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On determining structural wall layout during the adaptive reuse process of historic masonry buildings

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ABSTRACT

Defining modifications to a building's layout during the adaptive reuse of historic masonry buildings can be challenging since the existing structural grid constrains the transformations to be performed. This paper proposes a novel methodology for exploring modifications to a structural wall layout during the adaptive reuse process of historic buildings. The primary objective is to redefine structural wall arrangements to accommodate new openings and/or cuts in existing structural elements, offering designers flexibility in spatial arrangement modifications. Considering that existing buildings are subjected to damage, an evolutionary approach is used to define which wall segments can be removed from the existing layout, according to a multi-objective function that targets minimizing the presence of damaged elements and maximizing the presence of undamaged elements in the design, in addition to minimizing the building's eccentricity. The problem considers structural constraints based on the compressive capacity and minimum length of shear components. A computational strategy based on Genetic Algorithm is conceptualized as a tool for deriving potential layout solutions that adhere to structural requirements while facilitating the incorporation of new openings. By systematically evolving potential solutions over multiple generations, the algorithm navigates the design space to pinpoint areas within the original shear layout where material can be removed while respecting the given structural constraints. The methodology's validity is demonstrated through a case study situated in a UNESCO World Heritage Site, providing evidence of the practical application and success of the genetic algorithm approach in real-world scenarios. The findings presented in this paper contribute to the convergence of structural engineering and architectural preservation, offering a systematic and efficient means of determining structural wall layouts for the adaptive reuse of historic masonry buildings. Integrating computational techniques into the adaptive reuse process holds transformative potential, establishing a robust framework for sustainable urban development that honors and enhances the historical fabric of our built environment.

1. Introduction

1.1. Background

The world faces an unprecedented challenge as the United Nations estimates that by 2030, a staggering 3 billion individuals, equivalent to approximately 40% of the global population, will require access to suitable housing. This growing need translates

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into an astonishing demand for 96,000 new affordable and accessible housing units daily [1]. However, this surging demand for new housing also raises serious concerns regarding the environmental impact of the construction sector. This sector is responsible for approximately 37% of worldwide CO2 emissions, 34% of energy consumption, and 35% of waste generation [2]. In light of these critical issues, adaptive reuse (AR) emerges as a sustainable solution, offering a means to transform existing structures, revive historic neighborhoods, and meet the challenges of affordable housing [3–5].

Compared to traditional demolition and reconstruction, AR offers significant environmental advantages [6–8]. It reduces the need for new construction materials, thus lowering CO2 emissions and energy consumption associated with manufacturing and transportation. Additionally, AR minimizes waste generation by reusing existing structures rather than demolishing them and sending debris to landfills. The preservation of cultural heritage and the revitalization of historic neighborhoods are also important benefits of AR, providing continuity and maintaining the unique character of urban areas [9–11].

AR encompasses a range of construction interventions aimed at redefining the functional typology of existing buildings. Examples include converting a residential structure into commercial space, re-purposing industrial facilities for residential or commercial use, or transforming commercial properties for various other functions [12,13]. Determining the spatial arrangement of such buildings often proves to be a complex undertaking, as different experts bring distinct priorities to the table. Architects may emphasize spatial interactions, circulation, and lighting distribution, while engineers focus on placing structural elements to ensure strength and stability. Simultaneously, building owners aim to minimize material and labor costs [14].

This process is inherently challenging, even when applied to new construction projects. However, when dealing with existing structures, the design space is restricted, presenting various technical and functional challenges [15]. Furthermore, working with existing buildings can inflate project costs and timelines, mainly when dealing with vacant and aging structures, since they come with unknown conditions, i.e. damages and latent defects, as well as unknown design requirements for first use, i.e. loads and boundary conditions used for the initial design. Given these challenges, our work starts from the premise that the existing structural layout of a building can significantly constrain its adaptability to new functions [16]. Since space allocation often hinges on the type of reuse, each project is inherently unique and necessitates individual analysis. Therefore, identifying the most crucial elements of an existing structural layout can streamline the adaptation process. By focusing on these existing structural elements, we can facilitate the insertion of openings within existing structural elements and reconfiguration of the relationships between spaces and circulation areas. Our work proposes a computational approach for determining the optimal placement of openings in the structural wall layout during the adaptive reuse of historic masonry buildings.

1.2. Related work

Historic buildings often feature an unreinforced masonry wall structural system, a legacy of construction practices prevalent before the widespread adoption of reinforced concrete in the 20th century [17–19]. The intricate task of designing structural wall layouts significantly impacts the spatial distribution within a desired floor plan. Design is a highly complex task involving creativity, specialist knowledge, experience, and judgment concerning the objective and aesthetic aspects of a problem domain [20]. Studies started to include computers into the equation in the 1960s [21–24], emerging the field known as computer-aided architectural design (CAAD). With the advent of computational tools, there has been a paradigm shift toward more efficient designs [25–27], providing guidance, feedback, and optimization opportunities in building projects [28,29].

However, computer systems often are designed to consider structural and architectural requirements independently [30], particularly at the early stages of design projects. Combining structural performance with architectural requirements can streamline more flexible and adaptable designs [31,32]. In this context, optimization techniques can facilitate the efficient allocation of resources, enhance the integration of structural and architectural requirements, and ultimately produce more efficient design solutions [33,34]. Hofmeyer and Davila Delgado [35] developed a methodology to handle architectural flexibility with coevolutionary and genetic algorithms for building spatial and structural design. Solutions show that collaborative design, for example, via design modification in one domain (spatial) to optimize the design in another domain (structural), can be as effective as monodisciplinary optimization.

Steiner et al. [36] proposes a novel approach for the design of architectural floor plans by integrating structural layout analysis directly into the planning process. They introduce a planning tool that interactively enforces checks for the current design's structural stability and proposes how to stabilize it if necessary. Similarly, Boonstra et al. [37] developed a responsive grammar to design structural systems based on a building's layout geometry, while structurally assessing their performance. In addition, it compared the results achieved with the first method with an evolutionary algorithm approach used to optimally assign structural components to a building spatial design's geometry.

In the context of optimizing structural wall systems in floor plans, early work by Zhang & Mueller [14] introduced a modified evolutionary strategy for conceptual design in tall buildings. They proposed a modified evolutionary strategy for assisting the conceptual design of tall buildings, considering the minimization of the overall structural weight subjected to structural requirements (torsion, flexural, shear, and drift). In addition, basic architectural requirements were considered in the conceptual design, such as accessibility, allowing the accommodation of openings in the design.

Similarly, Lou et al. [38,39] explored optimization strategies for shear wall layouts in high-rise buildings. In the first work, the authors propose a strategy based on the Evolutionary Structural Optimization (ESO) method, where less strained elements are removed from the design throughout the optimization process. It aims to reduce the building's eccentricity, i.e. the difference between center of mass and center of stiffness, while complying with strength and serviceability requirements. Architectural requirements are accounted for by defining which elements are fixed in the design, for example, walls predefined as stairwells.

In the second work, the authors proposed a design methodology that relies on the tabu search (TS) algorithm. It targets optimizing the shear wall layout of high-rise buildings by minimizing the structural weight while complying with torsion and drift effects.

Recognizing the computational costs associated with optimization problems, Pizarro et al. [40] proposed a simplified model to quickly derive a building configuration's fundamental period, base shear, and moment. Defining quicker solutions can facilitate the model integration into machine learning pipelines or the swift optimization of solutions by assembling fitness functions that consider parameters like building weight, roof displacement, or base shear and moment, ultimately reducing search space and saving costs in the design process.

While these strategies excel in addressing conceptual structural wall layout solutions, there is a gap in the literature concerning their integration into the Adaptive Reuse (AR) process [41], especially accounting for the building's structural performance [42]. When analyzing the adaptive reuse literature [42], the current scenario is governed by studies focusing on strategic aspects, primarily motivated by sustainability requirements. In this context, current research proposes using circular economy (CE) strategies for the built environment. Frameworks based on CE can help to establish guidelines and demonstrate critical elements when aiming to achieve sustainable solutions for adaptive reuse [3,43–45]. Similarly, adaptive reuse models have been proposed to simplify the design process through documentation, clarification, and illustration of actions [4,15,46]. In summary, these articles propose similar conceptual frameworks, focusing on sequential steps or evaluative criteria for achieving sustainability requirements.

However, there is a limitation on research works focusing on the optimization and automation of the AR process. Usually, the implementation of AR projects relies on professional knowledge, leading to results with little quantitative or objective measure [47]. The work of Kim et al. [48] pioneers in defining an automated tool for a qualitative structural evaluation of architectural floor plans for remodeling purposes. However, a proposed design for adaptive reuse must be given, not accounting for evaluating different design solutions and, most importantly, optimizing the structural layout. The first attempt to integrate optimization approaches into building reuse problems identified in our review is the work of Sanchez et al. [49–51], which addresses a strategy to disassemble building components and facilitating their reuse. Similarly, Brutting et al. [52,53] and Van Marcke et al. [54] proposed optimization techniques to design steel truss structures by reusing existing truss components. Nevertheless, work has yet to define an optimization strategy to facilitate building conversion into a new use, especially focusing on floor plan configuration.

1.3. Problem overview

Aiming to address the literature gap, this work is governed by the following research question: "How can we computationally determine an optimized structural wall layout for adapting historic masonry buildings to new uses while maximizing material reuse and ensuring structural integrity?". Thus, consider a project that targets adapting a historic masonry building, designed initially as single-family housing, into multi-family apartments. Fig. 1 illustrates two solutions that prioritize the allocation of apartments close to existing openings, derived from a methodology defined by the author's previous work [55]. The case study building has openings in the facades and a shutter system facing exterior patios. In addition to daylight requirements, Solution 1 aims to preserve the existing walls while defining apartment boundaries, while Solution 2 aims to maximize the use of space. If we define a minimum threshold for the distance between two walls, trying to avoid narrow spaces inside apartments, then some cuts in existing walls must be introduced. At the same time, new subdivision walls must be allocated to delimit apartment spaces. These new and demolished segments of walls and openings can be used to quantify the costs of construction & demolition (C&D) as a function of the material volume.

Therefore, eventual modifications to the structural wall layout can be performed when adapting an existing building to a new use, especially when targeting the maximization of the existing space. This paper defines a computational approach to redefining the structural wall layout of a given floor plan while adapting historic masonry buildings. Since this work focuses on existing buildings, this paper assumes that the default input problem domain is a 2D building footprint representing the existing structural elements. When considering a masonry structural wall system, relevant elements for the analysis are the structural walls and their opening elements. In addition, existing buildings are subject to deterioration over time, leading to damage (e.g. cracks). The location of cracks is also included as input for the analysis.

