Multi-criteria analysis of rehabilitation techniques for traditional timber frame walls in *Pombalino* buildings (Lisbon)

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Abstract

This research aims to evaluate the intervention techniques currently adopted for the traditional timber frame wall, using a case study in downtown Lisbon.

Different rehabilitation solutions were identified and evaluated through a multi-criteria decision analysis using dedicated software (M-Macbeth, *Measuring Attractiveness by a Categorical-Based Evaluation technique*).

Five evaluation criteria, i.e. material compatibility and permanence, structural reliability and authenticity, and visual-tactile appearance, were selected for this specific context. A multidisciplinary panel of experts in conservation science were consulted for defining the performance descriptors, evaluation levels, and weightings of these criteria.

Results show that Macbeth is a useful decision-aid capable of handling multiple outputs generated from qualitative expert judgments. Lastly, the predominance of five best-scoring interventions within three design-related scenarios is discussed.

Highlights:

- Overview of rehabilitation techniques for traditional timber frame walls in *Pombalino* buildings (late-18th century);
- Ranking of repair and strengthening measures through a multi-criteria model;
- Presenting a multi-criteria procedure capable of evaluating several construction techniques within design-related scenarios;
- Recommendations for best rehabilitation techniques for these traditional structural components.

***Keywords*:** timber frame wall; *Pombalino* buildings; rehabilitation techniques; Macbeth analysis.

1. Introduction

Building rehabilitation is a challenging task due to conflicting priorities pursued by multiple stakeholders, e.g. experts in conservation science, municipalities, owners, and contractors. In fact, safeguarding the authenticity of historic construction can conflict with the reliability of the rehabilitation work, budgetary constraints, and/or limitations imposed by the presence of occupants in the building.

When a variety of non-numerable and non-homogeneous criteria have to be taken into account for the selection of the best solution among several options, the decision-making process can be supported by *Multi-criteria Decision Analysis* (MCDA)[1-2]. However, although MCDA models can guarantee transparency and interactivity, these methods are rarely applied for questions regarding the preservation of historic structures, e.g. for the evaluation of cultural assets regarding solutions for their reuse [3] or for the assessment of different rehabilitation techniques.

This research presents a straightforward methodology to guide decision-making related to the preservation of timber-framed heritage in seismic-prone zones. The evaluation process is addressed by dedicated software (M-Macbeth, *Measuring Attractiveness by a Categorical-Based Evaluation Technique*) capable of handling multiple outputs generated from qualitative expert judgments [4-5]. This study investigates the opportunities offered by multi-criteria analysis in analysing a case study of buildings in downtown Lisbon (so-called *Pombalino* buildings).

Following its devastation by earthquake, fire, and tsunami in 1755, the downtown of Lisbon was reconstructed in situ by employing a set of advanced anti-seismic techniques [6, 7]. This building stock covers an area of 23.5 hectares and consists of 62 blocks and 430 building lots.

The *Pombalino* structural system is based on a hyperstatic model composed of stone masonry external walls and a set of internal load-bearing timber frame walls that are connected to wooden floors by means of pre-carved posts or by nailing posts to beams embedded into the external facade (Fig. 1)[8, 9].

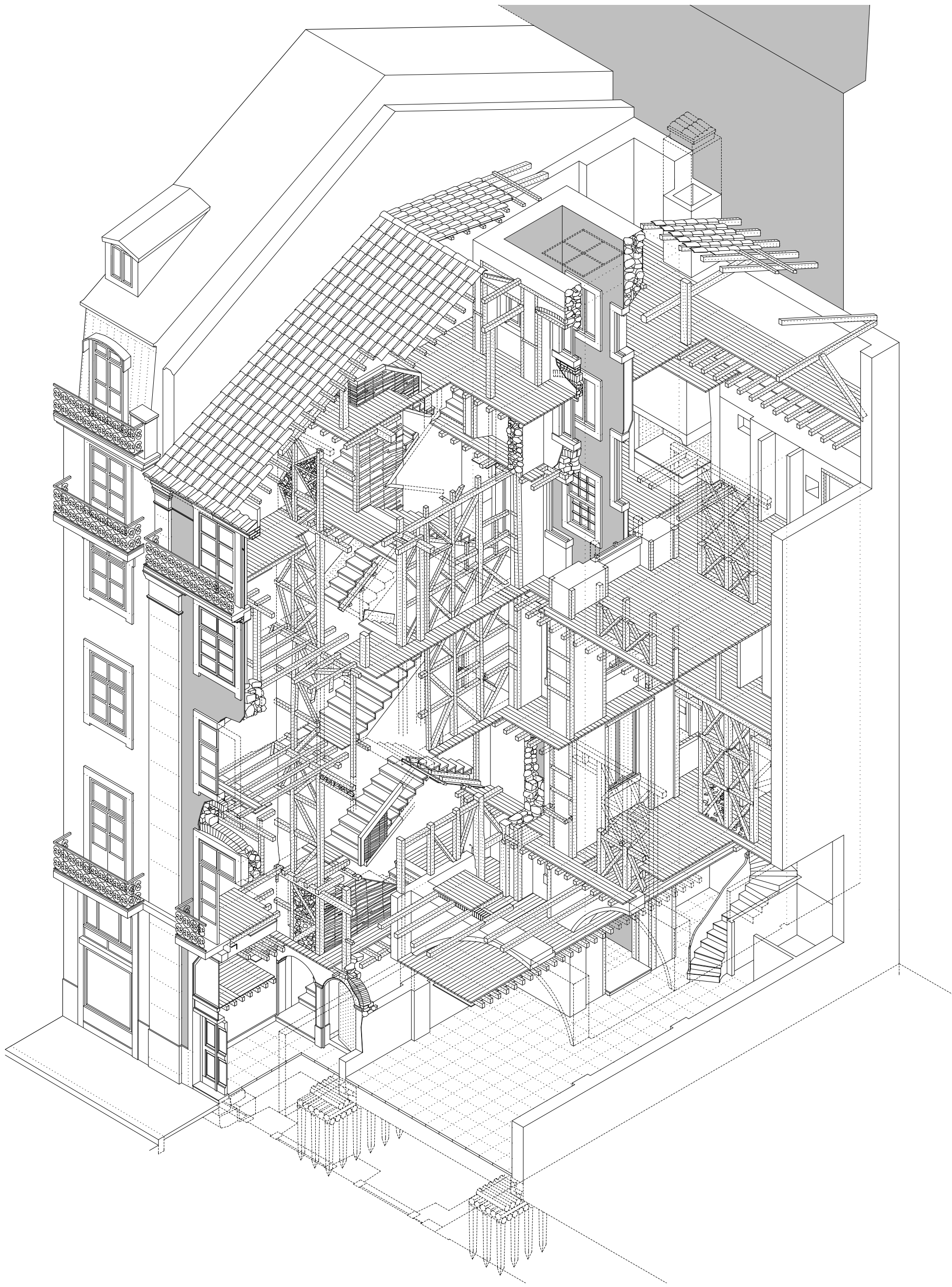


Fig. 1 – Axonometric view of a *Pombalino* building (18th century, Lisbon)

These three-dimensional timber frames above the first floor, reinforced by cross-bracing components (10x10cm or 10x8cm), are designed to withstand seismic actions through the ductile behaviour of the joints and the satisfactory interlocking of each construction component (Fig. 2). The ductility of the joints is directly related to the ability of the structure to deform nonlinearly without significant loss of strength, while the interlocking increases the maximum load and stiffness of the connection [10].

Pombalino construction, which was systematically employed from the late 18th century onwards in Lisbon's other districts as well, is remarkable evidence of a collective effort to reformulate time-tested local techniques and effect a comprehensive renewal of the city at urban, architectural, and structural levels [6].

Fig. 2 – Internal view of a *Pombalino* building, *Rua dos Fanqueiros*, Lisbon (left); original and replaced cross-bracing components (right)

Regardless of the significant value of these buildings and their central location, a remarkable decrease of occupancy was continuously registered from 1911 to 2011, with a loss of almost 90% of the population who initially lived in these houses [11]. This process of desertion was reflected in all the historical districts of the city, and it was followed by a considerable neglect of these constructions.

Countering this trend, significant real estate investment has been fostered in the last five years by the centrality of this building stock and new market demand linked mostly to the increase in tourist flow. The Portuguese government approved a special legal regime applicable from 2014 until 2020 devoted to the rehabilitation of these buildings with the aim of reducing the cost of interventions and fostering urban renewal. This building regulation exempts construction works from compliance with a number of requirements (e.g. habitability, accessibility, acoustic comfort, energy efficiency) and defines the minimum requirement of not reducing the structural and seismic safety of the existing structures [article 9, 12]. As recently underlined by the scientific community, the opportunity to set up an effective strategy for mitigation of seismic risk was therefore ignored by this government initiative [13].

Within this multifaceted historical context and in the absence of specific guidelines or technical rules, individual/private choices regarding intervention on historic buildings are frequently shortsighted. As shown in this work, interactive and collective deliberation is needed to support the decision makers (building owners or users).

The proposed methodology can also be used to assess interventions on a large number of load-bearing interior and/or exterior timber frame walls of traditional constructions in different geographical contexts [14, 15].

2. Rehabilitation techniques of timber frame walls (TF)

2.1. Brief notes on the main principles of interventions on historical buildings

Essential requirements for interventions on traditional construction systems can be found in international guidelines and charters for the safeguarding of architectural heritage [16-18] and they can be summarized as follows:

- (i) low intrusiveness and distinguishability;
- (ii) physical, mechanical, and chemical compatibility with the original materials;
- (iii) seismic upgrading by compliance with a reasonable equivalent safety.

Less intrusive interventions (i), which involve a minimization of loss of original material and the maintenance of the original structural model, should be privileged over any other solutions. The interventions should also fulfil the requirement of low visual impact. The replacement parts should match the material, design, species, grade, slope of grain, dimensional stability and decay resistance of the original components as closely as possible [19]. At the same time, the distinguishability of the intervention [17] is guaranteed by the regularity of the replaced components in geometry, grade, type of assembly and by their macroscopic characteristics of the wooden members (e.g. knots, interfacial discontinuities, shake, splits)(Fig. 2, right).

