A Multi-Criteria Model for the Comparison of Building Envelope Energy Retrofits

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Abstract. In light of the current EU guidelines in the energy field, improving building envelope performance cannot be separated from the context of satisfying the environmental sustainability requirements, reducing the costs associated with the life cycle of the building as well as economic and financial feasibility. Therefore, identifying the "optimal" energy retrofit solutions requires the simultaneous assessment of several factors and thus becomes a problem of choice between several possible alternatives. To facilitate the work of the decision-makers, public or private, adequate decision support tools are of great importance. Starting from this need, a model based on the multi-criteria analysis "AHP" technique is proposed, along with the definition of three synthetic indices associated with the three requirements of "Energy Performance", "Sustainability Performance" and "Cost". From the weighted aggregation of the three indices, a global index of preference is obtained that allows to "quantify" the satisfaction level of the i-th alternative from the point of view of a particular group of decision-makers.

The model is then applied, by way of example, to the case-study of the energetic redevelopment of a former factory, assuming its functional conversion. Twenty possible alternative interventions on the opaque vertical closures, resulting from the combination of three thermal insulators families (synthetic, natural and mineral) with four energy retrofitting techniques are compared and the results obtained critically discussed by considering the point of view of the three different groups of decision-makers.

INTRODUCTION

As part of decision support systems, multi-criteria analysis is an evaluation methodology of different alternatives to the solution of a problem on the basis of a number of predefined criteria that are shared by the actors involved. There are several multi-criteria analysis techniques and their application covers several sectors.

An important step in the construction of a multi-criteria model is the choice of a set of indicators that from objective data allow to synthetically "measure" the satisfaction level of various alternatives with respect to the predetermined criteria. The indicators and criteria should be sufficiently representative of the problem in question and relate to the objectives to be achieved.Their relative weight should also express an opinion that is shared by the decision makers.

In recent years, the use of these techniques has also increased in the development of procedures for the evaluation and choice of energy-environmental regeneration strategies of both historic and contemporary buildings (Mukherjee et al., 2007; Iwaro and Mwasha, 2013; Han et al., 2013; Mikučionienė et al., 2014; Vučićević et al., 2014; Kabak et al., 2014; Zagorskas et al., 2014; Ascione et al., 2015). Along with the aim of reducing energy consumption in winter and summer, translated into various regulatory requirements, there is also the concept of the optimal level of energy performance costs, i.e. a design founded on a balance between costs and benefits in the life cycle of the building. Another aspect currently being discussed is the measurement of the environmental sustainability of the intervention through appropriate indicators.

DESCRIPTION OF THE PROPOSED MODEL

The model presented in this paper makes use of the AHP multi-criteria analysis technique (Saaty, 1996), which stands for Analytic Hierarchy Process, and is based on three assessment criteria of the ith alternative housing retrofit technique: 1.) Energy Performance, "EP"; 2. Sustainability Performance, "SP"; 3. Cost, "C".

The "EP" criterion is associated to four indicators: 1.1) "EP_{gl}" Global Energy Performance Index evaluated in accordance to the calculation procedures set out by current national legislation (UNI/TS 11300); 1.2) "MP", Moisture Performance indicator, which considers the hygrometric behaviour under a steady state according to the UNI 13788; 1.3) "Y_{ie}", periodic thermal transmittance, which considers the thermal behaviour under dynamic conditions, calculated according to UNI 13786; 1.4) "$A_{sol,\ est}/A_{suputile}$", summer solar equivalent area per floor space units, which allows for the control of solar radiation through the glass casing components and is based on Attachment 1 to the Decree of June 26, 2015 .

The "SP" criterion examines the sustainability of the building envelope retrofit solutions, both in terms of the environmental impact of the materials used, while also considering, albeit in a qualitative way, other aspects such as the maintainability, reversibility and recyclability of the components. The environmental impacts are assessed according to a simplified LCA, *Life Cycle Assessment* that, through an *expert-based* weighting system (Pineda-Henson and Culaba, 2004; Hermann et al., 2006; Grillo, 2013), aggregates a single synthetic indicator of six categories of environmental impact (GWP, AP, EP, ODP, POCP, PE*nr*). From an operational point of view, the software *"Athena Impact Estimator for Buildings"*, developed in 2002 by the Canadian Research Institute, *Athena Sustainable Materials Institute* (ASMI) is used for the LCA analysis.

