, $R_{c,i}$, D_i are determined based on the results of a survey in a previous study (38.02% for reuse, 41.2% for recycling, 20.78% for disposal), noting that these values vary from one material to another, and from one country to another, and that the quantities that can be recycled and reused differ from those actually implemented [4]. However, the survey values were used as a first step in applying waste management principles in Syria.

Integrated Matrix Model for Construction Waste Management. This model relies on representing data and relationships between them using matrices, allowing for accurate calculation and systematic analysis of construction waste. By providing it with waste-related data from projects, this model also enables the development of an integrated plan for waste management and treatment.

The integrated matrix model will be based on compiling the previous mathematical model consisting of a row matrix, so that all materials are represented by the integrated matrix model which consists of the following.

1. Basic Quantities Matrix. This matrix represents the total quantities of materials used in the project.

$$Q = \begin{bmatrix} q_1 \\ q_2 \\ \vdots \\ q_n \end{bmatrix}, \tag{7}$$

where q_i – represents the quantity of material i in the project.

2. Waste Factors Matrix (Generation Factors Matrix). This is a diagonal matrix representing the waste factor for each material individually.

$$F = \begin{bmatrix} f_1 & 0 & \cdots & 0 \\ 0 & f_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & f_n \end{bmatrix}. \tag{8}$$

3. The Three Main Distribution Matrices. These matrices represent the percentages of waste that is reused, recycled, or disposed of the following.
   - Reuse Matrix (R_u):

$$R_u = \begin{bmatrix} r_{u1} & 0 & \cdots & 0 \\ 0 & r_{u2} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & r_{un} \end{bmatrix}. \tag{9}$$

   - Recycle Matrix (R_c):

$$R_c = \begin{bmatrix} r_{c1} & 0 & \cdots & 0 \\ 0 & r_{c2} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & r_{cn} \end{bmatrix}. \tag{10}$$

   - Disposal Matrix (D):

$$D = \begin{bmatrix} d_1 & 0 & \cdots & 0 \\ 0 & d_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & d_n \end{bmatrix}. \tag{11}$$

With the essential condition

$$R_c + R_u + D = I, \tag{12}$$

where I – identity matrix.

4. Calculation of Final Waste Matrices

A. Total Waste Matrix (W) calculated by multiplying the waste matrix by the quantities matrix resulting in an $n \times 1$ matrix

$$W = F \times Q. \tag{13}$$

B. Classified Waste Matrices. The total waste is distributed across different treatment methods – reuse (W_u), recycle (W_c) and dispose (W_d):

$$W_u = R_u \times W , \tag{14}$$

$$W_c = R_c \times W , \tag{15}$$

$$W_d = D \times W . \tag{16}$$

5. Steps for Building the Mathematical Model within the BIM Environment

Step One. Identifying the inputs represented by the project elements (columns, foundations, walls, and floors) in order to calculate the quantities of materials used in constructing these elements, preliminary to calculating the wasted quantities of concrete, concrete blocks, and floor tiles (Fig. 1).

