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Multi-Objective Optimization of Building Demolition

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Abstract. It is estimated that a significant portion of the waste generated by the construction industry originates from demolitions, a trend expected to intensify as buildings constructed in the latter half of the 20th century reach the end of their life cycle and the need for reconstruction in the same urban centres becomes increasingly necessary. In this context, the dismantling of building components, with the specific aim of enabling their reuse and recycling, has emerged as a promising strategy to mitigate the environmental impact of demolition. However, for this approach to become a viable alternative, it is essential to evaluate multiple - often conflicting - aspects, such as cost, time and sustainability. To address this problem, multi-objective optimization algorithms provide an effective framework, as they enable the identification and analysis of optimal trade-off solutions. This study aims to implement a multi-objective optimization algorithm to evaluate the best demolition strategies for a case study, based on compromise points that consider these elements simultaneously. Multiple demolition scenarios are explored, taking into account the methods currently practiced in Brazil. The findings of this study highlight the potential of optimization techniques to advance demolition practices by supporting decision-making.

Keywords: Demolition, Construction and Demolition Waste, Multi-Objective Demolition, Circular Economy, BIM.

1 Introduction

The end-of-life (EoL) stage of buildings accounts for the majority of waste generated during their lifecycle [1]. Demolition activities alone are estimated to account for approximately 50% of total construction and demolition waste (CDW) worldwide [2]. Given this impact, this stage has received increasing attention from the construction industry [3, 4], and several studies emphasize its critical importance, particularly highlighting the potential of adaptive reuse of buildings as a more sustainable alternative [2, 5].

In the pursuit of a more sustainable demolition process, decision-making plays a fundamental role in minimizing both execution time and operational costs, while also aiming to maximize material reuse. However, these objectives often conflict with one another. For instance, reducing execution time may require the use of additional labor or equipment, thereby increasing costs. In this context, identifying trade-off solutions that compose the Pareto front through multi-objective optimization techniques becomes a suitable approach.

Therefore, the objective of this study is to propose a multi-objective optimization approach aimed at identifying the most efficient strategies for four demolition scenarios within a case study. These scenarios are based on demolition methods commonly used in the Brazilian context. The focus lies on minimizing both project costs and execution time, providing support for informed and sustainable decision-making in demolition planning.

2 Demolition

Demolition can be defined as the planned process of dismantling building elements. This process involves technical, environmental, economic, and safety considerations. A successful demolition requires the execution of several key steps, including:

- Structural assessment: a detailed analysis of the building's condition and identification of potential risks;
- Planning and design: determination of appropriate methods, equipment, and scheduling;
- Monitoring: technical supervision throughout the execution, with a focus on safety and impact control;
- Waste management: proper disposal of demolition materials, in compliance with environmental regulations and aiming, whenever possible, for reuse or recycling.

Demolition inherently generates a significant amount of waste. An effective approach to managing this waste involves incorporating circular economy principles into the demolition process. This strategy promotes the recycling and recovery of materials that can be reintroduced into the economic cycle, thereby extending their useful life. Moreover, this approach helps to mitigate the negative environmental impacts associated with the improper disposal of demolition waste.

Kamrath [6] classify demolition materials into three categories based on their potential for recycling and reuse. The first category includes metals and glass, which can undergo high-temperature melting processes to be reformed into new products without a significant loss of quality. Metals such as steel and aluminum are commonly recovered, cleaned and remelted for use in construction and automotive industries, while glass products are typically crushed, cleaned, and melted to produce new glass containers or building materials that may have recycled glass (e.g., glass powder) incorporated into their composition.

The second group is composed of masonry components and concrete debris. These materials are usually crushed into smaller particles using mechanical crushers and then screened to produce recycled aggregates. These aggregates can be reused in road bases or as fill material, reducing the demand for virgin natural resources and minimizing landfill waste.

The third category pertains to materials that can be used for energy recovery through thermal processes. Wood and certain types of plastics fall into this group. These materials are often processed in waste-to-energy plants through combustion, gasification, or pyrolysis to generate electricity or heat. This approach not only diverts waste from landfills, but also contributes to energy production, although it must be carefully managed to minimize environmental impacts such as emissions and ash disposal.

3 Methodology

This section outlines the methodology adopted, including a description of the selected case study, a brief explanation of the national system methodology used as the source of data for the optimization problem, and the mathematical formulation of the multi-objective optimization problem.