The maintainability and reversibility of the technological solutions are measured through two qualitative indicators, "I_{MAIN}" and "I_{DfD}" respectively, based on scoring systems (Grillo, 2013).

The criterion "C" is ultimately associated with the two indicators of economic convenience, *Pay Back period* (PB) and *Profitability Index* (PI). A 5% discount rate, already corrected for inflation (European Commission, 2007-2013) is adopted. The period of analysis is assumed to be 25 years and that the life of the building envelope is redeveloped.

Having defined the criteria and indicators used in the model, it is possible to assemble the decision matrix for the comparison of "n" intervention alternatives and "Ai" for the building envelope energy retrofits.

TABLE 1. Decision Matrix for the comparison of "n" intervention alternatives and "Ai" for the building envelope energy retrofits.

	EP				SP			C	
	$EP_{gl,nr}$ [kWh/m^{2}anno]	Y_{IE} [W/m^{2}K]	$A_{sol,eq}/A_{su}$ [m^2/m^2]	MP [-]	I_{LCA} [-]	I_{DfD} [-]	I_{MAIN} [-]	PB [anni]	PI [-]
A_1									
A_2									
…..									
…..									
…..									
…..									
…..									
…..									
A_N									

The compilation of the matrix provides, for each technical alternative, the evaluation of the nine indicators ($EP_{gl,nr}$, Y_{IE}, $A_{sol,eq}/A_{su}$, MP, I_{LCA}, I_{DfD}, I_{MAIN}, PB, PI) in the respective units of measurement. After normalizing the elements of the matrix, it is possible through an *expert-based* weighting system to aggregate the nine indicators into three synthetic indices:

$$I_{EP} = a_1 EP^*_{gl,nr} + a_2 Y^*_{IE} + a_3 \frac{A_{sol,eq}}{A_{su}}^* + a_4 MP^*$$

$$I_{SP} = b_1 I^*_{LCA} + b_2 I^*_{DfD} + b_3 I^*_{MAIN}$$

$$I_C = c_1 PB^* + c_2 PI^*$$

where the coefficients a_1, a_2, a_3, a_4, b_1, b_2, b_3, c_1, c_2 express the relative weights, while the apex "*" expresses the normalized value of the indicator.

For the resolution of the matrix, the "SAW" technique is adopted (Ching-Lai and Kwangsun, 1981) through which it is possible to define the following global index, I_{ERES}, *"Energy Retrofit and Environmental Sustainability Index"*:

$$I_{ERES} = w_1 I_{EP} + w_2 I_{SP} + w_3 I_C$$

The attribution of the relative weights of the criteria and indicators associated with each method is through thepairs comparison technique. In particular, a study was carried out considering three different profiles of *decision makers* in order to have a sample that is representative of different points of view and needs (Donnarumma, 2016). The decisionmakers consulted belong to the following three categories: 1. *Public Administrators* (P.A.); 2. *Private Investors* (P.I.); 3. *Technicians* (T.). Table 2 reports the relative vectors of the weights.

TABLE 2. Vectors of the relative weights of the three criteria of the model (EP, SP, C) according to the evaluation of the three categories of decision makers.

	w_1(EP)	w_2(SP)	w_3(C)
$w_{P.A.}$ =	0,295	0,295	0,410
$w_{P.I.}$ =	0,306	0,204	0,490
$w_{T.}$ =	0,333	0,333	0,333

A sample of twenty industry experts including university professors, graduates and professional consultants (Donnarumma, 2016) were consulted to calibrate the vector of the weights of the indicators.

TABLE 3. Vectors of the relative weights of the indicators.

$EP_{gl,nr}$	Y_{IE}	$A_{sol,eq}/A_{su}$	MP	I_{LCA}	I_{DfD}	I_{MAIN}	PB	PI
0,286	0,286	0,202	0,226	0,550	0,250	0,200	0,40	0,60

APPLICATION OF THE MODEL

The described model is a further development of a reuse methodology whose description and application is reported in detail in a previous work by the authors (Donnarumma et al., 2015). Regarding the energy retrofit of the envelope of a factory, 20 alternative interventions on the transparent vertical closureswere compared, resulting from the combination of three thermal insulators groups – synthetic, mineral and natural – withfour energy retrofitting techniques (Table 4): 1. *External Thermal Insulation Composite Systems* (ETICS), group "A_1"; 2. *Internal Thermal Insulation Composite Systems* (ITICS), group "A_2"; 3. *Overcladding/Ventilated Façade*, group "A_3"; 4. *Recladding*, group "A_4".

