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Evaluation of retrofitting techniques for historical adobe constructions using a multi-criteria decision analysis: The case study of Chile

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Abstract

The evaluation of retrofitting techniques against multiple (often conflicting) criteria requires an expert-driven approach with in-depth context-based knowledge. This research evaluates the expected performance of retrofitting techniques for historical adobe constructions by integrating literature-data and expert assessment. Consideration is given to performance-based criteria (structural behaviour, material compatibility), values around cultural built heritage (degree of intrusion, retreatability), and local constraints (cost-effectiveness).

A multi-criteria decision analysis using MACBETH (*Measuring Attractiveness by a Categorical-Based Evaluation TecHnique*) is undertaken in this study in order to facilitate the selection process for retrofitting techniques within distinct damage scenarios.

The MACBETH model is applied to three historical adobe buildings in Chile using a weighted criteria matrix, while a sensitivity analysis is conducted to determine the stability of interventions. The best-scoring options for each damage pattern are then compared with national guidelines and the current practice.

Among the best-ranking solutions obtained from MACBETH models, the use of wooden corner keys makes it possible to effectively counteract flexural cracks or mid-height cracks, damage at intersections of perpendicular walls, corner-damage vertical cracks, and in-plane damage. Wooden tie beams are effective solutions for corner-damage vertical cracks. Geo-mesh also obtains a high score yet is limited by its cost and low reversibility.

Keywords: Historical adobe buildings; multi-criteria decision analysis; Participatory analysis; Retrofitting; Performance-based assessment; Chile

1. Introduction

Adobe or other sun-dried bricks are among the oldest and the most ubiquitous building materials in the world, due to their cost-effectiveness (availability of raw materials), good thermal properties (high thermal inertia), great versatility, high level of buildability, and continuous usage across centuries (AA.VV, 2016; Marcial Blondet et al., 2011; C. Costa et al., 2019; Michiels, 2015; Minke, 2006; Tarque et al., 2022). Beyond the economic feasibility of this construction solution and its high sustainability (net-zero carbon emissions), multiple stakeholders – including, but not limited to, local communities, engineers and architects, governments, and non-governmental organizations – have become aware of the social importance of keeping traditional construction knowledge alive, valorising cultural heritage, and providing long-term effectiveness of rehabilitation (or retrofitting) works.

Research communities and local heritage authorities are today placing significant emphasis on the recovery and improvement of traditional earth-based techniques in Chile. The construction of new adobe buildings has been progressively diminishing since 1940-60s due to their poor seismic performance and legislative requirements. However, adobe-based composite systems are still widely employed in informal settlements and rural areas (AA.VV, 2016; Karmelic, 2015). This knowledge is fundamental for the preservation of whole historical townscapes in several countries, especially in the Americas and Middle East. Attention has been drawn, especially since the 1960s, to preserving the irreplaceable cultural significance of historical adobe buildings (Cancino et al., 2014; Jorquera, 2012; Minke, 2006; Torkzaban, 2017). Many research efforts have been devoted to training heritage professionals and defining conservation guidelines for the repair and retrofitting of earthen architecture heritage: Latino-American programmes, *e.g.* those promoted by the Catholic University of Perú (Blondet et al., 2011); European projects, *e.g.* GAIA (1989) and Progetto Terra (1989-2007); and international projects, *e.g.* the *World Heritage Programme on Earthen Architecture* (WHEAP, 1989-2007), *Earthen Architecture* (2007-2017) promoted by the *UNESCO World Heritage Centre*. From the 1990s onwards, the Getty Conservation Institute has made advances on seismic performance design for historical adobe structures, shifting the priority from guaranteeing "earthquake-proof" construction to ensuring safety just against failure due to overturning (Tolles et al., 2002). The principal intervention criteria to be considered during the intervention on adobe buildings – structural authenticity, low degree of intrusiveness, structural safety, compatibility, and reversibility – are defined in (AIS, 2004; Marcial Blondet et al., 2011; ICOMOS/ISCARSAH, 2003; Ortega et al., 2017; Peña Mondragón & Lourenço, 2012; Tolles et al., 2002).

It is clear from this extensive literature that there is growing interest in defining large-scale seismic mitigation measures, based on accurate vulnerability assessment of the historical adobe building stock. However, codes and design standards are rarely applied in the common building practice (Jorquera, 2012). The seismic vulnerability of this construction system, worsened by lack of maintenance or by intrusive interventions, has dramatically caused severe building damage and high numbers of casualties during several earthquakes, especially between the Nazca plate and South American plate. Highly destructive seismic events include those in Chile (8.5 Mw, in 1922; Mw 9.5, in 1960; Mw 8.8, in 2010); Perú (Mw 8.4, in 2001); Mexico (7.1 Mw, in 2017; 8.0 Mw, in 1985); Ecuador (7.8 Mw, in 2016), as well as in the Middle East, as in the case of Iran (6.6. Mw, in 2003) (D'Ayala & Benzoni, 2012; Greco & Lourenço, 2021).

The principles for interventions established in the current legislative framework on adobe buildings often show conflict between performance-based criteria and cultural conservation values. Being able to consider varying weights of these criteria should prove useful in selecting the most appropriate solution for each specific context.

This study aims to fill this gap by defining value functions and weights of criteria. A multiple-criteria decision analysis (MCDA), which has been little explored in heritage reuse and retrofitting techniques until now (Caterino et al., 2008; Gentile & Galasso, 2021; Stellacci et al., 2020), is carried out in this work by integrating data from literature, experimental studies, current practice, and expert assessments. Specifically, a panel of nine experts is involved in this research for prioritizing a set of retrofitting techniques in historical adobe buildings. Among a plethora of MCDA, MACBETH (*Measuring Attractiveness by a Categorical-Based Evaluation TecHnique*) was selected for reconciling conflicting viewpoints of multiple stakeholders (Bana e Costa, 1994; Bana e Costa & Oliveira, 2002; Marttunen et al., 2015; Mustajoki et al., 2013; Stellacci et al., 2018). Compared with previous applications of MCDA to architectural heritage, this research contributes to show how typological analysis and damage patterns in historical buildings can be successfully combined with an open-ended, human-powered approach and a robust procedure for improving heritage management.

In this study, it is shown how principles of intervention established in the current legislative framework encompass multiple (and often conflicting) criteria, whose weights are not clearly identified. Rich information on seismic retrofitting techniques and expert evaluations are integrated in this study using MACBETH (Bana e Costa, 1994; Bana e Costa & Oliveira, 2002). This study contributes to the understanding of how the changes of the weights of criteria influence the expected performance of selected retrofitting techniques, within specific design scenarios that depend on the configuration of each historical building and related conservation priorities (*e.g.,* frescoes).

2. A look at traditional earth-based buildings: The Case study of Chile

The scientific community has defined guidelines for the conservation and repair of adobe constructions (AIS, 2004; Marcial Blondet et al., 2011; Ortega et al., 2017; Tolles et al., 2002). In such works there is consensus on the most commonly occurring seismic damage related to poor construction practices: poor connections between structural elements impede the distribution of horizontal loads and therefore enable the activation of out-of-plane mechanisms; out-of-plane wall collapse is associated to bending of the masonry; in-plane shear failure is mainly characterized by diagonal or X-cracking in the direction of the wall length. Additionally, lack of maintenance and unskilled workmanship harm the overall seismic behaviour of these buildings (Ortega et al., 2017). Moderate-to-thick adobe walls (height-to-thickness ratio limit- SL>8) are more stable against out-of-plane movement, exhibiting substantial structural ductility (Bhattacharya et al., 2014; Comerio, 2003; Michiels, 2015; Papanikolaou & Taucer, 2004; Tolles et al., 2002; Torres Gilles & Jorquera Silva, 2018). The seismic vulnerability of earthen-based buildings results from the low quality of their material components, causing degradation, micro-cracking, breakage, and wall detachment. Other vulnerable factors are heavy roofing and low in-plane resistance of the floors.

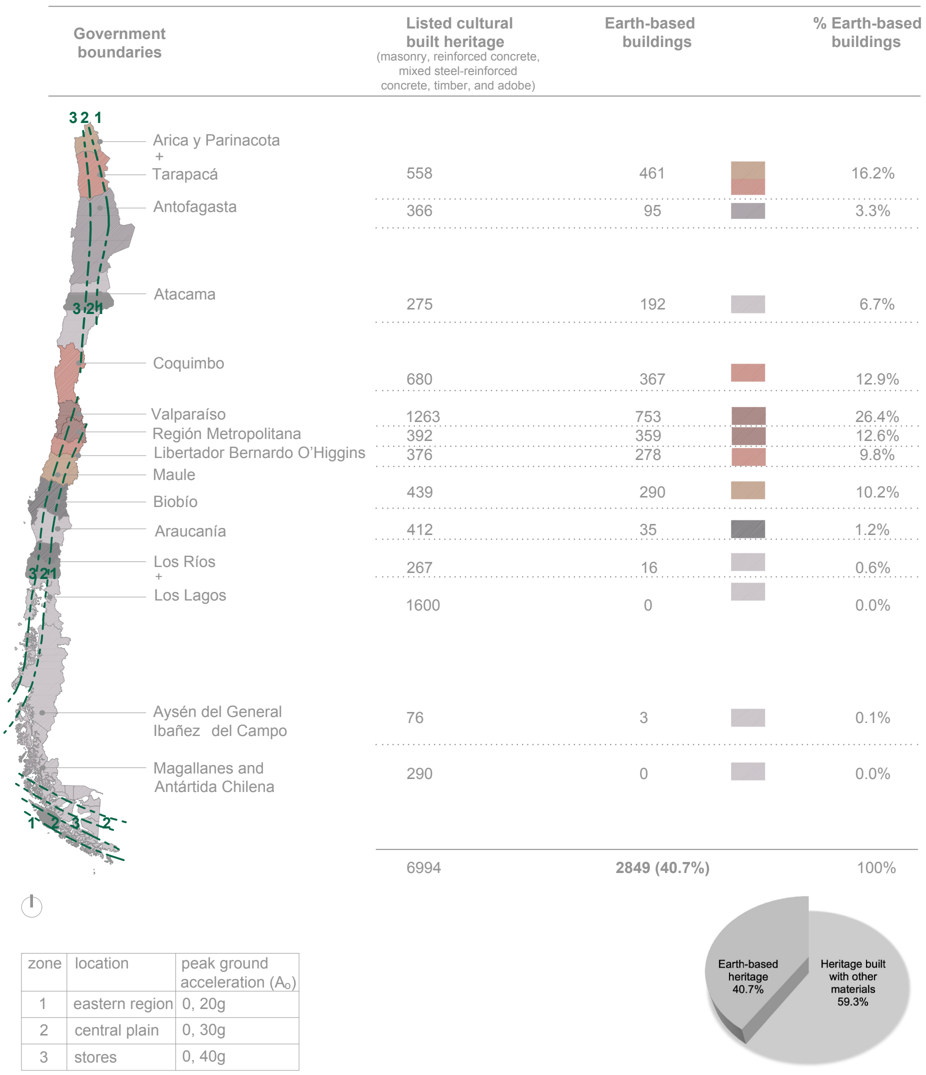
Chile is a highly seismic-prone country whose built heritage is made predominately in earth-based techniques across almost two thirds of its territory; it is therefore likely to be one of the most relevant showcases of the seismic vulnerabilities of historical adobe buildings (Jorquera, 2012; Karmelic, 2015). The variety of earth-based typologies in Chile owes to the geomorphological, climatic, and cultural conditions along the N–S extension (over 4,300 km), as well as on the wide range of uses from the pre-Columbian era onwards. Their diffusion and variety (*Figure 1*) also arise from long-standing adjustment of retrofit techniques to local constraints, together with the knowledge exchange between local and Spanish populations during the period of colonization (from the second half of the 16th to the 19th century) (Jorquera, 2012; Torres Gilles & Jorquera Silva, 2018). *Adobe*, *quincha* and *adobillo* are the most widely used techniques in historical buildings in Chile; the latter two are mixed earth and wood techniques (*Figure 1*) (Baquedano et al., 2021; Jorquera, 2012; Karmelic, 2015).