3.1 Object of Study

This work analyzes the E1 Building, located on the campus of the São Carlos School of Engineering, University of São Paulo (EESC-USP), Brazil. The overall building is illustrated by the 3D rendering in Fig. 1.

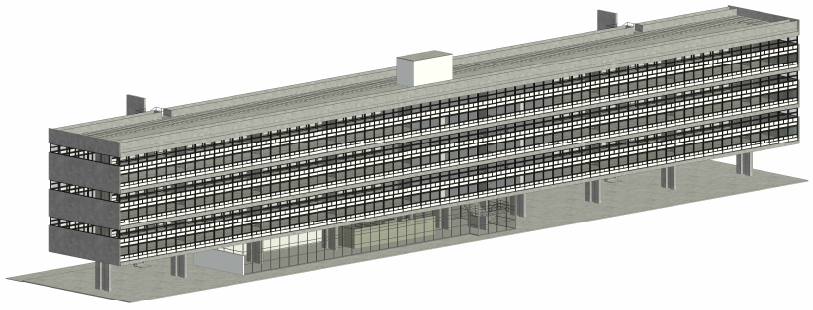


Figure 1. 3D rendering of the E1 Building

The E1 Building was modeled to generate an as-built Building Information Model (BIM) using Autodesk Revit, by a multidisciplinary team of architects, engineers, and researchers - Maximiano, Scheeren, Franco, Costa, Baldessin, Albano, Cuperschmid, Cerávolo, and Fabricio - as part of the project "HBIM and digital documentation of modern architectural heritage: protocol development based on a case study in E1" (2023), funded by CNPq. This digital model then facilitated a detailed material waste quantity takeoff, used in the demolition optimization problem, with the results summarized in Table 1.

Table 1. Quantity of material wastes

Component	Quantity	Unit
Columns and beams concrete	803.66	m^3
Slabs concrete	540.68	m^3
Ground floor concrete	16.24	m^3
Concrete block masonry	139.53	m^2
Partition wall	75.00	m^2
Metal frame	2169.50	m^2
Glass frame	262.00	m^2

The materials listed in Table 1 are distributed throughout the building as follows: the structural system is composed of reinforced concrete elements, while the external envelope consists of metal frames fitted with glass panels. On the ground floor, the entrance hall is enclosed by a combination of glass frames and sections of concrete block masonry. Internally, the spaces are subdivided using partition walls.

3.2 Cost and Productivity Metrics for Demolition

Given that the objective of this study is to minimize both the cost and duration of a demolition process, considering the Brazilian context, the required data for the optimization were obtained from Brazil's official reference for construction costs - the National System of Costs Survey and Indexes of Construction (SINAPI), developed by the Brazilian Federal Savings Bank (Caixa Econômica Federal) in collaboration with the Brazilian Institute of Geography and Statistics (IBGE).

SINAPI's framework distinguishes between Labor Hourly Cost for human resources and Equipment Hourly Cost for machinery. The Labor cost is comprehensive, including the professional's salary, social charges, and additional operational expenses like meals, transport, and personal protective equipment. The Equipment cost is further divided into the Productive Hourly Cost (CHP) and the Unproductive Hourly Cost (CHI). CHP represents the cost during active equipment operation, covering ownership expenses (depreciation, interest), maintenance, materials, and operator labor. Conversely, CHI accounts for costs when the equipment is idle, consisting of ownership costs and the operator's wages during inactivity [7].

Applying this framework, Table 2 presents the unit costs for the labor and equipment resources adopted in this study. The values were extracted from the SINAPI compositions, using April 2025 as the reference month.

The costs for labor - Bricklayer, Helper, and Site Foreman - are expressed in Brazilian Real per hour (BRL/h). For equipment, the values are presented in Brazilian Real per cubic meter (BRL/m^3) of demolished material, differentiated between CHP and CHI.

It is important to highlight the specific cost composition for the manual hydraulic breaker. For the demolition of beams and columns, a specific unit cost is adopted. However, for the demolition of a concrete floor, the breaker's cost is different, and its operation requires the additional use of an air compressor, whose cost is also detailed separately in the table.

