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Implications of masonry infill–related uncertainty on the optimal seismic retrofitting of existing buildings

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ABSTRACT: Many research efforts have focused on developing multi-criteria decision-making (MCDM) processes for selecting the optimal seismic retrofit alternative when several important decision variables (DVs) need to be considered. Those DVs can include, amongst others, economic, social, technical, or even environmental aspects. For what concerns the technical DVs related to the structural response of poorly-detailed existing buildings, investigation of the uncertainties involved in the process is still needed to understand whether and how they can affect the identification of the optimal retrofitting alternative. In this sense, this paper addresses the impact of the uncertainty related to the variability in the mechanical properties and modelling of masonry infills on the results obtained with the aforementioned MCDM processes to identify risk-based optimal combined seismic-energy retrofitting strategies for a case-study building, representative of typical school buildings in Italy. Following a preliminary structural and energy assessment, different retrofit alternatives are evaluated through a MCDM framework to select the optimal solution. Finally, the MCDM results are presented, highlighting the effects of the variability in the infill properties, a source of uncertainty that is commonly discarded.

1. INTRODUCTION

The occurrence of past earthquakes highlighted the vulnerability of masonry-infilled reinforced concrete (RC) buildings, which represent a large part of the overall building stock in Mediterranean countries. Most of these buildings were built before the introduction of modern codes; hence they lack appropriate seismic resistance. Moreover, the energy performance of this type of buildings is highly unsatisfactory, resulting in high energy consumption, significant costs, and increased CO_2 emissions (Gkatzogias et al. 2022).

Recently, significant focus has been given to the development and evaluation of combined seismic and energy retrofitting schemes, with a view to minimise the economic losses and environmental impacts and promote building renovation (e.g., Marini et al., 2017; Menna et al., 2021; Caruso et al., 2022, Clemett et al. 2023).

Given the wide range of possible structural and energy retrofitting schemes to couple in an integrated scheme, it is essential to proceed with methodologies that aim to identify an optimal integrated retrofit solution. Some of those methods, such as seismic resilience-based assessments, index-based methods, cost-benefit analyses and multi-criteria decision-making (MCDM) approaches, scrutinised and compared by Carofilis et al. (2022a), often consider a range of economic, social and technical decision variables (DVs) that are typically of interest to decision-makers. Different weights are usually given to the DVs, following the intuition of the decision maker or determined through more rigorous criteria. Technical DVs related to the structural response of existing buildings are of paramount importance due to their influence on the identification of the optimal retrofit alternative and are usually characterised by a higher weight when compared to other DVs. Accordingly, the effects of both aleatory and epistemic uncertainty on the seismic response parameters could have a relevant impact on the identification of the optimal retrofit alternative.

This paper addresses the impact of the epistemic uncertainty related to the variability in the mechanical properties of masonry infills on the results obtained with an MCDM procedure employed for selecting the optimal integrated retrofitting scheme of a school building located in Italy.