The novelty of this work lies in the implementation of a computational strategy for the adaptive reuse of historic buildings. This work aims to determine which elements are crucial for the design, allowing the accommodation of openings in the existing structural wall layout. Thus, the solution for the problem can be defined as a new structural wall layout (υ), where wall segments can be removed from the design space, representing new openings in the layout.

An evolutionary approach based on genetic algorithms (GA) is conceptualized to identify the new structural wall layout configuration, targeting the maximization of material reuse under basic structural analysis. A Python project is developed using Object-Oriented Programming (OOP) to implement the steps in the evolutionary process. In the proposed methodology, only internal elements from the original layout can be modified, preserving external elements to maintain the building's original shape.

A grid-based approach is defined to discretize the design space based on the internal walls and their openings. Considering that in a x–y axis, elements can be distributed parallel to x or y axis. Each element is abstracted as a grid line with its dimension information, length (l) and thickness (t), as illustrated in Fig. 2. Based on the initial structural wall layout, wall elements are split considering the opening elements and then subdivided into smaller segments. Then, segments of the wall element can be removed from the design space. Thus, the layout solution can be represented as a combination of preserved or removed elements. This process can be numerically represented by a binary variable (r): 0 for preserved elements and 1 for removed elements.

Fig. 3 summarizes this process, considering a small-scale building as an example. The structural walls schedule defined for the building is represented in plan view, along with the location of the cracks, is used to define the ground structure representing the

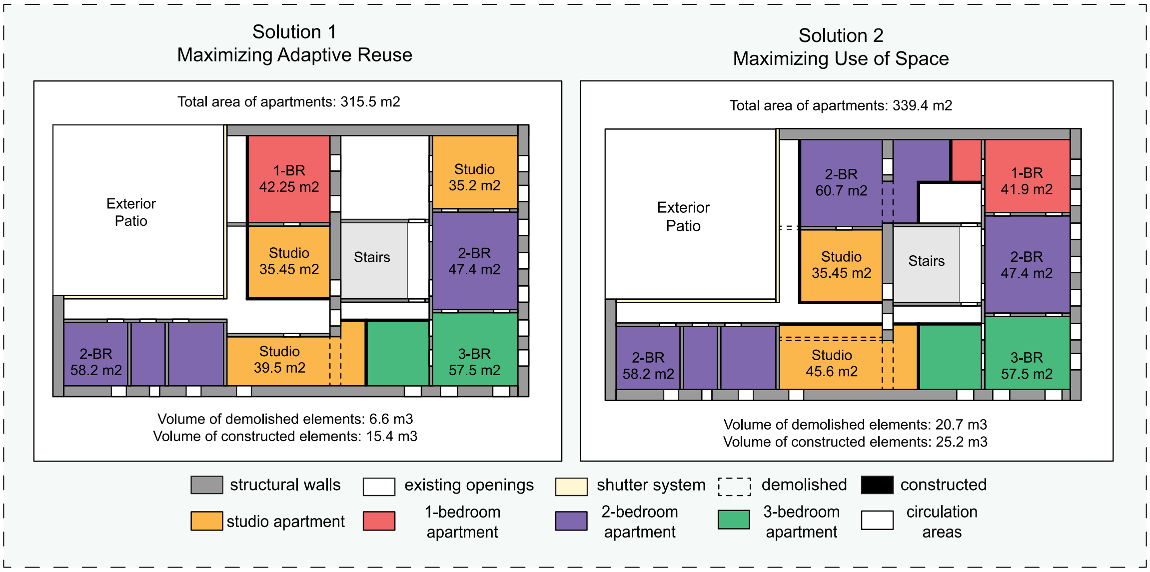


Fig. 1. Examples of two different adaptive reuse solutions, considering the allocation of multi-family apartments in the design space.

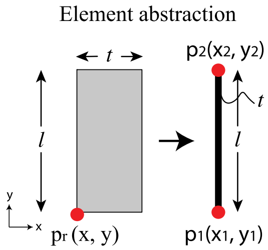


Fig. 2. Abstraction into a grid line for an element along the y axis.

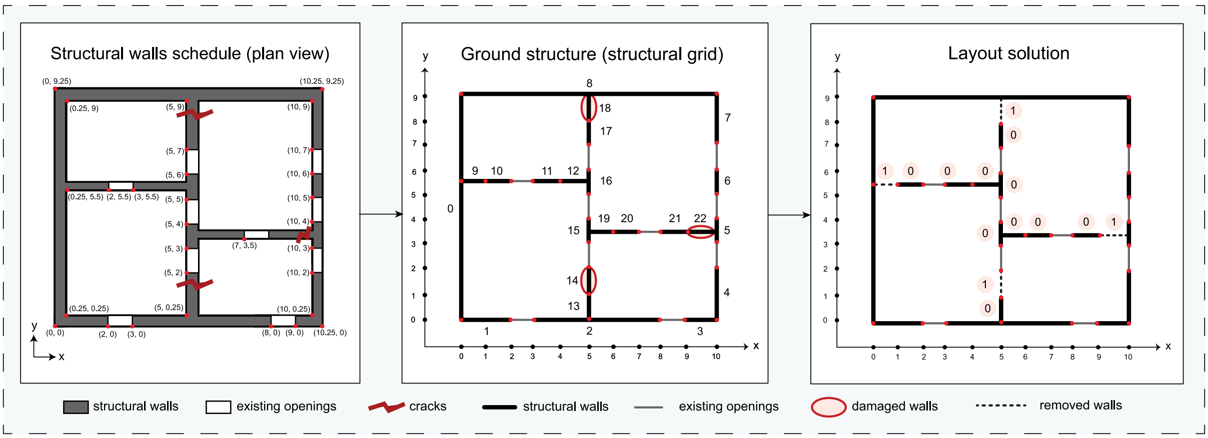


Fig. 3. Defining the input information for initializing the optimization process.

structural grid. Each element is split considering its openings and then subdivided into smaller segments, each 1 m in length. Thus, considering the system starting from index 0, the structure results in 8 external and 14 internal elements. Then, based on the cracks' location, elements 14, 18, and 22 are defined as damaged. A layout solution is exemplified, where elements 9, 14, 18, and 22 were removed from the design.

This paper is organized as follows. Section 2 details the general methodology proposed in this work, considering a small-scale case study building to facilitate illustrating the overall process. Section 3 validates the proposed methodology considering a real case study. Section 4 conducts a sensitivity analysis, aiming to investigate how the damage state, material properties, and geometric conditions in the input affect the optimum layouts. Conclusions and future work are detailed in Section 5.

2. General methodology

Genetic algorithms (GA) is an optimization technique inspired by the theory of natural evolution [56]. The fundamental principle of the GA is the survival of the fittest as it is in nature, which translates to iteratively selecting and evolving the best candidates in a population to optimize a given problem. GAs are well-suited for this problem due to their ability to handle complex, non-linear search spaces with discrete design variables [57]. The population-based search allows for the thorough exploration of potential layouts while avoiding local optima. Moreover, GAs have been successfully applied to similar structural optimization problems [14,33,35], providing confidence in their effectiveness for this application.

The evolutionary process begins by randomly generating a set of layout candidates, forming the initial population for the design problem. Each candidate is first evaluated for feasibility relative to the design constraints, which refers to checking the compressive stress and shear requirements for our problem. The set of candidates that pass for the feasibility check are defined as the feasible population. Then, each feasible candidate is evaluated considering the problem objective. This work targets achieving a solution that maximizes material reuse, translated as minimizing the amount of damaged elements and maximizing the amount of undamaged elements, while minimizing the torsion effects of the building. Thus, each candidate solution can be ranked according to its fitness score to multi-objective function defining the problem goal.

An iterative process commences by selecting the best parents to generate offspring, which are subsequently used as the new population for the design problem. This iterative process continues until it converges to an optimum solution. The proposed methodology is aimed to assist designers in identifying where cuts (or openings) can be introduced in the existing structural wall layout, providing flexibility in design space while planning the adaptive reuse process of an existing historic masonry building. This section summarizes the steps for the evolutionary process, considering the adaptive reuse as context to define and conceptualize the design problem.

2.1. Analyzing historic masonry buildings

Since this study focuses on achieving a new structural wall layout, it is necessary to define a strategy for evaluating the structural performance of each candidate solution. As a proof of concept, this research considers a simplified design code strategy, focusing on evaluating the overall compressive strength of elements and accounting for shear and torsion effects [58,59]. Drift will not dominate this study since it focuses on low-rise masonry buildings. Thus, the equations in this section are based on conventional relationships defined by the Brazilian design code for masonry structures [60]. This choice considers the context of the case study building in this paper, which is located in a UNESCO World Heritage Site in Brazil.

Low rise historic buildings usually have wood floors, abstracted as flexible bodies. Thus, the structural system is mainly composed of masonry walls. For evaluating the load distribution in the building, two sources of gravity loading are considered: (a) actions distributed in the floor (dead and live loads); (b) self-weight of wall elements (dead). This study considers the presence of joists in one direction, resulting in the load distribution from floors to the walls in that same direction. Thus, a function to calculate the floor load distribution is defined, depending on the joists' direction. The live load (ll) acting on floors is assumed as $2\ \mathrm{kN/m^2}$, while the dead load (dl) is assumed as $1.4\ \mathrm{kN/m^2}$. Under strength or ultimate limit state (ULS) design, buildings shall be designed to resist the most critical effects resulting from various combinations of factored loads. Thus, this study considers the following combination of loads:

$$ULS = 1.2dl + 1.6ll \tag{1}$$

The compressive capacity for each element is calculated considering the floor load distribution in addition to the self-weight, determined according to the material type. The factored compressive stress must be smaller or equal to the allowable compressive strength. The governing equation used in this study is given by:

$$1.4\frac{p_k}{A} \leq \frac{1}{2}0.7 f_{pk}\kappa \tag{2}$$

where p_k is the vertical loading, A is the cross sectional area, f_{pk} is the material strength and κ is the slenderness coefficient, given by:

$$\kappa = 1 - \left(\frac{h_e}{40t_e}\right)^3 \tag{3}$$

where h_e is the effective wall height, and t_e is the effective wall thickness.