Secondly, the concept of reversibility, following the recommendations of the Venice Charter [17], has today been supplanted by those of compatibility and retreatability (ii). In fact, the seismic retrofitting of mixed systems made of wooden components or the impregnation of a product within the porous network of mortars is not reversible [20, 21]. Compatibility requires that materials used for the treatment do not have negative consequences (e.g. harmful chemical reactions or formation of by-products), whereas retreatability implies that the present conservation treatment will not preclude or impede future treatments [21].

When the wall must be completely replaced due to its poor state of conservation, mechanical compatibility is an additional requirement. The new components should guarantee the same stiffness and ductility of the original construction system [20].

Safety level is another basic requirement (iii) not necessarily equal to what is mandatory for new constructions [22, 23]. However, considering that the analysed buildings belong to a highly seismic area, design provisions for ensuring an acceptable level of damage mitigation are a priority.

Besides these requirements, the selection of solutions for the rehabilitation process depends on budgetary constraints and occupancy of the building plot by tenants or owners. A multi-stage project with a sequence of discrete rehabilitation actions can be a successful strategy; this type of intervention falls into the "incremental rehabilitation" category, whose advantages are shown in several reports by the U.S. Federal Emergency Management Agency (FEMA) [24-25].

2.2. Overview of intervention techniques on timber frame walls (TF)

Interventions on historical timber-framed constructions in seismic areas are scarcely regulated at a European level, even though national provisions have been settled in various countries. References on seismic design codes can be found in Italy (e.g. OPCM 3274) [26] and in Germany, where the maintenance of timber-framed buildings is regulated by specific norms and generally carried out by a multi-disciplinary team [27].

In the absence of a consistent European legislative framework, the authors referred to seven types of seismic upgrades as defined by FEMA [24].

The intervention sub-categories specified in Table 1 were evaluated by Coías [9] in reference to the *Pombalino* buildings, taking into account budgetary and feasibility constraints. Global structural strengthening (intervention strategy n.4) is recommended when the components show inadequate ductility and strength to resist large lateral deformation. As alternatives to strengthening and stiffening, mass reduction, seismic isolation, and supplemental energy dissipation (1a, 5a, 5b) are not considered feasible for this type of construction system.

Intervention strategy	**Solutions for *Pombalino* buildings**	**Advantages**	**Limitations**
1) Local modifications of the original configuration or 2) Removal or minimisation of existing irregularities and discontinuities	a) Demolition of extra (new) storeys;	Maintenance of original layout; safeguarding of building's architectural value	Inconvenience to users; reduction of floor area; requires high level of workmanship; decrease in financial value
	b) Removal of incompatible elements, e.g. elevator shafts, concrete slabs, overhanging or inappropriate structures (rear facade)		
	c) Removal of (new) openings and alterations in the interior layout		
3) Global structural stiffening	a) Stiffening timber frame walls and floors		Inconvenience to users; high level of workmanship; reduction of floor area
	b) New walls or structures		
4) Global structural strengthening	a) Strengthening with composite materials, without modifying the geometry of the walls or increasing their weight		Requires high level of workmansh
	b) Partial grouting with reinforced concrete		
	c) Local strengthening (e.g. connections of the timber elements and of the masonry walls)		
	d) Closure of openings by precast cement elements	Pratical feasibility	Alteration of original configuration; increase in mass
5) Mass reduction	a) Demolition of additional storeys or removal of non-traditional partitions		Inconvenience to users; reduction of floor area; decrease of the financial value
	b) Removal of heavy furnshings		
6) Seismic isolation	a) Inserting compliant bearings between the superstructure and the foundation	Reducion of seismic impact on structures	Excessive cost; requires high level of workmanship; low effectiveness for light and flexible components
7) Supplemental energy dissipation	a) Special devices for isolation for ground shaking	Maintenance of original layout, safeguarding of building's architectural value	Requires high level of workmanship and cutting-edge methods
	b) Seisimic dissipator devices for walls		

Table 1 – Strategy solutions reprocessed from [9]

Considering that extra floors in *Pombalino* buildings are fully integrated in the external configuration of the original construction for a number of reasons (e.g. alignment of the openings, roof/dormer geometry, architectural features), their demolition (1a) would incur a loss of the architectural value of the building, as well as a reduction of floor area and inconvenience to the users. This is also incompatible with the decision-makers' interests, due to a considerable decrease in the financial value of the investment.

This research regards interventions for structural stiffening and strengthening in timber-frame walls (TF)(3a, 4a, 4b, 4c). Although conceived as a load-bearing structure that is included in a composite system interlocked with other components, TF was analysed independently from the timber joists and the external walls in order to focus attention on specific interventions for this component.

This work regards TF determined as retrofittable through visual grading and non-destructive testing (NDT). As a precondition for being repaired or strengthened, the timber framework will guarantee some residual capacity if the level of conservation, the effective cross-section, and deformations are acceptable [19]. It should also be pointed out that all interventions involve the removal of the surface finish, which should be preceded by a detailed documentation of the pre-intervention status quo [17].

A set of specific interventions was identified for each of the four sub-components: timber framework, infill, joints, and surface finish (Fig. 3, Table 2).

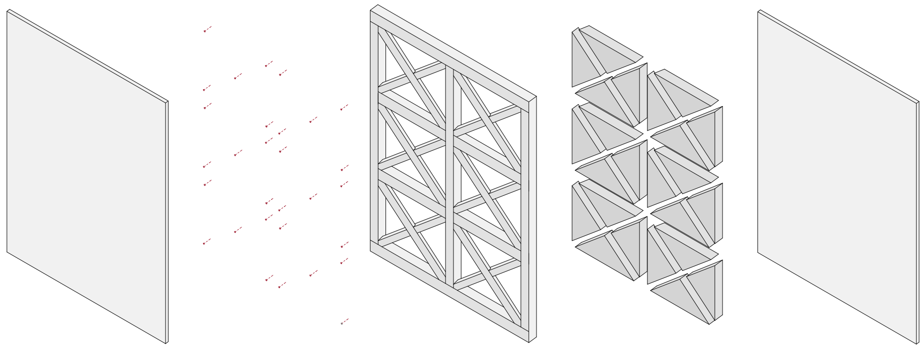


Fig. 3 – Sub-components of timber-frame wall (TF)

Individual options identified for those sub-components were regrouped into 131 combinations, which were in turn divided into eleven groups according to the type of the intervention on the wall structure (F+I)(Table 3).

These 131 combinations were selected with the aim of grouping similar solutions across the sub-components in order to arrive at interventions that would be homogeneous for the whole wall. Such a homogeneous intervention would entail reasonable economic and practical feasibility, i.e. minimum number of types of material and skills required in the work site.

The definition of the main aim of the rehabilitation works is a crucial step; in fact, conservative repair implies preserving the original structural layout through the use of compatible products and techniques, i.e. with similar physical-mechanical features, and avoiding harmful chemical reactions or by-products. Conversely, slightly more intrusive interventions address the structural features with the main aim of meeting higher target reliability levels of the structure.

Timber frame wall components		Main aim	Sub-Intervention	Description	References
WALL STRUCTURE	FRAMEWORK	Removal of causes of degradation (e.g. corroded iron elements and decayed timber elements) and preservation or reconstitution of the structural continuity of the wall	**F1**	**Removal of decayed timber elements and replacement with autoclaved timber components**	Appleton [8]; Appleton and Domingos [30]; Campanella and Mateus [31]
			F2	**Substitution of decayed timber elements with wooden prosthesis using:**	
			F2a	Structural timber glue	Tsakanika-Theoharis [32]
			F2b	CFRP or GFRP bars+ Epoxy resin	Pizzo et al.[28]; Cruz et al. [29]; Gonçalves et al.[33]
			F2c	Steel rods + Epoxy resin	Poletti and Vasconcelos [10]
			F2d	Stainless steel screws	Tsakanika-Theoharis [32]
			F3	**Introduction of stainless steel structure by using:**	
			F3a	Stainless steel cross-bracing	Appleton [8]
			F3b	Stainless steel beams/columns with bolted and welded plates	Mascarenhas [7]
			-	Diagonal damper	Gonçalves et al. [33]
	INFILL		**I1**	**Partial removal of infill and repair of the brick or rubble masonry with natural hydraulic lime mortar**	Appleton and Domingos [30]; Bianco [34]
			I2	**Total or partial replacement of the existing infill by using:**	
			I2a	Clay bricks (or roof tiles) grouted with hydraulic lime mortar	Appleton [8]; Gonçalves et al.[33]; Bianco [34]
			I2b	Hollow bricks grouted with cement mortar	Appleton and Domingos [30]
			I2c	Mineral wool	Appleton and Domingos [30]
			I3	**No infill**	Poletti and Vasconcelos [10]
	FRAMEWORK+ INFILL		**F4+I4**	**Restoring the wall to its original condition and placement of reinforced rendering**	Appleton [8]; Appleton and Domingos [30]; Gonçalves et al.[33]
JOINTS		Local recovery and strengthening of the original function	**J1**	**Recovery of carpentry joints by using:**	
			J1a	Wooden pegs and pins	Tsakanika-Theoharis [32]
			J1b	Stainless steel nails	Bianco [34]; Poletti and Vasconcelos [10]
			J2	**Strengthening carpentry joints:**	
			J2a	Stainless steel bolts	Poletti and Vasconcelos [10]
			J2b	Stainless steel plates with bolts	Gonçalves et al.[34]; Poletti and Vasconcelos [10]
			J2c	Self-tapping stainless steel screws	Poletti and Vasconcelos [10]
			J2d	NSM (steel bars or FRP bars)	Cruz et al.[29]; Poletti et al. [35]
			J2e	EBR (GFRP or CFRP)	Cóias [9]; Poletti and Vasconcelos [10]
SURFACE FINISH		Protection of the surface wall	**S1**	**Mono or multi-layer plaster by using:**	
			S1a	NHL-based and/or lime-based render reinforced by fiberglass mesh	Appleton [8]
			S1b	HL or cement-based mortar	
			S2	**Cement-based mortar with metal mesh (or fibreglass) with acrylic (or polymer) render/additives**	Appleton [8]; Appleton and Domingos [30]; Gonçalves et al. [33]
			S3	**Lining panels:**	
			S3a	Plasterboard	Appleton and Domingos [30]
			S3b	Strips of wood with lime-based mortar	Tsakanika-Theoharis [32]
			S4	**Surface film:**	
			S4a	Transparent scumble glaze	Campanella and Mateus [31]
			S4b	Coating finish with pigment	