Figure 1. Historical earth-based buildings: from left to right: adobe blocks in Lolol (Baquedano); *quincha* in Totoral (Cortez, 2014); *adobillo* in Valparaíso (Jiménez, 2014)

To define effective mitigation measures, it is first necessary to relate the building type to data from the seismic zoning map, defined in terms of Peak Ground Acceleration (PGA) (Calvi et al., 2006). *Figure 2* shows the distribution patterns of earth-based buildings in Chile in the seismic zoning map, identifying shaking intensities according to Chilean code NCh433.Of 96 (NCh 433, 1996). Adobe buildings are mostly spread across rural areas, along the Andean zone and Central Valley, the highest seismic risk areas of the country. Considerable effort has been devoted to carrying out on-site surveys of traditional adobe building typologies (including traditional dwellings, churches, convents, and colonial *haciendas*) in each region in Chile (DA-MOP, 2000), especially by the National Monuments Council (CMN, hereafter) in order to define appropriate intervention strategies.

Expected impacts of strength- *vs* stability-based design are identified in the *Getty Seismic Adobe Project* (GSAP) and *Seismic Retrofitting Project* (SRP), extensively discussed in literature, and incorporated in the current construction legislation on earth-based construction in Chile, NCh3332 (Cancino et al., 2014; Michiels, 2015; Tolles et al., 2002; Torres Gilles & Jorquera Silva, 2018). Since the strength-based techniques address the elastic performance of the adobe walls, these are deemed more relevant than the stability-based techniques, which address the post-elastic performance by delaying the formation of cracks (Michiels, 2015; Tolles et al., 2002). After the 2010 Mw 8.8 Chile Earthquake in 2010 (D'Ayala & Benzoni, 2012), the rehabilitation of damaged adobe houses was a priority, due to their number – 81,149 houses, 27% of the total destroyed houses (DA-MOP, 2000; MINVU, 2010). Efficient techniques to retrofit monuments and housings have been implemented, *e.g.* in *Posada del Corregidor*, *La Matriz Church*, *San Ignacio Calera Tango School,* and the *villa in Zuniga*, to mention just a few (AA.VV., 2012; CNCA, 2013; UNESCO, 2011). Compliance to the building codes, *e.g.* NCh 3332 (NCh 3332, 2013), is often hampered by homeowners' low economic resources, lack of awareness regarding heritage value, or inadequate control procedures and maintenance. Moreover, in the last two decades, the upward pressure on house prices in central areas, the need to upgrade adobe buildings, and their poor conditions, worsened by lack of maintenance, have contributed to the demolition of whole historical adobe neighbourhoods instead of appropriate middle- or long-term interventions.

INVENTORY OF BUILT HERITAGE BY THE MINISTRY OF PUBLIC WORKS (2000)



Government boundaries	Listed cultural built heritage (masonry, reinforced concrete, mixed steel-reinforced concrete, timber, and adobe)	Earth-based buildings	% Earth-based buildings
Arica y Parinacota + Tarapacá	558	461	16.2%
Antofagasta	366	95	3.3%
Atacama	275	192	6.7%
Coquimbo	680	367	12.9%
Valparaíso	1263	753	26.4%
Región Metropolitana	392	359	12.6%
Libertador Bernardo O'Higgins	376	278	9.8%
Maule	439	290	10.2%
Biobío	412	35	1.2%
Araucanía	267	16	0.6%
Los Ríos + Los Lagos	1600	0	0.0%
Aysén del General Ibañez del Campo	76	3	0.1%
Magallanes and Antártida Chilena	290	0	0.0%
	6994	**2849 (40.7%)**	100%

zone	location	peak ground acceleration (A_0)
1	eastern region	0, 20g
2	central plain	0, 30g
3	stores	0, 40g

NCh433.Of 96 (INN, 1996)

Figure 2. Distribution patterns of earth-based buildings in Chile, data from (Karmelic, 2015) (credits: Stefania Stellacci)

3. Decision environment and research methodology

To select the most suitable retrofitting techniques, among those indicated in *Table 1*, an expert-driven approach is required. Since this decision environment, defined as the collection of data, alternatives, values, and preferences, is complex and uncertain, the application of Multi-criteria Decision Analysis (MCDA) is extremely useful in orienting intervention works, especially under conditions of scarcity. As stated in the literature (Tolles et al., 2002), the team called on to inform critical stakeholders' decision-making should include a preservation architect, a structural engineer specialized in traditional construction techniques and conservation, a social historian, an architectural historian, a conservator, and representatives of securing or government funding agencies. Homeowners and inhabitants, cultural resource managers, and contractors should also be involved in the decision-making project. Maitland and Woodside (Maitland & Woodside, 2017) emphasize the role of the structural engineer in different yet complementary areas, such as the assessment of structural adequacy, assessment of cultural heritage significance, risk assessment, heritage impact statements, condition assessment, input into conservation plans, proposals, and documentation of conservation work, and contract administration for conservation works.

Table 1 shows each type of damage and the respective retrofitting techniques, whose performance will be evaluated by the panel of experts. These techniques are chosen due to their wide application in several buildings in Chile. Other techniques, whose effectiveness has been proven in literature, such as rope mesh (Tarque et al., 2022) and steel plates (Ruiz et al., 2022), were not analysed in this study since their use is not common in Chile nowadays.

Table 1. Damage patterns and retrofitting techniques (RT) of historical adobe buildings (RT commonly applied in Chile)

		Retrofitting techniques (RT)											
		Wooden bond beam	Reinforced concrete bond beam	Partial plywood diaphragm	Horizontal and vertical steel (or nylon) rods and straps	Center-core rods and steel (or nylon) rods	Geomesh	Electrowelded mesh	Wooden tie beam	Steel tie rod	Steel anchors (doweling)	Wooden corner keys	Stone (or adobe) buttresses
Damage		**T1**	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**	**T11**	**T12**
Out-of-plane (Gable-end wall)	**D1**					X	X	X			X		
Out-of-plane (Flexural craks or mid-height cracks)	**D2**	X	X	X	X	X	X	X	X	X	X	X	X
In-plane damage	**D3**	X	X	X	X	X	X	X					
Corner damage - Vertical cracks	**D4**						X	X	X	X	X	X	
Corner damage - Diagonal and cross cracks	**D5**					X	X	X					
Damage at intersection of perpendicular walls	**D6**						X	X	X	X	X	X	
Cracks at openings	**D7**					X	X	X			X		
Slippage between walls and wood framing	**D8**				X				X	X	X		
Horizontal upper-wall cracks	**D9**					X	X	X					
Damage at wall or tie-rod anchorage	**D10**						X	X					

Following the common workflow used within MCDA, this study is divided into i) problem structuring and selection of the MCDA technique (*§3.1*-*3.2*); ii) criteria; iii) options (*§3.3*); iv) selection of case studies and identification of related damage patterns (*§3.4*); v) results and discussion (*§3.5*). A multidisciplinary panel of nine heritage preservation experts contributes to phases ii) and iii).

3.1. Problem structuring and MCDA selection

The seismic response of the building depends on the soil-structure interaction and multiple factors related to the building typology and its state of conservation, such as its geometric configuration, its lateral load-resisting system, the properties of the materials, the connections between each structural and non-structural component, the stiffness of the horizontal diaphragms, and the boundary conditions (Brzev, S., Scawthorn, C., Charleson, A. W., Allen, L., Greene, M., Jaiswal, K., & Silva, 2013; Comerio, 2003; de Felice, 2011; Papanikolaou & Taucer, 2004). Although building performance depends on a variety of factors, patterns of expected damage can be identified by analytical and empirical approaches (*vulnerability functions*) (Papanikolaou & Taucer, 2004), which can inform macro- or meso-scale analysis or integrate existing datasets, such as *Building Taxonomy for the Global Earthquake Model* (GEM) (Brzev, S., Scawthorn, C., Charleson, A. W., Allen, L., Greene, M., Jaiswal, K., & Silva, 2013; Jiménez et al., 2018). MCDA has so far been little explored in heritage reuse and retrofitting techniques (Caterino et al., 2008; Gentile & Galasso, 2021), and the selection of the best multi-criteria tool is still controversial. Several scholars have extensively addressed a MCDA method selection framework (Ishizaka & Nemery, 2013; Wątróbski et al., 2019), but decision-makers (DMs) or analysts usually choose the method that they are familiar with (Yan Li & Thomas, 2014). The most common MCDA are AHP (*Analytic Hierarchy Process*), TOPSIS (*Technique for Order of Preference by Similarity to Ideal Solution*), MAUT (*Multi-Attribute Utility Theory*), and MACBETH. This latter method was chosen in this study for its efficiency, number of applications, and strict check for consistency (Ishizaka & Nemery, 2013). Above all, MACBETH was chosen for its ability to incorporate a large number of preferences (or subjective evaluations) through pairwise comparison judgments. Its approach is based on *synthesizing criteria*, where a low score for one criterion may be compensated by high score for another criterion (Roy, 2005; Vincke, 1992).

Experts generally prefer to make comparisons through semantic judgments by expressing attractiveness of preferences between every element of evaluation rather than by assigning a direct numerical value to the weightings of criteria or each performance level (Bana e Costa, 1994; Stellacci et al., 2018). MACBETH can thus be tailored in order to match analysts' specific requirements, through a co-participative decision-making process. By providing a complete ranking based on an additive aggregation approach, it also automatically resolves contradictions between the interests of individual actors or those arising from semantic inconsistency. Potential inconsistencies are detected in the complete matrix of judgements by linear programming (Bana e Costa & Vansnick, 1999). The M-MACBETH software identifies the minimum number of judgements, which should be modified to guarantee consistency and suggest modifications. The additive aggregation model is well-known, being used in many real-world applications and easy understandable (Bana e Costa, 1994; Bana e Costa & Oliveira, 2002; Marttunen et al., 2015; Mustajoki et al., 2013) since *"its technical parameters have a clear and easily explicable substantive interpretation*" (Bana e Costa et al., 2003). It overcomes difficulties inherent in ordinal aggregations (Condorcet's Paradox, Arrow's theorem). The software uses an interval scale, whereas the Analytic Hierarchy Process (AHP), also a full aggregation method, uses a ratio scale. Constructing such scales calls for interacting with multiple decision-makers. Their preferences represent the average or typical opinion of the whole group. MACBETH is also user-friendly for its intuitive graphical interface and processing speed, so DMs can easily learn to use it. It provides error detection for inconsistent judgments in the pairwise comparison matrix and suggests solutions. It is also an interactive tool that make it possible to analyse the sensitivity of every output based on the variations of judgements, performances, and scores, or weights.