To account for shear effects, this work considers an empirical approach that considers the minimum length for shear walls (l_s), as proposed by Boothby (2023) [61]. Essentially, the minimum length can be defined as:

$$l_s = f_m N_s d \tag{4}$$

where f_m is a factor that depends on the material type, equal to 40 for unreinforced masonry, N_s represents the number of stories, and d is the dimension opposite to the direction of shear wall elements.

Torsion effects can be substantial under wind or seismic loading, especially when the building is asymmetric. This can be mitigated by minimizing the eccentricity, which computes the difference between the center of mass and the center of stiffness. Thus, the building's eccentricity can be determined by the following equation:

$$e(v) = \sqrt{(x_{cs} - x_{cm})^2 + (y_{cs} - y_{cm})^2} \tag{5}$$

in which x_{cs} and y_{cs} are the coordinates for the center of stiffness, and x_{cm} and y_{cm} are the coordinates for the center of mass.

First, the center of mass is computed, considering:

$$x_{cm} = \frac{\sum x_i A_i}{\sum A_i}, y_{cm} = \frac{\sum y_i A_i}{\sum A_i} \tag{6}$$

where A_i represents the area of each element and x_i, y_i represent the coordinates of the center of mass of each element, in the x and y direction, respectively. With i representing the index of each element, ranging from 1 to the total number of structural elements.

Then, the center of stiffness is computed according to:

$$x_{cs} = \frac{\sum x_i k_i}{\sum k_i}, y_{cs} = \frac{\sum y_i k_i}{\sum k_i} \tag{7}$$

where k_i represents the stiffness for each element. Laboratory tests of solid shear walls have shown that behavior can be depicted at low force levels using conventional principles of mechanics for homogeneous materials [62]. In such cases, the lateral in-plane stiffness of a solid cantilevered shear wall, k, can be calculated using the following equation:

$$k = \frac{1}{\frac{h_e^3}{3E_m I_g} + \frac{h_e}{3A_v G_m}} \tag{8}$$

where h_e represents the effective height of the wall, A_v is the shear area, E_m is the masonry Young's Modulus, G_m is the masonry Shear Modulus and I_g is the moment of inertia of the gross section. To account for the damage state in the analysis, a factor of 0.5 times the elastic and shear modulus is used to consider the cracking effects in the masonry [63].

The removal of elements primarily affects the load distribution in the design. The load distribution is determined by identifying the tributary area for each element. The ground structure and the candidate solution of the case study building in Fig. 3 are used to compare the effect of removal of elements in the load distribution. Joists are assumed to be distributed along the x direction, resulting in the floor load distributed only into wall elements in the y direction. It is important to note that the floor load distribution does not consider opening elements.

Fig. 4 presents the comparison in the tributary area distribution between the candidate solution and the initial layout. Essentially, the load from a removed element will be transferred to the elements located in the immediately preceding and subsequent y-coordinates. The tributary area of element 14 (7.5 m^2) would be distributed to elements 0 (+3.75 m^2) and 4 (+3.75 m^2), while the load of element 18 (5 m^2) would be distributed to elements 0 (+2.5 m^2) and 7 (+2.5 m^2). Thus, element 0 would result in a total tributary area equivalent to 28.75 m^2, element 4 equal to 10 m^2, and element 7 equal to 8.75 m^2

2.2. Evaluating a candidate solution in terms of structural stability

The goal of this study is to determine a stable structural wall solution that allows accommodating eventual new openings. Usually, when optimizing structural wall layouts for new projects, the objective is to minimize the structural weight, respecting structural constraints, for example, flexure, shear, torsion, and drift [14]. In contrast, this research focuses on existing buildings. Thus, our target is to determine solutions that preserve existing elements as much as possible, thus maximizing material reuse. However, to define where elements can be demolished to incorporate eventual openings, an opposite objective must be introduced. Our hypothesis considers minimizing the existence of damaged elements in the solution while minimizing the eccentricity of the system. This would lead to more stable designs and avoid removing only damaged elements.

Thus, a layout solution (v) is evaluated considering the multi-objective function:

$$minimize : w_1 e(v) + w_2 f(v) + w_3 g(v) \tag{9}$$

where $e(v)$, $f(v)$ and $g(v)$ and represent the functions to quantify the system's eccentricity, the removal of undamaged elements in the design, and the presence of damaged elements, respectively. The three functions will have values ranging from 0 to 1, aiming to have a normalized distribution. Therefore, distribution weights (w_1, w_2, and w_3) can be defined.

The eccentricity $e(v)$ is defined according to Eq. (5), previously presented. To quantify $f(v)$ and $g(v)$, we define functions that consider the length of elements since they can have different sizes according to the structural grid. Thus, the removal of undamaged elements $f(v)$ can be quantified using a function that calculates the percentage of undamaged elements removed from the solution in terms of the total undamaged elements:

$$f(v) = \frac{\sum l'_u}{\sum l_u} \tag{10}$$

where l'_u represents the length of undamaged elements removed from the solution v, while l_u represents the length of undamaged elements in the initial layout.

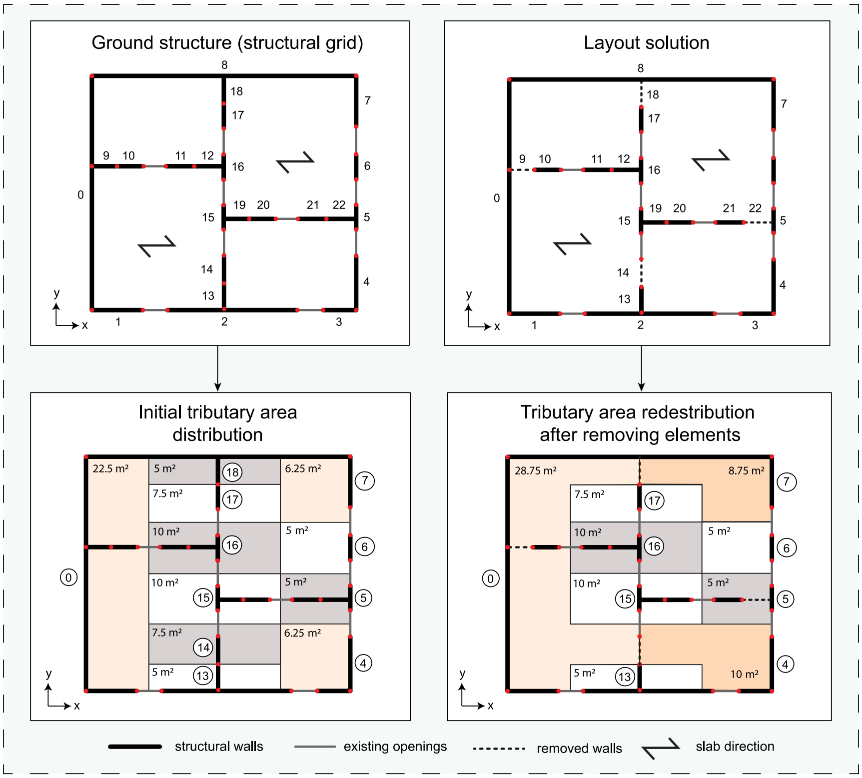


Fig. 4. Variation in the tributary area distribution when considering elements removed from the initial layout.

Similarly, damage presence $g(v)$ can be quantified using a function that calculates the percentage of damaged elements removed from the solution in terms of the total damaged elements:

$$g(v) = 1 - \frac{\sum l'_d}{\sum l_d} \tag{11}$$

in which l'_d represents the length of damaged elements removed from the solution v, while l_d represents the length of damaged elements in the initial layout. The function is written so that the maximum and minimum values are inverted to maximize the removal of damaged elements, thus minimizing the presence of damaged elements.

Each candidate v is subjected to the structural constraints in terms of the compressive and shear effects. To quantify the compressive capacity, Eq. (2) can be modified to determine the compressive ratio (c_r):

$$c_r = \frac{4 f_k}{f_{pk} \kappa} \tag{12}$$

where f_k represents the nominal stress (p_k/A).

The compressive ratio (c_r) for each wall element must be smaller or equal to 1, considering that Eq. (2) includes the safety coefficients. The shear effects are determined by verifying if the shear wall length is greater than the minimum (l_s), according to Eq. (4).

2.3. The evolutionary process for determining the new structural wall layout

The Python project is developed using Object-Oriented Programming (OOP) principles. OPP is a programming paradigm centered around the concept of *objects*, which are instances of classes. These objects represent both data (variables) and behaviors (functions). Fig. 5 presents the main classes for implementing this work, which are detailed along in this subsection to explain the evolutionary process.

Considering that floor plan elements are represented as grid lines, points defining a line are given as input. In addition, information on the elements' damaged state is used as a binary variable for the design process. Each element can be classified as damaged (1) or undamaged (0). Thus, a class *Element* is defined to store the relevant information on the structural wall elements and openings.

Since the analysis focuses on a given ground structure representing structural wall layout, a class *WallLayout* can be defined, being initialized by a list of *Element* objects. To effectively calculate the load distribution into a given floor plan, we must specify

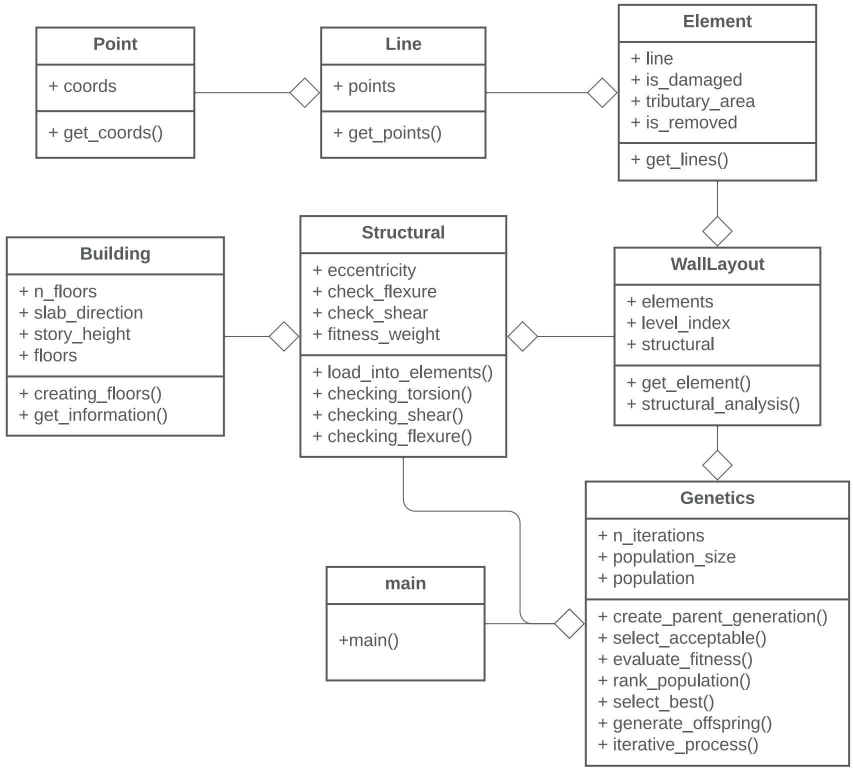


Fig. 5. A UML diagram to illustrate the interaction between classes for the computational implementation of the evolutionary approach.