Table 2. Unit costs of labor and equipment for demolition

Resource	BRL/h	BRL/m^3	
		CHP	CHI
Bricklayer	30.19	-	-
Helper	26.42	-	-
Site Foreman	42.77	-	-
Manual Hydraulic Breaker	-	30.07	27.88
Manual Hydraulic Breaker (Concrete Floor)	-	33.04	31.07
Air Compressor (Concrete Floor)	-	32.23	8.42
Excavator	-	352.74	134.85

3.3 Multi Objective Optimization Problem

The SINAPI service compositions define the resources and their respective quantities required to produce a functional unit of each service. This information enabled a detailed and structured formulation of the cost and time calculations based on the resources employed. According to the Technical Notebook of Demolition and Removal Compositions, SINAPI outlines three methods for concrete demolition: (i) manual demolition using hand tools, (ii) mechanical demolition using a manual hydraulic breaker, and (iii) demolition using a hydraulic excavator. However, for concrete flooring, only manual demolition and mechanical demolition using a manual hydraulic breaker are considered feasible. For all other building components, only manual removal was considered, due to the specific constraints of the case study.

To analyze the demolition process, a parametric model was developed to estimate the total duration and cost of the project. The decision variables (x_r) correspond to the allocation of human and mechanical resources, which include: Number of bricklayers (BL); Number of helpers (H); Number of manual hydraulic breakers (MHB); Number of excavators (EX).

The demolition process was organized into two sequential and distinct phases, reflecting the differing characteristics of the services involved. The first phase comprises the demolition of elements such as masonry, partitions, and window frames, which are predominantly performed manually. The second phase focuses on the demolition of concrete elements, which presents different operational requirements. This two-phase structure is reflected in the resource allocation strategy, whereby the number of bricklayers and helpers is independently defined for each phase - denoted as BL_1 and H_1 for Phase 1, and BL_2 and H_2 for Phase 2.

Based on the available methods and the two-phase structure, four distinct demolition scenarios were defined. Each scenario is characterized by a unique combination of techniques and a corresponding vector of decision variables, $\mathbf{X}$:

- **Scenario 1: Full Manual Demolition.** All components are demolished manually. The decision variable vector includes only human resources: $\mathbf{X} = \{BL_1, H_1, BL_2, H_2\}$;
- **Scenario 2: Partial Mechanical Demolition (Breaker).** Manual hydraulic breakers are used for reinforced concrete components, with all other tasks performed manually: $\mathbf{X} = \{BL_1, H_1, BL_2, H_2, MHB\}$;
- **Scenario 3: Partial Mechanical Demolition (Excavator).** Excavators are used for reinforced concrete components, with all other tasks performed manually: $\mathbf{X} = \{BL_1, H_1, BL_2, H_2, EX\}$;
- **Scenario 4: Full Mechanical Demolition.** Excavators are used for reinforced concrete and a manual hydraulic breakers for concrete flooring, with remaining tasks performed manually. The corresponding decision variable vector is: $\mathbf{X} = \{BL_1, H_1, BL_2, H_2, MHB, EX\}$.

For clarity in the subsequent equations, the notation and abbreviations used in the problem formulation are summarized in Table 3.

Table 3. Notation and abbreviations

Abbreviation	Description
D_T	Demolition Total Duration
S	Set of sequential project phases
D_s	Duration of the sequential phase $s \in S$
d_i	Duration of task i in hours
I_s	Set of tasks within the phase s
q_i	Waste quantity for the task i
$e_{i,r}$	Productivity coefficient for task i with the resource r
x_r	Quantity of resource r
C_h	Cost associated with human resources
C_m	Cost associated with mechanical resources
C_{sf}	Cost associated with site foremen
C_T	Demolition Total Cost
$t_d w$	Daily working time
DC_r	Daily cost of resource r

Duration: The Demolition Total Duration (D_T) is calculated as the sum of the durations of its sequential phases,

as shown in Eq. (1). The model consists of a set of phases S that must be executed in sequence. Each phase $s \in S$, in turn, contains a set of tasks I_s, whose total duration D_s is the sum of the durations of each individual task.

$$D_T = \sum_{s \in S} D_s = \sum_{s \in S} \left[\sum_{i \in I_s} \left(\max \left\{ \frac{q_i \cdot e_{i,r}}{x_r} \right\} \right) \right]. \tag{1}$$

As expressed in Eq. (1), the duration of an individual task is determined based on the bottleneck principle, wherein multiple resources may operate in parallel. In this context, the overall task duration is governed by the resource that requires the longest time to complete its assigned portion of the work.

Cost: Human resource costs are modeled on a daily work basis, whereas mechanized task costs are considered directly proportional to the volume of service executed.