Due to the variety of the MCDA – around 100 alternatives – the task of choosing one is itself a problem that can discourage potentially interested groups (Saaty & Ergu, 2015; Stellacci et al., 2018; Yan Li & Thomas, 2014).

To gain insight into the various MCDA software *vs* M-Macbeth and understand what could be improved, a comparative analysis was done within the IMPERIA project (Mustajoki et al., 2013), whose results are coupled with the considerations resulting from this study, summarized in *Table 2* (Stellacci, 2018).

Table 2. Evaluation of MCDA *vs* M-MACBETH performance (Stellacci, 2018)

Criteria evaluation	**Descriptors**	**Scale evaluation**	**M-Macbeth scale**	**other MCDA software (total 24)**	**Comments on M-Macbeth performance in relation to other MCDA tools**
1. Process support	general purpose software	Y or N	Y	Y=19; N=4; - =1	Some expertise is typically required. Biases e.g. in the weight elicitation may arise from an improper use of the method. Some decision analysis modules have implemented on-line guidance (*PUrE2*, *PlanEval*). Some improvement (*e.g.* tab-paneled interface) should be introduced into M-Macbeth.
	process support		N	Y=9; N=15	
	hand-in-hand guidance		N	Y= 4; N=20	
	level of expertise required	1L, 2L, 3L	3L	3L=17; 2L=4; 1L=2;	
2. Model construction	hierarchical model	Y or N	Y	Y=18; N=4; - =2	The model construction of all software is quite similar, based on hierarchical organization of the criteria, a matrix-like consequence table for inputting the criteria-wise data of the alternatives into the model. M-Macbeth is user-friendly because it allows easy management of data input phase.
	consequences table		Y	Y=19; N=3; - = 2	
	visual scoring		Y	Y=18; N=4; - = 2	
3. Criteria weighting	visual weighting	Y or N	Y	Y=18; N=4; - = 2	Almost half of the software provides support for both AHP and MAVT/MAUT. M-Macbeth is one of the few that provide support for both outranking and MAVT/MAUT methodologies. Unlike M-Macbeth, some software provides explicit support for modelling uncertainty/imprecision (i.e. *Analytica*, *DecideIT*, *GMAA*).
	MAUT/MAVT		Y	Y=18; N=4; - = 2	
	swing		N	Y= 11; N=11; - =2	
	outranking		Y	Y=3; N=20; - = 1	
	modelling of uncertainty/imprecision		N	Y=8; N=14; - = 2	
	decision trees		N	Y=3; N=19; - = 2	
4. Analysis of the results	visual graphs	Y or N	Y	Y=21; N=1; - =2	Similarly to the majority of the software, M-Macbeth provides visual graphs of results, such as thermometer and x-y graphs. In addition to the traditional one-way sensitivity analysis, M-Macbeth could be improved by including statistical approaches or by improving the x-graphs (by adding a third dimension with the size of the ball indicating the alternative).
	overall values		Y	Y=19; N=3; - =2	
	sensitivity analysis		Y	Y=19; N=3; - =2	
	x-y graphs		Y	Y=16; N=6; - =2	
	written report		N	Y=8; N=14; - =2	
5. Group decision support	group model	Y or N	N	Y=6; N=16; - =2	The majority of MCDA software supports the group facilitation in no explicit way or not at all, with the exception of few tools (*e.g. 1000Minds*, *D-Sight*, *MakeItRational, Web-HIPRE*, *PlanEval*).
	excel model		N	N=15; Y=7; - =2	
6. Other information I	application areas	descriptive	generic	various (*e.g.* general, generic, forest management or planning, renewable energy	The majority of MCDA software (including M-Macbeth) are general-purpose. Some specific tools are tailored for forest planning (*Craft*, *MESTA*), for air quality modelling (*PUrE2*), and renewable energy resources.
	useful or innovative features from the EIA/MCDA viewpoint		various graphs	various (*e.g.* tab-based web interface, brainstorming SMAA-like analysis of weights)	As regards process support, tab-panels should be applied in all software since they provide an indication of the phases of the process and guidelines for carrying out the process, as well as for going back and forth between the phases. Macbeth's two-or-more dimensional graphs are useful.
7. Other information II	people/organisations behind the software	-	Bana e Costa, De Corte, Vansnick	-	Approximately half of the software was developed by academics and the others by commercial actors. The developers of academic software typically provide the software for free, but with a restriction to academic or non-profit purposes. M-Macbeth was developed commercially and is available; its free demo version limits the number of evaluation criteria to five.
	price	€, £,$	Free demo/ academic or professional license	depends on the license	

This multi-criteria analysis follows the structuring phase defined in literature (*Figure 3*, adapted from the diagram published in (Bana e Costa et al., 2003). The first phase regards the model structuring, *i.e.,* the discussion of fundamental point of views (PV1, PV2, …PVk) or criteria that are organized in a tree form or hierarchically (*value tree*). The judgements are validated by M-MACBETH and, in case of inconsistencies, this software makes suggestions in the matrix of judgements. MACBETH preference information concerning differences of attractiveness for each criterion is “precardinal” when it is compatible with ordinal information (Bana e Costa et al., 2003). It is shown in a numerical display or graphically, using a “thermometer”. Different types of sensitivity analysis can be addressed in MACBETH with textual or graphical changes (using keyboard or by dragging the mouse) that are reflected upon the global scores.

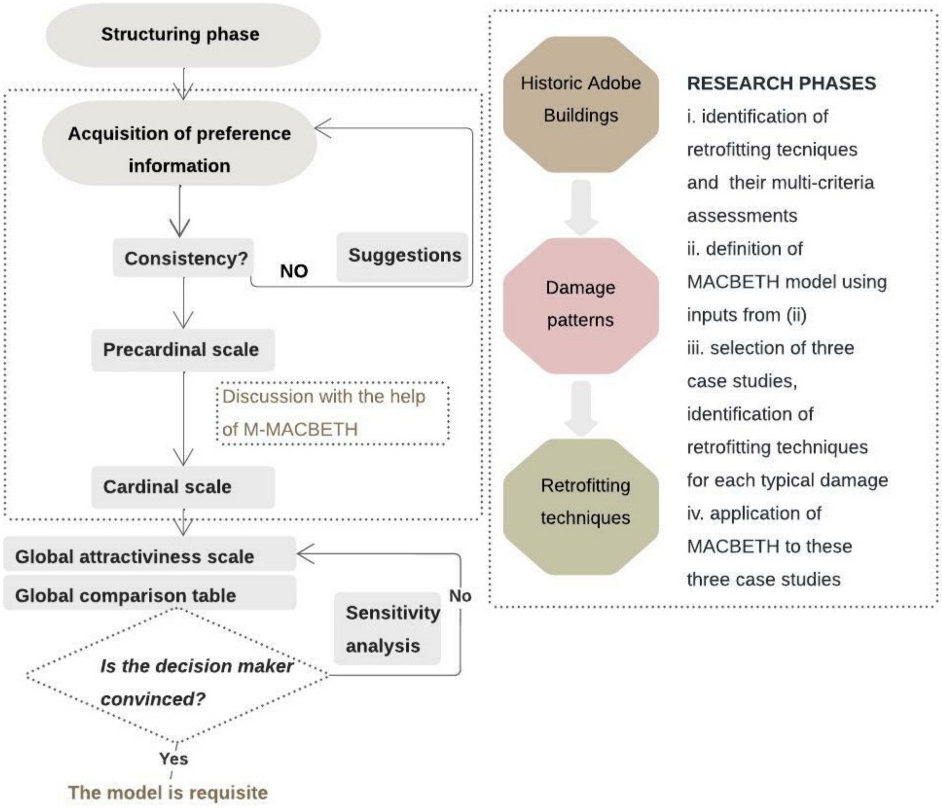


Figure 3. MACBETH decision aid process, adapted from (Bana e Costa et al., 2003), and research phases (credits: Stefania Stellacci)

This study is oriented around three thematic axes: historical adobe buildings, damage patterns, and retrofitting techniques. The preliminary phases of this research (*Figure 3*, right) regard the setting up of a MACBETH model considering a set of criteria (with no dominating criterion) for evaluating retrofitting techniques for historical adobe constructions (i-ii). Then, this model is applied to three selected case studies to score a set of retrofitting techniques that are able to counteract typical damage patterns occurred for each building under analysis, determining *local priorities* or criteria weights (iii-iv). Finally, a sensitivity analysis on weights is addressed to understand the relative value of options, *i.e.,* analyse the transformation of global scores of the interventions when the weight of a criterion is changed.

3.2. Evaluation criteria, retrofitting techniques, and performance evaluation levels

The expected performance of a set of retrofitting techniques in counteracting particular damage patterns is evaluated in this research based on the integration of literature databases and expert assessment of performance-based criteria (structural behaviour – SB, material compatibility – MC), cultural built heritage values (degree of intrusion – DI, retreatability – Re), and local constraints (cost-effectiveness – CE). Nine internationally renowned researchers from Portugal, Chile, and Peru – experts in structural behaviour of unreinforced masonry buildings, earthen architecture conservation, and codes design standards – replied to a self-reported questionnaire. *Table 3* shows the qualitative performance evaluation levels defined in this study, while *Tables 4a* and *4b* show the qualitative assessments for each technique commonly used to retrofit historical adobe buildings, as obtained from the literature (Barrow et al., 2006; Marcial Blondet et al., 2011; A. Costa et al., 2017; Lourenço et al., 2019; Michiels, 2015; Misseri et al., 2020; Ortega et al., 2017, 2018; Peña Mondragón & Lourenço, 2012; Reyes et al., 2019; Tolles et al., 2002; Torrealva et al., 2006).