NSM: Near Surface Mounted; CFRP: Carbon Fibre Reinforced Polymer; GFRP: Glass Fibre Reinforced Plastic;
EBR: Externally Bonded Reinforcement; NHL: Natural Hydraulic Lime
text - not included in Macbeth analysis due to its limited application in current practice

Table 2 – Interventions for each sub-component of the timber frame wall (TF)

These alternatives include traditional methods (e.g. local replacement of decayed components by similar ones) or innovative materials (e.g. synthetic resins, fibre-reinforced polymers FRP) and new methods (e.g. externally bonded or near-surface-mounted – NSM – reinforcements) [28]. When prosthesis is required to strengthen the timber framework, the selected materials vary from improved traditional components (e.g. treated wooden members, plywood) to timber coupled with modern products (e.g. FRP, epoxy resin, NSM).

Similarly, improved traditional components or non-traditional materials can be used to replace the infill or the surface finish. Clay bricks and roof tiles belong to the first category, whereas mortars with hydraulic cement-based binder, render reinforced by fiberglass mesh, gypsum boards, and wood derivatives are examples of the latter. Finally, strengthening techniques for carpentry joints range from stainless-steel rods to externally bonded structural systems, such as Fibre Reinforced Polymer (FRP) systems [29].

Advantages and disadvantages as well as details and predictable failure modes of each intervention were extrapolated from an extensive literature review of current practice and experimental results [8, 9, 29-37].

In order to streamline the large number of possible combinations, the following separate interventions are equated in Table 3:

- *F3a=F3b*: due to comparable mechanical behaviour;
- *I1=I2a*: different mechanical performances of these types of infill (brick or rubble masonry versus clay bricks or roof tiles) are not significant, since both include hydraulic lime mortar, which produces a similar response for the shear transfer mechanism and dissipative capacity.
- *J1a=J1b*: though there were different performance parameters of wooden versus metallic carpentry joints, such as moisture condensation in the timber-steel elements interface and low visual compatibility [36], these solutions can be equated for similar energy dissipation mechanisms and good ductility. Both dowel-type connections allow a mutual rotation of the elements.

Intervention	Wall Structure	Joints	Surface Finish
Group 1			
TF01	F1+I1 (*or* F1+I2a)	J1a (orJ1b)	S1a
TF02			S3a
TF03			S3b
TF04		J2a	S1a
TF05			S3a
TF06			S3b
TF07		J2b	S1a
TF08			S3a
TF09			S3b
TF10		J2c	S1a
TF11			S3a
TF12			S3b
TF13		J2d	S1a
TF14			S3a
TF15			S3b
TF16		J2e	S1a
TF17			S3a
TF18			S3b
Group 2			
TF19	F1+I2b	J1a (*or* J1b)	S1b
TF20			S2
TF21			S3a
TF22			S3b
TF23		J2a	S1b
TF24			S2
TF25			S3a
TF26			S3b
TF27		J2b	S1b
TF28			S2
TF29			S3a
TF30			S3b
TF31		J2c	S1b
TF32			S2
TF33			S3a
TF34			S3b
TF35		J2d	S1b
TF36			S2
TF37			S3a
TF38			S3b
TF39		J2e	S1b
TF40			S2
TF41			S3a
TF42			S3b

Intervention	Wall Structure	Joints	Surface Finish
Group 3			
TF43	F1+I2c	J1a (or J1b)	S2
TF44			S3a
TF45			S3b
TF46		J2a	S2
TF47			S3a
TF48			S3b
TF49		J2b	S2
TF50			S3a
TF51			S3b
TF52		J2c	S2
TF53			S3a
TF54			S3b
TF55		J2e	S2
TF56			S3a
TF57			S3b
Group 4			
TF58	F1+I3	J1a (or J1b)	S3a
TF59			S3b
TF60			S4a
TF61			S4b
TF62		J2a	S3a
TF63			S3b
TF64			S4a
TF65			S4b
TF66		J2b	S3a
TF67			S3b
TF68			S4a
TF69			S4b
TF70		J2c	S3a
TF71			S3b
TF72			S4a
TF73			S4b
TF74		J2d	S3a
TF75			S3b
TF76			S4a
TF77			S4b
TF78		J2e	S3a
TF79			S3b
TF80			S4a
TF81			S4b

Intervention	Wall Structure	Joints	Surface Finish
Group 5			
TF82	F2a+I1 (*or* F2a+I2a)	J1a (or J1b)	S1a
TF83			S2
TF84			S3a
TF85			S3b
Group 6			
TF86	F2b+I1 (*or* F2b+I2a)	J1a (or J1b)	S1a
TF87			S2
TF88			S3a
TF89			S3b
TF90		J2a	S1a
TF91			S3a
TF92			S4a
TF93		J2b	S1a
TF94			S3a
TF95			S4a
TF96		J2c	S1a
TF97			S3a
TF98			S4a
TF99		J2d	S1a
TF100			S3a
TF101			S4a
Group 7			
TF102	F2c+I1 (*or* F2c+I2a)	J1a (orJ1b)	S1a
TF103			S3a
TF104			S3b
TF105		J2a	S1a
TF106			S3a
TF107			S3b
TF108		J2b	S1a
TF109			S3a
TF110			S3b
TF111		J2c	S1a
TF112			S3a
TF113			S3b
TF114		J2d	S1a
TF115			S3a
TF116			S3b
TF117		J2e	S1a
TF118			S3a
TF119			S3b

Intervention	Wall Structure	Joints	Surface Finish
Group 8			
TF120	F2d+I2b	-	S1b
TF121			S2
TF122			S3a
TF123			S3b
Group 9			
TF124	F2d+I2c	-	S1b
TF125			S2
TF126			S3a
TF127			S3b
Group 10			
TF128	F3a (*or* F3b)	-	S2
TF129			S3a
Group 11			
TF130	F4+I4	-	S1b
TF131			S3a

Table 3 – Combinations of interventions on timber frame wall (TF)

3. Ranking of the rehabilitation techniques for timber frame walls (TF)

3.1. Macbeth analysis

A comprehensive comparison of Multi-Criteria Decision Analysis (MCDA) methods was addressed by Mustajoki et al. [2]. Due to the large number and great diversity of MCDA methods, it is difficult to justify the choice of a specific method for adressing a demanding decision problem. Arrow alleges that none of the existing MCDA methods can be considered faultless for all types of decision-making problems [1, 37, 38].

In keeping with all MCDA methods, Macbeth overcomes the limitation of mono-criteria models by including multiple and heterogeneous attributes. The efficacy of Macbeth has been demonstrated in different contexts, e.g. environmental planning, urban strategies, and eco-system management [4-5]. This problem-solving model is commonly used in literature by itself or coupled with other models like *Data Envelopment Analysis* (DEA) and *Utilitèt Additives* (UTA) [39, 40].

Macbeth was chosen by the authors for its ability to incorporate a large number of preferences (or amount of subjective information) built through pairwise comparison judgments [4]. It can thus be tailored in order to match the specific requirements of the analysts, through a co-participative decision-making process. It also resolves contradictions between interests of single actors or with inconsistent scores by providing a complete ranking based on an additive aggregation approach [4].

In this research, a panel of experts (i.e. chemists, architects, and timber engineers) judged the performance of alternatives for each sub-component of the wall; this set of criteria-wise performances was numerically ranked in terms of attractiveness.

Macbeth is a user-friendly tool, since it can deal with inconsistent judgments in the pairwise comparison matrix and suggest solutions. This software is also intuitive, due to the graphical user interfaces (e.g. *thermometer*), and interactive, due to the possibility of analysing the sensitivity of every output based on variations of judgements, performances, and scores or weights [4,5].

However, this interactive model is time-consuming as it requires more questions than other elicitation methods (e.g. the swing weighting), especially when dealing with a high number of alternatives, criteria, and performance levels.

Additionally, other MCDA models use more accessible software packages than M-Macbeth; some are compatible with Microsoft Office (e.g. *Promax*, *Pure2*) and have MS Excel-like interfaces to input the data, or they can provide written reports (i.e. *1000Minds*, *Decision Tools*, *Hiview 3*, *Logical Decisions*, *MakeItRational*, *PlanEval*, *TESLA*, *V.I.S.A. Decisions*) [2].

3.2. Evaluation criteria

Five evaluation criteria and their respective performance descriptors were extrapolated from the commonly agreed guidelines for the conservation of architectural heritage (section 2.1) (Table 4). This set of criteria satisfies Roy's axioms: exhaustibility, cohesion, and non-redundancy [41].

- *Material compatibility* (MC) regards the physical, chemical, and mechanical matching of the new (or reused) components to the original ones. MC is related to the impact of intervention on historical buildings in terms of durability and effectiveness.

- *Material permanence* (MP) regards the intrusiveness of the intervention and thus the possible material variation of the authenticity of the original components. It is inversely proportional to the volume of the material to be removed.