2. OPTIMAL COMBINED SEISMIC AND ENERGY EFFICIENCY RETROFITTING

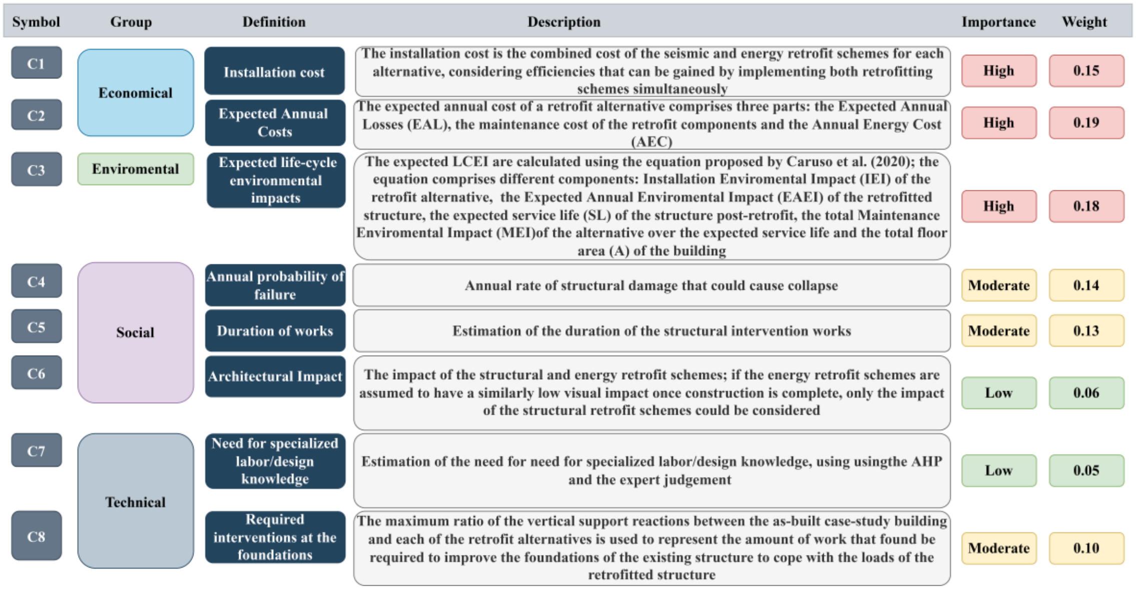
2.1. Multi-criteria decision-making framework

One of the most appealing frameworks for the identification of the optimal combined seismic and energy efficiency retrofitting intervention is based on an MCDM approach, which considers the performance of different retrofit alternatives across a broad range of decision variables (DVs) and uses a weighted average method to identify the optimal solution. This methodology, employed in the present study, has been described extensively in Caterino et al. (2008) and Carofilis et al. (2022a).

The process initiates with the identification of a set of DVs, with which the performance of each retrofitting alternative will be assessed, and to each of which a weight is assigned as a function of its importance. The Analytical Hierarchy Procedure (AHP) (Saaty 1980) or decision-maker expertise can be used to define the weight values. Once the values for each DV are obtained, a decision matrix (DM) can be assembled, containing the associated values for each retrofit intervention. The values of the DM are then normalised and the ideal and least ideal solutions for each decision variable are determined, allowing a comparison with each of the proposed design alternatives. To do so, the n-space Euclidean distance between the DM values for the design alternative and the ideal and least ideal alternatives is used. Finally, the relative closeness of each alternative to the least ideal solution is calculated, and the alternative with the highest relative closeness (i.e., the furthest alternative from the least ideal) is chosen as the preferred solution.

2.2. Decision Matrix and Weight Vectors

The DVs and corresponding weights applied in this study are depicted in Figure 1, following the study by Clemett et al. (2023). The weight vector was defined employing the AHP and the professional judgment of the authors. DVs like C1, C2, and C3 are considered more relevant, demonstrated by the value of their corresponding weights, while C6 and C7 are considered less relevant. The choice of the weight vector was found to be the most significant source of uncertainty in the MCDM procedure and, consequently, in their results, as reported by Carofilis et al. (2022b). Interested readers are referred to Clemett et al. (2023) for more details on the MCDM framework used herein, as well as on the definition of both decision matrix and weight vectors.