Table 3. Evaluation criteria and performance evaluation levels of retrofitting techniques

EVALUATION CRITERIA	PERFORMANCE EVALUATION LEVEL
Structural Behaviour (SB) Degree of improvement in mechanical behaviour in terms of resistance, ductility, and energy dissipation.	*Good*: Effectiveness in reduction of severe building damage and life-safety risks Significant improvement in mechanical behaviour (*i.e.* ductility, resistance) by minimizing the post-elastic movements of cracked adobe blocks
	Moderate: Effectiveness in reduction of damage during moderate to severe events by minimizing the post-elastic movements of cracked adobe blocks.
	Poor: Low effectiveness of seismic damage mitigation or inappropriate to the building condition.
	Very Poor: No significant improvement in mechanical behaviour or even worsening of seismic response
Material Compatibility (MC) Compatibility between the materials and technical devices used for repair/strengthening the building and its components. It is measured by analysing damage to existing materials after the intervention.	*Good:* Minimal physical, chemical, and mechanical impact on the building materials.
	Moderate: Moderate compatibility with the original building and components
	Poor: Low compatibility with the original building and components
	Very Poor: Inappropriateness in terms of mechanical, chemical, architectural features
Degree of Intrusion (DI) Alteration/impact of the original system to architectural, typological, and constructional values of the building. It is measured by evaluating the integrity and authenticity of the building after the intervention.	*Good:* Minimal and respectful intervention. While the preservation of the original structural system and its materials is guaranteed, authenticity or integrity are fulfilled.
	Moderate: Minimal loss of authenticity and integrity of the structure.
	Poor: Significantly invasive intervention. Loss of property values on a significant area of the building.
	Very Poor: Invasive intervention. High loss of structural elements. Loss of authenticity of materiality. Loss of structural integrity.
Retreatability (Re) Ability of the original component or structure to back to the state how it was, without suffering relevant damage or permanent deterioration.	*Good:* Easily reversible and removable intervention.
	Moderate: Moderate level of reversibility and low probabilities of loss of structure integrity.
	Poor: Loss of original material or deterioration is very likely to occur. The structure may lose very significant areas of original material. In some cases, repair or replacement of the damaged material is acceptable.
	Very Poor: In case of removal of the intervention, a large amount of original material cannot be preserved. This intervention could imply a loss of relevant architecture details and construction features.
Cost-effectiveness (CE) Cost and operational feasibility: raw material, labour, equipment, transportation infrastructure, stabilization and surface treatments, running cost (*e.g.* temporary cover) maintenance.	*High (20):* Use of low-cost and locally available materials, and easy installation.
	High average (40): Use of relatively inexpensive materials and easy installation. Installation may require specialised infrastructure or additional costs due to the remoteness of rural areas.
	Average (60): Use of relatively inexpensive materials and easy installation. In some cases, materials may not be available in the area and may require additional transport and storage costs.
	Low Average (80): Use of relatively inexpensive materials and easy installation. In some cases, materials may not be available in the area and may require additional transport and storage costs. Adequate expensive infrastructure for implementation and/or to be stored.
	Low (100): Expensive interventions and difficult installation. Use of high-cost materials that require specialised personnel.

To streamline the expert assessment, these researchers assigned a semantic score against three evaluation criteria. This evaluation consists of a single opinion for each performance level of structural behaviour (SB), material compatibility (MC), and degree of intrusion (DI). The assessments of retreatability (Re) are based on literature, and cost-effectiveness (CE) is derived by consulting local heritage professionals, namely building companies and architects in Chile.

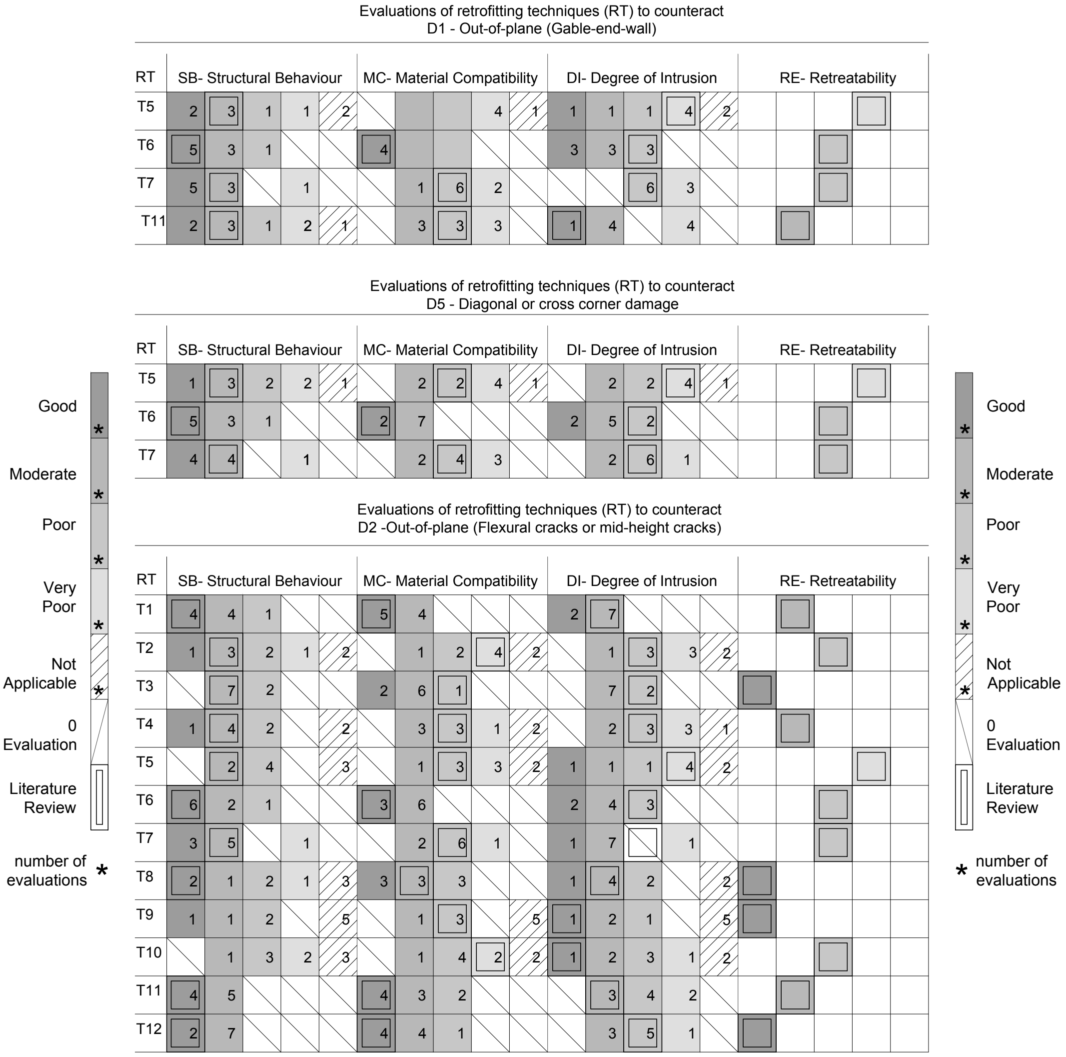
Table 4a. Retrofitting techniques (T1-T6) and qualitative assessments

Retrofitting techniques (RT)	**Qualitative assessments of RT under SB: structural behaviour; MC: material compatibility; DI: degree of intrusion; RE: retreatability; CE: cost-effectiveviness**	
T1. Wooden bond beam (Michiels, 2015; Ortega et al., 2017; Papanikolaou & Taucer, 2004; Tolles et al., 2002; Costa et al, 2017; Misseri et al, 2020)	SB	Prevents overturning, provides out-of-plane strength and stiffness and in-plane continuity. Limited (or almost null) reduction of initial cracking within the elastic range.
	MC	Traditional technique and materials compatible with adobe system buildings. The wood should be dry to avoid damage to adobe blocks.
	DI	Its application may require removal of the original roof structure and causing loss of historical fabric.
	Re	Acceptable loss of fabric. High re-treatability.
	CE	Low-cost material and locally available. Easy Intervention.
T2. Reinforced concrete bond beam (D'Ayala & Benzoni, 2012; Michiels, 2015; Tolles et al., 2002)	SB	Provides strength and stiffness to the out- of-plane walls. Being executed as a continuous element along length of wall, it guarantees in-plane continuity. The connection between the beam and the masonry can fail during moderate ground motions. Although the execution of concrete beam has similar effects on the structural response as that of T1, the concrete beam is much stiffer.
	MC	Low compatibility.
	DI	The removal of a large portion of the original roof structure in the upper sections and of the bricks row wall is required for anchoring and installing the irons and concrete infill. It is invasive and destructive technique.
	Re	Rarely reversible since connections to the adobe wall must be very rigid and its removal would cause loss of the wall.
	CE	The execution of concrete is usually feasible and inexpensive, but the grouting compatible with the adobe might not readily available.
T3. Partial plywood diaphragm (Michiels, 2015; Tolles et al., 2002)	SB	Provides in-plane continuity along the wall. Divides forces between in-plane and out-of-the-plane walls.
	MC	The advantage of having a partial and flexible diaphragm is its limited stiffness that avoids excessive load transfer to the perpendicular walls that might fail in shear.
	DI	This intervention only requires a connection at the top of the wall or at floor level and can be harmoniously integrated into the building's roof or floors.
	Re	It can be easily removed.
	CE	Plywood may not be available in remote areas.
T4. Horizontal and vertical steel (or nylon) rods and straps (Barrow et al., 2006; Michiels, 2015; Tolles et al., 2002)	SB	Inhibit overturning and increases resistance to horizontal loads, provide anchorage with roof or floor structure and extra In-plane continuity. Prevent kicking out in-plane along the length walls. Vertical elements can greatly increase the ductility of the walls.
	MC	Metallic or other materials introduced into a mixed (timber-earth) system may present risk of corrosion and thermal expansion of the material.
	DI	Small intervention under the external plaster with a low invasive procedure. Straps can be covered by rendering.
	Re	Easily removable or treatable. Drilling in the wall must be performed to connect the shoulder straps to the ceiling beams.
	CE	Relatively high cost and material may not be available in remote areas.
T5. Center-core rods and steel or nylon rods (Peña Mondragón & Lourenço, 2012; Tolles et al., 2002; Bondet et al, 2011)	SB	Prevent out-of-plane failure of thin adobe walls by increasing the ductility of the wall. Act as shear dowels in thicker adobe walls. They can prevent corner failure and ou-of-plane collapse of grable-end-walls.
	MC	The selection of suitable mortar, compatible with adobe, is essential. Depending on the rods and holes diameter, center-core elements could act as hard points, causing damage to the adobe wall. Block failures can be caused in areas with different stiffness and strength.
	DI	It does not visually affect the structure; the intervention can be performed without altering original coatings. It is highly invasive in the structure as it incorporates new elements inside the adobe blocks. Since the access to the top of the wall is necessary to execute T5, the roof can get damaged.
	Re	Impossible to remove core-center rods due to grouting.
	CE	Costly technique requiring skilled workmanship.
T6. Geomesh (Michiels, 2015; Peña Mondragón & Lourenço, 2012; Torrealva, Vargas Neumann, and Blondet, 2006; Reyes et al, 2019)	SB	The mesh provides restraint to out-of-plane rocking and overturning of wall panels. Covering the mesh with a rendering will increase the initial shear strength and stiffness of the wall. The mesh provides in-plane continuity as well as continuous element along length of the wall. The geomesh is compatible with the earth building to high levels of acceleration.
	MC	Geomesh is compatible with the deformation of the earth wall. Lime based renderings are adequate due to their permeability.
	DI	It affects the integrity of the building, since original rendering must be removed, but the base of their structure is not modified. It is not recommended in original decorative apparatus (wall paintings, frescoes).
	Re	It is an almost reversible technique, although requiring the removal of the rendering and of the ties crossing the wall around the mesh.
	CE	Costly technique requires skilled workmanship.