The synthetic insulating materials considered in the analysis are: sintered polystyrene foam treated with graphite, EPS +graphite, group "I_1"; PU foam, *PU-rigid foam*, group "I_2". Among the mineral insulating materials, there is *Rockwool*and calcium silicate hydrate (C-S-H) slabs: these insulating belong to the group known as "I_3". Finally, *Wood Fiber*is the natural insulation,"I_4" group. The generic alternative to the retrofitting of the building enevelope will therefore be identified with the pair "A_i - I_j" (Table 5).

TABLE 4. Intervention techniques and types of insulation considered.

RETROFITTING METHOD		I_1	I_2	I_3	I_4
		SYNTHETIC INSULATION		MINERAL INSULATION	NATURAL INSULATION
A_1	ETICS	EPS + graphite	PU-rigid foam	Rockwool	Wood Fiber
A_2	ITICS	-	PU-rigid foam	a) C-S-H	Wood Fiber
		-	-	b) Drywall + rockwool	-
A_3	OVER-CLADDING	-	PU-rigid foam	Rockwool	-
	VENT. FACADE (Gres/Alum)	-	PU-rigid foam	Rockwool	Wood Fiber
A_4	RECLADDING	-	PU-rigid foam	Rockwool	Wood Fiber
		-	PU-rigid foam + C-S-H		-

Two Internal Thermal Insulation Composite Systems (ITICS) are taken into consideration: 1. Direct application of the insulating panels to the existing wall; 2. realisation of a counter wall separatedfrom the existing wall by an air gap. *Overcladding* (O.C.) is generally the overlayyingonto the existing facade of a new envelope. In this case, it was considered as a covering system consisting of sandwich panels and an anchorage to the substructure of the existing wall, creating an air gap. The panel has two aluminum sides and a central insulating core of either polyurethane (A_3-I_2) or rockwool (A_3-I_3).

The technology of the ventilated façade is different from overcladding since it has an external face, ventilated air cavity and an insulating layer attached to the existing wall. The outer layer, supported and anchored to the existing wall by means of metal sections, can be made of various materials; the analysis considered an external face consisting of either 10 mm Gres stone slabs (A_3-I_j-Gres) or 4 mm aluminum composite panels (A_3-I_j-Alum).

Finally, *recladding* includes the demolition of the existing vertical closures and the realising of a new envelope with temperature-humidity characteristics that meet regulatory requirements. After evaluating, for each alternative, the indicators described above, the decision matrix was drawn up (Table 5).

TABLE 5. Compilation of the multicriteria comparison matrix of the building envelope energy retrofit alternatives.