<table>
<tr><th>Criterion</th><th colspan="2">Sub-criterion</th><th>Performance Descriptors</th></tr>
<tr><td rowspan="3">Material Compatibility (MC)</td><td colspan="2">physical compatibility</td><td>porosity and pore size distribution, variation of the moisture transport properties, such as absorption and drying rate, thermal, and hygric dilatation</td></tr>
<tr><td colspan="2">chemical compatibility</td><td>chemical composition and reactions, solubility</td></tr>
<tr><td colspan="2">mechanical compatibility</td><td>hardness, cohesion, and deformation</td></tr>
<tr><td>Material Permanence (MP)</td><td colspan="2">degree of intrusiviness</td><td>permanence of original components after the intervention</td></tr>
<tr><td rowspan="2">Structural Reliability (SR)</td><td colspan="2">resistance</td><td>horizontal and vertical load capacity</td></tr>
<tr><td colspan="2">ductility and energy dissipation</td><td>lateral deformation capacity; ability to deform and mechanically degrade without collapse</td></tr>
<tr><td rowspan="2">Structural Authenticity (SA)</td><td rowspan="2">consistency with the:</td><td>original structural layout</td><td>mass distribution, stiffness, and load concentration</td></tr>
<tr><td>structural wall typology and joint type</td><td>dissipation capacity of walls and joints</td></tr>
<tr><td rowspan="2">Visual-Tactile Appearance (VTA)</td><td colspan="2">visual appearance</td><td>visual permanence of the original features before and after the intervention (thickness, colour, gloss)</td></tr>
<tr><td colspan="2">tactile appearance</td><td>tactile permanence of the features before and after the intervention (roughness)</td></tr>
</table>

Table 4 – Evaluation criteria and performance descriptors

- *Structural reliability* (SR) is evaluated by comparing the mechanical behaviour of the component (e.g. resistance, ductility, and energy dissipation) before and after the intervention.

- *Structural authenticity* (SA) is based on the level of modification of the original structural system (either geometrical or structural configuration of timber frame walls), which influences the structural performance in terms of stiffness, mass distribution, and loading level.

- *Visual-tactile appearance (VTA)* regards the aesthetic compatibility of the intervention on wall surface appearance. The aesthetic compatibility typically belongs to the material compatibility (MC); however, it was considered in this dedicated criterion in order to avoid redundant evaluations.

3.3. Problem structuring

This process included two main steps: the evaluation of 131 rehabilitation techniques based on each criterion (section 3.2) in a 0-100-scale by the experts (Fig. 4, 1st- 4th step) and the definition of three scenario models (Fig. 4, 5th step).

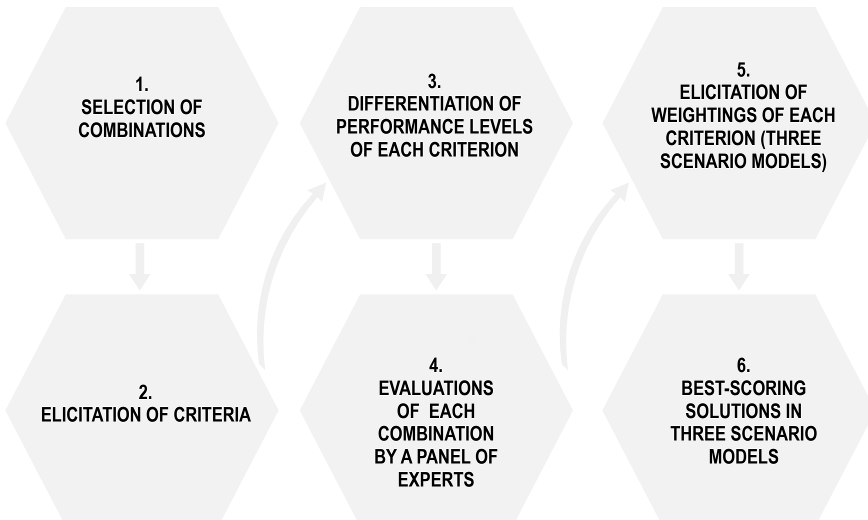


Fig. 4 – Workflow analysis

The panel of technical experts on historic timber frame buildings was composed of two representatives for each field: chemistry, timber engineering and architecture. The elicitation of the best-scoring solutions was influenced by their respective disciplinary sphere. Chemists evaluated the alternative options under MC criterion, architects (experts of architectural heritage preservation) under MP and VTA criteria, and timber engineers under SR and SA criteria.

Once the qualitative performance descriptors of each criterion were established (Table 4), the experts determined the respective performance evaluation levels (high, moderate, low, or very low)(Table 5), whose interval values were defined through Macbeth pairwise questioning procedure.

Criterion	Performance Levels	
Material Compatibility (MC)	**High (H)**	Properties are similar physically (e.g. very similar porosity and pore size distribution, very low variation of the moisture transport as absorption and drying rate, no thermal and hygric dilatation), chemically (e.g. identical chemical composition, no harmful chemical reaction, similar solubility) mechanically (e.g. hardness, cohesion and deformability similar to the original material). Additionally, the treatment will have a long-term durability.
	Moderate (M)	Slightly or moderately different physical-mechanical features (e.g. moderate variation of the porosity and pore size distribution,moderate variation of the hardness/cohesion, moderate variation of drying and hygroscopic behavour, different chemical features, no harmful chemical reaction or byproducts).
	Very Low (VL)	Different from the original properties (e.g. chemical composition and solubility, formation of byproducts, remarkable difference in hardness and deformability, very different drying behaviour).
Material Permanence (MP)	**High (H)**	Negligible replacement of original components.
	Moderate (M)	Limited replacement of original components.
	Low (L)	Significant replacement of original components.
	Very Low (VL)	Complete replacement of original components.
Structural Reliability (SR)	**High (H)**	Significant improvement of mechanical behavior (resistance, ductility, and energy dissipation).
	Moderate (M)	Moderate improvement of mechanical behavior (resistance, ductility, and energy dissipation).
	Low (L)	Low improvement of mechanical behavior (resistance, ductility, and energy dissipation).
	Very Low (VL)	Non significant improvement or even worsening of the mechanical behavior (resistance, ductility, and energy dissipation).
Structural Authenticity (SA)	**High (H)**	The original geometry and structural configuration are mantained.
	Moderate (M)	About the same geometry and structural configuration as the original ones.
	Low (L)	Different from the original geometry and structural configuration.
	Very Low (VL)	Very different from the original geometry and structural configuration.
Visual-Tactile Appearance (VTA)	**High (H)**	Visual, tactile, and spatial features are similar to the original.
	Moderate (M)	Spatial features are similar to the original, wheras the tactile consistency is different.
	Low (L)	Increase of thickness, differences in tactile and material consistency.
	Very Low (VL)	Relevant differences in thickness and in tactile, material, and colour consistency.

Table 5 – Performance levels for each criterion based on experts' judgments

In order to obtain numerical values, it was necessary to more clearly define the distances involved between the various evaluation levels. These would vary for judgments about different subcomponents. The experts defined the difference of attractiveness between two levels of performance by selecting the most suitable adjective among seven semantic categories included in the Macbeth method (no, very week, week, moderate, strong, very strong, or extreme).

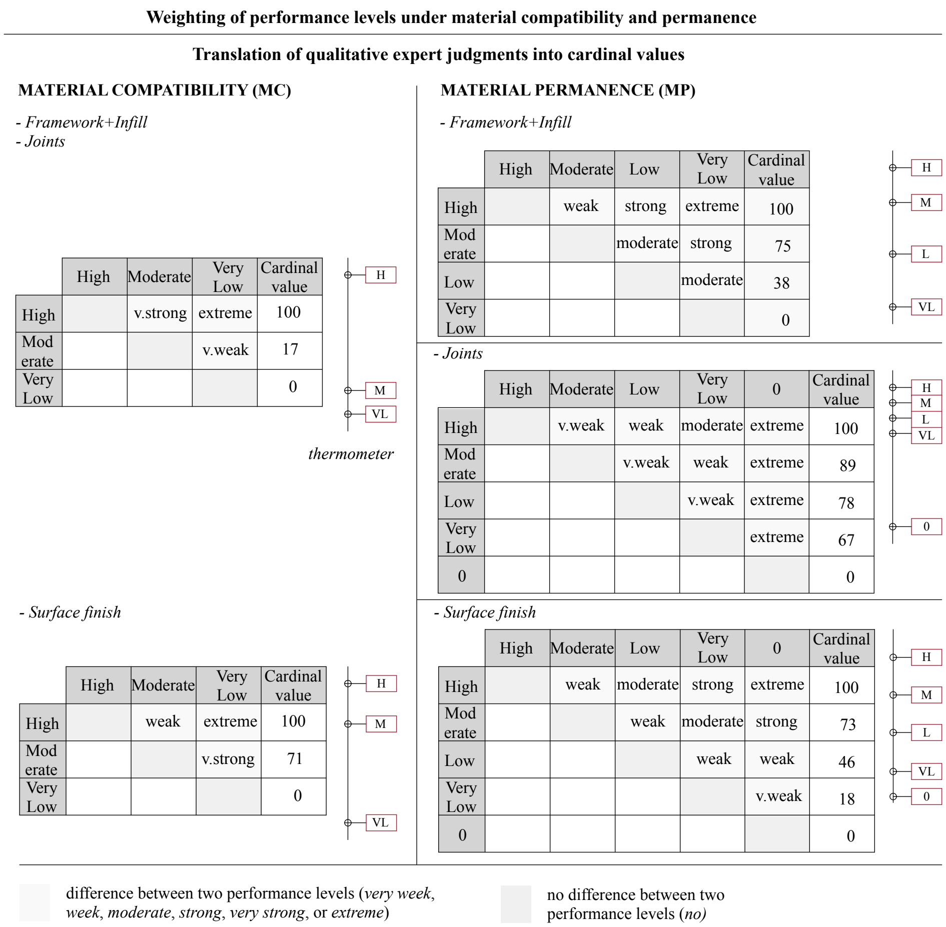


Fig. 5 – Macbeth judgment matrices related to the difference of attractiveness between the performance levels of MC and MP

It was therefore possible to determine under the Material Compatibility criterion, for example, that the difference in attractiveness between *High* and *Moderate* evaluations was "very strong" in reference to Framework Infill and Joints, while when considering Surface Finish the difference between *High* and *Moderate* was seen as "weak". These qualitative expert judgments were translated into cardinal values by M-Macbeth (Figs. 4, 5).