Table 4b. Retrofitting techniques (T7-T12) and qualitative assessments

Retrofitting techniques	**Qualitative assessments of RT under SB: structural behaviour; MC: material compatibility; DI: degree of intrusion; RE: retreatability; CE: cost-effectiviness**	
T7. Electrowelded mesh (Michiels, 2015; Peña Mondragón & Lourenço, 2012; Torrealva, Vargas Neumann, and Blondet, 2006)	SB	The mesh provides restraint to out-of-plane rocking and overturning of wall panels. Covering the mesh with a rendering will increase the initial shear strength and stiffness of the wall. The mesh provides in-plane continuity as well as continuous element along length of the wall. The electro-welded mesh is compatible with the earth building to high levels of acceleration,since it prevents cracking at higher levels of seismic intensity but does not work in conjunction with an adobe wall for severe seismic displacements.
	M	The electrowelded mesh prevents the building collapse, but its use can cause corrosion.
	DI	It affects the integrity of the building, since original rendering must be removed, but the base of their structure is not modified. It is not recommended in original decorative apparatus (wall paintings, frescoes).
	Re	It is an almost reversible technique, although requiring the removal of the rendering and of the ties crossing the wall around the mesh.
	CE	Costly technique requires skilled workmanship.
T8. Wooden tie beams (Michiels, 2015; Peña Mondragón & Lourenço, 2012)	SB	This technique provides stability and continuity to different parts of the structure, so it is used to improve the overall strength of the building and to enhance lateral support. Prevents overturning, provides interconnection between parallel walls, provides out-of-plane resistance and stiffness. It does not provide in-plane continuity. Risk of pull-out failure. The anchorage is crucial as stress concentrations can cause local damage. Ties can cause vertical cracks between different wall sections and thus instability of such walls.
	MC	Tie wooden beams are compatible with earth-based materials. Caution should be taken at the supports, where wood decay could occur.
	DI	It is low invasive technique. Slender and limited intervention. It could change the visual perception of large open spaces.
	Re	It can be installed without impact to the roof, although it may require protruding of outer walls or reconstruction of top sections of the wall. It is easily removable.
	CE	Low-tech and inexpensive technique.
T9. Steel tie rods (Michiels, 2015; Peña Mondragón & Lourenço, 2012)	SB	This technique provides stability and continuity to different parts of the structure, so it is used to improve the overall strength of the building and to enhance lateral support. Prevents overturning, provides interconnection between parallel walls, provides out-of-plane resistance and stiffness. It does not provide in-plane continuity. Risk of pull-out failure. The anchorage is crucial as stress concentrations can cause local damage. Ties can cause vertical cracks between different wall sections and thus instability of such walls.
	MC	The use of stainless-steel tensors avoids corrosion and thermal expansion of the components, which can cause cracks or loss of historical materials.
	DI	It is low invasive technique. Slender and limited intervention. It could change the visual perception of large open spaces.
	Re	It can be installed without impact to the roof, although it may require protruding of outer walls or reconstruction of top sections of the wall. It is easily removable.
	CE	Low-tech technique, it is more expensive than the wooden tie, depending on the type of steel used.
T10. Steel anchors (doweling) (Michiels, 2015; Peña Mondragón & Lourenço, 2012; Tolles et al., 2002)	SB	The placement of dowel bars prevents the separation of intersecting walls under low and moderate ground motions. However, the efficiency of this intervention can be reduced during earthquake due to the differences between in-plane and out-of-plane motions, especially in presence of thick adobe walls. They will have little effect during strong ground motions, when damage will occur at or near the junction of walls, beyond the location of the dowels.
	MC	The use of stainless steel avoids corrosion and the expansion of the elements that can lead to cracks or deterioration of the original material. Easily available cementitious grouts might be incompatible.
	DI	It is a minimal intervention. No interference with wall painting. Doweling requires only small holes to be drilled into the historic fabric.
	Re	The execution of cement-based or epoxy-based grout is irreversible.
	CE	High cost-effectiveness (the cost of the dowels is low).
T11. Wood corner (Michiels, 2015; Ortega et al., 2018)	SB	Delays cracking of perpendicular walls, allows the walls to continue working together when cracked.
	MC	Traditional technique, the wood is highly compatible with the adobe.
	DI	It regards just limited zones around the corners, yet it can affect renderings and wall paintings at the corner.
	Re	Relatively easy to remove, but it causes permanent damage in the adobe blocks of the corners.
	CE	The materials are available and cost-effective. Relatively easy technique to be implemented even if requires intense work
T12. Stone (or adobe) buttresses (Michiels, 2015; Ortega et al., 2018; Peña Mondragón & Lourenço, 2012)	SB	Limit the out-of-plane damage, if well sized, well connected and with an adequate foundation.
	MC	It is a traditional reinforcement technique, with a high material compatibility.
	DI	This technique does not impact the interior layout of the building, but its exterior appearance is highly impacted.
	Re	Although the connections to the original adobe masonry may require the partial removal of the plaster and the wall, this technique is reversible since does not affect the wall section.
	CE	Inexpensive intervention, highly availability of raw materials.

Each criterion's evaluation performance levels retrieved from the literature review (LR) (Ishizaka & Nemery, 2013; Marttunen et al., 2015; Minke, 2006; Roy, 2005; Stellacci et al., 2018; Tolles et al., 2002; Wątróbski et al., 2019; Yan Li & Thomas, 2014) are compared with expert evaluations (EV). To clarify this step, *Figure 4* shows the EV of those retrofitting techniques aimed at counteracting the D1, D2, and D5.



RT (Retrofitting Techniques): T1. Wooden bond beam; T2. Reinforced concrete bond beam; T3. Partial plywood diaphragm; T4. Horizontal and vertical steel (or nylon) rods and straps; T5. Center-core rods and steel (or nylon) rods; T6. Geomesh; T7. Electrowelded mesh; T8. Wooden tie beams; T9. Tie steel rods; T10. Steel anchors (doweling); T11. Wood corner keys; T12. Stone (or adobe) buttresses

Figure 4. Semantic assessments of retrofitting techniques integrating expert evaluations (EV) and literature review (LR) (credits: Stefania Stellacci)

As shown in *Figure 4*, there is not always consensus among the experts (*e.g.,* D5, T5). To aggregate these into a single overall performance level (WS_e), the expert evaluations numeric values were translated as follows: *Good:* 2; *Moderate:* 1; *Poor:* -1; *Very Poor:* -2, then multiplied by the number of evaluations (Num. ev):

$WS_e = \sum Ne.\ x\ Num.\ ev.$ (*a*)

where *WS_e*: Weighted Semantic Evaluation; *N_e*: Numeric Evaluation; *Num.ev.*: number of evaluations

The resulting WS_e corresponds to a semantic value according to the thresholds defined by the authors: 23 to 13= good, 13 to 0 = moderate; 0 to 13 = poor; -13 to -26 = very poor.

Scores falling exactly on the range boundaries are treated as belonging to the lower of the values. All the obtained evaluation levels (*Table 5*), reflecting the multiple and conflicting standpoints of the evaluators, are then introduced into MACBETH models as input.

To sum up, each MACBETH model is created to define the performance of a single damage pattern shown in *Table 1* according to four criteria (SB, MC, DI, Re) with the same weight (with no dominating criterion). The options to be evaluated are the set of retrofitting techniques identified in *Tables 4a* and *Table 4b.* The evaluation levels for each criterion result from the analysis made by the panel of nine experts.

3.3. Case selection and damage patterns

The case studies for testing MACBETH modelling have been selected for their cultural value and the extent to which they are representative as common adobe building typologies in Chile (indicated in bold in *Figure 5*): the *Andean church*, the *single-storey dwelling with continuous façade and exterior arcade*, and the *colonial church*. These case studies, shown in *Figure 6*, are all National Monuments (DA-MOP, 2000; Law N° 17.288, 1970). The occupancy category of case studies No.1 and 3 is type II – government buildings, municipal buildings, and buildings for public services or public utility. Case No. 2 is of type I – residential buildings (NCh 3332, 2013). These case studies have also been selected for the variety of potential agents involved during their refurbishment/retrofitting. The target groups for this research include policymakers or local governmental authorities when the adobe constructions are churches or monuments (case studies No.1 and No.3) and private homeowners (case study No. 2).

Location, relevant preservation law, a brief description of the construction system, and the main damage after two major earthquakes (*Table 5*) are indicated for each case studies.

Table 5. Earthquakes in Tarapacá (2005) and Maule (2010)

Location (date)	Magnitude	Epicentre	Depth	Peak Ground Acceleration (PGA)	Case studies
Tarapacá (2005)	Mw 7.8	Latitude/Longitude: 19°59' 13"S 69°11'49"W	115.6 km depth	0.26g in Iquique 0.72g in Pica	Location Case study No.1 220 km south of the Church of Parinacota
Maule (2010)	Mw 8.8	Latitude/Longitude: -35° 54' 32.40" S -72° 43' 58.80" W	30.1 km depth	0.38g in the village of Nirivilo 0.72g in the Village of Guacargue	Location Case study No.2 village of Nirivilo Location Case study No.3 Village of Guacargue

Figure 5. Territorial distribution of construction typologies in Chile
(map (Jorquera, 2012), photographs © www.monumentos.cl) (credits: Pilar Baquedano Juliá)

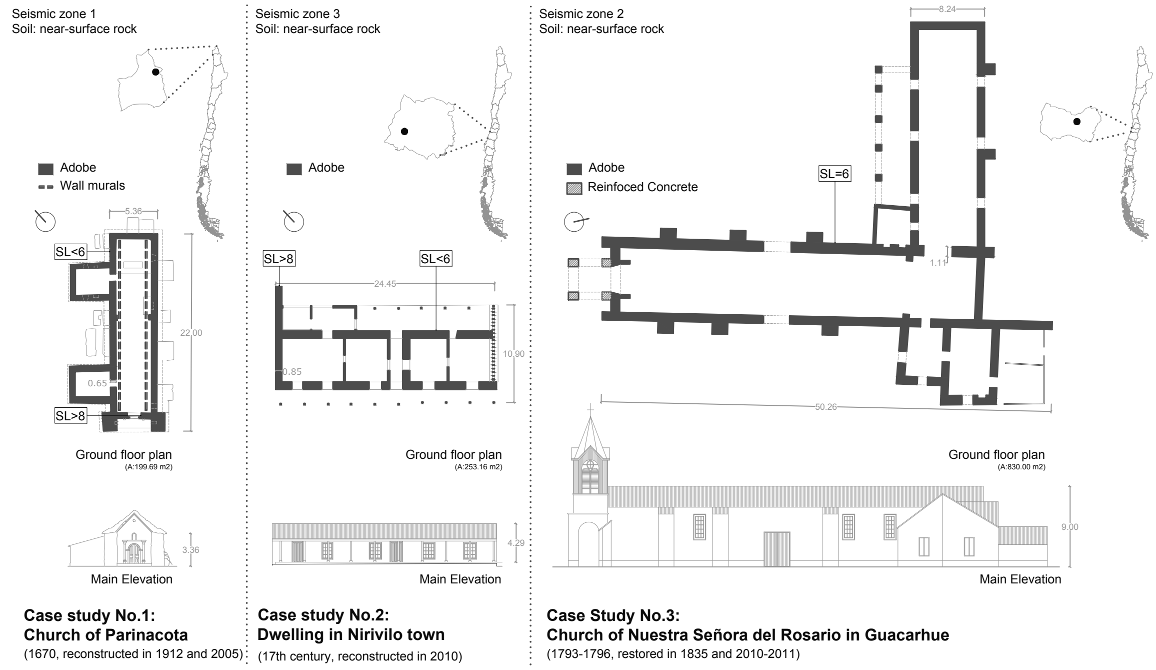


Figure 6. Geometric configuration and location of the case studies (credits: Stefania Stellacci)

Case study No.1:

The *Church of Parinacota* is located in the town of Parinacota, in the *Altiplano of the Arica y Parinacota* Region. It is part of a group of more than 80 Andean heritage churches known as "*Churches of the Altiplano*" (AA.VV., 2012), executed after the arrival of the Spaniards and the establishment of the commercial and cultural route called *La Plata de Potosí*. Declared a Historical Monument by the CMN in 1979, this church embodies the adaptation of the Spanish-Arab cultural tradition to local constraints by the Spaniards. This church has a rectangular nave plan with two side chapels (*Figure 6*). The isolated complex in stone and clay and includes a bell tower, perimeter wall, and exterior arches made of unmortared stone. The 16th century Andean Baroque church contains artefacts related to the Jesuits and Franciscans, and their evangelization of the indigenous communities. The interior of this small construction is enriched by watercolour frescoes (last third of 17th century) and a rustic wooden altarpiece. The foundations are made of stone bounders and mud mortar of 0.3m to 0.7m in height across uneven ground. The walls in adobe masonry (0.55x0.30x0.12m) are reinforced by four rustic stone masonry buttresses to the east. The ceiling consists of a roof framing made of beams and a collar beam with reed fabric and totora covered with straw (*paja brava*, *coirón*). Its structure is made of *Queñua* wood, a tree that grows in high-rise areas, and it lacks nails, since the joints are made with animal leather.