		EP				SP			C	
Alternative di intervento		$EP_{gl,nr}$	Y_{IE}	MP	A_{sol}/A_{su}	I_{LCA}	I_{DfD}	I_{MAIN}	PB	PI
		[kWh/m^{2}anno]	[W/m^{2}K]	[-]	[m^2/m^2]	[-]	[-]	[-]	[anni]	[-]
ETICS	A_1-I_1	119,688	0,033	0,75	0,02	372571	0,25	36	4,42	0,73
	A_1-I_2	117,456	0,033	0,75	0,02	373600	0,25	36	4,55	0,70
	A_1-I_3	117,536	0,030	0,75	0,02	367324	0,25	36	4,63	0,69
	A_1-I_4	119,641	0,027	0,75	0,02	287966	0,25	36	4,64	0,68
ITICS	A_2-I_2	117,815	0,051	0,50	0,02	370266	0,25	44	4,35	0,75
	A_2-I_{3a}	117,550	0,041	0,25	0,02	364058	0,25	44	4,85	0,64
	A_2-I_{3b}	119,744	0,045	0,25	0,02	398365	2,00	58	4,67	0,68
	A_2-I_4	117,719	0,041	0,25	0,02	289441	0,25	44	4,67	0,71
O-C	A_3-I_2	117,511	0,035	0,75	0,02	413604	2,50	50	5,37	0,55
	A_3-I_3	119,567	0,034	0,75	0,02	407825	2,50	50	5,75	0,49
VENT. FACADES	A_3-I_2-Gres	116,370	0,029	0,75	0,02	491165	1,50	50	6,62	0,39
	A_3-I_3-Gres	115,884	0,027	0,75	0,02	484888	1,50	50	6,82	0,37
	A_3-I_4-Gres	116,020	0,026	0,75	0,02	474653	1,50	50	6,68	0,38
	A_3-I_2-Alum	115,965	0,033	0,75	0,02	415339	1,50	50	7,04	0,35
	A_3-I_3-Alum	115,724	0,032	0,75	0,02	409079	1,50	50	7,27	0,33
	A_3-I_4-Alum	115,831	0,032	0,75	0,02	365958	1,50	50	7,20	0,33
RECLAD	A_4-I_2	119,793	0,280	0,75	0,02	714429	2,50	76	6,94	0,36
	A_4-I_3	119,906	0,260	0,75	0,02	447370	2,50	72	6,79	0,37
	A_4-I_2-I_3	119,792	0,040	0,75	0,02	597415	0,25	60	7,97	0,27
	A_4-I_4-S	119,610	0,090	0,75	0,02	409056	2,50	66	6,85	0,36
	min	115,72	0,03	0,25	0,02	287966	0,25	36	4,35	0,27
	max	119,91	0,28	0,75	0,02	714429	2,50	76	7,97	0,75

The next phase involved the standardization and calculation ofthe I_{ERES} according to the three profiles of the decision makers involved.

RESULTS

The results are presented below in graphs (Figure 1). The technical solutions with a higher I_{ERES}, those that are "preferred" by the three categories of decision-makers, belong to the ETICS "A_1" group. In particular, the alternative "A_1-I_4" with external insulation in wood fiber has the highest index value for each of the three decison makers. This is followed by, with slightly a lower I_{ERES}, the three internal insulation solutions, "A_2-I_2" with polyurethane foam panels, "A_2-I_4" with fiber wood panels, and "A_2-I_{3B}" a counter wall with gypsum and rock wool fiber-reinforcedslabs. The two overcladding solutions with polyurethane sandwich panels, "A_3-I_2", or in rockwool, "A_3-I_3", have I_{ERES}values close to those of the internal insulation alternatives.The alternative "A_3-I_2" has, from the point of view of public (PA) and technical (T) decision makers,an higher I_{ERES} index compared than that of the alternatives "A_2-I_2", "A_2-I_4", "I_{3B}-A_2"and"A_3-I_3". The four solutions of the group "A_1" and the solution "A_2-I_2" are particularly "preferred" by the Private Investor that gives a greater relative weight to the "C" criteria.