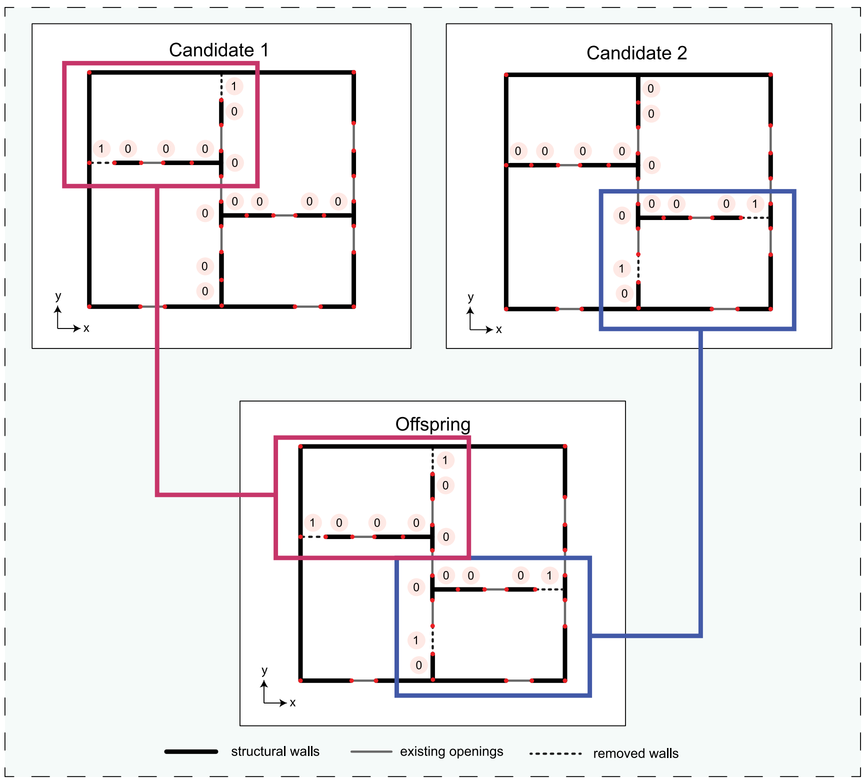


Fig. 6. Crossover operation to generate offspring.

Table 1
Mechanical characteristics of masonry types.
Source: Meireles et al. 2012 [63].

Masonry type	E (GPa)	δ (kN/m^3)	f_{pk} (MPa)	f_{sk} (MPa)
Stone	2.8	22	7	0.105
Rubble	1.23	20	2.5	0.043
Brick	1.5	18	3.2	0.076

the level corresponding to its location in the building, as well as the total number of stories. Those variables are also included as an input for the analysis. Thus, a class *Building* summarizes the building configuration, containing a list of floor plan elements for each story of the building.

Since the removal of elements affects the building structural performance, a class *Structural* is defined to evaluate a candidate layout to the problem. This class includes functions to calculate the load distribution into structural wall elements and the building's eccentricity, as well as to check for the problem's constraints (axial and shear). The axial check verifies the compressive ratio for each wall element in a candidate layout according to Eq. (12), while the shear check compares the shear wall length the minimum shear length using Eq. (4).

Thus, the iterative process can be started, considering functions defined into the class *Genetics*. First, it initializes the initial population, by randomly generating a number of candidates for the design problem. The population size (N) can be defined as a user input in the iterative process. Each candidate in this study is a *WallLayout* object, in which the variable *is_removed* (r) for each *Element* object in the set defining the ground structure is randomly initialized as 0 (preserved) or 1 (removed).

Then, it runs the structural analysis for each candidate and verifies the problem's constraints. A candidate is not acceptable if at least one element in the candidate solution does not pass the axial check, as well the candidate does not pass for the shear check. Only structurally feasible candidates are selected for the iterative process. Next, each candidate is evaluated and ranked according to their fitness score considering the objective function defined by Eq. (9). The best parents are used to generate offspring throughout the iterative process. The number of best parents can be defined according to a parameter, the parent ratio (r_p). It represents a percentage of the total population and can also be defined as a user input.

To generate offspring, two random parents are selected, and the binary variable r for each wall is derived from randomly choosing either parent. Fig. 6 illustrates this process, which is known as the crossover operation, in which an offspring is generated by combining information on two candidates. In addition, the mutation operation can also be performed, in which the r binary variable is modified to the opposite value for randomly selected walls in a candidate layout. The mutation operation is applied to a number of candidates based on a specified percentage of the population, defined by the variable mutation ratio (r_m) Then, the new population is formed by combining the best parents with the generated offspring. This process is repeated until it reaches the convergence, where it either achieves a predefined target value for the objective function (t_f) or the maximum number of iterations (i_{max}). Fig. 7 summarizes the genetic algorithm process.

3. Evaluating the methodology

Geometric and material characteristics will vary depending on the building typology considered in the analysis. In this section, a building located in the Historic Center of São Luís (HCSL) is considered a case study for testing the proposed methodology. However, the methodology is general and may be considered for other historic masonry buildings. Buildings in the HCSL share similar characteristics with buildings of the Pombalino style in Portugal. Since not enough information on the structural characterization of buildings in the HCSL could be found, this paper considers the structural characterization of Pombalino buildings. Usually, this typology consists of stone masonry elements on the ground floor while external elements are made of rubble masonry on the upper floors. In contrast, internal elements are abstracted as brick masonry [63]. Table 1 summarizes the mechanical characteristics of these three masonry types.

Since information varies within stories, this analysis will focus on the first-floor layout. Thus, external walls are considered rubble masonry with a thickness equal to 80 cm, while internal walls are considered brick masonry with a thickness equal to 25 cm. To initialize the analysis, elements are subdivided, aiming to have a larger design space for testing which elements are crucial for the design. The structural grid considers 1-m-long elements, resulting in 95 internal elements. Fig. 8 introduces the input for the case study, representing the geometry and element subdivision, as well as the damage state. Elements 63, 73, 81, 82, and 116 are assumed to be damaged.

The building floor plan is 28 m by 19 m and is three stories high. Joints are distributed along the x-direction, resulting in the floor load distribution into wall elements in the y-direction. Considering the input geometry, the floor plan eccentricity is equal to 0.158 m, and the minimum shear wall length (l_s) is equal to 33.6 m. The total shear wall length is equal to 73 m, considering only wall elements along the y-direction. An initial structural analysis is performed to evaluate the existing condition of the building. The maximum compressive capacity ratio, according to Eq. (12), is equal to 0.99.

The evolutionary process considering the defined multi-objective function, according to Eq. (9) is tested. However, aiming to verify the effects of the eccentricity in the final results, two different $e(v)$ functions are tested. The first analysis accounts only the eccentricity of the candidate, as stated by Eq. (5). The second analysis considers a modified $e(v)$, as given:

$$e(v) = \frac{e_c}{e_0} \tag{13}$$

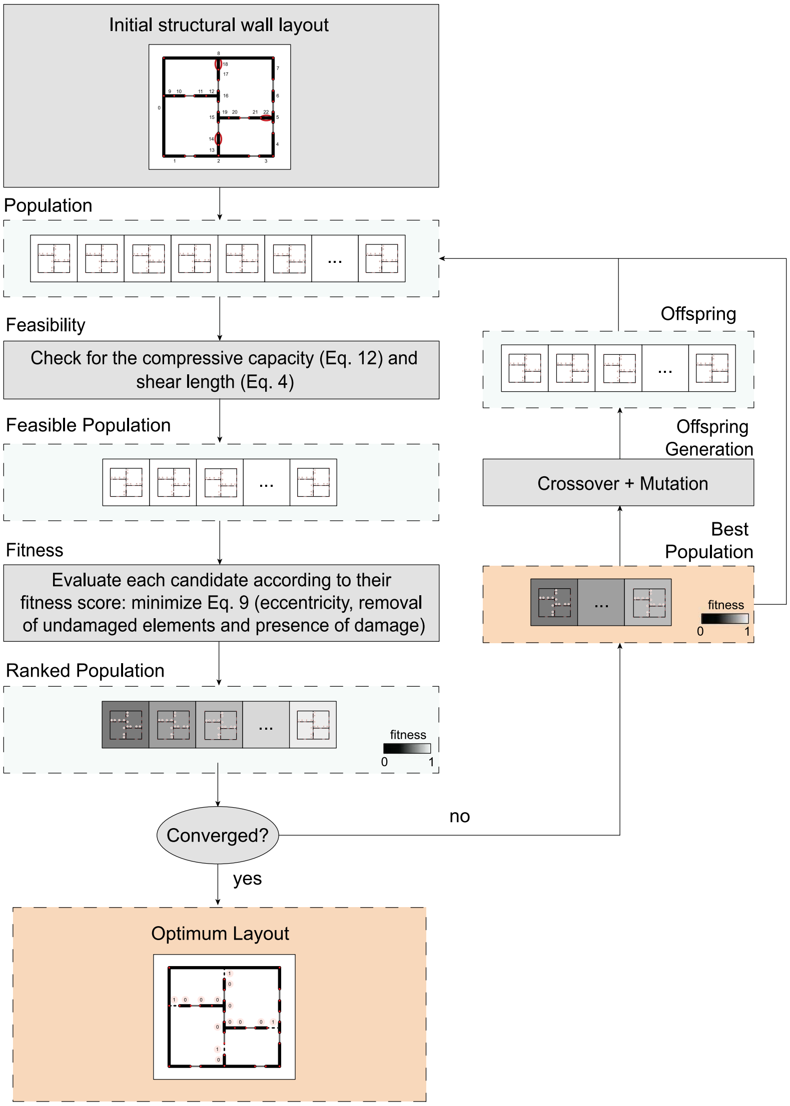


Fig. 7. Flowchart representing the iterative process for the Genetic Algorithm.