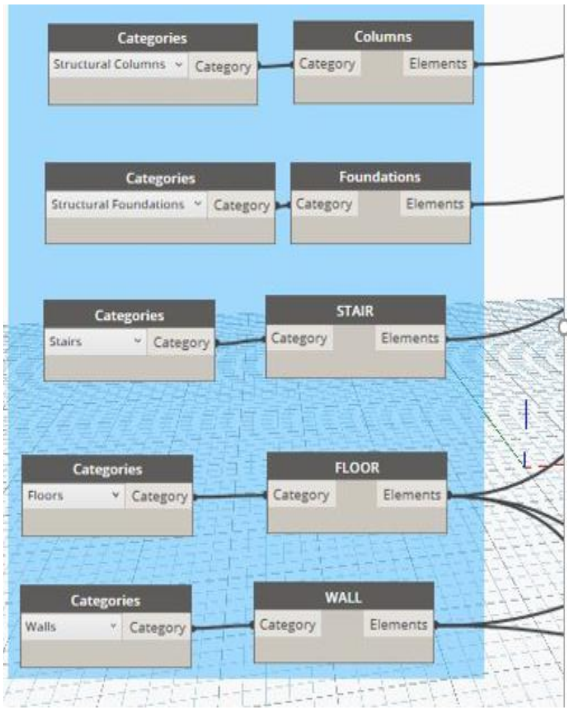

Fig. 1. **Identifying the inputs represented by the project elements:** screenshot of Revit interface showing selected structural and architectural elements like columns, walls, floors

Step Two. After identifying the project's elements, the quantities of concrete, concrete blocks, and tiles were calculated based on Python language as shown in Fig. 2 and 3.

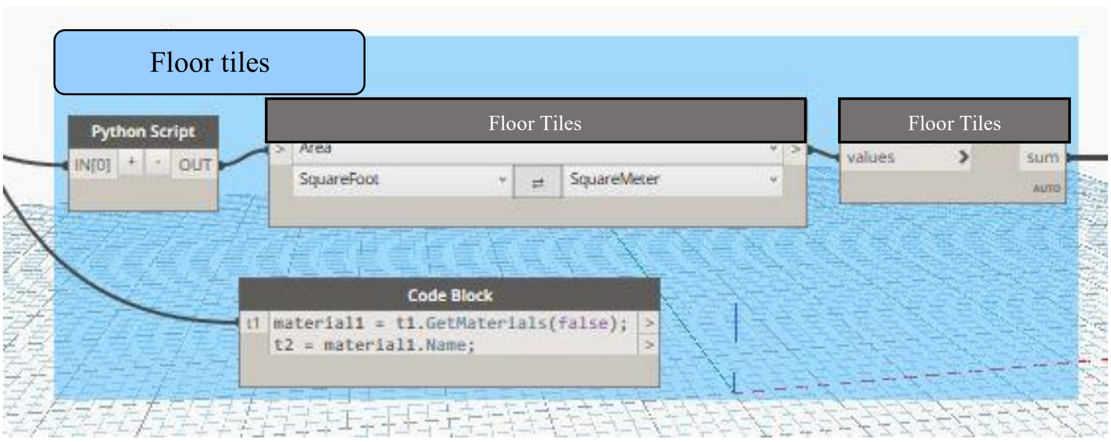

Fig. 2. **Determining the quantities of inputs represented by the project elements (floor tiles):** screenshot of Dynamo visual script showing nodes for quantity take-off, likely connected to Revit elements