Symbol	Group	Definition	Description	Importance	Weight
C1	Economical	Installation cost	The installation cost is the combined cost of the seismic and energy retrofit schemes for each alternative, considering efficiencies that can be gained by implementing both retrofitting schemes simultaneously	High	0.15
C2		Expected Annual Costs	The expected annual cost of a retrofit alternative comprises three parts: the Expected Annual Losses (EAL), the maintenance cost of the retrofit components and the Annual Energy Cost (AEC)	High	0.19
C3	Enviromental	Expected life-cycle environmental impacts	The expected LCEI are calculated using the equation proposed by Caruso et al. (2020); the equation comprises different components: Installation Enviromental Impact (IEI) of the retrofit alternative, the Expected Annual Enviromental Impact (EAEI) of the retrofitted structure, the expected service life (SL) of the structure post-retrofit, the total Maintenance Enviromental Impact (MEI)of the alternative over the expected service life and the total floor area (A) of the building	High	0.18
C4	Social	Annual probability of failure	Annual rate of structural damage that could cause collapse	Moderate	0.14
C5		Duration of works	Estimation of the duration of the structural intervention works	Moderate	0.13
C6		Architectural Impact	The impact of the structural and energy retrofit schemes; if the energy retrofit schemes are assumed to have a similarly low visual impact once construction is complete, only the impact of the structural retrofit schemes could be considered	Low	0.06
C7	Technical	Need for specialized labor/design knowledge	Estimation of the need for need for specialized labor/design knowledge, using usingthe AHP and the expert judgement	Low	0.05
C8		Required interventions at the foundations	The maximum ratio of the vertical support reactions between the as-built case-study building and each of the retrofit alternatives is used to represent the amount of work that found be required to improve the foundations of the existing structure to cope with the loads of the retrofitted structure	Moderate	0.10

Figure 1 Decision Matrix and Weight Vectors (according to Clemett et al. 2023)

3. INFILL VARIABILITY AND EPISTEMIC UNCERTAINTY

Despite the high-level of uncertainty surrounding the masonry infill properties, constant mechanical and geometrical properties are typically assumed in seismic risk assessment studies both at single-building and regional scale. Furthermore, a proper identification and propagation of uncertainty in the collapse assessment of existing structures are of paramount importance when detailed nonlinear structural analysis methodologies are adopted; hence an explicit consideration of the variability in the masonry infill characteristics should be considered for a refined collapse and loss estimation. Recently, to overcome the lack of in-situ test results on masonry infills, a macro-distinction approach of different masonry infill typologies was proposed by Mucedero et al (2020), based on masonry infill strength. Five masonry infill typologies were selected as representative of the existing masonry infill typologies used in RC residential buildings, and their representativeness was proved with respect to the ranges of masonry infill properties provided in an experimental tests database available in the literature. Several studies investigated the impact of different sources of epistemic and aleatory uncertainty on the seismic assessment of RC buildings, although little attention was paid to the impact of the uncertainty related to the variability of masonry infill properties, in a thorough manner. Recently, O'Reilly and Sullivan (2018), using the Correlated Latin Hypercube Sampling method, proposed by Olsson et al. (2003), have investigated and quantified the uncertainty associated with different modelling parameters for existing RC frames in Italy, with and without masonry infills. More recently, Mucedero et al. (2022) further integrated the estimation of modelling uncertainty in existing buildings, using a case-study masonry-infilled RC frame from an extensive building stock (Mucedero et al., 2021), representative of existing RC frames built in Italy between 1970 and 1980, and covering some important aspects that were unaddressed by previous research studies. More details are provided in (Mucedero et al., 2022). With such considerations in mind, this study investigates the implications of masonry infill–related uncertainty on the seismic retrofitting of existing buildings, combined, in an optimal manner, with energy retrofitting. The overall impact of a more robust characterisation and propagation of uncertainty is therefore evaluated.

4. CASE-STUDY SCHOOL BUILDING

The case-study school building is a RC building with unreinforced masonry infills (URM) infills located in Isola del Gran Sasso d'Italia (Italy) and built between the 1960s and 1970s (Prota et al. 2020). The school is a two-storey building, with a floor area of approximately 630m2 and interstorey heights of 3.75m and 4.25m for the first and second floor, respectively. The structural system consists of two-way RC moment resisting frames in the longitudinal and transverse directions, and URM infills are present along the building façade with large openings to accommodate windows and doors.

In this study, the masonry infills were assumed to have the same geometry and material properties as the medium-strong masonry infill typology in the macro-level classification proposed by Mucedero et al. (2020). A more detailed description of the building, along with its architectural plans and elevations, can be found in Prota et al. (2020).