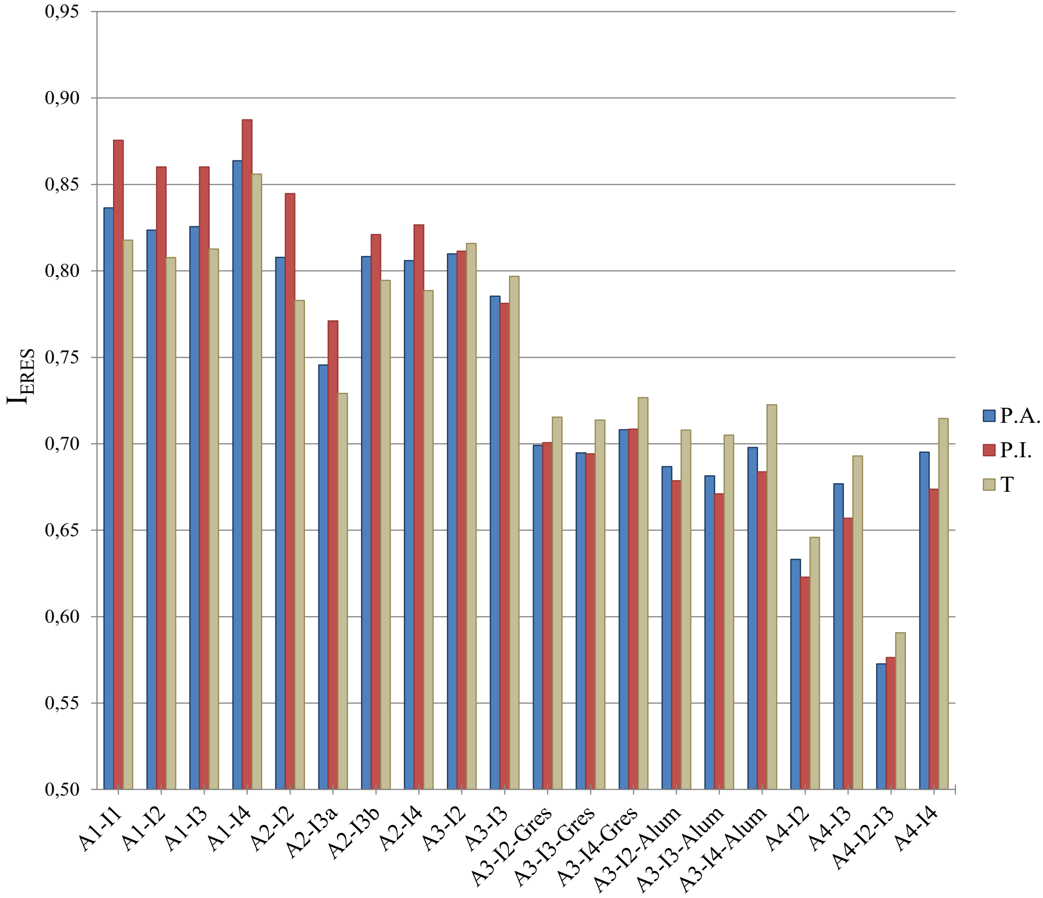

FIGURE 1. Results of the IERES of 20 alternative retrofit proposals in relation to the three categories of decision-makers: public administrators (P.A.), private investors (P.I.), technical professionals (T.).

It is possible to analyse each alternative, including those with the highest I_{ERES}, in relation to the three criteria of assessment "EP", "SP" and "C", as well as according to the perspectives of the three categories of decision makers "P.A.", "P.I." and "T". Among the nine alternatives with the highest I_{ERES}, those considered optimal according to a judgement "shared" by the three decision makers, i.e. "A_1-I_4", "I_{3B}-A_2" and "A_3-I_2" (Figure 2)were evaluated.

In relation to the three criteria, the I_{ERES} function can be represented on a Kiviat diagram as being triangular. In order to identify the "optimal" solution, it is worth simultaneously evaluating the following conditions: 1. area of the triangle, since the larger the area, the higher the I_{ERES} value; 2. "balance" of the criteria, a condition that is more satisfied as the figure tends to an equilateral triangle; 3. "commonality of the decision" which is when the triangles associated with different decision-makers tend to coincide.

On the basis of these conditions, the "optimal" alternative is "A_3-I_2" (Figure 2). It is also worth noting that: the alternative "A_1-I_4" is relatively satisfactory in relation to the criteria of cost "C" and energy performance "EP"; the solution "A_2-I_{3B}" is the judged as being economically satisfactory (Figure 3), slightly more sustainable than "A_1-I_4" but energetically less efficient than the latter and "A_3-I_2".