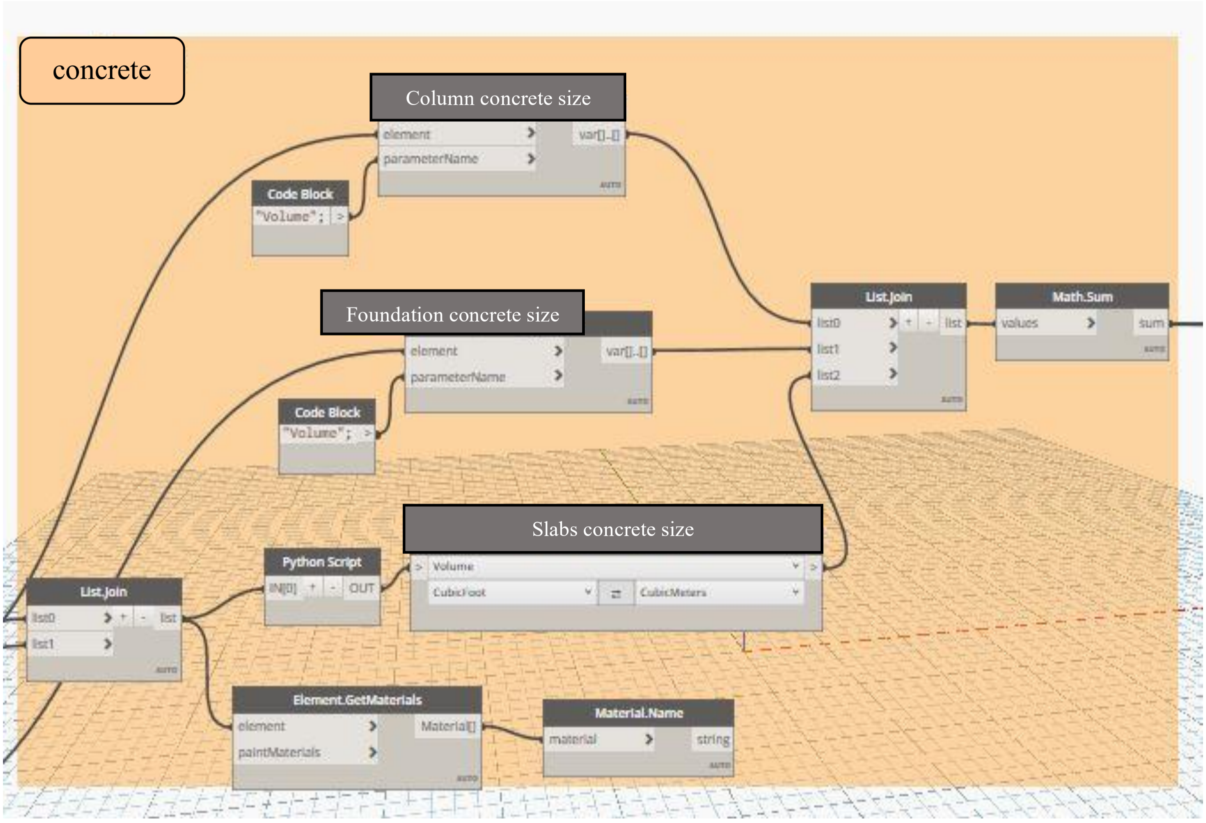

Fig. 3. **Determining the quantities of inputs represented by the project elements (concrete):** screenshot of Dynamo visual script showing nodes for quantity take-off, likely connected to Revit elements

Step Three. After completing the quantity calculation, the amount of wasted material was estimated based on the waste factors shown in the survey for each construction material. Then, the quantity of waste eligible for reuse, eligible for recycling, and waste requiring disposal was calculated based on the mathematical approach built using Python language, as in Fig. 4 and 5.