The building is assumed to be located in three different locations in Italy in order to investigate the influence of different combinations of climatic conditions and seismic hazard levels on the choice of the optimal retrofit alternative. The three locations, namely Città di Castello, Isola del Gran Sasso d'Italia and Catania, are characterised by cold (C), moderate (M) and warm (W) climates, respectively, and similar moderate to high levels of seismicity.

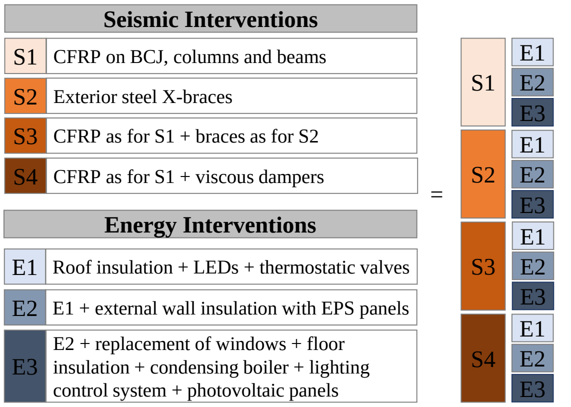
4.1. Selected seismic and energy retrofitting schemes

Following a preliminary seismic and energy assessment, where the main deficiencies of the case-study structure were identified, different seismic and energy retrofit measures (SRMs and ERMs, respectively) were applied to the case-study building. A summary of the SRMs and ERMs is given in Figure 2.

The four SRMs schemes are: S1 – local strengthening with carbon CFRP; S2 – global strengthening with additional concentric steel braces; S3 – CFRP strengthening combined with additional concentric steel braces; and S4 – CFRP strengthening combined with additional viscous dampers. Additionally, for all SRMs, a seismic gap between the URM infills and the RC frame was introduced, reducing both the column-infill interaction and the shear forces acting on the columns.

Regarding the improvement of the energy performance of the building, three different combinations of ERMs, foreseen by the Italian Ministerial Decree (2015), were considered aiming to reduce heat losses to the external environment and increase the energy efficiency of systems operating within the given building. The modelling assumptions for each EMRs can be found in Clemett et al. (2023).

Finally, the four seismic interventions were coupled with each energy intervention, leading to twelve possible retrofit alternatives. Each coupled intervention is designated by SiEi, where Si and Ei correspond, respectively, to the reference number of the considered seismic and energy retrofit schemes.



Seismic Interventions	
S1	CFRP on BCJ, columns and beams
S2	Exterior steel X-braces
S3	CFRP as for S1 + braces as for S2
S4	CFRP as for S1 + viscous dampers

Energy Interventions	
E1	Roof insulation + LEDs + thermostatic valves
E2	E1 + external wall insulation with EPS panels
E3	E2 + replacement of windows + floor insulation + condensing boiler + lighting control system + photovoltaic panels

Figure 2 Selected seismic and energy retrofitting schemes.

4.2. Seismic and Energy Performance Assessment

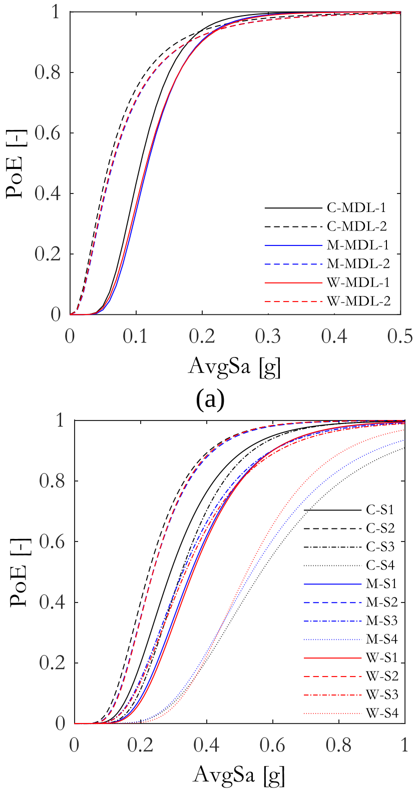
A comprehensive performance-based seismic assessment and loss analysis of the case-study building was carried out, following the PEER-PBEE methodology (FEMA 2018a). The seismic hazard at each of the three selected sites was characterised, and twenty pairs of ground motions were selected for each using the average spectral acceleration (AvgSa)-based selection. Using these records, the quantification of the structural response through multiple-stripe analysis (MSA) for each site was performed and, subsequently, the collapse fragility parameters were derived.