The damage from the 2005 earthquake is as follows: D2: Cracks at the intersection of walls between the main nave and baptistery. Cracks and water leakage leading to high structural damage; D3: Cracks and detachment of exterior wall plaster; D6: Overturning in the lateral walls of the main nave, due to lack of locking between walls and buttresses, causing extensive damage of 17th century murals.

Case study No.2:

This traditional dwelling is located in the historical town of Nirivilo, in the Maule region, exemplifying the construction culture of the Central Valley. It was declared a Historical Monument by the National Monuments Council in 1985. This single-storey single-family house building has a rectangular plan, and its continuous façade is protected by an arcade facing the public road. Its foundations are made of stone blocks with mud mortar or concrete, exceeding the wall width by at least 10cm, with a depth of around 60cm. The structure is made of adobe masonry with walls 0.70m thick and 3.30m high, and the tympanum reaches 4.70m high. The roof structure is made of trusses (span: 90 cm), braced with five queen posts nailed to each tie beam, wooden planks (thickness: 35mm) of *coligue*, a Chilean bamboo-like plant, a thermal insulating layer of mud (thickness: 15-25mm), and handmade clay tiles (*colonial tile* or Spanish tiles).

The damage from the 2010 earthquake is as follows: D4: Vertical cracks and loss of corner lock in intersection with left and right-side wall of the main building block (D4); D7: Cracks in openings and lintels; Other: Roof claddings and coating fall.

Case study No.3:

The church of *Nuestra Señora del Rosario in Guacarhue* was built by Gioacchino Toesca in 1778 and reconstructed after the 1835 earthquake according to the original drawings. Declared a National Monument in 1991, it exemplifies the *colonial church*, one of the most common architectural types of the Central Valley (*Figure 6*). The extensive reconstruction in 2011-2012, executed by the *Altiplano Foundation* and promoted by Under-secretariat of Regional and Administrative Development (Chile's government), included the execution of *quincha* walls, substitution of arches, alteration of the roof, execution of buttresses, and structural consolidation of the adjacent chapel. The church has two naves that form an "L" shape, laterally reinforced by stone buttresses. Its foundations are made of stone and brick. The walls are constructed of adobe, reinforced with wooden ladders and mud mortar. The lintels above the openings are made of *canelo* wood (a highly valued native species), while *quincha* porticoes serve as the access to the church. The roof is made of timber trusses cladded with original clay tiles. The damage after the 2010 Maule earthquake was extensive, with 80% of the church being heavily damaged. The wall of the principal nave collapsed with failure of the wall corners, while the altar, the aisle, and the bell tower were highly damaged. This study regards: D3: Diagonal cracks and detachment of plasters; D4: Vertical cracks at the wall corners; D7: Windows in the lateral nave exhibiting lack of orthogonality in their faces and diagonal cracks above lintels.

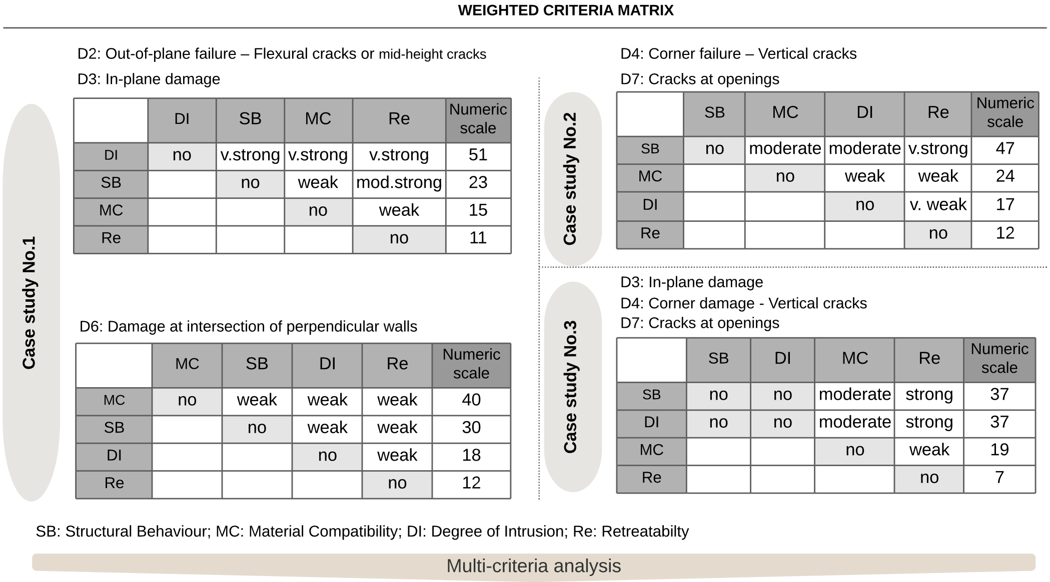
The National Monuments Council (CMN) establishes intervention guidelines in line with those identified within SRP (Tolles et al., 2002) (i-iii, case No.1; i, case No.2; i, case No. 3), also drawing attention to the preservation of specific architectural and artistic features (ii, case No.1; iii, case No.2) and to community engagement throughout the retrofitting design and execution (iv-v, case No.1) (Ortega et al., 2018), *Table 6*:

Table 6. Intervention guidelines (CMN, 2012)

	Case study (Decree Law)		
Principles of intervention (National Monuments Council)	**No. 1. Church of Parinacota (Decree Law No.1158/1979)**	**No. 2. Dwelling in Nirivilo town (Decree Law No.1162/1985)**	**No. 3. Nuestra Señora del Rosario in Guacarhue (Decree Law No.344/1991)**
Minimal intervention on historic fabric	x	x	x
Life-safety protection	x		x
Preservation of interior spatiality and decorative features	x	x	x
Alterations while preserving the main morpho-typological features		x	
Structural compatibility between the original load-bearing system and the retrofitted system	x		x
Preference to traditional construction techniques and local materials (*e.g.* adobillo, mud plaster, revoque de barro)			x
Structural retrofitting (*e.g.* additional buttresses in adobe or steel-timber structures)		x	x
Involvement of local workers and builders throughout the intervention	x		
Long-term maintenance undertaken by local communities	x		

However, the principles of intervention established in the current legislative framework in Chile (indicated in a non-hierarchical list in *Table 5*) are often conflicting, and the weights of the criteria are not clearly specified. MACBETH facilitates the decision-making process by defining value functions and weighting coefficients (Bana e Costa, 1994).

In this research, the weight of each criterion varies in each case study depends on architectural and construction features and the multi-layered values at stake. Its “attractiveness” is assessed by translating the experts’ pairwise semantic judgments into numeric scale parameters (*Figure 7*).



WEIGHTED CRITERIA MATRIX

Case study No.1

D2: Out-of-plane failure – Flexural cracks or mid-height cracks
D3: In-plane damage

	DI	SB	MC	Re	Numeric scale
DI	no	v.strong	v.strong	v.strong	51
SB		no	weak	mod.strong	23
MC			no	weak	15
Re				no	11

D6: Damage at intersection of perpendicular walls

	MC	SB	DI	Re	Numeric scale
MC	no	weak	weak	weak	40
SB		no	weak	weak	30
DI			no	weak	18
Re				no	12

Case study No.2

D4: Corner failure – Vertical cracks
D7: Cracks at openings

	SB	MC	DI	Re	Numeric scale
SB	no	moderate	moderate	v.strong	47
MC		no	weak	weak	24
DI			no	v. weak	17
Re				no	12

Case study No.3

D3: In-plane damage
D4: Corner damage - Vertical cracks
D7: Cracks at openings

	SB	DI	MC	Re	Numeric scale
SB	no	no	moderate	strong	37
DI	no	no	moderate	strong	37
MC			no	weak	19
Re				no	7

SB: Structural Behaviour; MC: Material Compatibility; DI: Degree of Intrusion; Re: Retreatabilty

Multi-criteria analysis

Figure 7. Weighted criteria matrix (credits: Stefania Stellacci)

The expected performance of those retrofitting techniques able to counteract those damage patterns indicated in the CMN reports (CMN, 2012; Ord. CMN N° 1319, 2011; Ord. CMN N° 2774, 2014) are analysed using M-MACBETH. The performance of those retrofitting techniques that could be implemented to counteract typical damage patterns is evaluated under the previously defined set of criteria.

The post-earthquake damage was identified in two different areas in case study No. 1 (*Figure 6*): D2 and D3 occurred in the nave, which is decorated by 17th century wall murals; D6 was identified only in the baptistery wall. Low intrusiveness should be more prioritized in the retrofitting technique for the first damage scenario (D2 and D3) than in the second damage scenario (D6) – degree of intrusion (DI) is the most relevant criterion in the first damage scenario because of the wall murals, while DI is the third in importance for D6. In case studies No. 2 and No. 3 (*Figure 6*), the damage patterns are located in a single area, and the priority of the DI criterion is the same for D4 and D7 and for D3, D4, and D7, respectively.

3.4. Application of MCDA models to three case studies and sensitivity analysis

The scores related to three case studies and obtained by MACBETH reflect the set of performance levels for each criterion, obtained by the weighted sum of evaluations (a), shown in *Table 7*.