This function describes the eccentricity of a candidate (e_c) as a percentage of the eccentricity of the original layout (e_0), which in this case study resulted in 0.158 m. It is important to note that both variables are calculated as stated in Eq. (5). In addition, for both analyses, the distributed weights are defined aiming to consider similar weighting to both the adaptive reuse and the eccentricity. Thus, the distribution weights are defined as: $w_1 = 0.5$ and $w_2 = w_3 = 0.25$.

To start the GA process, the population size is defined as 2000 individuals and the maximum number of iterations equal to 15. The population ratio for selecting the best parents in the offspring generation is equal to 10%, and the mutation ratio is equal to 30%. The optimization process took around 366 and 384 s, for analysis 1 and 2, respectively, in a Intel(R) Xeon(R) W-2223 CPU @ 3.60 GHz, with 16 GB RAM computer, considering the defined GA parameters.

To verify the improvement in the performance over the iterative process, one can analyze the maximum, mean, and minimum values for the fitness score, eccentricity, and length of removed walls. Fig. 9(a) demonstrates the evolution in the fitness score for both analyses. Since analysis two accounts for the eccentricity as a percentage of the initial eccentricity, the fitness score results in a larger range when compared to analysis one. Despite this, the minimum fitness score for analysis two converges to similar values to the minimum fitness score for analysis one. Analysis one had an initial minimum fitness score equal to 0.1462, decreasing to 0.0341 in iteration 15, a reduction of around 77% of the initial value. In contrast, analysis two had an initial minimum fitness score equal to 0.3566, decreasing to 0.0587 in iteration 15, a reduction of around 84% of the initial value.

Since the fitness function is a combination of functions related to the eccentricity and the total length of removed walls, we can also compare the variation of these parameters over the iterative process. Fig. 9(b) demonstrates the evolution in the eccentricity for

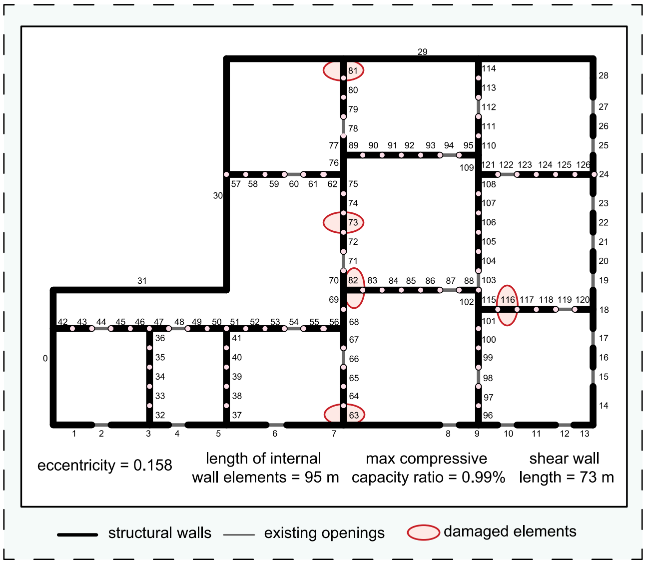
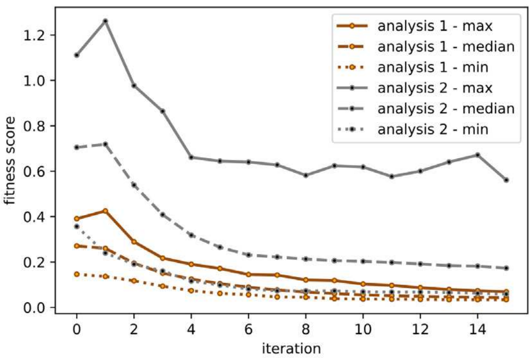
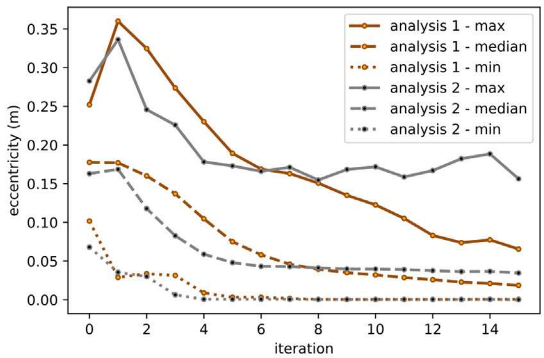


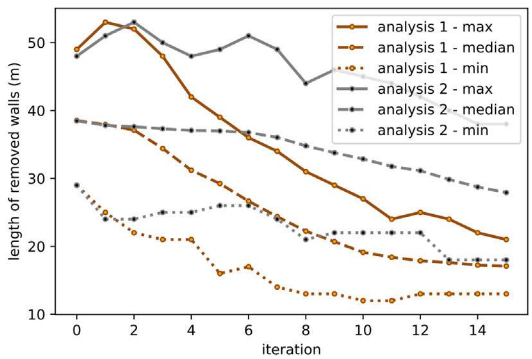
Fig. 8. Input information for the case study building.



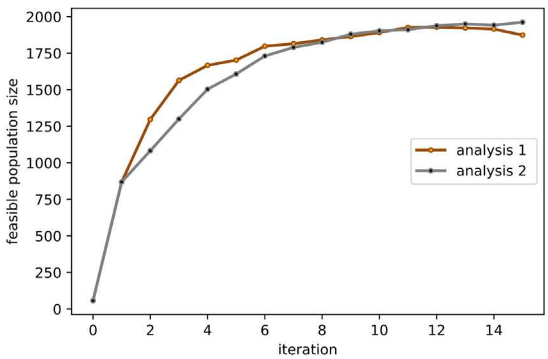
(a) Fitness score.



(b) Eccentricity.



(c) Length of removed walls.



(d) Population.

Fig. 9. Evolution of parameters throughout the iterative process.

both analysis. The initial minimum eccentricity for analysis one is equal to 0.1017, converging to a minimum eccentricity equal to 0.0005 in iteration 15. For analysis two, the initial minimum eccentricity is equal to 0.0680, converging to a minimum eccentricity

Table 2
Weights for the multi-objective function considering the three different testing conditions.

Analysis	Fitness			Eccentricity			Length removed			Population
	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	
Initial 1	0.391	0.271	0.146	0.252	0.178	0.102	49	38.5	29	57
Initial 2	1.115	0.705	0.357	0.283	0.163	0.068	48	38.5	29	57
Final 1	0.0689	0.0429	0.0341	0.066	0.019	0.0005	21	17	13	1874
Final 2	0.5611	0.1731	0.0587	0.156	0.035	0.0001	38	28	18	1962

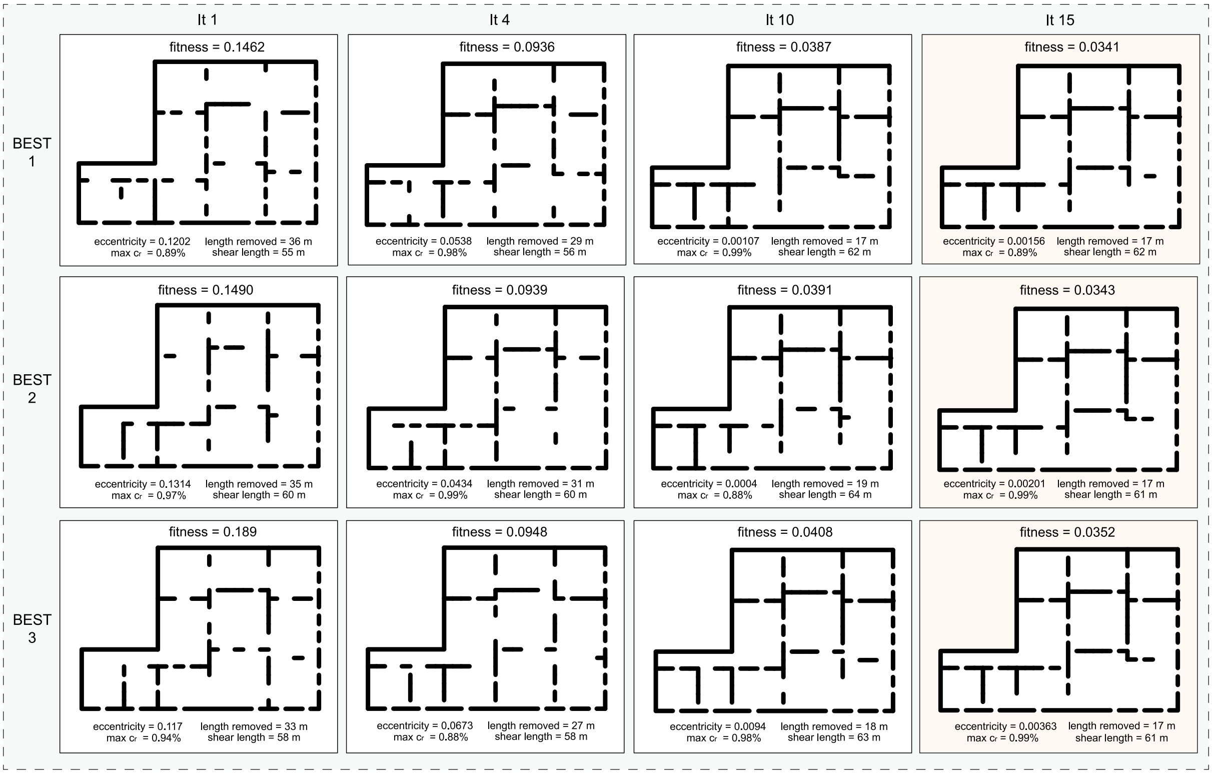


Fig. 10. Layout solutions for the three best candidates for iterations 1, 4, 10 and 15, considering analysis 1.

equal to 0.0001 in iteration 15. In addition, when comparing the two analyses, the mean values converge to similar amounts; however, analysis one presents as smaller range between maximum and minimum values.

When analyzing the results for the total length of removed elements, as demonstrated in Fig. 9(c), both analyses start with similar maximum, mean and minimum values. However, with time, analysis one converges to a smaller variation between the maximum and minimum value, varying from 13 m to 21 m. In contrast, analysis two results in a variation of 18 m to 38 m. Throughout the iteration, the initial minimum length of removed elements for analysis one decreased from 29 m to 13 m in iteration 15. For analysis two, the initial minimum length of removed elements decreased from 29 m to 18 m in iteration 15.