The median AvgSa (θ) and dispersion (β) values were modified to account for modelling uncertainties. Two sets of dispersion values were considered: the first set refers to an approach that does not include infill variability and premature RC shear failure (O'Reilly and Sullivan (2018)), named herein as MDL-1, whereas the second one corresponds to the recent integrated values proposed by Mucedero et al. (2022), named herein as MDL-2. Due to the gap between the URM infill and the RC frame introduced in all retrofitting schemes, the MDL-1 β values were used in the assessment of the retrofitting conditions.

Finally, a detailed loss assessment for the as-built and the twelve retrofit alternatives at each site was performed, using the PACT software (FEMA 2018b), and considering the component inventory of damageable components in the building and assumptions provided in Clemett et al. (2022).

The collapse fragility curves, considering the two dispersion sets for the as-built condition, are provided in Figure 3a. As also pointed out in Mucedero et al. (2022), a much lower median intensity of collapse is obtained when considering MDL-2, with respect to MDL-1. Nevertheless, for higher probability of collapse, the differences in terms of collapse fragility curves between the two dispersion sets diminish, and the curves almost coincide.

The collapse fragility curves for the four seismic retrofitting schemes, as a function of the three locations investigated, are provided in Figure 3b. The results provide a preliminary ranking of the seismic retrofitting schemes, based only on structural response, and regardless of the locations investigated (similar seismic hazard level): the best intervention is S4, followed by S3 and S1, which are almost similar, and finally S2. The global retrofit intervention, such as S2, without local retrofit, has the worst structural performance, since it is not able alone to overcome the high demand/capacity ratio of poorly-detailed structural members.



(a)

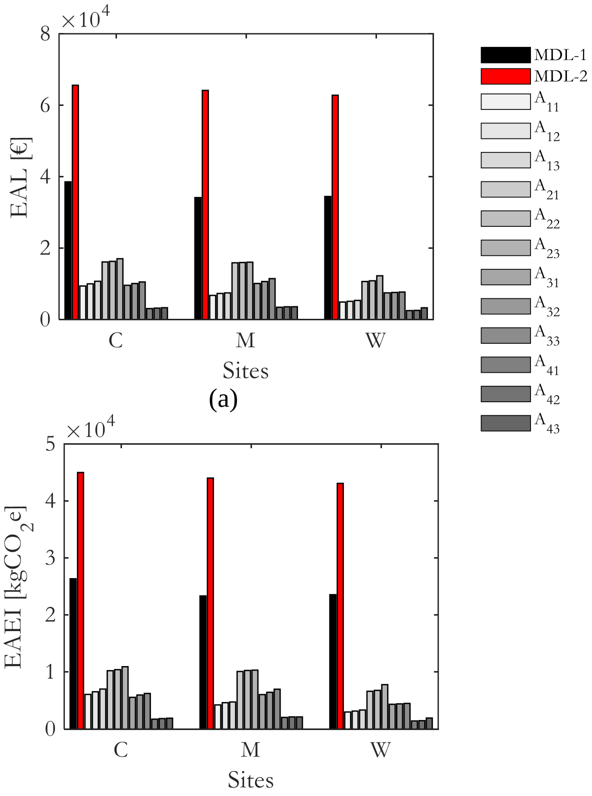
(b)

Figure 3 Fragility curves for each location investigated: (a) as-built condition considering MDL-1 and MDL.2; (b) retrofitted condition.