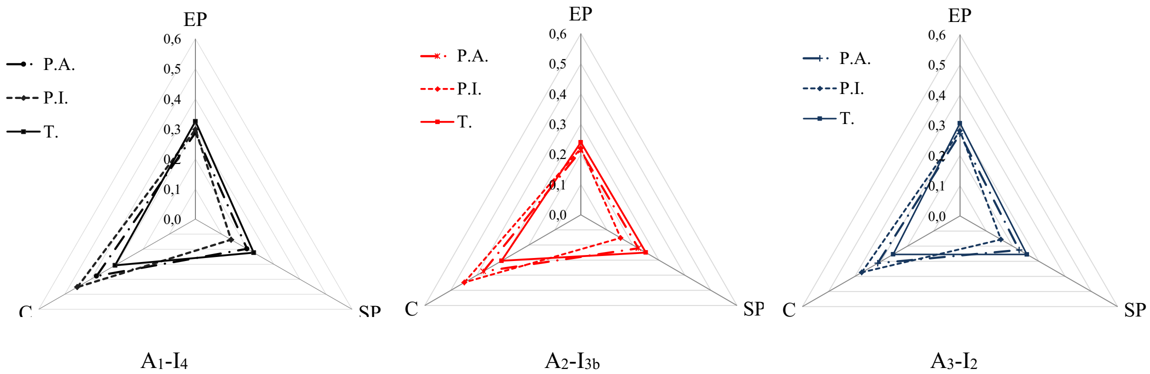

FIGURE 2. Kiviat diagram of the function I_{ERES} of the alternatives with respect to the evaluation criteria (EP, SP, C) and the decision makers (P.A., P.I., T.).

The solution "A_3-I_2" is one that, albeit slightly more expensive than the other two (the cheapest is I_C), adequately satisfies the three conditions set out, with it being balanced in relation to the three evaluation criteria and shared by the three decision-makers. The analysis carried out confirms how the private decision maker "P.I." tends to have a more unbalanced behaviour towards optimizing costs, while the technical decision maker "T." is generally more balanced. The following figure is a proposed design hypothesis of overcladding the façades (Figure 3).

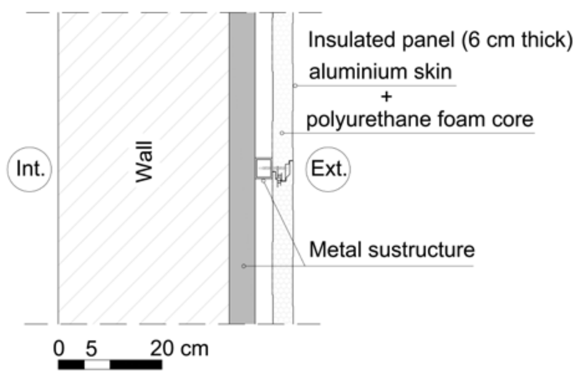

FIGURE 3. Section of the intervention project "A_3-I_2" of the building envelope energy retrofit with an overcladding technique.

CONCLUSIONS

The proposed model is a decision-making tool to compare alternative technical solutions of building envelope energy retrofit and make the “optimal” choices based on the criteria of cost, energy efficiency and environmental sustainability. Each of these three criteria is associated with a performance index that results from the weighted sum of pre-defined quantitative or qualitative indicators. In particular, the environmental sustainability of the building envelope retrofit solutions is “measured” in terms of the environmental impact of the materials used through a simplified LCA analysis, which considers both, in a qualitative way, other aspects such as the maintainability, the reversibility of the intervention as well as the recyclability of the components. Finally, it proposes a unique global index, IERES or “Energy Retrofit and Environmental Sustainability Index”, which allows to succinctly express the overall level of satisfaction of the i-th alternative.

Following the application of the model to twenty different retrofit interventions, the technique with the best performance seems to be that of external insulation systems (ETICS). The most “satisfactory” insulating material, among those considered in this study, is wood fibre in the form of rigid panels. The solution which shows the maximum convergence of preference among the three groups of decision-makers - Public Administrators, Private Investors, and Technicians - is the overcladding technique with aluminium panels and a central insulating core made of polyurethane, which has many merits such as the almost total reversibility of the intervention and good reusability and recyclability of the components.

Moreover, it is worth noting that the proposed model is an “implementable” tool since it can be appropriately updated and extended with the introduction of new indicators and, at the same time, is “versatile” due to it being applicable to both operations related to a single part of the building envelope as well as a building complex as a whole.

The model is intended for various operators – public administrations, private companies, technicians – with it being especially useful in the preliminary stage of defining the efficiency measures better in correspondence to the needs expressed by the decision-making groups involved.

Some problems that could be the subject of future research have also emerged from the study: the reliability of the input data (e.g. there is currently no national Italian LCI reference database), the degree of subjectivity for opinions expressed according to the qualitative rating scales (this could be partly solved by using only quantitative indicators), the influence of the relative weights of the criteria on the final results, which can be quantified using sensitivity analysis and limited through techniques such as the Delphi method (Dalkey and Helmer, 1963).

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