Techno-economical Analysis based on a Parametric Computational Evaluation for decision process on envelope technologies and configurations

Lavinia Chiara Tagliabue [a,*], Giuseppe Martino Di Giuda [b], Valentina Villa [c], Enrico De Angelis [b], Angelo Luigi Camillo Ciribini [d]

[a] *Department of Information Engineering DII, University of Brescia, Via Branze 38, 25123 Brescia, Italy*
[b] *Department of Architecture, Built Environment and Construction Engineering ABC Politecnico di Milano, Via Ponzio 31, 20133 Milan, Italy*
[c] *Department of Structural, Geotechnical and Building Engineering DISEG, Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129 Torino, Italy*
[d] *Department of Civil, Environmental, Architectural Engineering and Mathematics DICATAM, University of Brescia, Via Branze 43, 25123 Brescia, Italy*

Energy saving is crucial for existing buildings which is present a huge potential of improvement by a strong energy retrofitting. Often, the existing envelope components are not adequately insulated and deep refur-bishment is required to comply current regulations to improve energy efficiency and address Nearly Zero Energy Building (NZEB) goals. The strategies to enhance buildings energy performance involve heating and cooling demands strongly dependent by envelope quality (i.e. insulation, thermal mass, internal gain storage capacity and solar heat gains exploitation). Commonly, the suggested main retrofit interventions on envelope are glazed surfaces replacement, Solar Heat Gain Coefficient (SHGC) reduction and thermal transmittance (U value) improvement by additional insulation layers or even components replacement. However, it is worthy to note that the resulting thickness of the external envelope and the payback time of the interventions are important supports for decision-making. The environmental issue related to CO_2 emissions during the operational phase of the building is encompassed into the standard energy certifica-tion of the asset and the conversion factors to define fuels' impacts are available and updated. However, the calculation excludes the environmental impact due to energy used for materials' production and few official information sources provide accredited values, e.g. the Environmental Product Declaration (EPC). Going towards a Zero Energy Building, which reduces its environmental impact during the run-ning phase, embodied energy claims an increasing weight. Thus, materials and components with low embodied energy should be favoured and endorsed. For this reason, the most influential rating systems worldwide available for building sustainability assessment (e.g. LEED, BREEAM, etc.) updated their check-lists including criteria related to reduced energy for extraction, production and materials transportation on the field.

The technological optioneering of envelope solutions to achieve both energy efficiency and eco-nomic affordability is inevitably based on and supported by multicriteria assessment frameworks. These frameworks should include energy, environmental and economic parameters to define the technological suitability in different climate conditions identifying accurate optimization points, e.g. thickness of the insulation layer or heat storage capacity, considering energy saving and management costs in the life cycle. When actual optimization processes are required, computational parametric tools support to ease the options' performance comparison and to compute different combinations. Nowadays some tools are available into the main authoring software on the energy simulation market. Although different tools could be adopted, the need of transparency and custom workflows is crucial. In the present research, a specific multi-criteria methodological approach enables to outline a synoptic dia-gram for each considered climate to compare the envelope technological solutions by aggregating LCA (Life Cycle Analysis) and LCC (Life Cycle Cost) factors. For LCA, Embodied Energy (EE) of the envelope materials and Primary Energy (EP) used during the running phase have been considered. For LCC Invest-ment Cost (C) of the materials to enhance a baseline performance and related operational costs of the building based on Net Present Value (NPV) and Discounted Payback Period (DPP) have been adopted.

The present study focuses as first on the construction coherency of different technologies used to define the external envelope of a test room, able to manage the energy flows resulting from different external conditions. Subsequently the definition of the technological basket, a parametric analysis based on reducing thermal losses and increase solar gains has been performed defining the most suitable technologies and façade configuration in three representative climate conditions at national level by calculating heating and cooling demand and related primary energy.

Keywords:
Multicriteria evaluation
Building parametric performance
Cost optimality
Energy retrofit
Envelope technology optioneering

* Corresponding author.
E-mail address: lavinia.tagliabue@unibs.it (L.C. Tagliabue).