The obtained fragility curves were then used to perform a detailed component-based loss assessment (FEMA P-58) of the two as-built conditions (MDL-1 and MDL-2) and the twelve retrofit alternatives at each site. The results obtained in terms of expected annual losses (EAL) and expected annual environmental impacts (EAEI) for both the as-built condition and for each retrofit combination are provided in Figure 4, per investigated location.

The more recent dispersion values (MDL-2) confirmed higher EAL and EAEI losses with respect to those taken from previous studies (MDL-1). Also, the annual probability of failure (C4), is strongly affected by the dispersion sets considered, with a median increment of 45% when MDL-2 is employed. As such, the increments in EAL, EAEI and the annual probability of failure (APF) clearly affect the final ranking of the MCDM procedure, since the weights associated with these DVs are higher than the other ones.

The energy performance of the as-built and retrofitted configurations at each site was performed by Clemett et al. (2023), using EDILCLIMA (2021), and those results are used herein. The parameters considered to evaluate the energy performance were the primary energy performance (PEC), equivalent CO_2 emissions, annual energy costs (AEC), and Italian energy class ratings. The energy performance assessment performed by Clemett et al. (2023) showed a progressive improvement, from E1 to E3, in the energy performance of the case-study building, in line with the severity of the intervention.



(a)

(b)

Figure 4 EAL and EAEI for the as-built condition (with MDL-1 and MDL-2) and each of the 12alternatives, for each location investigated.

4.3. MCDM results and discussion

Once the results of the seismic and energy assessment were obtained, the decision matrices were assembled. Some DVs, such as C2, C3 and C4, were normalised with respect to the results obtained from the as-built condition. The weight vectors are defined according to Figure 1. The preferential ranking obtained from each analysis is presented in Table 1, in which the alternative in position one is considered the most preferred option, and the alternative in position 12 is the least preferred. Since two different sets of dispersion values for the as-built condition are considered, two sets of rankings for each site are presented, while their differences, in terms of ranking, are highlighted in grey. Moreover, the relative closeness values (Table 1) lie in the range (0,1), with 1 corresponding to the ideal solution, and can be used to understand how strongly one solution is preferred over another.

The MCDM results for MDL-1 show that the seismic retrofit scheme had a more significant effect on the overall ranking of an alternative than the energy retrofit scheme, at least for the warmer sites, M and W. The S4 scheme is the most preferred option, followed by S3, S2, and finally, S1. For C site, S3 is preferred, integrated with the E3 energy scheme.

Considering the ranking obtained with MDL-2, some changes are noticed, with respect to MDL-1. For site M, a reversal of the ranking intervention in positions 6 and 7 is observed. For site W, the changes are more important; indeed, MDL-2 seems to play a more significant role under warmer climate. Although the S4 retrofitting scheme remains the optimal one, the corresponding integrated energy schemes are different. Conversely, no changes in the ranking are noticed for the colder site, C.

In general terms, for sites M and W, the more recent dispersion values led to a ranking in descending order, with schemes S4 and E3 on the top, whilst S1 and E1 rank last. The relative closeness values are practically unaffected by the two different sets of epistemic uncertainty. These results show that, as heating demands increase, the impact of the energy retrofit alternatives on the ranking order becomes more important and consequently, more energy-efficient retrofit alternatives are the preferred solutions. It is interesting to note that, in case of MDL-1, the first-ranked alternative is different for each of the sites, whereas, in case of MDL-2 the first-ranked alternative is only different for the colder site, which denotes a preponderant role of the significant epistemic uncertainty in buildings of this sort. Given that a seismic gap was introduced for all retrofitting schemes, the impact of the infill variability is limited to the as-built condition. Therefore, considering retrofit schemes without the seismic gap, could lead to further implications on the optimal seismic retrofitting of existing buildings.