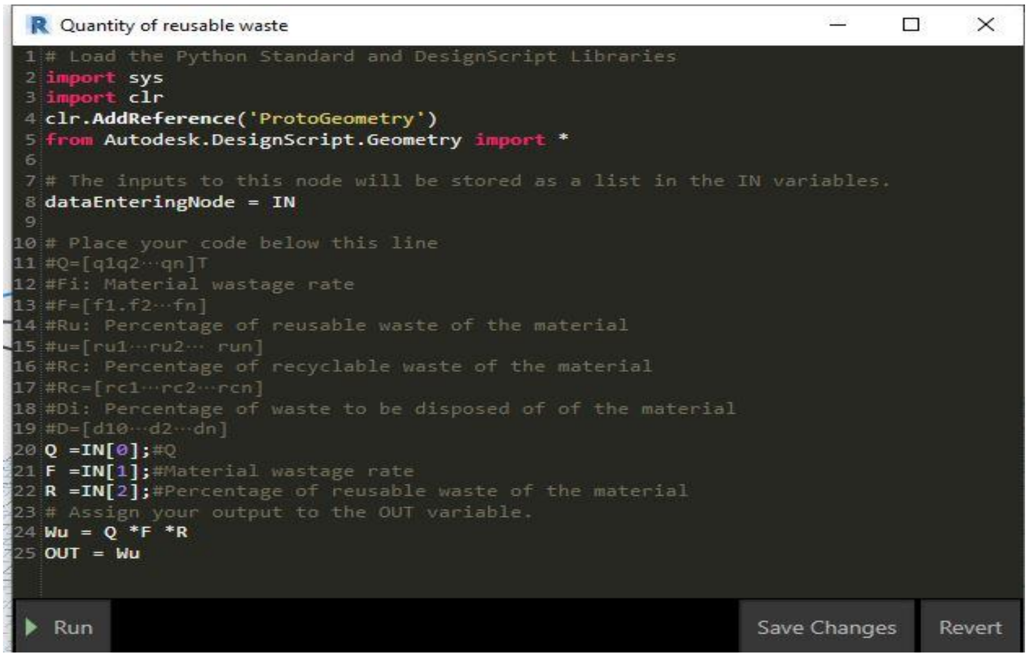

Fig. 4. **Determining the ratios of waste treatment options for project elements:** screenshot of Dynamo Python node showing assignment of percentages for Recycle, Reuse, Dispose based on material type

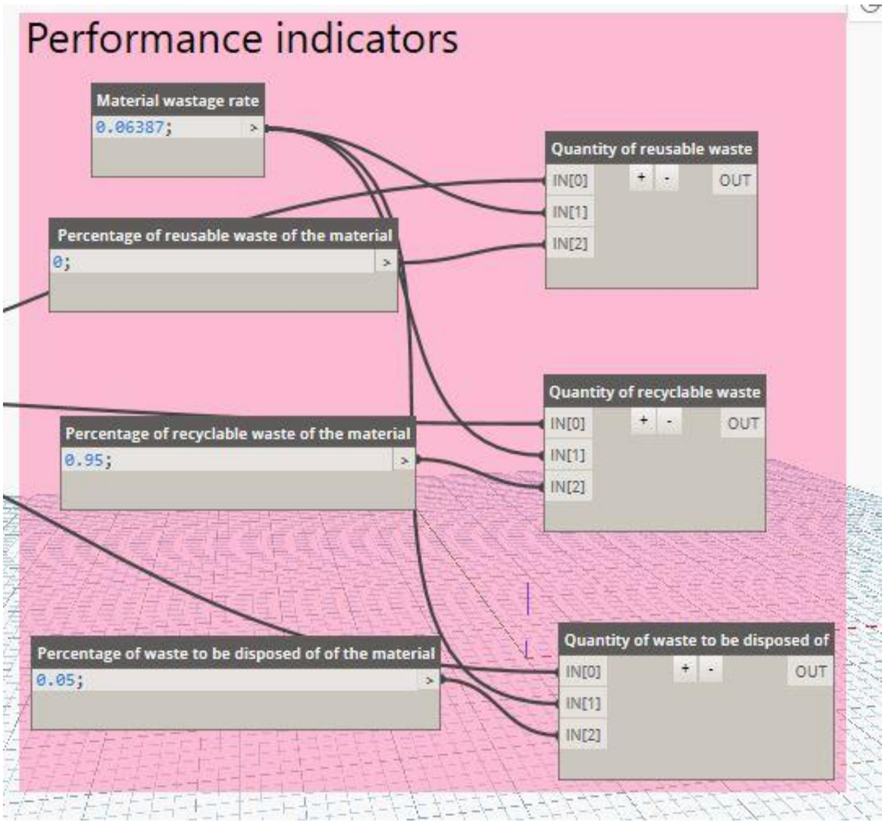

Fig. 5. **Determining the quantity of waste according to treatment options for project elements:** screenshot showing calculated values for W_u, W_c, W_d, maybe output to Excel or displayed in a list

Results and discussion

Results of applying the model within BIM to concrete material in a previously modeled project [4]:

The results of predicting treatment options for the studied materials were exported to Excel sheets. Table 2 shows the expected quantitative ratios for concrete material during the execution phase.

The program also outputs predictions for the percentages of treatment options for other construction materials in the same way, as shown in the Table 3.