Nomenclature

Variables and parameters, Note

U	Thermal transmittance (W/m^{2}K)
M_s	Surface mass (kg/m^2)
Y_{ie}	Periodic thermal transmittance (W/m^{2}K)
T_l	Time lag (h)
D_f	Decrement factor (attenuation)
H	Heating energy demand (kWh/year)
C	Cooling energy demand (kWh/year)
COP	Coefficient of performance (kWh_t/kWh_{el})
EER	Efficiency energy ratio (kWh_t/kWh_{el})
EP	Primary energy (kWh/year)
C_i	Investment cost (€, €/m^2)
EE	Embodied energy (MJ/m^2)
Extra-EP	Extra primary energy, for parametric variables (kWh/year)
Extra-Cost	Extra cost, for parametric variables (€, €/m^2)
Extra-EE	Extra embodied energy, for parametric variables (MJ/m^2)
NPV	Net present value (€)
DPP	Discounted payback period (years)
C_t	Cash flow at time t (€)
t	Time of the investment (years)
r	Rate of return (%)
S	Dispersing surface (m^2)
V	Heated volume (m^3)

Published Journal Article available at: https://doi.org/10.1016/j.enbuild.2017.10.004

1. Introduction

Currently, the environmental issues and the related responsibil-ities of the built environment are widely recognized. Accordingly, contemporary architecture adopted and borrowed the idea of energy efficiency as fundamental requirement of the design options and Architecture, Engineering and Construction (AEC) sector is driven by. The new design should thus associate multiple require-ments [1] ranging from the optimization of local resources [2](i.e. weather parameters and construction materials) to the indoor environmental quality based on technological and constructive solutions towards Nearly Zero Energy targets [3,4]. An energy-efficient building is envisioned, actually, as an asset able to assure indoor comfort conditions for the users, minimizing the use of non-renewable resources. The thermal, visual, acoustic comfort and the indoor air quality (IAQ) are not exclusive duties of systems and plants, however environmental, typological and technological solutions cooperate to enhance the standard levels required in a cost effective way [5,6]. The building envelope is no more a mere separation layer between indoor and outdoor environments, it is as a dynamic skin in a real-time variable interaction with boundary conditions [7] in the life cycle, from the design phase, to the construction and operational phase [8]. Computational parametric methods [9,10] allow to manage complexity and multicriteria analyses [11,12] needed to consider and evaluate different options and optimization phases promote the realization of a more sustainable building, which is adaptable to even more restrictive energy and cost requirements evolving during time [13–15].

The present research emphasizes the building envelope [16], conceived as an organized and integrated set of functional layers of materials, components and systems able to convert, improve, decrease and modify the thermal flows coming from outside. The aim of the presented analyses is to provide guidelines of technological suitability for the renovation of existing buildings [17,18] by a) energy retrofitting of the envelope components or b) preservation of the structural partitions with new technological components in between or c) adding new volumes promoted by incentives programmes realized with new technologies. For this reason the technological basket assumed includes traditional stratifications [19,20] and further innovative wooden products that are currently promoted for their energy, environmental and healthy characteristics [21].

The goal of the research is to investigate the energy performance, the economic investment and benefits on running costs and environmental outcomes in term of embodied energy of conventional and innovative envelope solutions [22] in order to suggest a level of applicability [23] of different retrofit solutions and stratifications [24] in specific climate conditions [25]. The multicriteria framework allows comparing in parallel the environmental and energy impact with cost effectiveness including different parameters into a main decision scheme. The test room adopted into the analysis has a simple geometry to outline the variability referred to the envelope role of active skin. The importance of the contribution is mainly given by the methodological approach and parametric tool application for technological optioneering, which nowadays is crucial for automatization of decision making process in the design phase of new and refurbished buildings.

2. Methodological approach

The multicriteria methodological approach is LCA and LCC oriented and provides a synthetic visualization of the placement of technological solutions into the suitability field of application. The energy and economic issues are drivers of the AEC sector towards evolving procedures and digital environments to promote a pre-evaluation and design optineering enabling mature choices and reducing future performance gaps and economic waste. The digital environment promotes also an automatization and autonomization of the decision processes could be improved by clear and detailed KPIs (key performance indicators) to express performance. Hence, multiple areas of knowledge and evaluation criteria are to interrelate to turn on a machine-readable set of properties that can guide the design choices. The proposed methodology includes energy and economic factors: Embodied Energy (EE) of envelope options and Primary Energy (EP) used in the running phase and investment cost (C) of retrofit solutions to enhance a baseline performance and the operational costs as Net Present Value (NPV) and Discounted Payback Period (DPP).