Table 7. Performance levels of each criterion

Case Study No.1

D2- Out-of-plane-Flexural cracks or mid-height cracks

RT	SE	MC	DI	Re
T1	Good	Good	Moderate	Moderate
T2	Poor	Very poor	Very poor	Poor
T3	Moderate	Moderate	Poor	Good
T4	Moderate	Poor	Poor	Moderate
T5	Poor	Very poor	Very poor	Very poor
T6	Good	Good	Poor	Poor
T7	Moderate	Poor	Poor	Poor
T8	Moderate	Moderate	Moderate	Good
T9	Moderate	Poor	Moderate	Good
T10	Poor	Very poor	Poor	Poor
T11	Good	Good	Moderate	Moderate
T12	Good	Good	Poor	Good

D3 - In plane damage

RT	SE	MC	DI	Re
T1	Good	Good	Moderate	Moderate
T2	Moderate	Very poor	Poor	Poor
T3	Moderate	Poor	Poor	Good
T4	Moderate	Moderate	Moderate	Moderate
T5	Poor	Poor	Very poor	Very poor
T6	Good	Good	Poor	Poor
T7	Moderate	Poor	Very poor	Poor

D6 - Damage at the intersection of perpendicular walls

RT	SE	MC	DI	Re
T6	Good	Good	Poor	Poor
T7	Moderate	Poor	Poor	Poor
T8	Poor	Moderate	Moderate	Good
T9	Poor	Poor	Moderate	Good
T10	Moderate	Poor	Good	Poor
T11	Good	Good	Moderate	Moderate

Case Study No.2

D4 - Corner damge (Vertical)

RT	SE	MC	DI	Re
T6	Good	Good	Poor	Poor
T7	Moderate	Poor	Poor	Poor
T8	Moderate	Moderate	Moderate	Good
T9	Moderate	Poor	Moderate	Good
T10	Poor	Poor	Moderate	Poor
T11	Good	Good	Moderate	Moderate

D7 - Cracks at openings

RT	SE	MC	DI	Re
T5	Moderate	Poor	Very poor	Very poor
T6	Good	Good	Poor	Poor
T7	Moderate	Poor	Poor	Poor
T9	Poor	Poor	Poor	Poor

Case Study No.3

D3 - In-plane damage

RT	SE	MC	DI	Re
T1	Good	Good	Moderate	Moderate
T2	Moderate	Very poor	Poor	Poor
T3	Moderate	Poor	Poor	Good
T4	Moderate	Moderate	Moderate	Moderate
T5	Poor	Poor	Very poor	Very poor
T6	Good	Good	Poor	Poor
T7	Moderate	Poor	Poor	Poor

D4 - Corner damage (Vertical)

RT	SE	MC	DI	Re
T6	Good	Good	Poor	Poor
T7	Moderate	Poor	Poor	Poor
T8	Moderate	Moderate	Moderate	Good
T9	Moderate	Poor	Moderate	Good
T10	Poor	Poor	Moderate	Poor
T11	Good	Good	Moderate	Moderate

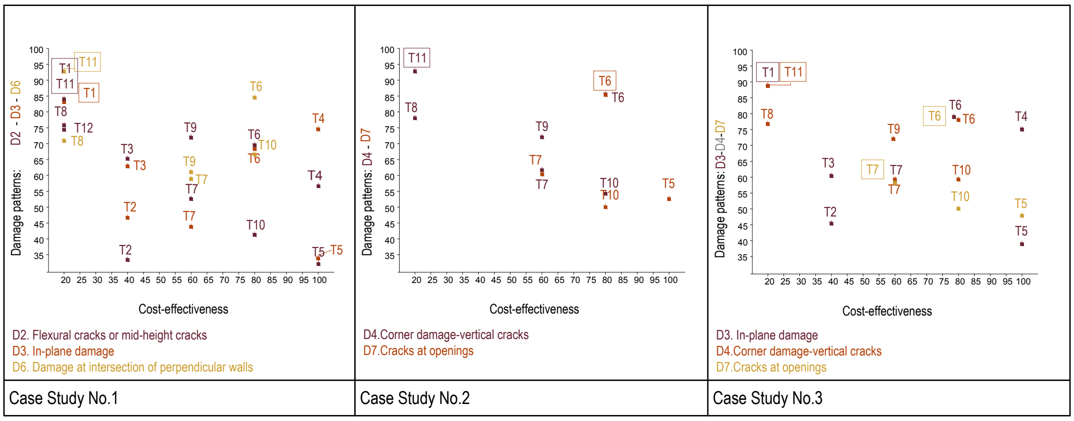
D7 - Cracks at openings

RT	SE	MC	DI	Re
T5	Moderate	Poor	Very poor	Very poor
T6	Good	Good	Poor	Poor
T7	Moderate	Poor	Poor	Poor
T9	Poor	Poor	Poor	Poor

RT: Retrofitting techniques; SB: Structural Behaviour; MC: Material Compatibility; DI: Degree of Intrusion; Re: Retreatability

The ranking of these interventions depends on the degree of importance (or weight) of the criterion applied to each specific part of the building to be retrofitted. These scores are compared considering the cost-effectiveness of each intervention. Based on both the initial weighted performance for the four criteria indicated and cost-effectiveness (evaluated for each technique on a scale of 0-100), the most effective intervention techniques are identified in squares in *Figure 8* for each type of damage.

PERFORMANCE OF RETROFITTING TECHNIQUES
under SB: Structural behaviour; MC: Material Compatibility; DI: Degree of Intrusion; Re: Retreatability; CE: Cost-effectiveness



T1. Wooden bond beam; T2. Reinforced concrete bond beam; T3. Partial plywood diaphragm;T4. Horizontal and vertical steel (or nylon) rods and straps; T5. Center-core rods and steel (or nylon) rods; T6. Geomesh; T7. Electrowelded mesh; T8. Wooden tie beams; T9. Steel tie rods; T10. Steel anchors (doweling); T11. Wood corner keys; T12. Stone (or adobe) buttresses

Figure 8. Overview of evaluations obtained by MACBETH (credits: Stefania Stellacci)

For case study No.1, D2 has the best retrofitting option set as T1 and T11 (highest performance and lower cost), in D3, T1 e T4 have similar scores (difference less than 10%), but T4 presents double the cost-effectiveness score. In D6, T11 and T6 are the only solutions with a performance score higher than 75% (the assumed limit for the performance selection), but T6 presents a much higher score for cost-effectiveness (4 times higher).

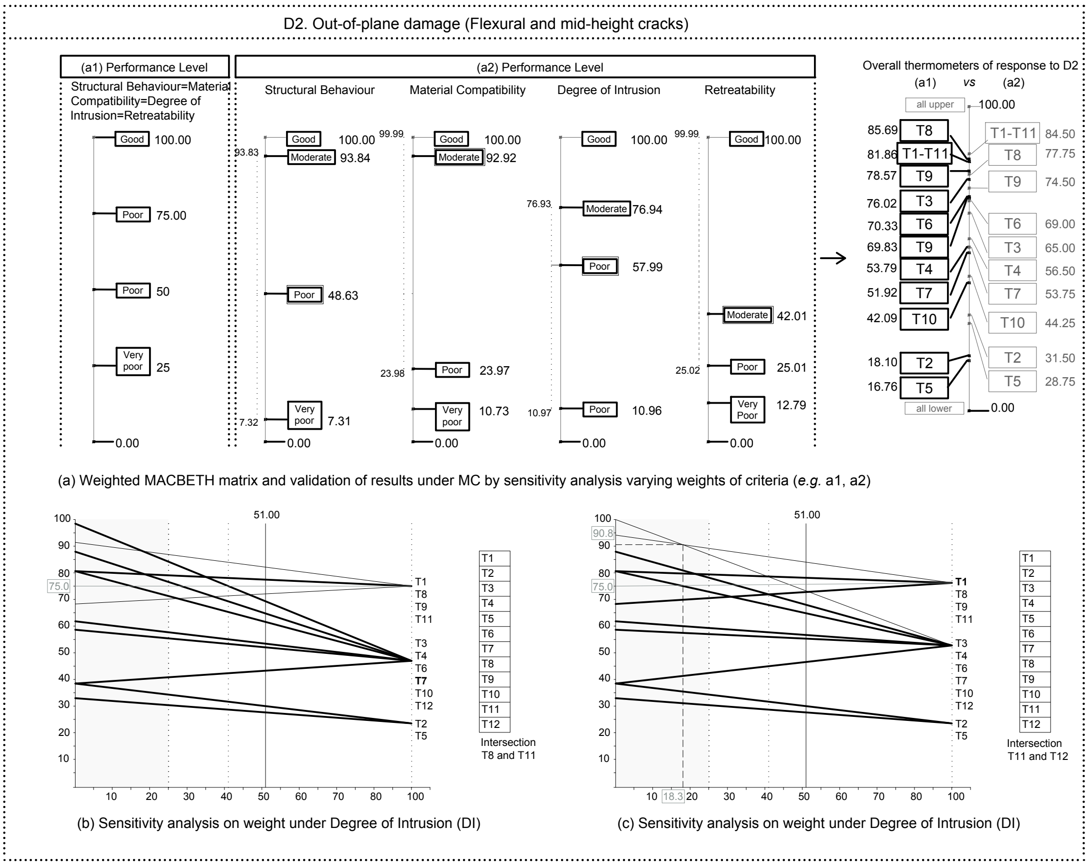
For case study No. 2, D4 has only three solutions out of six with a score higher than 75%. Two of these (T11 and T8) present a god score for cost-effectiveness, while T6 presents a cost-effectiveness score 4 times worse, meaning that it is not recommended in terms of costs and application. D7 has only one solution with a score higher than 75%, namely T6. The next best solution, T7, has a difference in score of more than 20%; therefore, while T6 has a lower cost-effectiveness evaluation, its higher performance justifies its use.

For case study No. 3, the interventions to counteract D3 that present a score higher than 75% are T1, T6 and T4. The best solution in terms of performance and cost-effectiveness is T1, while T6 and T4 have similar performance scores (just 3% apart), but T4 is much less attractive in terms of cost-effectiveness (with a 20% difference). For D4, three solutions have a score higher than 75%, namely T11, T6, and T8. T11 represents the best solution both in terms of performance and in terms of cost-effectiveness. T6 and T8 have similar performance (less than 2% of difference), but the cost-effectiveness is at opposing ends of the spectrum, with T6 being four times worse than T8. For D7, the only solution with a performance above 75% is T6, similar to case study No. 2.

A sensitivity analysis is conducted to validate the results and determine the stability of interventions based on criterion weight, which indicates the extent to which this is preferred by the model after changes to the variables. It shows that the results do not vary beyond a certain range and thus gives an indication of the soundness of the decision. The results presented in this study show the variation for each criterion within each damage type, not the weighted damage result. The sensitivity analysis is performed to compare the influence of weighting on the interventions for the different damage criteria. Regarding case study No.1, the attractiveness of interventions may vary when weights concerning each criterion are changed (*Figure 9a1-a2*). The thermometer values of each criterion may be changed, with effects visible for the criterion's scale or the global scale for each damage type (*Figure 9a*). This makes it possible to visualise the influence of each criterion on the results and see how important the correct scoring is within each criterion. Changing the weight in the local thermometer of each criterion effectively changes the "distance" between each judgement given (from very poor to good), thus making it possible to better distinguish the effectiveness of the interventions. Similarly, changing the weight of each criterion, will also show the changes in rank of the interventions at a global scale.

For case study No.1, the original local weights for the four weighting references (very poor, poor, moderate, and good) were 25%, 50%, 75% and 100% respectively (*Figure 9a*, *a1*). *Figure 9a-a2* shows how the attractiveness of each intervention may vary within the criterion and consequently for the global evaluation when these weights are altered. Significantly changing the weights in this case led to different evaluations for the interventions and T8 became the most attractive option.