Lastly, Fig. 9(d) demonstrates the evolution in the feasible population size per iteration. For both analyses, the feasible population size after the random initialization resulted in a initial population equal to 57 parents. In the final iteration, the feasible population was equal to 1874 for analysis one and 1962 for analysis two. This happens because after the offspring generation some of the newly formed candidates may not comply with the defined constraints. Table 2 summarizes the maximum, mean, and minimum values for these parameters, considering the initial and final results for both analyses.

Figs. 10 and 11 illustrate the best three structural wall layout candidates in the first, fourth, tenth, and final (fifteenth) generation for analysis one and two, respectively. In these layouts, only walls elements are represented, disregarding the openings. This translates into the most required shear wall elements in the design. For each candidate, information on its fitness score, eccentricity, length of removed walls, compressive ratio, and shear wall length is presented. Table 3 summarizes the final results of the optimization process for the three best solutions, showcasing the fitness value, as well as the eccentricity and the length of the removed walls. As previously stated, analysis one achieves smaller values of the fitness function due to how it accounts for the eccentricity, but both analyses achieve fairly similar final eccentricity values. In addition, the best designs in analysis two had more elements removed than in analysis one.

Table 3
Weights for the multi-objective function considering the three different testing conditions.

Solution	Fitness		Eccentricity		Length removed	
	Analysis 1	Analysis 2	Analysis 1	Analysis 2	Analysis 1	Analysis 2
Best 1	0.0341	0.0587	0.00156	0.0001	17	26
Best 2	0.0343	0.0621	0.00201	0.0047	17	22
Best 3	0.0352	0.0629	0.00363	0.0023	17	25

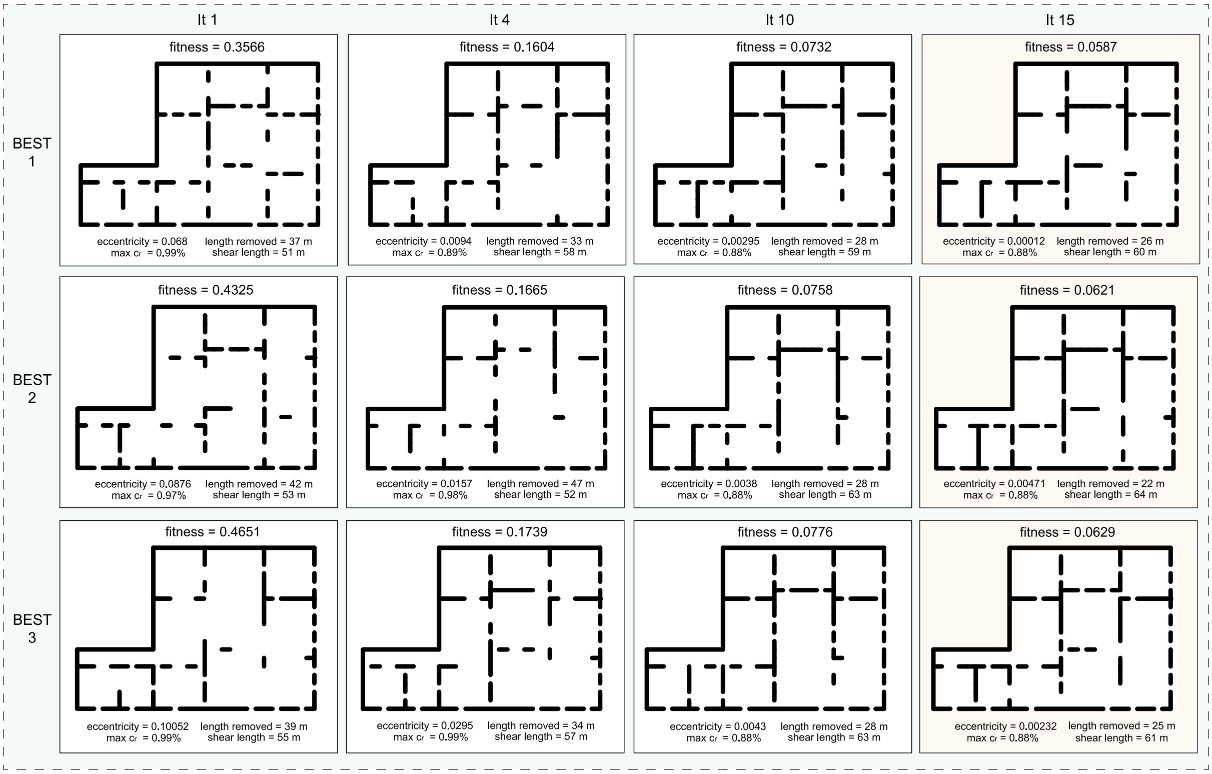


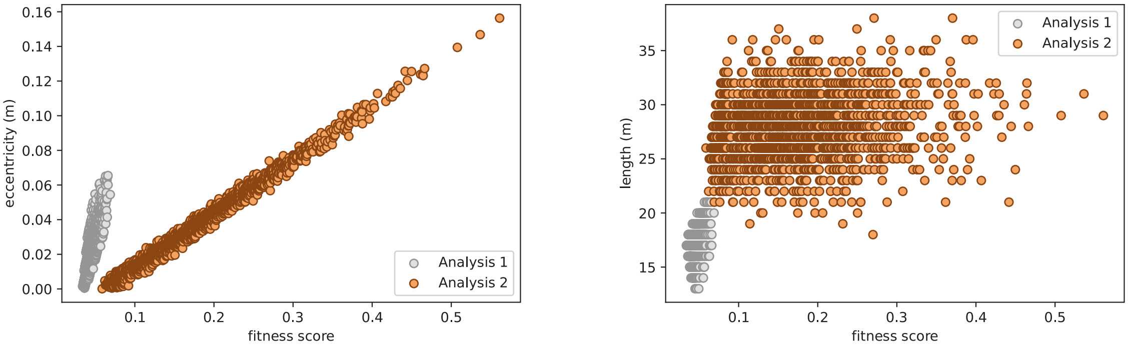
Fig. 11. Layout solutions for the three best candidates for iterations 1, 4, 10 and 15, considering analysis 2.

Lastly, aiming to illustrate the variation in the distribution of the design candidates in the final iteration, two scatter plots are defined in Fig. 12. Fig. 12(a) shows the relationship between the two analyses' fitness score and eccentricity. In analysis one, the fitness score in the final iteration converged to a smaller range of values while showing more variation in analysis two. Despite that, the minimum fitness score solution for each analysis corresponded to similar values in eccentricity. Fig. 12(b) shows the relationship between the two analyses' fitness score and the total length of removed walls. Similarly, the fitness score in the final iteration converged to a smaller range of values while showing more variation for analysis two. In analysis one, the best solutions resulted in less material being removed compared to analysis two. This can be explained by the fact that the eccentricity included as a ratio from the value in the original design results in a more significant weight for the eccentricity in the multi-objective function. Thus, the function in analysis two results in a higher removal of material to balance the eccentricity.

4. Sensitivity analysis

This section will focus on conducting a sensitivity analysis to identify how the input variables affect the optimization process. Three different input variables are investigated: damage state, material strength of internal structural walls, and the thickness of walls. For each input variable, three different values are tested. Regarding the damage state, 5% (d1), 10% (d2), and 15% (d3) of elements are defined as damaged (Fig. 13).

These percentages were chosen to represent a range of damage scenarios that are likely to be encountered in real-world adaptive reuse projects. A damage state of 5% represents a relatively low level of damage, which is common in historic buildings that have been regularly maintained or have undergone minor deterioration over time. A 10% damage state represents a moderate level of damage, which may be observed in buildings that have experienced some neglect or exposure to adverse conditions. A 15% damage state represents a more significant level of damage, which could be the result of severe deterioration, past structural issues, or



(a) Fitness score and eccentricity. (b) Fitness score and length of removed elements.

Fig. 12. Distribution of design candidates in the final iteration for analysis one and two.

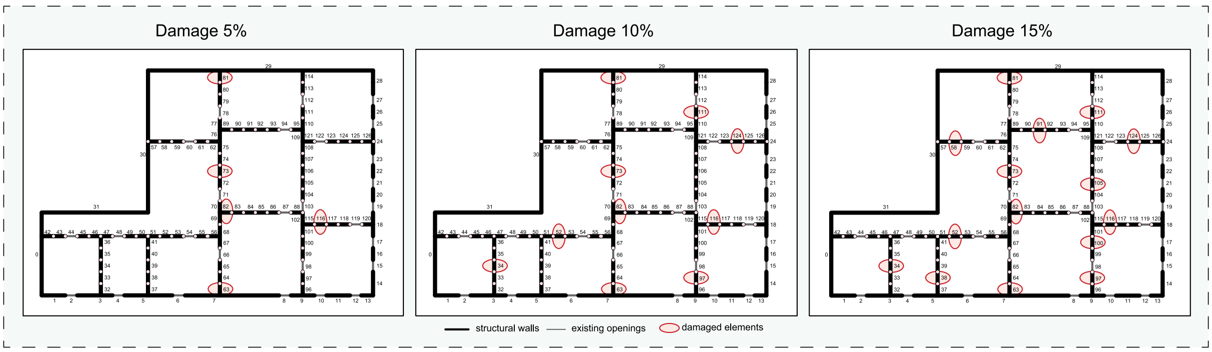


Fig. 13. Different damage states.

exposure to extreme events such as earthquakes or fires. We did not include higher damage state percentages because such extensive damage would likely render the building unsafe or unfeasible for adaptive reuse without major interventions or reconstruction which are beyond the scope of this paper. In cases of extreme damage, the focus would typically shift from layout optimization to more fundamental questions of structural stability, safety, and the viability of the adaptive reuse project itself.

Regarding the material strength of internal walls, the compressive strength was tested as the original value for brick masonry presented in 3, f_{pk} = 3.2 MPa (m1), then increased to f_{pk} = 4.1 MPa (m2), and then to f_{pk} = 5 MPa (m3). Similarly, the Young's module also increases, following a proportion of $E = 500f_{pk}$ [64]. In terms of the material strength of the walls, these values were selected based on the range of compressive strengths typically observed in historic brick masonry [59]. The original value (m1) represents a baseline scenario, while the increased values (m2 and m3) allow us to assess the impact of higher material strengths on the optimization results, which could be relevant for adaptive reuse projects involving retrofitting or strengthening interventions.

Lastly, the thickness of the walls is tested as 25 cm (t1), as described in the previous section, 35 cm (t2), and 45 cm (t3), which is typically observed for internal walls in historic masonry buildings. Since the input variables tested can have three different values, this results in a combination of 27 possibilities. To facilitate analyzing the results, the following subsections describe how each variable affects the optimization process. The optimum solution is quantified in terms of the final eccentricity, the total length of removed elements, and the maximum compressive stress.