A test room allows evaluating different technological solutions to simulate a building envelope located in three different climate

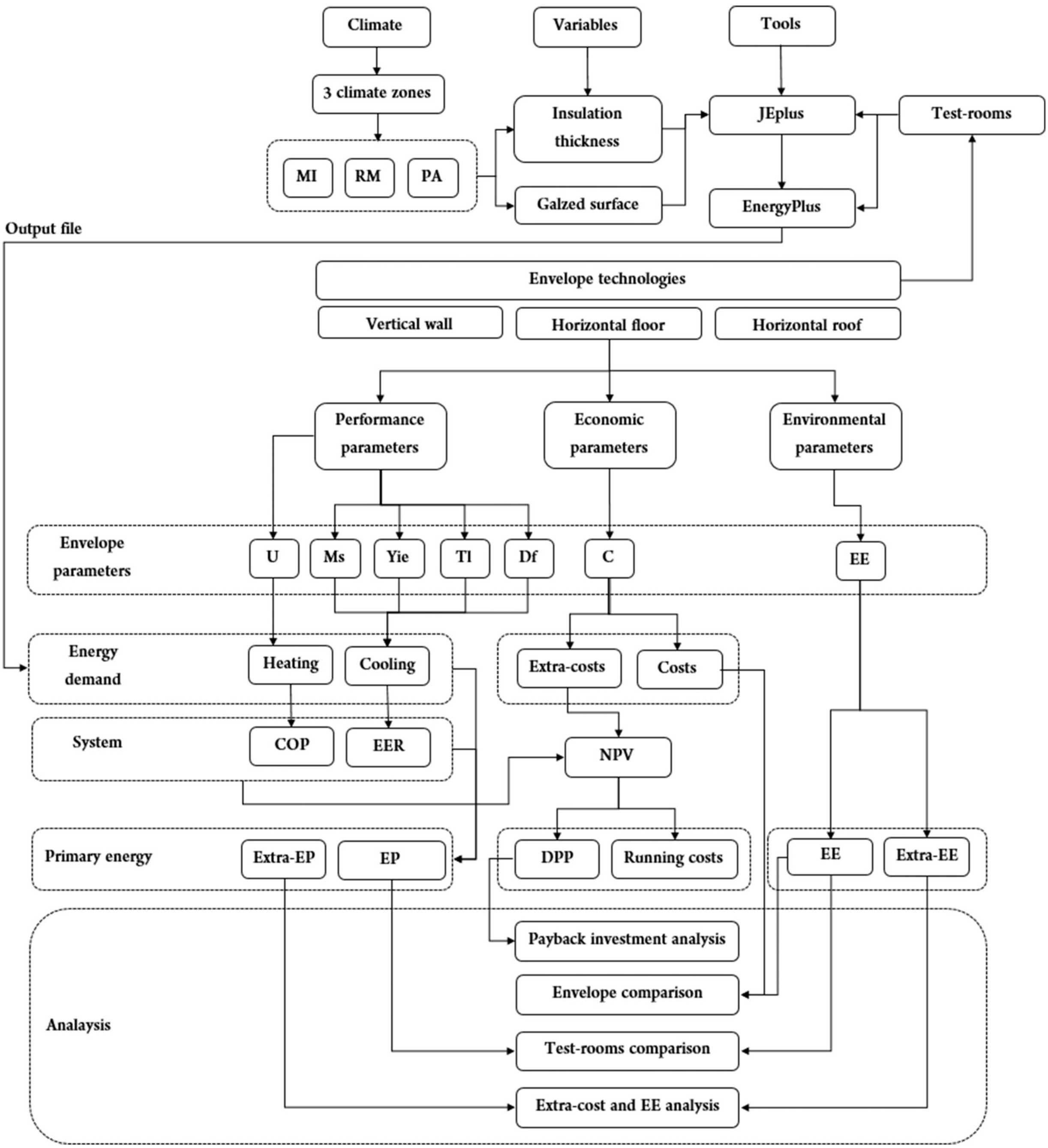

Fig. 1. Methodological framework of the research work, technologies and parametric variables.

conditions to deal with environmental flows between outdoor and indoor conditions. A vertical wall, a floor slab and a flat roof defined through technological options create the test room. The test room is representative of a space in which the indoor conditions are the result simultaneous interaction and regulation made by the partitions characteristics with the natural energy and material flows [26] excluding the building morphology variable. The research focuses the attention on energy performance design [27] of the building envelope through the main thermal performance parameters included in the national regulation. The parameters are related to envelope performance in winter (i.e. thermal transmittance) and summer period (i.e. surface mass, periodic thermal transmittance, decrement factor and time lag) of the different components (i.e. vertical and horizontal, opaque and transparent) used to define the test room [28]. The methodological framework of the research work is depicted in (Fig. 1).