The difference of attractiveness between the sub-components of TF was determined through the same pairwise procedure for all criteria except for the visual-tactile appearance

(VTA). In fact, VTA is related only to the surface finish, and thus the evaluations were performed directly for the whole wall (Fig. 7).

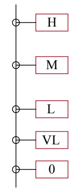
Weighting of performance levels under structural reliability and authenticity

Translation of qualitative expert judgments into cardinal values

STRUCTURAL RELIABILITY (SR)

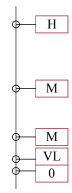
- Framework+Infill

	High	Moderate	Low	Very Low	0	Cardinal value
High		weak-mod	strong	v.strong	extreme	100
Moderate			mod-strg	strong	v.strong	71
Low				moderate	strong	41
Very Low					moderate	20
0						0



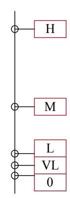
- Joints

	High	Moderate	Low	Very Low	0	Cardinal value
High		moderate	v.strong	v.strong	extreme	100
Moderate			mod-strg	moderate	moderate	58
Low				weak	weak	25
Very Low					v.weak	8
0						0



- Surface finish

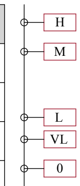
	High	Moderate	Low	Very Low	0	Cardinal value
High		strong	extreme	extreme	extreme	100
Moderate			moderate	moderate	moderate	47
Low				weak	weak	15
Very Low					v.weak	7
0						0



STRUCTURAL AUTHENTICITY (SA)

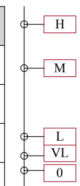
- Framework+Infill

	High	Moderate	Low	Very Low	0	Cardinal value
High		weak-mod	strong	v.strong	extreme	100
Moderate			mod-strg	strong	v.strong	80
Low				moderate	strong	35
Very Low					moderate	20
0						0



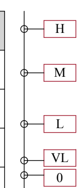
- Joints

	High	Moderate	Low	Very Low	0	Cardinal value
High		moderate	v.strong	v.strong	extreme	100
Moderate			mod-strg	moderate	moderate	70
Low				weak	weak	25
Very Low					v.weak	10
0						0



- Surface finish

	High	Moderate	Low	Very Low	0	Cardinal value
High		moderate	strong	v.strong	extreme	100
Moderate			moderate	strong	v.strong	70
Low				weak-mod	moderate	35
Very Low					v.weak	10
0						0



difference between two performance levels (*very week*, *week*, *moderate*, *strong*, *very strong*, or *extreme*)

no difference between two performance levels (*no*)

Fig. 6 – Macbeth judgment matrices related to the difference of attractiveness between the performance levels of SR and SA

Weighting of sub-components of timber frame wall under five criteria

Translation of qualitative expert judgments into cardinal values

MATERIAL COMPATIBILITY (MC)

	MC_*S*	MC_*F+I*	MC_*J*	Cardinal value
MC_*S*		v.weak	strong	50
MC_*F+I*			strong	42
MC_*J*				8

Weighting of sub-components of timber frame wall

MATERIAL PERMANENCE (MP)

	MP_*F+I*	MP_*S*	MP_*J*	Cardinal value
MP_*F+I*		weak	extreme	56
MP_*S*			v.strong	38
MP_*J*				6

Weighting of sub-components of timber frame wall

STRUCTURAL RELIABILITY (SR)

	SR_*J*	SR_*F+I*	SR_*S*	Cardinal value
SR_*J*		positive	positive	55
SR_*F+I*			positive	35
SR_*S*				10

Weighting of sub-components of timber frame wall

STRUCTURAL AUTHENTICITY (SA)

	SA_F+I	SA_J	SA_S	Cardinal value
SA_F+I			positive	45
SA_J			positive	45
SA_S				10

Weighting of sub-components of timber frame wall

VISUAL-TACTILE APPEARANCE (VTA)

	High	Moderate	Low	Very Low	0	Cardinal value
High		v.strong	extreme	extreme	positive	100
Moderate			weak-str	mod-str	positive	44
Low				v.weak -weak	positive	22
Very Low					positive	11
0						0

Weighting of sub-components of timber frame wall

F+I= Framework+Infill; *J*=Joints; *S*= Surface finish

Fig. 7 – Macbeth judgment matrices related to the difference of attractiveness between each sub-component of TF in each criterion

Additionally, the threshold between what constitutes repair versus strengthening measures is proposed below by using the weighted assessment of the combinations in the SR criterion. The threshold value (t_{r-s}) was determined by calculating the weighted average of the evaluation level defined as "low" (EL_p) of the SR criterion, as shown in eq. 1:

$$t_{r-s} = \sum_i (ELp_i \cdot WF_i) \quad (1)$$

where WF_i is the weighting of each sub-type of intervention (rehabilitation technique) used to determine each partial value score of the evaluation under SR criterion.

The result for $t_{r\text{-}s}$ can be rounded up to 30 (eq. 2):

$$t_{r\text{-}s} = 41 \times 0.35 + 25 \times 0.55 + 15 \times 0.10 = 29.6 \qquad (2)$$

where 41, 25, and 15 are the value scores of the evaluation level 'low' attributed respectively to F+I, J, and S (Fig. 4), whereas 0.35, 0.55, and 0.10 are the weightings respectively attributed to F+I, J, and S (Fig.6, Table 6, numbers in bold).

Criterion	Sub-component of TF	Weighting	Evaluation level (EL)			
			H	M	L	VL
Material compatibility (MC)	F+I	0.42	100	17	-	0
	J	0.08	100	17	-	0
	S	0.50	100	17	-	0
Material permanence (MP)	F+I	0.56	100	75	38	0
	J	0.06	100	89	78	67
	S	0.38	73	45	18	0
Structural reliability (SR)	F+I	**0.35**	100	71	**41**	20
	J	**0.55**	100	58	**25**	8
	S	**0.10**	100	47	**15**	7
Structural authenticity (SA)	F+I	0.45	100	80	35	20
	J	0.45	100	70	25	10
	S	0.10	100	70	35	10
Visual-tactile appearance (VTA)	-	-	100	44	22	11

Table 6 – Summary chart of cardinal values calculated from Macbeth matrices

The next step of this analysis consisted of the assignment of a relative weight to each criterion. This step involved setting up separate Macbeth models corresponding to three design-related models (Fig. 8, Value tree). These are listed according in ascending order of intrusiveness of the intervention, depending in turn on the degree of authenticity and on the level of structural safety of the building (Table 7).

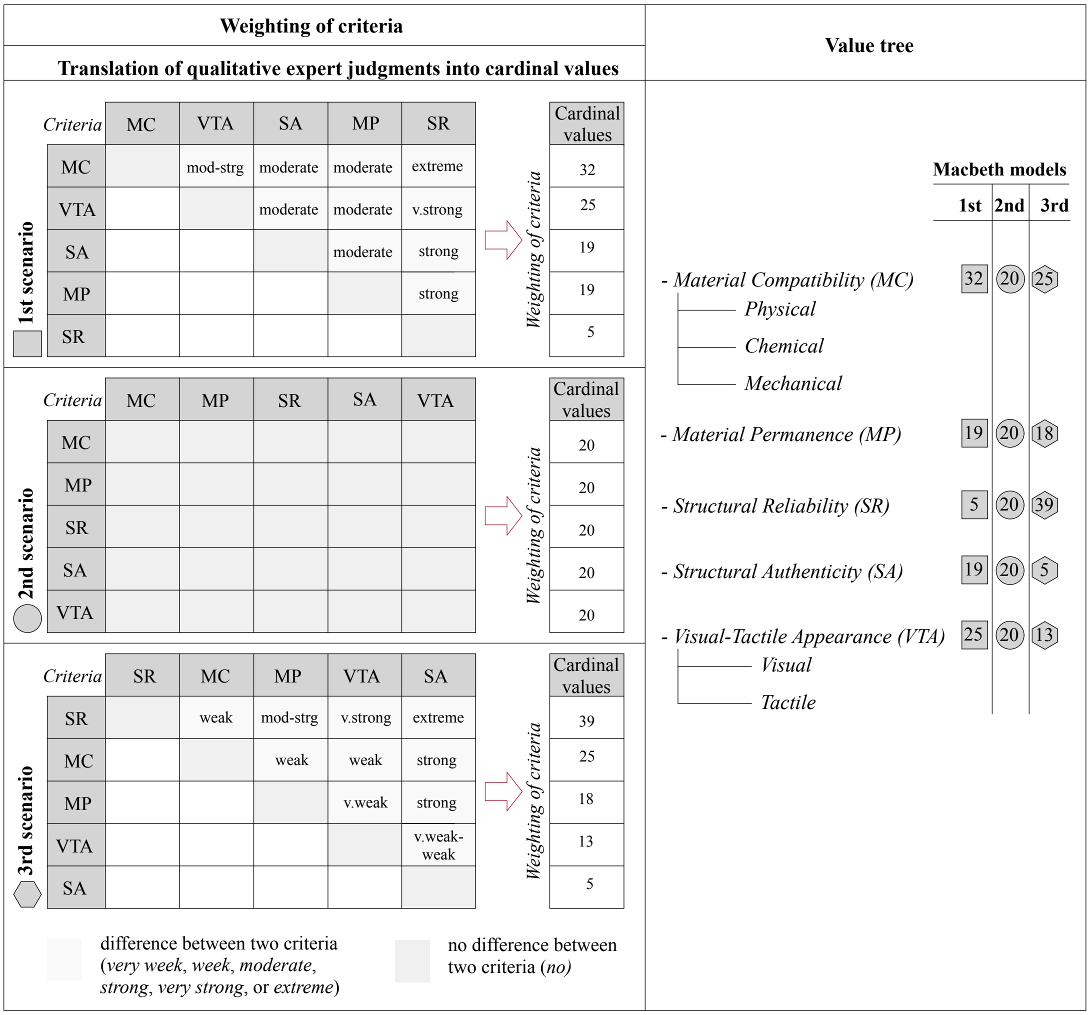


Fig. 8 – Macbeth judgment matrices related to the difference of attractiveness between each criterion (three scenario models)

Finally, each scenario, to which the value scores of the options are associated, can be selected by the decision-maker (building owner or users) on the basis of the state of conservation of the building components (Table 7).