4.1. Evaluating different damage states

To analyze how different damage rates affect the optimum design, each damage level must be fixed at a time, resulting in three analyses with nine combinations of different thicknesses of walls and material strength. Fig. 14 summarized the results for each analysis, investigating the effects on the eccentricity, length of removed walls, and maximum stress.

In terms of eccentricity, we can observe that the combination of material 2 and thickness 2 (m2-t2) has a higher eccentricity for damage level one. In contrast, material 3 with thickness 3 (m3-t3) has a higher eccentricity for damage level two, and material 1 with thickness 3 (m1-t3) has a higher eccentricity for damage level three. Despite that, eccentricity values show a reasonable range for all nine combinations for each damage level, with the maximum value being less than 0.006 m.

Regarding the total length of removed walls, one can observe that the different combinations of material strength and thickness of walls do not significantly affect the removal of elements, having a range between 23 and 26 for the nine different analyses.

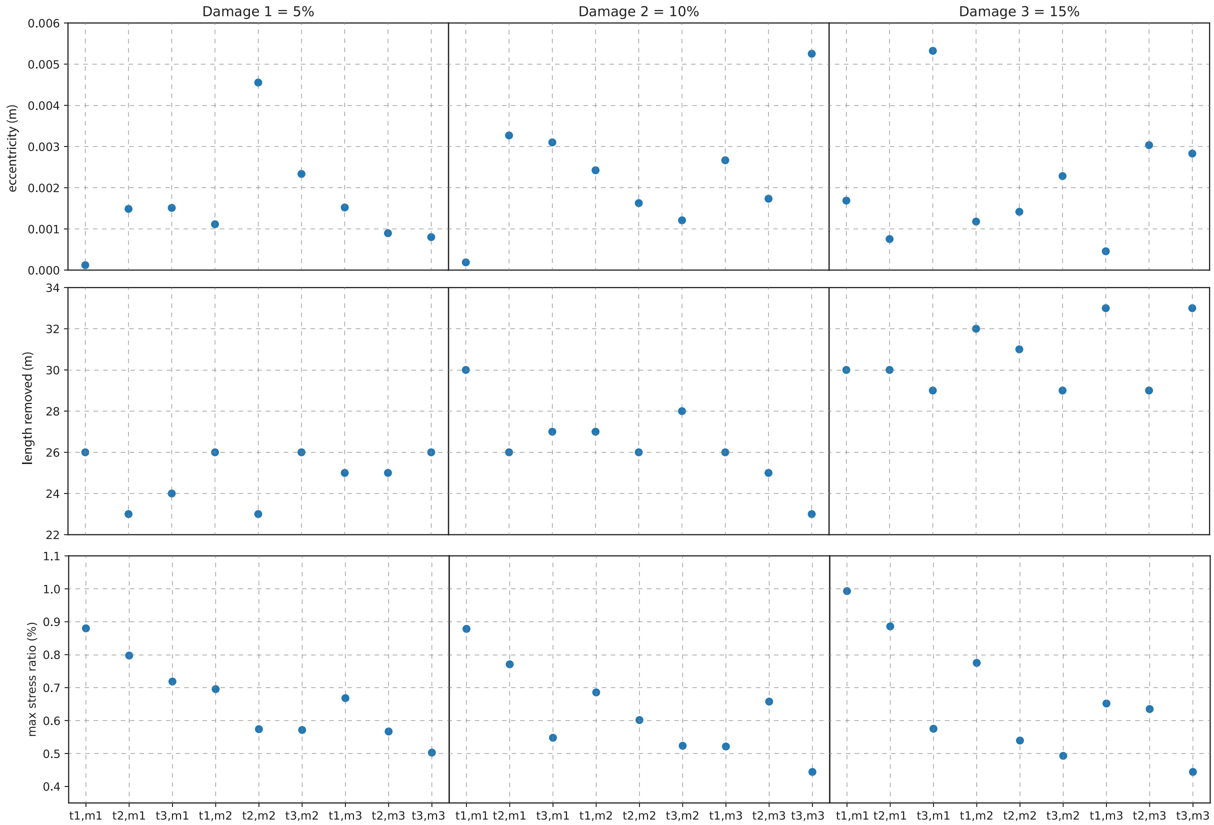


Fig. 14. Variation in eccentricity, length removal, and maximum compressive stress ratio considering the three different damage state rates.

In contrast, smaller values for the thickness of walls result in higher removal of elements, in general, for damage levels two and three. In addition, for damage level three, the optimum layout resulted in slightly larger values of removed elements. This can be explained by the fact that one of the functions in the multi-objective problem aims to minimize the amount of damaged elements in the solution. Lastly, in terms of the maximum stress ratio, the combination of thinner elements and smaller values of material strength (combination t1-m1) results in a higher stress concentration, while thicker elements and higher values in material strength (combination t3-m3) result in minor stress concentration.

4.2. Evaluating different material strength

Similarly to the damage analysis, each material strength value is fixed at a time, resulting in three analyses with nine combinations of different damage states and thicknesses of elements. Fig. 15 summarized the results for each analysis, investigating the effects on the eccentricity, length of removed walls, and maximum stress.

Regarding eccentricity, we can observe that damage 3 with thickness 3 (d3-t3) has a higher eccentricity for material strength 1. In contrast, damage 1 with thickness 2 (d1-t2) has a higher eccentricity for material strength 2, and damage 2 with thickness 3 (d2-t3) has a higher eccentricity for material strength 3. Despite that, eccentricity values show a reasonable range for all the nine combinations for each material strength, with the maximum value being less than 0.006 m. For material strength 1, the combination of damage 1 with thickness 1 (d1-t1) and damage 2 with thickness 1 (d2-t1) resulted in smaller eccentricity values, almost equal to zero. Similarly, for material strength 3, the combination of damage 3 and thickness 1 (d3-t1) resulted in smaller eccentricity values, almost equal to zero.

In terms of the total length of removed walls, we can observe that damage 2 with thickness 1 (d2-t1) and damage 3 with all three thickness values (d3-t1; d3-t2, and d3-t3) have slighter higher values for material strength 1. Similarly, damage 3 with all three thicknesses has higher values for material strengths 2 and 3. For material strength 3, it is worth mentioning that combinations for damage levels 1 and 2, with the three thicknesses, result in smaller values of length removal. Lastly, regarding the maximum stress ratio in the optimum solution, one can observe that smaller values of material strength (m1) result in higher ranges of stress ratio.

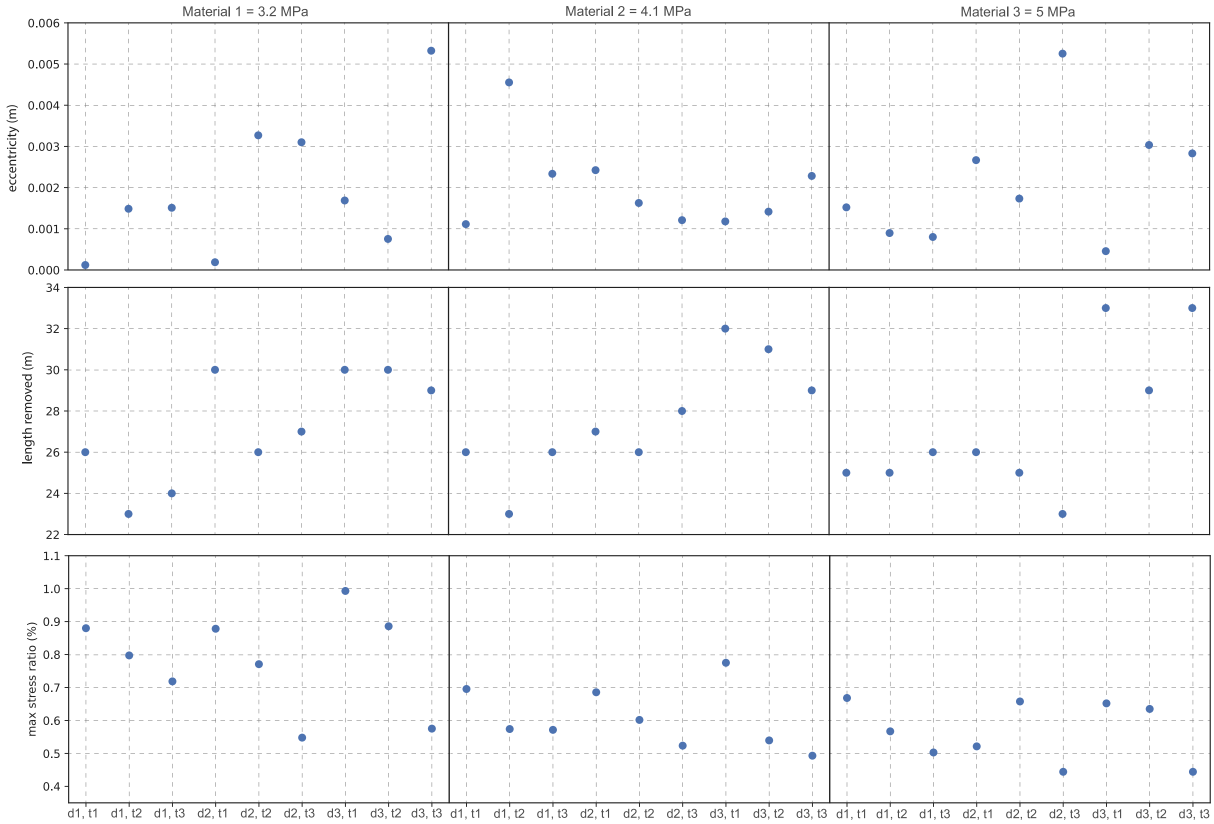


Fig. 15. Variation in eccentricity, length removal and maximum compressive stress ratio considering the three different material strength rates.

4.3. Evaluating different thickness of wall elements

Lastly, aiming to evaluate how different values for the thickness of wall elements affect the optimum design, each thickness value must be fixed at a time, resulting in three analyses with nine combinations of different damage states and material strength. Fig. 16 summarized the results for each analysis, investigating the effects on the eccentricity, length of removed walls, and maximum stress.

In terms of eccentricity, we can observe that, in general, the analyses for thickness 1 (t1) result in smaller values of eccentricity (<0.003). For thickness 2 (t2), a combination of damage level 1 and material strength 2 (d1, m2) leads to a higher eccentricity in the set. In contrast, for thickness 2 (t3), combinations of damage 2 with material 3 (d2, m3) and damage 3 with material 1 (d3, m1) result in higher values of eccentricity.