In Section 3.1, Table 1 lists the previous parameters referred to the technological options together with the economic and environmental parameters (i.e. cost and embodied energy). Moreover, the technical and constructive compatibility of the wall, floor and roof slabs technologies have been considered by virtual test rooms where the technologies have been aggregated and combined as described in Section 3.1, Table 2.

Dynamic simulations have been carried out by test rooms through a parametric computational tool such as EnergyPlus [29] and jEPlus [30].

The parametric calculation [31,32] includes the technological configuration of the changing vertical surface including a window on the south façade, the floor slab and the flat roof. Energy perfor-

Table 1
Opaque envelope performance parameters (Insulation thickness 5 cm).

Performance parameters	Thermal					Economic	Environmental
Symbol Units	U [W/m^{2}K]	M_s [kg/m^2]	Y_{ie} [W/m^{2}K]	Tl [h]	Df [–]	C [€/m^2]	EE [MJ/m^2]
Walls (CV)							
CV-BP	0.52	1069.25	0.0460	12h11′	0.0886	60.75	717.50
CV-MTC	0.54	555.5	0.0497	10h40′	0.0922	24.07	413.50
CV-MP	0.52	505.5	0.0490	11h2′	0.0943	54.73	1408.50
CV-MSF	0.51	434.5	0.0549	10h57′	0.1078	51.74	1231.00
CV-MF	0.44	355.5	0.0436	12h26′	0.0993	43.74	1033.50
CV-MFP	0.38	255.5	0.0515	11h59′	0.1356	48.74	1453.50
CV-II	0.49	257.54	0.1620	9h19′	0.3308	74,74	757,60
CV-IICA	0.47	257.58	0.1548	9h21′	0.3295	74.74	757.60
CV-BC	0.46	435.5	0.0356	12h57′	0.0774	27.27	640.70
CV-BCC	0.34	175.5	0.0592	11h31′	0.1744	37.96	703.50
CV-SA	0.29	73.5	0.1562	6h17′	0.5388	86.80	690.28
CV-SACA	0.28	73.54	0.1512	6h30′	0.5402	86.80	690.28
CV-SP1	0.13	92.78	0.0113	15h45′	0.0876	75.34	1299.41
CV-SP2	0.16	87.78	0.0333	12h19′	0.2082	68.82	1214.41
CV-XL1	0.24	136.38	0.0059	17h28′	0.0247	171.40	1412.41
CV-XL2	0.38	128.88	0.0242	15h9′	0.0638	167.00	1247.41
Floor slabs (SFV)							
SFV-TG	0.55	354.00	0.1185	9h35′	0.2155	72.82	1123.25
SFV-LC	0.51	568.00	0.0473	13h16′	0.0928	108.33	1377.15
SFV-VA	0.58	233.1	0.2291	6h47′	0.395	85.68	1468.15
SFV-PCA	0.55	913.25	0.0306	14h12′	0.0558	335.10	1404.15
SFV-A	0.57	237.8	0.2452	6h25′	0.4302	76.06	1206.19
SFV-L	0.49	276.00	0.0589	11h45′	0.1204	106.58	1043.55
Roof (SC)							
SC-LC	0.47	578.00	0.032806	13h36′	0.0698	121.11	1634.55
SC-CA	0.53	646.00	0.050827	10h39′	0.0959	125.09	1511.55
SC-A	0.53	220.8	0.215445	7h10′	0.4065	81.99	1409.59
SC-L	0.40	123.5	0.08004	10h44′	0.2001	109.01	1039.30
SC-XL	0.32	216.88	0.008224	20h29′	0.0257	229.21	1886.71
SC-V-XL	0.25	351.05	0.001075	29h11′	0.0043	219.58	2401.52

Table 2
Combination of opaque envelope technologies analyzed in the test rooms.