Pre-existing conditions of the building		Scenario model	Criteria Weightings (%)					1st quarter best-scoring solutions
Degree of integrity and authenticty	Level of structural safety		MC	SR	SA	MP	VTA	
High	Satisfactory	1st	32	5	19	19	25	TF01:88. 67 TF04=TF10: 84.55 TF82=TF86=TF102: 74.99
Medium	Satisfactory	2nd	20	20	20	20	20	TF13: 78.40 TF07: 77.19 TF01: 76.16
Low/Very Low	Unsatisfactory	3rd	25	39	5	18	13	TF13: 78.24 TF07: 77.94

Table 7 – Scenarios and best-scoring solutions obtained by Macbeth analysis

4. Results and discussion

4.1. A set of incomparability and consistency of pairwise evaluations

A set of incomparability, arising from possible diverging judgments of the experts on the different criteria [1] can be identified, for example in relation to a pairwise comparison of the global scores of material compatibility (MC) versus structural reliability (SR)(Fig. 9, Table 6). In fact, the individual scores of these solutions reach the highest value for MC and low values for SR. This reflects the different weightings attributed to the repair measures on the joints (J1a or J1b) in the calculation of the global assessment for these criteria. When evaluating MC, the intervention on the joints is weighted by a very low value (0.08), whereas it is weighted by a high value (0.55) when referring to the structural reliability (Table 6).

Another incomparability arises in the case of lack of replacement of the infill (F1+I3, Table 3): in the set of solutions between TF58 and TF81, MC ranges from 86 to 79, whereas VTA equals 11, as shown in Table 8 (left).

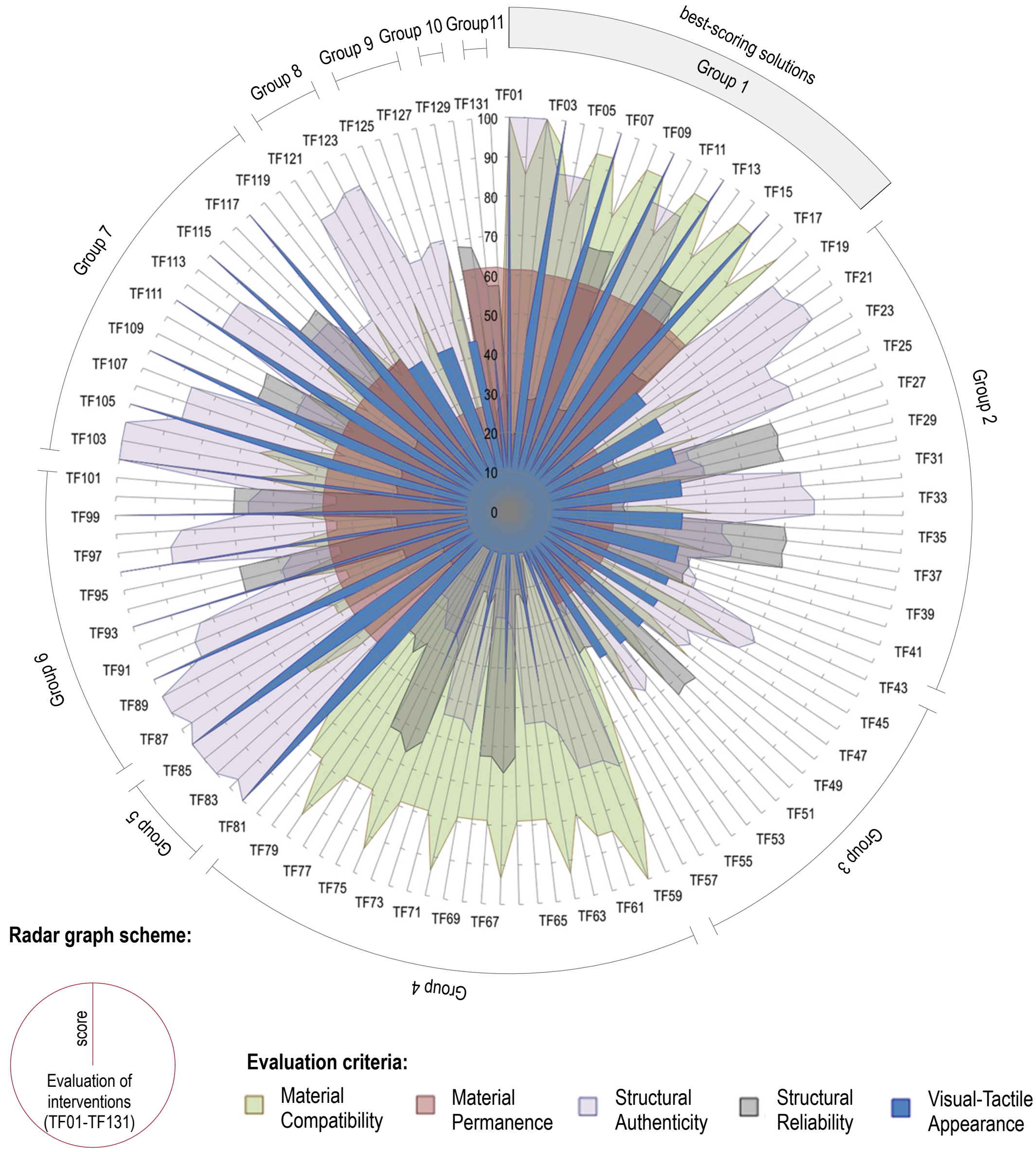


Fig. 9 – Evaluations under five criteria: Incomparability and consistency

On the other hand, the evaluations of MC and of SA show consistent outputs (Table 8, left).

Intervention	Evaluations		
	SR	MC	SA
TF01	19	100	100
TF02		86	
TF03	20	100	
TF04	29	93	87
TF06	30		
TF10	29		
TF12	30		
TF59	16	100	70
TF63	25	93	

INCOMPARABILITY (SR–MC)

CONSISTENCY (MC–SA)

Intervention	Evaluations	
	MC	VTA
TF02, TF58, TF60 TF61	86	11
TF05, TF08, TF11, TF14, TF17, TF19, TF62, TF64/TF66, TF68/TF70, TF72/TF74, TF76/TF78, TF80, TF81	79	11

INCOMPARABILITY (MC–VTA)

Table 8 – Incomparability and consistency of pairwise evaluations (on left: MC vs SR, MC vs SA; on right: MC vs VTA)

The best-scoring solutions for MC also score the best for SA (e.g. TF01-TF03, Group 1). However, this consistency is not found when the surface finish is made of cement mortar (S1b), or of cement-based mortar with metal mesh and acrylic render (S2). In these cases, the solutions achieve only moderate scores for SA, due to the low weighting (0.10) applied to the surface finish under SA. Conversely, the low scores for MC result from the high weighting attributed to surface finish (0.50)(Table 6).

4.2. Predominance of five best solutions in three selected scenarios

In order to provide a preliminary screening of the results, all combinations characterized by a low global weighted score in all three scenarios (lower than 50) were discarded; 74 options were thus excluded from the following analysis.

Based on the different target reliability levels – repair or strengthening measures – each distinct solution was evaluated as a function of its specific applicability to each scenario:

- The first scenario consists of repair measures whose structural reliability values are lower than 30 (28 options);
- The second scenario consists of a combination repair and strengthening measures (39 options);
- The third scenario consists of strengthening measures whose structural reliability values are higher than 30 (29 options).

The high weighting of material compatibility (MC) in all scenarios (Table 7) results in the best-scoring solutions all belonging to Group 1 (Figs. 9, 10).