To calculate the cost associated with human resources (C_h), the sum of the daily costs of the allocated workers is multiplied by the duration (in days) of each task (d_i). This duration is determined by dividing the total phase duration (D_s) by the number of daily working hours ($t_{dw} = 8$ hours) established in Brazilian Labor Laws, as expressed in Eq. (2).

$$C_h = \sum_{i \in I_s} \left[\sum_{r} \left(\frac{d_i}{t_{dw}} \right) .DC_r.x_r \right]. \tag{2}$$

For mechanical resources, the cost (C_m) is computed by multiplying the service quantity (e.g., cubic meters of concrete to be demolished) by the sum of the CHP and the CHI the allocated resource, excavator and/or manual hydraulic breaker:

$$C_m = \sum_{i \in I_s} \left[q_i . \left(CHP + CHI \right)_r \right]. \tag{3}$$

Additionally, the cost model includes the expense associated with the site foremen (C_{sf}), which is calculated by multiplying the total project duration (in days) by the daily cost of this resource. In this study, one site foreman is considered. Therefore, the total cost (C_T) is given by the sum of the costs associated with human resources (bricklayers, helpers and site foreman), and the mechanical resources (manual hydraulic breakers and excavators):

$$C_T = C_{sf} + C_h + C_m. \tag{4}$$

Thus, the optimization problem can be defined as finding the vector $\mathbf{X}^*$, which contains the decision variables representing the resources allocated in each scenario, which minimizes D_T and C_T, Eq.(1) and Eq.(4), respectively.

The constraints for the optimization problem stem from resource availability in each scenario. These limits were set by allocating 15 m² of workspace per pair of workers and balancing mechanical resources for practical operations. Table 4 details the corresponding lower (lb) and upper (ub) bounds for the design variables.

Table 4. Design variables range limits

Variable	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
	lb	ub	lb	ub	lb	ub	lb	ub
BL_1	1	30	1	10	1	15	1	10
H_1	1	50	1	20	1	30	1	30
BL_2	1	30	1	10	1	15	1	20
H_2	1	50	1	20	1	30	1	40
MHB	-	-	1	20	-	-	1	30
EX	-	-	-	-	1	2	1	2

It should be noted that the design variables are defined in the discrete domain as they must be integers.

The multi-objective optimization problem is solved using the Elitist Genetic Algorithm, a variant of NSGA-II [8]. This algorithm constructs the Pareto front by prioritizing the fittest individuals while also preserving population diversity. The algorithm was implemented with the following parameters: a population size of 1000 and a maximum of 1000 generations, both scaled by the number of design variables; objective and constraint function tolerances of 10^{-3}; intermediate crossover; and adaptive feasible mutation. The numerical simulations relevant to the development of the work are carried out using Matlab software.

4 Results

The analysis of the Pareto fronts (Fig. 2), presented in separate plots due to the significant difference in the orders of magnitude of the objective function values, demonstrates that Scenario 1 is dominated by all other scenarios. Any mechanized alternative (Scenarios 2, 3, and 4) proves to be both significantly faster and more cost-effective. This reinforces the conclusion that a fully manual demolition approach is neither economically nor temporally viable for a project of this scale.