Code	Wall (CV)	Floor (SFV)	Roof (SC)
CV-BP_SFV-L_SC-L	stone blocks	ventilated slab of wood	wooden roof
CV-MTC_SFV-TG_SC-L	brick with raw earth	ventilated slab flooring blocks on legs	
CV-MP_SFV-LC_SC-LC	solid brick	ventilated slab cement	cement mix with brick
CV-MSF_SFV-LC_SC-LC	semi-tubular brick	mix with brick	
CV-MF_SFV-LC_SC-LC	hollow brick		
CV-MFP_SFV-LC_SC-LC	hollow brick with pores		
CV-II_SFV-LC_SC-LC	insulation layer.		
CV-IICA_SFV-LC_SC-LC	insulation layer in the air gap		
CV-BC_SFV-VA_SC-CA	concrete blocks	ventilated slab on	reinforced concrete
CV-BCC_SFV-VA_SC-CA	foamed concrete blocks	under floor cavity	
CV-SA_SFV-A_SC-A	aquapanel system	ventilated steel slab	steel roof
CV-SACA_SFV-A_SC-A	aquapanel system with air gap		
CV-SP1_SFV-PCA_SC-L	platform system	slab of reinforced	wooden roof
CV-SP2_SFV-PCA_SC-L	platform system without internal insulation	concrete foundation	
CV-XL1_SFV-PCA_SC-XL	x-lam system	platform	x-lam roof
CV-XL2_SFV-PCA_SC-XL	x-lam system without internal insulation		
CV-XL1_SFV-PCA_SC-V-XL	x-lam system		green roof in x-lam

mance of the test room equipped with the technological options by a procedure enabling at verify the energy demand during the running phase of the building in dynamic regime (based on EnergyPlus Weather files *.epw data) for three Italian climate zones representative of the main national climate scenarios (i.e. Milan, Rome and Palermo) have been compared.

A simplified process in jEPlus software allowed varying the following simulation parameters of the test room [33]: a) insulation layer thickness, b) percentage of the glazed/opaque south façade c) weather file. Thus, the yearly energy demand for heating and cooling in the different configurations, stated the variables' steps of variation, have been simulated.

Furthermore, the embodied energy (EE) of the envelope optioneering has been computed as environmental indicator of the amount of energy spent before the installation of the envelope components in the construction site, which means during the production of the building materials of the different envelope solutions. The embodied energy values calculated for the vertical walls and horizontal slabs result from available databases [34,35]. Hereafter, the research matches the technical envelope materials characteristics with the environmental impacts parameters additionally with the economic factors such as the unit costs of the envelope materials used in the test room. The aim is to assume the holistic vision encompassed into the sustainability concept that is the core point of the worldwide-diffused rating systems [36]. At national level, a number of labelling systems are growing and acquiring relevance in the real estate market (e.g. energy accreditation, seismic certification, Building Information Model (BIM)

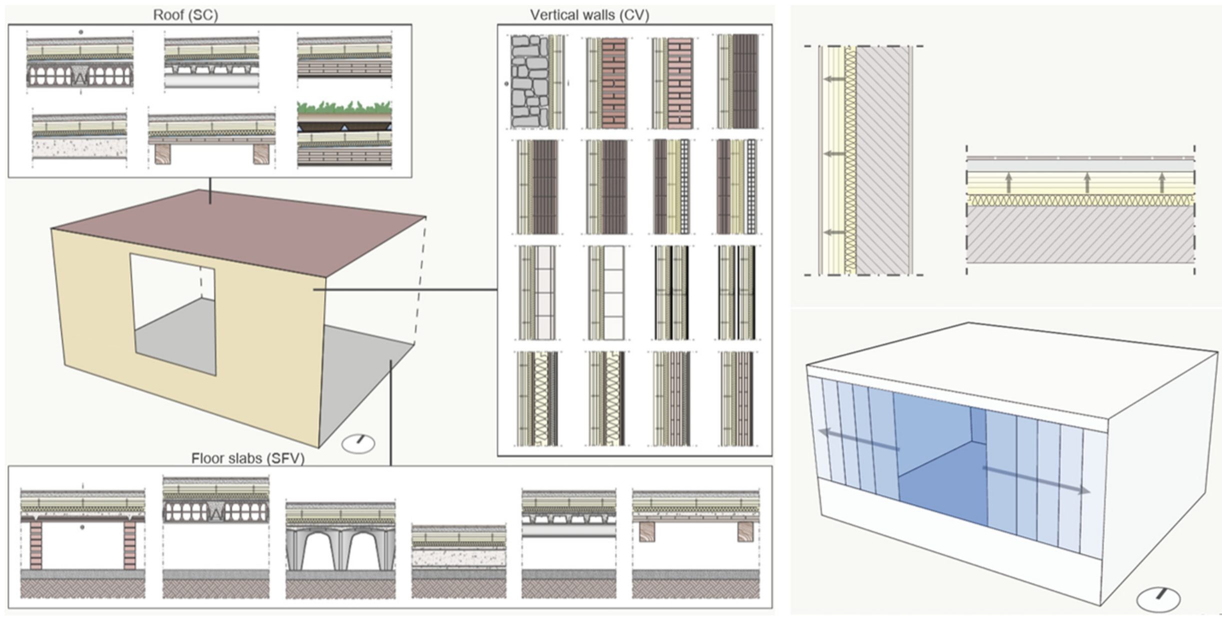

Fig. 2. Combination of the technological solutions into the test-room and parametric variables.