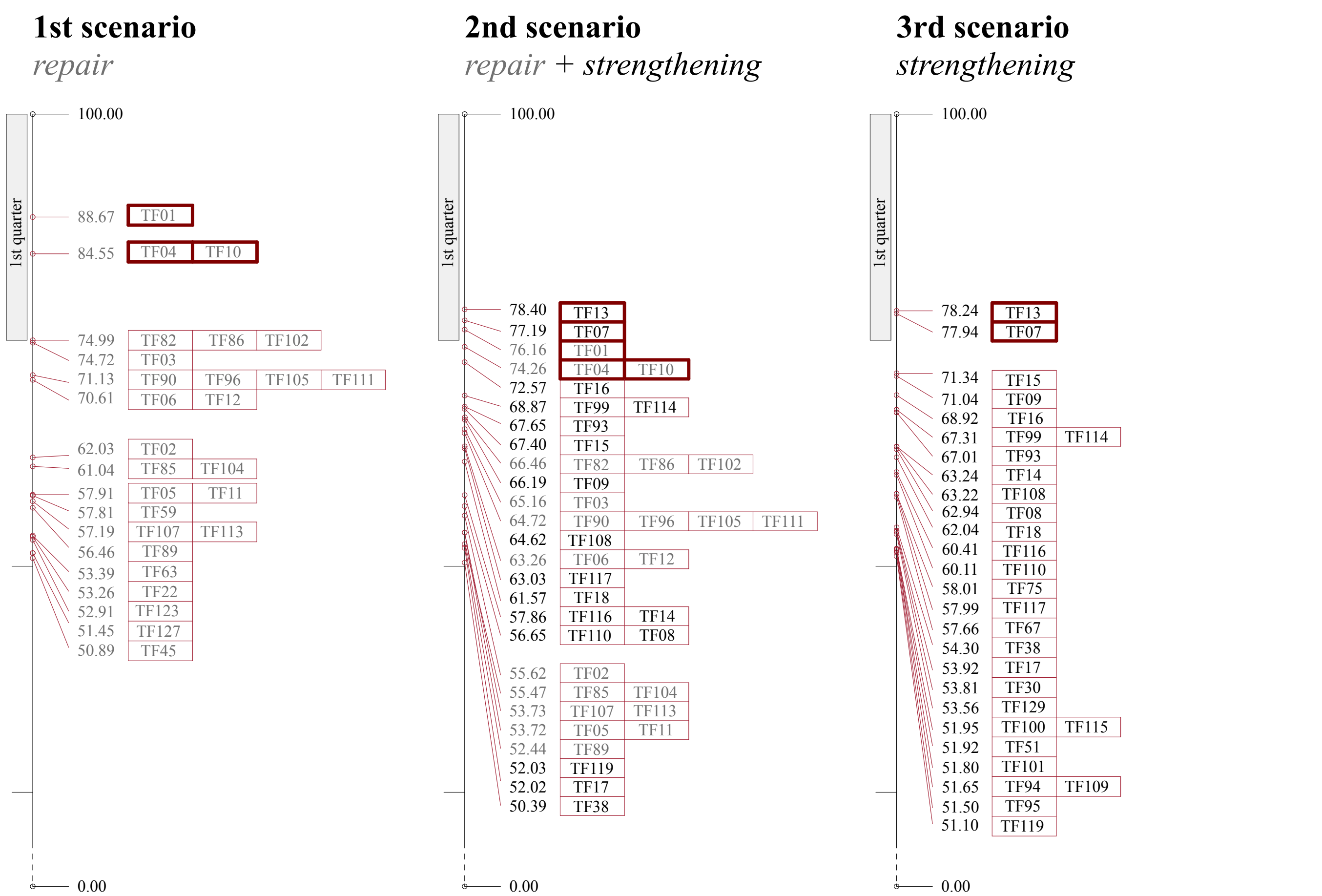


Fig. 10 – Visual scoring: 1st, 2nd, 3rd scenario

The best set of solutions to adopt within these three selected scenarios is highlighted in Table 9:

Intervention	Aim	Sub-type of intervention: FRAMEWORK+INFILL (F+I)	Sub-type of intervention: JOINTS (J)	Sub-type of intervention: SURFACE FINISH (S)
TF01	*repair*	**F1:** Substitution of local decayed timber elements with autoclaved timber components *+ either* **I1:** Partial removal of infill and repair of the brick or rubble masonry *or* **I2a:** Replacement of infill using clay bricks (or roof tiles) and hydraulic lime mortar	**J1a:** Recovery of carpentry joints using: wooden pegs and pins *or* **J1b:** stainless steel nails	**S1a:** Mono or multi-layer plaster by using NHL-based and/or lime-based render reinforced by fiberglass mesh
TF04	*repair*		**J2a:** Strengthening carpentry joints using stainless steel bolts	
TF07	*strengthening*		**J2b:** Strengthening carpentry joints using stainless steel plates with bolts	
TF10	*repair*		**J2c:** Self-tapping stainless steel screws	
TF13	*strengthening*		**J2d:** Strengthening carpentry joints using NSM (steel bars or FRP bars)	

Table 9 – Best-scoring solutions obtained by Macbeth analysis

These five best-scoring solutions consist of similar interventions on timber framework, infill, and surface, whereas they differ on four types of intervention for the joints. Therefore, under the same interventions on the wooden components and surface finish, additional criteria can be taken into account for the comparison of these best solutions, i.e. the average costs and time required to repair or strengthen the joints.

A proper carpentry joint recovery can be carried out only by an experienced timber framer by drilling peg holes and using wooden pegs and pins (draw boring). Additionally, repair procedures are quite time demanding. Recourse to bolts or self-tapping screws can save time and keep costs low (not more than 12€ per wall), whereas the use of steel plates, although not time-consuming (the application can be accomplished in one day), substantially increases the costs (approximately 130€ per wall). Lastly, retrofitting performed with NSM steel flat bars is somewhat more affordable than steel plates (around 100€ per wall), yet it takes 8 days to retrofit one wall (1 day for opening the slots and 7 days to apply the glue and let it dry). Moreover, precise workmanship is required to open the slots.

4.3. Research limitations and forthcoming perspectives

The main limitations of this study regard different aspects: problem structuring, scope of application, gaps in scientific understanding (or dissemination of experimental data) related to the original components, and potential disconnect between the evaluation in theory and the real result of the interventions (arising from questions of quality of workmanship).

Firstly, this research process is time-consuming due to the large number of model inputs and the poor interoperability and interface of data. On the other hand, the fast processing of the outputs makes it feasible to re-run the analysis while varying specific inputs.

Secondly, the authors are evaluating the impact of a set of interventions on a single construction component whose behaviour actually depends on the global performance and interactions of other members. The experts' judgments are affected by uncertainty around the real configuration of this composite system.

Thirdly, despite a considerable scholarly interest in this type of wall and the current need to recover timber-framed buildings in several countries (including Portugal), several knowledge gaps can be still identified. Experts' uncertainty arises from a lack of information related to the impact of the combined rehabilitation measures of all sub-components of the timber frame wall. Recent laboratory campaigns in Portugal on un-reinforced and reinforced tested specimens of TF clarify the influence of the infill and the effectiveness of the interventions on the joints in the mechanical behaviour but do not provide sufficient data as regards the interaction of the structure wall (F+I) and the surface finish (S) under static and cyclic loadings [10, 33]. As matter of fact, the placement of surface finish on the specimens was completely neglected in these frame tests, although an increase of the stiffness and of the mechanical strength of the whole system can be induced by a simple modification of the surface finish thickness. Conversely, the seismic performance of plastered timber frames of traditional Turkish buildings (*himis*) under reverse-cyclic loading was evaluated by Aktas and Turer [42].

Additionally, experts' evaluations are probabilistic. These concern ideal solutions and thus neglect several factors that may occur at the work site, one of which is related to the quality of workmanship. In fact, as noted by Aktas and Turer for traditional timber-framed systems in Turkey and also valid for this case study, the quality of workmanship strongly influences the reliability of the intervention for the lateral load–displacement relationships and for the overall behavior of the wall. These scholars observe a variation in quality for work done even by the same group of builders on a limited set of frames. In particular, the quality of the connection (e.g. number of nails at each connection and their driving angles), which influences the strength and stiffness, may vary from frame to frame within the same wall. Poor detailing, lack of proper reinforcement in the joint region, or lack of proper infill geometry can cause brittle failure mechanisms at the local level [42]. This makes it difficult to generalize the findings of these frame tests, and thus may affect the objectivity of the evaluation under the SR criterion.

Regardless of these aspects, the novelty of this research is two-fold: firstly, an overview of the current intervention techniques for traditional timber frame walls is provided from an extensive survey; secondly, the involvement of a technical panel of experts on rehabilitation techniques is examined under a variety of criteria.

Although built heritage conservation demands a multi-disciplinary approach and involves multifaceted cultural and economic value, the current practice is largely determined by the requirements or preferences of relatively few decision makers. As an alternative, a well-informed, interactive, and transparent procedure is called for. To this end, this research includes the involvement of multi-disciplinary experts in conservation sciences throughout all phases of problem structuring (Fig.4).

Once the decision-making process has been concluded, the following questions can be addressed:

1. Which are the greatest advantages and drawbacks of using Macbeth or other multi-criteria analysis tool in the domain of the built heritage rehabilitation?

The benefits of using of Macbeth analysis are the involvement of multi-disciplinary experts and the possibility of evaluating different options under tailor-made parameters for the domain of cultural heritage, i.e. non-numerable, non-homogeneous, and conflicting criteria. Experts frequently have difficulty assigning a direct numerical value to the weightings of criteria and their performance levels. As shown in this research, they feel more comfortable in making comparisons through semantic judgments by expressing the importance (or attractiveness) of preferences between every element of evaluation.

The goal is to reach a consensus within a group of experts, some of whose standpoints are conflicting, by fostering a debate during the attribution of semantic value to the difference between each pair of attributes.

2. From the different standpoints of the group of experts, which alternatives are expected to score best?

The expected best-scoring alternatives for each group of experts, with the respective value scores processed by Macbeth, are almost entirely different depending on field of expertise.

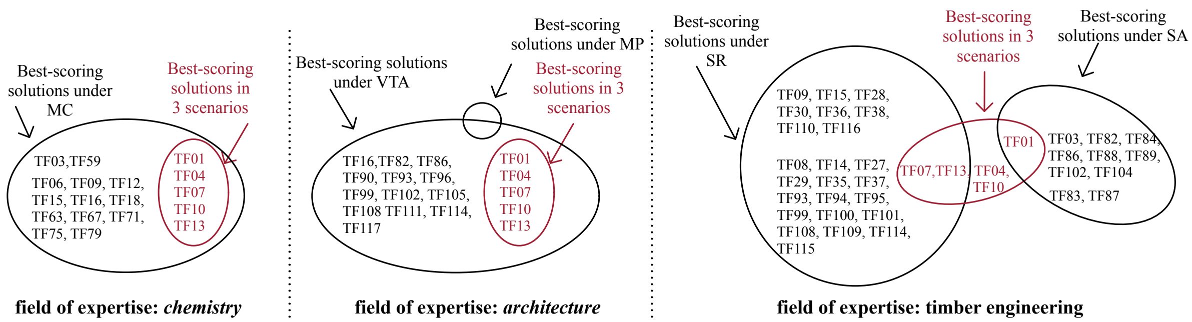


Figure 11 – Expected best-scoring solutions from different fields of expertise

A comparison of the 1st quarter of the best solutions (Table 7) and the expected best-scoring alternatives, which reflect the experts' preferences (value scores >70/100, Fig.11), shows that most of Macbeth's results were predictable, especially for the chemist and architect groups. We can note that the best-scoring solutions for MP criterion do not reach 70/100, because all the analysed solutions involve surface removal (Fig.11).

3. Can a compromise be found between multiple and conflicting aims and practical solutions in current rehabilitation works?