In terms of the total length of removed elements, one can observe that, in general, combinations with damage level 3 with all three material strength values lead to higher removal of elements. For thickness 2, combinations with damage level 1 and material strength 1 and 2 (d1, m1; d1, m2) lead to smaller values, while the combination of damage level 2 and material strength 3 (d2, m3) results in smaller values of material removal for thickness 3. Lastly, in general, combinations for thickness 3 (t3) result in smaller values of maximum stress ratio in the optimum solutions.

5. Conclusions

When adapting an existing building, the existing structural grid constrains the modifications to be performed. Thus, this paper has proposed a new methodology for determining modifications to a structural wall layout during the adaptive reuse process of historic buildings. In summary, an evolutionary approach is used to define which wall components can be removed from the existing layout, according to a multi-objective function that targets minimizing the presence of damaged elements and maximizing the presence of undamaged elements in the design, in addition to minimizing the building's eccentricity. The problem considers structural constraints based on the compressive capacity and minimum length of shear components.

This work considers a weighted multi-objective function. For that reason, it investigates the effect of different weights on the optimum responses. In summary, considering a function that accounts more for the eccentricity leads to a larger removal of elements in the design. In addition, this paper investigated how different input variables influence the optimization process, especially in terms of parameters for the multi-objective function (eccentricity and length of removed elements) and the maximum compressive stress.

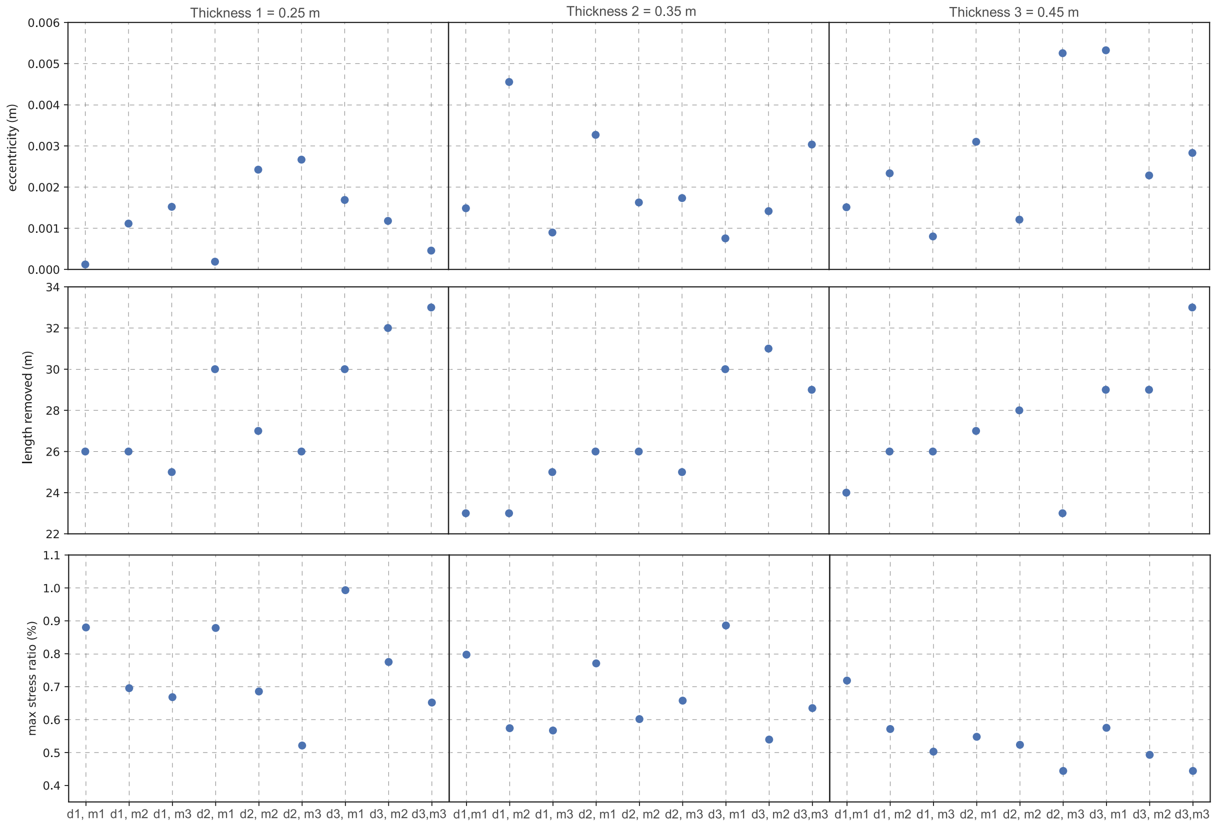


Fig. 16. Variation in eccentricity, length removal and maximum compressive stress ratio considering the three different wall thickness values.

In conclusion, one can observe that despite different values, the process converges to almost null values in terms of eccentricity, which contributes to the building's stability. The amount of removed elements shows a slight variation for different input variables, which is mostly related to the fact that the optimization will try to remove more material to either balance the eccentricity or to reduce the presence of damage in the design. The most influential aspect of input variables is related to the compressive stress constraint.

The methodology can be used to facilitate the adaptive reuse process, determining which elements are more necessary in the design and which elements can eventually be removed. Considering the optimum solution obtained in analysis two in Section 3, Fig. 17 presents an example of an adaptive reuse project. The spatial allocation prioritizing existing facade openings results in 2 studios, two 1-bedroom and one 2-bedroom. In addition, common areas such as laundry rooms or storage spaces can be allocated to spaces with no existing facade openings. After allocating multi-family apartments to an existing floor plan, designers can verify which wall elements can be removed from the design, facilitating modifying the spatial relationship. For example, removing the internal wall segments determined as allowable to be removed inside each apartment facilitates the resolution of the internal circulation within these apartments. If the project allows introducing new facade openings, a new GA analysis can be performed, including the facade wall segments as elements in the grid to determine if they can be removed or maintained. In the given example, this could introduce more apartments where common areas are defined.

The methodology considers only the removal of existing elements during the adaptive reuse process. When removing elements, stress distribution occurs in the floor plan layout. Therefore, the existing design has a specific limit of removal or modification since the remaining elements must preserve the stress distribution. Thus, future work includes integrating strengthening elements in the process to allow higher flexibility in the adaptive reuse process. In addition, integrating spatial constraints, such as minimum distance between wall segments or verifying the allocation of apartments with minimum area for internal rooms (living room, bedrooms, etc.), into the process can generate more robust solutions. In fact, future work plans on considering both spatial and structural requirements to generate a variety of floor plans solutions for the adaptive reuse of historic masonry buildings. This will be achieved by combining the grammar-based approach developed in previous works [55,59] with the methodology presented in this paper.

Furthermore, while the approach presented in this paper allows for a straightforward integration of the damage state as a binary variable into the optimization process, it may not fully capture the nuances and severity of damage in real-world structures. However, it is important to note that defining damage scales can be challenging and subjective, as different buildings in various contexts

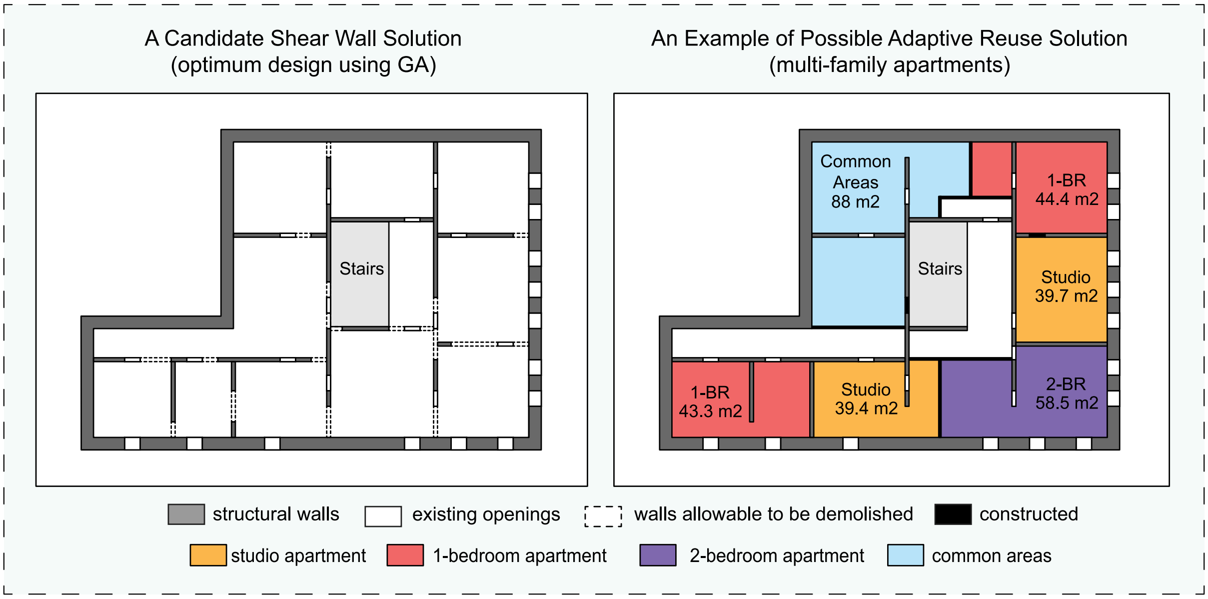


Fig. 17. An example of adaptive reuse solution considering the optimum structural wall layout achieved using the GA process.

already use different scales that have inconsistencies [65,66]. The binary representation used in this study offers a more consistent and easily interpretable approach for the optimization process, as it reduces the complexity and potential subjectivity associated with multi-level damage scales.

Future work could explore the incorporation of more refined damage models into the optimization framework. This could involve using multi-level damage scales tailored to specific building typologies or regions, or even integrating more advanced damage assessment techniques, such as non-destructive testing or computer vision-based methods [67,68]. By doing so, the optimization process could potentially yield more accurate and context-specific results, further enhancing the effectiveness of the proposed methodology for adaptive reuse projects. Additionally, future studies could investigate the sensitivity of the optimization results to different damage modeling approaches, comparing the binary representation with more refined models. This would provide valuable insights into the trade-offs between model complexity, subjectivity, and optimization performance, guiding the development of more robust and efficient damage assessment strategies for adaptive reuse applications.

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CRediT authorship contribution statement

Daniele M.S. Paulino: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Heather Ligler:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Rebecca Napolitano:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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