information detail level). However, the patchy landscape of the labelling methods could lead to users' confusion and reduction of transparency and coherency in the data knowledge and deployment [37]. For example the class A in energy labelling is a different value with a different unit compared to the class A in the seismic certification and for BIM, a level A could represent the lower class of specification and not the best performance class. A multicriteria and holistic approach such as the criteria checklist adopted by the rating systems could be beneficial to introduce a whole asset quality where all the related aspects should be organized and evaluated. Moreover, a further effort to interrelate them into a systemic vision unveiling possible fields of implementation [38] when designing energy refurbishment or new performance assessment methods [39] are pursued and could be supported by diagrams and matrixes instead of parallel concepts promoted by lists.

Economic analyses emphasize the investment cost due to envelope systems using the Discounted Payback Period (DPP) related to the increased insulation thickness and glazed façade, which on the other hand reduce the running costs for heating and cooling [40]. The energy demand calculated by dynamic simulation allows to define the primary energy, referred to the conversion factor associated to the national grid, attains to the test room considered as equipped with a geothermal heat pump (GSHP) complying the current national regulation [41].

The multicriteria framework of evaluation based on energy, environmental and cost enables to compare technologies described by performance parameters, demands and primary energy, embodied energy, and finally, suitability is discussed through synoptic diagrams (Figs. 6–8), which are merged and synthetized in a guideline table (Fig. 9) to define a level of opportunity of technological use in a specific climate condition.

The aim of the performed calculations is to underline the key indicators for a comprehensive database of the performance aspects, associated to technological options in order to endorse an informed decision process based on climate features [42] and thus including the basic energy saving principles [43] before to turn to renewable energies [44]. The analysis of the key indicators and performance parameters identifies the influence of each of them in the matrix of correlation defining the asset quality [45,46].The paper describes in detail the methodological approach for envelope optioneering evaluation [47] to efficiently support design, refurbishment and construction choices [48,49].

3. Test room definition

Therefore, the variable energy performance with different technological envelope solutions and façade configurations has been calculated on the test room. The test room is intended as a part of a main multi-storey building [50,51]; for that reason the vertical south façade and the horizontal slabs are exposed to outdoor conditions [52]. The performance is calculated changing the vertical and horizontal surfaces according to the technological components described in Section 3.1.

The test room is a single thermal zone 6.00×5.00 m, height 3.00 m with a glazed south façade (Fig. 2).

The present study considers envelope technologies pervasive at national level [53] both traditional (e.g. stone, brick masonry, concrete blocks, adobe/earth brick, brick and reinforced concrete slab and wooden roof) and more innovative (e.g. Acquapanel system, X-lam system and Platform system, reinforced concrete slab with air cavity, steel slab and roof, green roofing) [54,55].

In detail, the tested technological solutions include n. 16 wall types, n. 6 floor slabs and n. 6 roofs adopted to define the test rooms and each technology has been catalogued on the basis of the thermal, economic and environmental performance parameters (Fig. 3).

A detailed description of the technological solutions and envelope characteristics are summarized in the following Tables 1–3 in Section 3.1.

3.1. Tecnological optioneering

Consequently the test room is virtually built by the vertical wall, floor slab and horizontal roof technological components considering a variable thickness of the insulation layer to comply the national regulation in the three different climate zones as described in Section 3.3.

The insulation layer has been evaluated as variable in each configuration ranging from 5 cm to 15 cm as described in Section 3.2. In the following Table 1 the performance parameters according to Fig. 1 and related to the technological components depicted in