The five best-scoring solutions identified in Table 9 integrate standpoints and preferences of a multi-disciplinary panel of experts within three design-related scenarios. Balancing a variety of criteria, these solutions can be recommended by the technicians to the building owner and finally employed by the contractors.

5. Conclusions

The rehabilitation of historic buildings is a complex task, affected by different instances arising from users' and property developers' interests, code-required actions, and the need to preserve the cultural significance of the construction. Conflicting aims pursued by multiple stakeholders can threaten the cultural value of the architectural heritage, especially in contexts of high real estate demand, as is currently the case in downtown Lisbon.

In this research, the question of the best rehabilitation techniques for the traditional timber frame wall is examined under a variety of criteria by dedicated software (M-Macbeth, *Measuring Attractiveness by a Categorical-Based Evaluation Technique*).

The main limitations of this research were identified during the problem structuring and throughout the assessments of the rehabilitation techniques influenced by a lack of adequate specific information (or dissemination of experimental data) related to the original components and by the quality of workmanship, which may significantly affect this analysis.

Future applications of the Macbeth analysis can support the selection of the best practice for different types of vertical structure of braced timber frame buildings, i.e. masonry reinforced with timber frames, rubble store masonry or partitions walls.

This methodology can be further applied to other scenario models that embrace different requirements of the owners or users, e.g. energy saving and cost effectiveness.

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References

[1] A. Ishizaka, P.Nemery, Multi-criteria Decision Analysis: Methods and Software, John Wiley & Sons New Yersey (2013).

[2] J. Mustajoki, M. Marttunen, Finnish Environment Institute, Searching for ideas for developing a new EIA-specific multi-criteria software. Comparison of Multi-Criteria Decision Analytical Software (2013).

[3] V. Ferretti, E. Comino, An integrated framework to assess complex cultural and natural heritage systems with Multi-Attribute Value Theory, Journal of Cultural Heritage 16 (2015) 688–697. http://dx.doi.org/10.1016/j.culher.2013.12.007

[4] C.A. Bana e Costa, A methodology for sensitivity analysis in three-criteria problems: a case study in municipal management, European Journal of Operational Research 33 (1988) 159-173.

[5] C. A. Bana e Costa, R.C. Oliveira, Assigning priorities for maintenance and repair and refurbishment in managing a municipal housing stock, European Journal of Operational Research138 (2)(2002) 380-391.

[6] M.H. Barreiros, Urban Landscapes: Houses, Streets and Squares of 18th Century Lisbon, Journal of Early Modern History, Volume 12 (3) (2008) 205-232.

[7] J. Mascarenhas, Sistemas de Construção – V, O Edifício de Rendimento da Baixa Pombalina de Lisboa, Livros Horizonte, Lisbon (2004).

[8]J. Appleton, Reabilitação de Edifícios Antigos. Patologias e tecnologias de intervenção, Edições Orion, Lisbon (2003).

[9] V. Cóias, Reabilitação Estrutural de Edifícios Antigos - Alvenaria, Madeira -Técnicas pouco intrusivas, Argumentum & Gecorpa, Lisbon (2007).

[10] E. Poletti, G. Vasconcelos, Seismic behaviour of traditional timber frame walls: experimental results on unreinforced walls, Bulletin of Earthquake Engineering 13 (2015) 885–916. doi: 10.1007/s10518-014-9650-9

[11] INE - Census in Portugal from 1864 to 2011, available in: http://censos.ine.pt/xportal/xmain?xpid=INE&xpgid=censos_historia_pt

[12] Decree-Law no. 53/2014 (2014) Exceptional and temporary legal framework for the rehabilitation of existing buildings or fractions, Official Journal (PT) Ser 1(69) 2337–2340. Available at https://dre.pt/application/file/25344956

[13] J.P. Branco; V. Campos, Building regulation and Existing Buildings: Setting the Requirements on Structural Safety in Portugal, Historical Earthquake-Resistant Timber Framing in the Mediterranean Area. Eds. Cruz, H.; Saporiti Machado, J.; Campos Costa, A.; Xavier Candeias, P.; Ruggieri, N.; Manuel Catarino, J. (2016) 253-262.

[14] J. Ortega, G. Vasconcelos, H. Rodrigues, M. Correia, P.B. Lourenço, Traditional earthquake resistant techniques for vernacular architecture and local seismic cultures: A literature review, Journal of Cultural Heritage (2017), In press

[15] R. Langenbach, Don't Tear It Down! Preserving the Earthquake Resistant Vernacular Architecture of Kashmir (2009).

[16] ICOMOS–ISCARSAH, International Scientific Committee for Analysis and Restoration of Structures of Architectural Heritage, Principles for the Analysis, Conservation and Structural Restoration of Architectural Heritage (2004).

[17] ICOMOS, Venice Charter. Venice, Italy: Second International Congress of Architects and Technicians of Historic Monuments (1964).

[18] UNESCO, Centre Operational Guidelines for the Implementation of the World Heritage Convention (2005).

[19] H.Cruz, D.Yeomans, E.Tsakanika, N. Macchioni, A. Jorissen, M. Touza, M. Manucci, P.B. Lourenço, Guidelines for On-Site Assessment of Historic Timber Structures, International Journal of Architectural Heritage 9 (2015) 277-289. http://dx.doi.org/10.1080/15583058.2013.774070

[20] A.G. Cattanach, G.W. Alley, A.W. Thornton, Appropriateness of Seismic Strengthening Interventions in Heritage Buildings: A Framework for Appraisal, NZSEE Conference (2008) 6.

[21] R. van Hees, R. Veiga, Z. Slížková, Consolidation of renders and plasters, Materials and Structures 50 (12)(2017) 65. doi. 10.1617/s11527-016-0894-5

[22] MCHA, Guidelines for Evaluation and Mitigation of Seismic Risk to Cultural Heritage, Gangemi editore, Rome (2007).

[23] NP EN 1998 – 1: 2010. Norma Portuguesa, Eurocódigo 8 – Projecto de estruturas para resistência aos sismos. Parte 1: Regras gerais, acções sísmicas e regras para edifícios, IPQ, Lisbon (2010).

[24] FEMA (Federal Emergency Management Agency), Guidelines for the Seismic Rehabilitation of Buildings (1997).

[25] FEMA (Federal Emergency Management Agency), Incremental Seismic Rehabilitation of Retail Buildings (2014).

[26] OPCM 3274: 2003 - Primi elementi in materia di criteri generali per la classificazione sismica del territorio nazionale e di normative tecniche per le costruzioni in zona sismica.

[27] ÖNORM EN 1998-1:2011- 06-15. Eurocode 8: Auslegung von Bauwerkengegen Erdbeben -Teil 1: Grundlagen, Erdbebeneinwirkungen und Regeln für Hochbauten.

[28] B. Pizzo, N. Macchioni, P. Lavisci, M. De Ciechi, On-site consolidation systems of old timber structures. In C. Bertolini Cestari, T. Marzi, E. Seip, P. Touliatos (Eds.) Proceedings Interaction Between Science, Technology and Architecture in Timber Construction, Elsevier Science, Heritage Series, Collection Patrimoine (2004) 323-352.

[29] H. Cruz, J.P. Moura, J.S. Machado, The use of FRP in the strengthening of timber-reinforced masonry load-bearing walls, in: P.B. Lourenço, P. Roca (Eds.), Historical constructions (2001) 847-856.

[30] J.C. Appleton, I. Domingos, Biografia de um Pombalino, Lisbon, Livros Horizonte (2009).

[31] C. Campanella, J.M. Mateus, Obras de conservação e restauro arquitectónico: condições técnicas especiais (2003), Lisbon, CML.

[32] E. Tsakanika-Theohari, The constructional analysis of timber load bearing systems as a tool for interpreting Aegean Bronze Age architecture, Verein zur Förderung der Aufarbeitung der Hellenischen Geschichte e.v. (Eds.), Proceedings of the Symposium Bronze Age Architectural Traditions in the Eastern Mediterranean: Diffusion and Diversity, Weilheim, Munich (2010) 127-139.

[33] A.M. Gonçalves, J. Gomes-Ferreira, L. Guerreiro, F. Branco, Seismic retrofitting of timber-framed walls, Materiales de Construcción 64 (36)(2014) e040. http://dx.doi.org/10.3989/mc.2014.06913

[34] A. Bianco, La casa baraccata. Guida al progetto e al cantiere di restauro, Rome, GBeditoria (2010).

[35] E. Poletti, G. Vasconcelos, M. Jorge. Application of near surface mounted (NSM) strengthening technique to traditional timber frame walls, Construction and Building Materials (76) (2015) 34 -50. https://doi.org/10.1016/j.conbuildmat.2014.11.022

[36] C. Ceraldi, C. D'Ambra, M. Lippiello, A. Prota, Restoring of timber structures: connections with timber pegs, European Journal of Wood and Wood Products (2017)1-15 doi: 10.1007/s00107-017-1179-6.

[37] Arrow, K.J., Social choice and Individual values (1951), Wiley, New York.

[38] Kujawski, E., Multi-Criteria Decision Analysis: Limitations, Pitfalls, and Practical Difficulties (2003) http://escholarship.org/uc/item/0cp6j7sj

[39] J.C. Soares de Mello, E.G. Gomes, M.H. Soares de Mello, M.P.Lins, Método multicritério para seleção de variáveis em modelos DEA, Pequisa Operacional (15) (2002) 55-66.

[40] L.A. Rangel, J.C. Mello, E.G. Gomes, L.F. Gomes, Avaliação da interiorização dos cursos da Universidade Federal Fluminense com o uso conjugado dos métodos UTA e MACBETH, Investigação Operacional 23 (1) (2003) 49-69.

[41] B. Roy, Multicriteria Methodology for Decision Aiding, Dordrecht, Kluwer Academic (1996).

[42] Y.D. Aktas, A.Turer, Seismic performance evaluation of traditional timber hımış frames: Capacity spectrum method based assessment, Bulletin of Earthquake Engineering (14)(2016) 3175-3194. doi:10.1007/s10518-016-9943-2