5. CONCLUSIONS

This study dealt with the implications of masonry infill–related uncertainty on the optimal seismic retrofitting of existing buildings. A case-study school building was investigated, considering two different estimates of epistemic uncertainty and different combinations of climatic conditions and seismic hazard levels. More complete (higher) dispersion sets of epistemic uncertainty led to a median increment of about 45% on the expected annual losses, expected annual environmental impact and annual probability of failures for each site. Given the relative importance of these decision variables in the adopted multi-criteria decision-making procedure, and how their values are affected by the selected set of epistemic uncertainty, the importance of carefully defining the epistemic uncertainty for collapse assessment is high when choosing optimal retrofit interventions. The preference rankings obtained herein are affected by the adopted epistemic uncertainty mostly for moderate and warm climates.

Further investigation considering different case-study buildings, climatic conditions and seismic hazard levels is however essential to draw general conclusions on the role of masonry infill–related uncertainty in the optimal seismic retrofitting of existing buildings.

Table 1 Rankings of the retrofit alternatives at each location obtained using MCDM procedure.

Ranking	**C**				**M**				**W**			
	MDL-1		***MDL-2***		***MDL-1***		***MDL-2***		***MDL-1***		***MDL-2***	
	Alt.	Rel. Clos.	Alt.	Rel. Clos.	Alt.	Rel. Clos.	Alt.	Rel. Clos.	Alt.	Rel. Clos.	Alt.	Rel. Clos.
1	**S_3E_3**	0.641	**S_3E_3**	0.641	**S_4E_3**	0.650	**S_4E_3**	0.632	**S_4E_2**	0.650	**S_4E_3**	0.649
2	**S_4E_3**	0.618	**S_4E_3**	0.618	**S_4E_2**	0.612	**S_4E_2**	0.617	**S_4E_1**	0.644	**S_4E_2**	0.636
3	**S_3E_2**	0.610	**S_3E_2**	0.610	**S_4E_1**	0.591	**S_4E_1**	0.595	**S_4E_3**	0.633	**S_4E_1**	0.624
4	**S_4E_2**	0.608	**S_4E_2**	0.608	**S_3E_3**	0.564	**S_3E_3**	0.592	**S_3E_2**	0.583	**S_3E_3**	0.609
5	**S_3E_1**	0.590	**S_3E_1**	0.590	**S_3E_2**	0.546	**S_3E_2**	0.570	**S_3E_3**	0.581	**S_3E_2**	0.608
6	**S_4E_1**	0.584	**S_4E_1**	0.584	**S_2E_3**	0.538	**S_3E_1**	0.561	**S_3E_1**	0.569	**S_3E_1**	0.592
7	**S_2E_3**	0.544	**S_2E_3**	0.544	**S_3E_1**	0.528	**S_2E_3**	0.558	**S_2E_2**	0.523	**S_2E_2**	0.553
8	**S_2E_2**	0.524	**S_2E_2**	0.524	**S_2E_2**	0.496	**S_2E_2**	0.523	**S_2E_1**	0.523	**S_2E_1**	0.550
9	**S_2E_1**	0.515	**S_2E_1**	0.515	**S_2E_1**	0.494	**S_2E_1**	0.517	**S_2E_3**	0.490	**S_2E_3**	0.519
10	**S_1E_3**	0.399	**S_1E_3**	0.399	**S_1E_3**	0.447	**S_1E_3**	0.455	**S_1E_2**	0.443	**S_1E_1**	0.449
11	**S_1E_1**	0.357	**S_1E_1**	0.357	**S_1E_1**	0.413	**S_1E_1**	0.420	**S_1E_1**	0.443	**S_1E_2**	0.449
12	**S_1E_2**	0.355	**S_1E_2**	0.355	**S_1E_2**	0.411	**S_1E_2**	0.419	**S_1E_3**	0.441	**S_1E_3**	0.447

Alt.: Alternatives
Rel. Clos.= relative closeness values

6. ACKNOWLEDGEMENTS

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