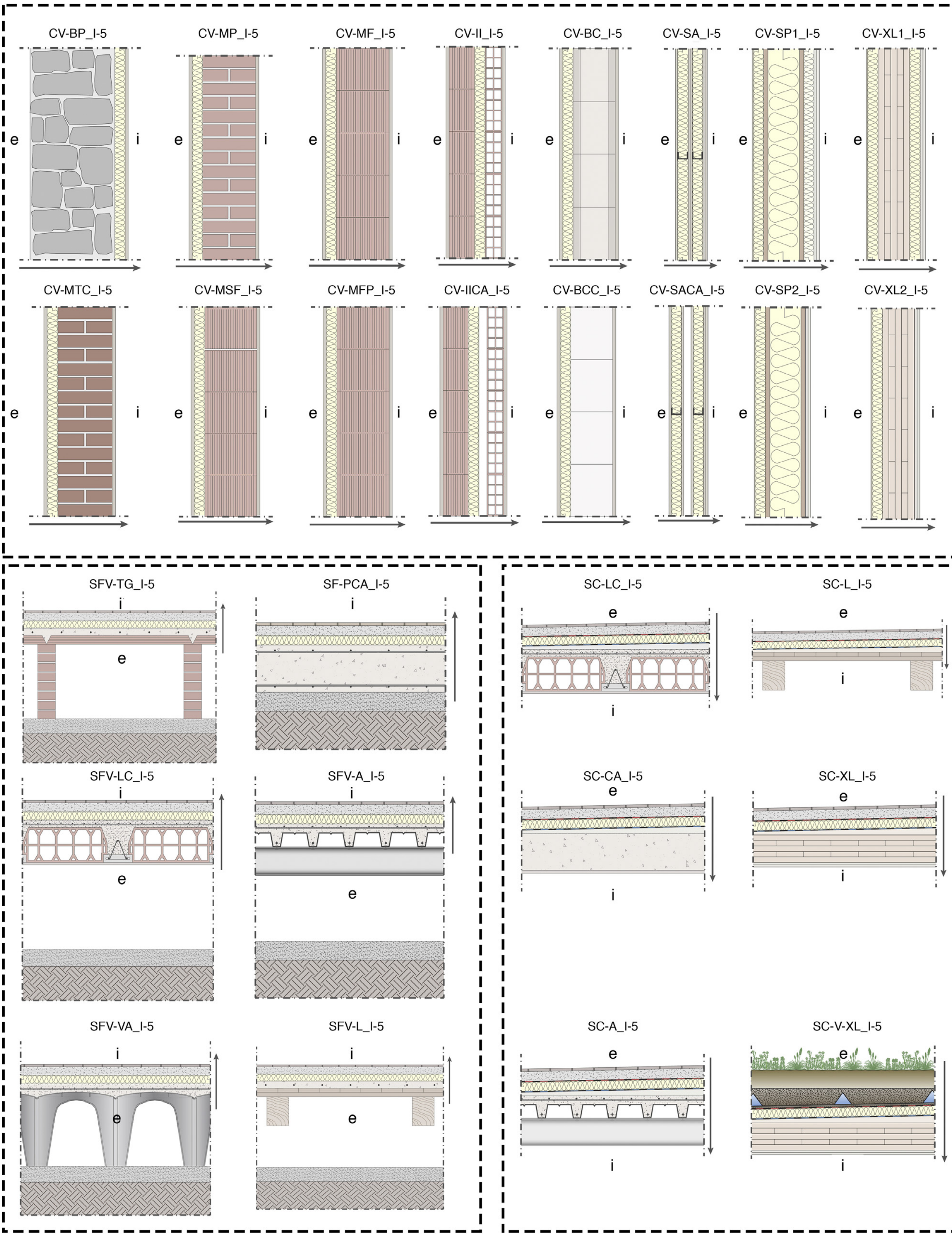

Fig. 3. Technological description of the envelope: walls, floor slabs and roof.

Figs. 2 and 3 are reported for the baseline technological components equipped with a 5 cm insulation layer. The performance parameters as reported in the following tables are listed below:

- Thermal parameters:
  - Thermal transmittance U [W/m^{2}K];
  - Surface mass M_s [kg/m^2];

Table 3
Insulation thickness parametric variable and U value for the technological solutions.