Table 2

Time-based prediction of quantitative treatment options for concrete waste, temporal distribution of concrete waste according to treatment plan (2024, 2025)

Month	Waste Quantity, m^3	Recycle, m^3	Reuse, m^3	Disposal, m^3	Waste Quantity, m^3	Recycle, m^3	Reuse, m^3	Disposal, m^3
	2024				2025			
January	0.00	0.00	0	0	34.24	14.10	13.02	7.12
February	178.00	73.34	67.68	36.99	5.58	2.30	2.12	1.16
March	13.88	5.72	5.28	2.88	34.24	14.11	13.02	7.12
April	28.44	11.72	10.81	5.91	34.24	14.11	13.02	7.12
May	7.28	3.00	2.77	1.51	34.24	14.11	13.02	7.12
June	34.24	14.11	13.02	7.12	28.66	11.81	10.90	5.96
July	34.24	14.11	13.02	7.12	34.24	14.11	13.02	7.12
August	34.24	14.11	13.02	7.12	34.24	14.11	13.02	7.12
September	34.24	14.11	13.02	7.12	34.24	14.11	13.02	7.12
October	28.66	11.81	10.90	5.96	19.91	8.20	7.57	4.14
November	34.24	14.11	13.02	7.12	19.91	8.20	7.57	4.14
December	34.24	14.11	13.02	7.12	28.66	11.81	10.90	5.96

Table 3

Distribution of waste treatment options for floor tiles (2025, 2026)

Month	Waste Quantity, m^2	Recycle, m^2	Reuse, m^2	Disposal, m^2	Waste Quantity, m^2	Recycle, m^2	Reuse, m^2	Disposal, m^2
	2025				2026			
January	0	0.0	0.0	0.0	105.3	43.38	40.04	21.88
February	107.8	44.41	40.99	22.40	–	–	–	–
March	210.6	86.77	80.07	43.76	–	–	–	–
April	105.3	43.38	40.04	21.88	–	–	–	–
May	210.6	86.77	80.07	43.76	–	–	–	–
June	105.3	43.38	40.04	21.88	–	–	–	–
July	210.6	86.77	80.07	43.76	–	–	–	–
August	105.3	43.38	40.04	21.88	–	–	–	–
September	175.5	72.31	66.73	36.47	–	–	–	–
October	140.4	57.84	53.38	29.18	–	–	–	–
November	140.4	57.84	53.38	29.18	–	–	–	–
December	175.5	72.31	66.73	36.47	–	–	–	–

Integrating the matrix-based mathematical model, grounded in the visual modeling capabilities provided by BIM, offers significant potential for predicting construction waste treatment options at an early stage of the project. This will enable project management to develop appropriate plans for handling waste that must be disposed of on the one hand, while on the other hand, waste that can be reused will be transformed into a resource that reduces project costs. In some cases, such as floor tiles [4], it can reduce both cost and time. The model will also identify materials that need to be recycled and establish comprehensive plans for managing construction waste in a manner that achieves sustainability criteria.

Conclusions

The following pathways are suggested as approaches for developing the presented model.

1. Develop a local database of waste and treatment ratio to assist with model generalisation.
2. Create a graphical user interface (GUI) for use in the BIM environment and connect it to schedules. The graphical user interface may be useful for technical integration.
3. Complete comparative feasibility studies and perform life cycle assessments (LCA) to improve the economic and environmental considerations in the approach.
4. Establish policies and guidelines for use of the model within public projects and disseminate the tool as an open-source resource to allow for co-development.

Author contributions

Conceptualization, H.A.; methodology, HA. and M.S.; software, HA.; validation, H.A. and M.S; formal analysis, H.A and M.S..; investigation, H.A and M.S.; data curation, H, A.; writing – original draft preparation, H.A.; writing – review and editing, HA. and M.S.; visualization, H.A., M.S.; project administration, H.A.; funding acquisition, H.A All authors have read and agreed to the published version of the manuscript.

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