Figure 9b shows the sensitivity analysis in case study No. 1 for DI, which had the highest weighting judgment (51%). In applying the DI criterion to damage D2, the positions of suggested interventions do not vary as long as the criterion weight stays between 42% and 100%. Hence, T1 and T9 are the most attractive options starting from a weight of DI of 41%, as their lines (which are superimposed) do not intersect any other interventions, meaning they remain the most attractive options even for varying criterion weight (*Figure 9b*). The intersecting lines give a general idea of the range in which an intervention has the best performance. For example, T8 and T11 never intersect, meaning T11 will always have the better performance (*Figure 9b*). Comparing instead T11 and T12 (*Figure 9c*), the two lines intersect and T12 becomes the most effective option for criterion weight values lower than 18.3%.



(a) Weighted MACBETH matrix and validation of results under MC by sensitivity analysis varying weights of criteria (*e.g.* a1, a2)

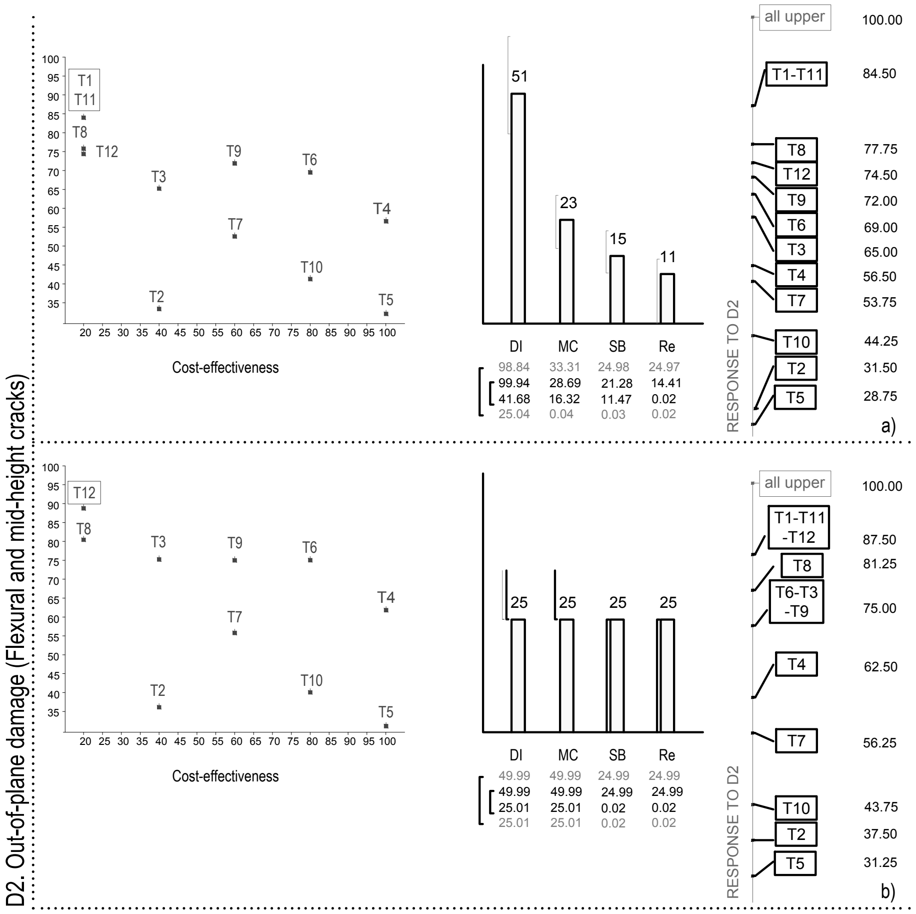
(b) Sensitivity analysis on weight under Degree of Intrusion (DI)

(c) Sensitivity analysis on weight under Degree of Intrusion (DI)

Figure 9. Validation of computer-generated rankings under (a) MC (Material Compatibility); (b) DI (Degree of Intrusion) by sensitivity analysis, intersection between T8 and T11 and (c) DI (Degree of Intrusion) by sensitivity analysis, intersection between interventions T11 and T12 (credits: Stefania Stellacci)

When changing the criterion weight, the software allows a certain range of movement proportional to the original weights adopted, *i.e.,* it is not possible to completely revolutionize the weights, for which a new analysis would be necessary.

By changing the importance of a criterion within the multi-criteria analysis for the case study in question, the global analysis, and therefore the choices presented to the expert user, may be altered. For example, when assigning the same weight to DI and MC, T12 surpasses T8 in terms of attractiveness. A sensitivity analysis allows to further validate the analysts’ choices by offering understanding of the levels of attractiveness even under differing views of how the criteria should be weighted.



T1. Wooden bond beam; T2. Reinforced concrete bond beam; T3. Partial plywood diaphragm;T4. Horizontal and vertical steel (or nylon) rods and straps; T5. Center-core rods and steel (or nylon) rods; T6. Geomesh; T7. Electrowelded mesh; T8. Wooden tie beams; T9. Steel tie rods; T10. Steel anchors (doweling); T11. Wood corner keys; T12. Stone (or adobe) buttresses

Figure 10. Case study No.1, D2, Comparison of Sensitivity analysis in two sets of weights of criteria replace (credits: Stefania Stellacci)

Figure 10 displays the varying performance of the analysed techniques under varying criterion weights, within the consistent ranges of judgement accepted by M-MACBETH. The weights of each criterion are represented in histogram form, whose value can be manually changed within the threshold defined in M-MACBETH. *Figure 10* shows the global scores and the criteria weights used for case study No. 1, considering damage D2. In the histogram, the weights for each criterion (obtained by the pairwise comparisons, whose translations in cardinal value was presented in *Figure 7*) are shown as well as the range in which they can change without altering the scores.

In altering the weights outside of these ranges, the analysis results are altered. Figure 10 shows how by giving the same weight to all 4 criteria, the response to D2 changes, in terms of scores, *i.e.,* performance, for each intervention. In this case, T12 becomes a more attractive solution (increasing its score by 17%), tying its score with T1 and T11, which still maintain the best-ranked solution. The sensitivity analysis gives the analyst a better idea on how the weights assigned to each criterion influence the potential choice of the technical solutions.

4. Discussion of results

The comparison between the best-ranked techniques obtained by M-MACBETH and the interventions that Chilean heritage-related institutions executed after the 2005 and 2010 earthquakes shows the dominance of traditional techniques and materials, as recommended by the CMN, especially in case study No.1 (*Table 8*). Wooden tie beams were inserted in the roof (T8) to counteract D2 (flexural or mid-height cracks), while horizontal steel rods and straps (T4) were placed to counteract D3 (in-plane damage), linking the lateral chapels and buttresses to the longitudinal walls. In the areas without any relevant paintings, the wall reinforcement was done using geo-mesh (T6). These interventions are also recommended by M-MACBETH, together with wooden corner keys (T11) for D2 and D6 (damage at the intersection of perpendicular walls), although the best-ranked solutions according to M-MACBETH are wooden bond beams (T1).

Beside the replacement of the wall with timber-based partitions (an option not included in this study), the wall consolidation at the corner of the house in Nirivilo (case study No. 2) was made using electro-welded mesh (T7). A higher-ranked solution is the geo-mesh (T6), although this is more expensive than T7. Code NCh 3332 does not define a preferred solution between electro-welded mesh (T7) and geo-mesh (T6), which has led to the indiscriminate use of electro-welded mesh.

Similar results regard the *church of Nuestra Señora del Rosario* in Guacarhue (case study No.3). Indeed, it should be underlined that the implemented post-earthquake works there may be deemed a full reconstruction rather than a retrofitting. In fact, the works in this church included the complete reconstruction of the main nave, the execution of new connections (staircases) and the enlargement of stone buttresses. To counteract D3 (in-plane damage), these results show the use of wooden bond beams (T1) as the best solution. For D4 (corner damage-vertical cracks), wooden corner keys (T11) may be the best solutions. Regarding D7, M-MACBETH suggests the use of geo-mesh (T6), whereas electro-welded mesh (T7) was applied in the whole building.

Table 8. Implemented interventions *vs* Interventions recommended by MACBETH

Case study	**Implemented retrofitting techniques (during post-earthquake reconstructions)**	**Best ranked retrofitting techniques (MACBETH score >75/100)**
No.1. *Church of Parinacota*	T8; T4; T6	**D2:**T1, T11 (84.50), CE: High; T8 (77.50), CE: High
		D3:T1 (84.25), CE: High; T4 (84.25), CE: Low
		D6:T11 (92.50), CE: High; T6(85.00), CE: Low average; T8 (77.50), CE: High
No. 2. *Dwelling in Nirivilo town*	T7	**D4:**T11 (92.75); CE: High; T6 (85.50), CE: Low average; T8 (78.00), CE: High
		D7:T6 (85.50); CE: Low average; T7 (61.75); CE: Average
No. 3. *Church of Nuestra Señora del Rosario in Guacarhue*	Full reconstruction (including T7)	**D3:**T1 (89.00), CE: High; T6 (78.00), CE: Low average; T4 (75.00); CE: Low
		D4:T11 (89.00), CE: High; T6 (78.00), CE: Low average; T9 (76.75), CE: Average
		D7:T6 (78.00); CE: Low average

CE: Cost-effectiveness

5. Conclusions

In this research, multi-criteria analysis using MACBETH was applied to evaluate a set of retrofitting techniques, considering a stability-based approach under a set of criteria. This model was applied to three historical adobe constructions, expressions of local technical culture classified as National Monuments of Chile by the National Monuments Council (CMN, 2010, 2012). These constructions were retrofitted after being seriously damaged during two seismic events (7.8 Mw, in 2005; 8.8 Mw, in 2010).

This analysis shows that the use of wooden corner keys is the best-ranking solution to counteract flexural cracks or mid-height cracks, damage at the intersections of perpendicular walls, corner damage vertical cracks, and in-plane damage. Wooden tie beams are an equally high-scoring solution for corner damage vertical cracks. Geo-mesh also presents a high score, but it constitutes an expensive and irreversible solution.

In broader terms, this study has shown that the case-by-case approach is essential to support decision-makers (DMs) or decision-advising groups (*i.e.,* local practitioners, private building owners, cultural resource managers and authorities, and builders), especially in contexts with limited economic resources, such as Chile. Homeowners, cultural resource managers, and builders can use this expert-driven approach towards the selection of the best techniques for homogenous classes of buildings (a building taxonomy model) according to a set of damage patterns. By considering the singularities of each case study and coping with limited resources, these solutions should provide feasible and adequate life-safety protection while meeting the principles of architectural conservation (minimal intervention, material compatibility, and retreatability) and proving adequate in terms of quality/price ratio.

This method can support DMs to elicit the most suitable intervention towards more sustainable management of the building stock in earthquake-prone areas. It can also be employed to evaluate other design practices for homogenous classes of buildings, *i.e.,* using a taxonomic approach.

Since the accuracy of the model depends on the number of inputs including expert evaluations, possible future research could look to expand the panel of experts from other institutions. Additionally, future studies may investigate in more detail which retrofitting techniques are being used in other case studies in Chile and Latin America, *e.g.,* rope mesh and steel plates (Ruiz et al., 2022; Tarque et al., 2022), and compare those with the results obtained using MCDA tools.

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