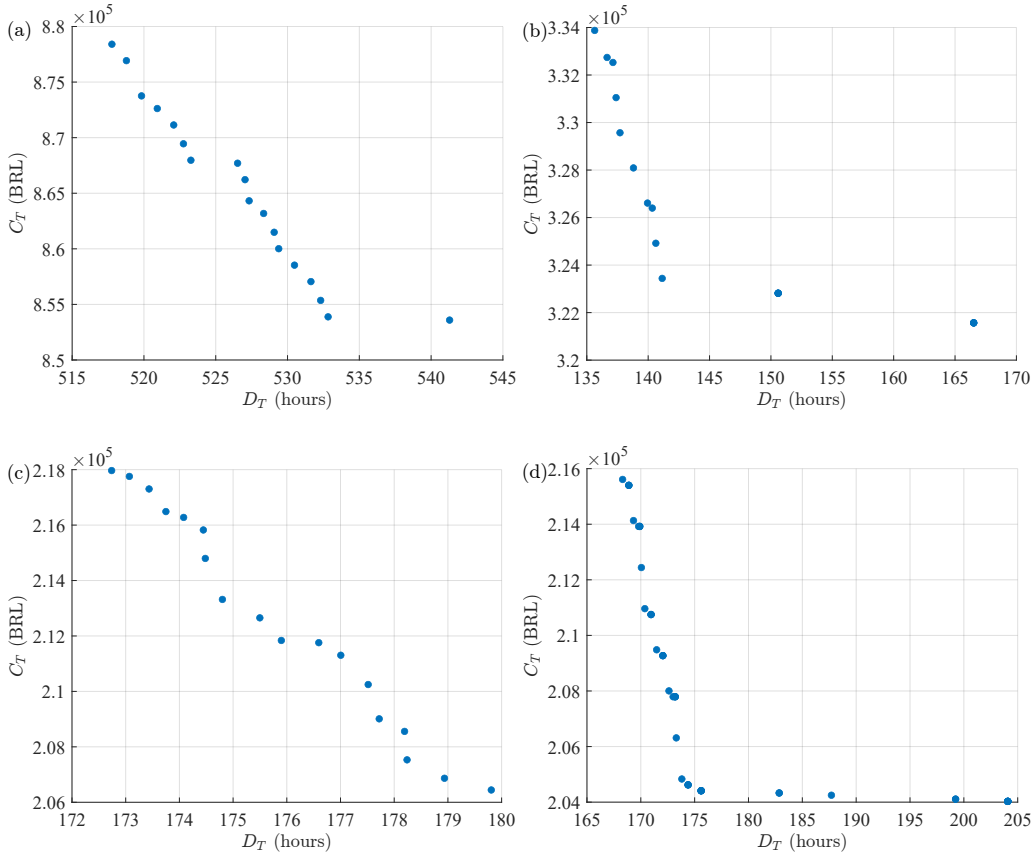


Figure 2. Pareto fronts for the evaluated scenarios: (a) Scenario 1; (b) Scenario 2; (c) Scenario 3; (d) Scenario 4

Scenario 2, which involves the use of a MHB for concrete demolition, shows a substantial improvement in efficiency compared to the fully manual scenario. However, it remains dominated by Scenarios 3 and 4 in terms of cost. In Scenarios 3 and 4, the excavator is responsible for demolishing the main concrete components and acts as the critical resource for minimizing overall Project cost. It is notable, however, that the associated costs of these scenarios are nearly identical. In the proposed configuration (with the adopted constraint values presented in Table 4), both excavator-based scenarios exhibited longer execution times than Scenario 2. However, when the upper bound for the number of excavators was increased to 4, both Scenarios 3 and 4 became the most advantageous in terms of time and cost. This highlights the importance of evaluating the characteristics of the demolition project - particularly its scale and physical constraints - to determine whether deploying multiple excavators is feasible.

The slight difference between Scenarios 3 and 4 is due solely to the demolition method for the concrete floor. Since this area is very small compared to the rest of the structure (Table 1), the performance difference between the manual method (Scenario 3) and using a breaker (Scenario 4) does not significantly affect the overall results.

A particularly noteworthy observation concerns the near-vertical slope of the Pareto fronts in Scenarios 2 and 4 - both of which involve the use of the MHB. This steep slope indicates that substantial increases in cost yield only minimal reductions in total project duration. This phenomenon can be attributed to the high productivity of the MHB. Once a sufficient number of manual breakers is deployed, the associated task is completed rapidly and ceases to be the project's bottleneck. At that point, the critical path shifts to other, non-mechanized tasks - particularly those in Phase 1 - which are not affected by the number of MHB. Beyond this saturation point, increasing the number of manual breakers continues to raise costs but no longer contributes meaningfully to time savings. This behavior has important implications for project management. The "knee" of the Pareto curve - just before it becomes vertical - represents the optimal number of MHB to be employed. Beyond this point, further investment yields diminishing returns, as the total project duration becomes constrained by other activities. Identifying this point allows decision-makers to allocate resources more effectively, avoiding unnecessary expenditures while still achieving optimal performance.

5 Conclusions

The comparative analysis of the Pareto fronts highlights the crucial role of mechanization in ensuring the feasibility of demolition projects with a scope similar to that of the present case study. Among the evaluated strategies, the use of a hydraulic excavator proved to be the most cost-effective overall, achieving the lowest total cost among the mechanized alternatives while maintaining efficient project durations. Nonetheless, it is important to emphasize the notable performance of the manual hydraulic breaker, which offers a significant improvement over fully manual demolition. Depending on the scale of the structure and the resources available, this method may represent the most advantageous solution in certain contexts. These findings underscore the importance of carefully analyzing the characteristics of the object to be demolished - particularly its scale and construction components - in order to select the most appropriate demolition strategy. Given the complexity and variability inherent to demolition projects, there is a clear need for further research to expand on these findings, incorporating different building types, demolition methods, and contextual factors. Continued investigation in this field will contribute to developing more efficient, cost-effective, and sustainable demolition practices.

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