Code	Units	I-5	I-8	I-10	I-12	I-15
Insulation thickness	cm	5	8	10	12	15
Walls (CV)						
CV-BP	W/m^2K	0.52	0.35	0.29	0.24	0.20
CV-MTC		0.54	0.37	0.31	0.26	0.21
CV-MP		0.52	0.36	0.3	0.26	0.21
CV-MSF		0.51	0.35	0.3	0.25	0.21
CV-MF		0.44	0.32	0.27	0.24	0.20
CV-MFP		0.38	0.29	0.25	0.22	0.18
CV-II		0.49	0.35	0.29	0.25	0.21
CV-IICA		0.47	0.34	0.28	0.24	0.20
CV-BC		0.46	0.33	0.28	0.24	0.20
CV-BCC		0.34	0.26	0.23	0.20	0.17
CV-SA		0.29	0.19	0.16	0.13	0.10
CV-SACA		0.28	0.19	0.15	0.13	0.10
CV-SP1		0.13	0.12	0.11	0.11	0.10
CV-SP2		0.16	0.14	0.13	0.12	0.11
CV-XL1		0.24	0.21	0.19	0.17	0.15
CV-XL2		0.38	0.29	0.26	0.23	0.19
Floor slabs (SFV)						
SFV-TG	W/m^2K	0.55	0.37	0.31	0.26	0.22
SFV-LC		0.51	0.35	0.30	0.25	0.21
SFV-VA		0.58	0.39	0.32	0.27	0.22
SFV-PCA		0.55	0.36	0.31	0.26	0.22
SFV-A		0.57	0.38	0.31	0.26	0.21
SFV-L		0.49	0.36	0.31	0.26	0.22
Roof (SC)						
SC-LC	W/m^2K	0.47	0.34	0.29	0.25	0.20
SC-CA		0.53	0.37	0.30	0.26	0.21
SC-A		0.53	0.36	0.30	0.25	0.21
SC-L		0.40	0.30	0.26	0.22	0.19
SC-XL		0.32	0.26	0.23	0.21	0.18
SC-V-XL		0.25	0.21	0.19	0.17	0.15

Table 4
Glazed surface parametric variable for the test rooms, performance parameters.

Performance parameters	Thermal					Economic	Environmental
Description	Symbol	Size [m^2]	U_w [W/m^2K]	g [%]	t_{vis} [%]	C [€/m^2]	EE [MJ/m^2]
Double glazing with air gap, aluminium frame	V	variable	2.2	0.7	0.9	375.00	1733.60

  - Periodic thermal transmittance Y_{ie} [W/m^2K],
  - Time lag T_l [h];
  - Decrement factor D_f [−]
- Economic parameter:
  - Cost of the technological solution C_i [€/m^2];
- Environmental parameter:
  - Embodied Energy EE [MJ/m^2].

The technological components have been compared on each parameters to evaluate the single performance to extract enlightening information about compliance with regulation requirement and benchmarking however, the research work focused on the synthesis into a single diagram able to include the whole multicriteria framework evaluation. The thermal parameters contribute to the energy demand for heating (mainly U, M_s) and cooling (mainly M_s, Y_{ie}, Tl, Df).The energy issue is considered in the life cycle to combine the values into a comprehensive energy KPI including primary energy and the embodied energy summed on a yearly basis. A 30 years period of useful life of the building is considered.

In Table 1 the cost and the embodied energy due to the structural elements of the light solutions (CV-SACA, CV-SP1, CV-SP2) (e.g. mullions. crossbeams. etc.) are reported in Table 7 and they have been computed for each technology, extensively documented in the research and included in the results calculation. The technological solutions have been combined to define n. 17 test-rooms as described in Table 2.

The thermal performance of each test room has been calculated changing the climate conditions, varying the parametric size of the south glazed surface and the insulation thickness in the vertical and horizontal components considered as possible energy retrofit strategies.

In addition to the opaque envelope technologies, the transparent envelope of the test room was thermally characterized considering a window with aluminium frame and a double glass pane with air filled gap (U_w = 2.2 W/m^2K; SHGC = 0.7).

3.2. Parametric variables

As described above, the considered parametric variables are twofold: the insulation layer thickness and the size (in this case the width) of the south facing window as a percentage referred to the floor useful surface as a minimum size of 40% stemming from the national regulation (Fig. 2). In Table 3 the variables and the values assumed in the parametric analysis carried out with jEPlus software, which runs the Energy Plus calculation engine, about insulation layer variation and U value assumed by the technological components are shown. The variables' variation are defined with specific values of the insulation thickness according to actual components (i.e. 5, 8, 10, 12, 15 cm).

In Table 4 the transparent envelope parametric variable is described in the baseline configuration (i.e. the window surface

Table 5
Values assumed by the parametric variable for the test rooms, performance parameters.

Parameters		Geometrical			Economic	Environmental
Code	Floor percentage [%]	façade percentage [%]	Glazing surface [m^2]	Dimensions [m]	C [€]	EE [MJ/m^2]
V-12.5	12.5	21	3.75	1.875 × 2.00	1406.25	6501.00
V-20	20	33	6.00	3.00 × 2.00	2250.00	10401.60
V-25	25	42	7.50	3.75 × 2.00	2812.50	13002.00
V-30	30	50	9.00	4.50 × 2.00	3375.00	15602.40
V-35	35	58	10.50	5.25 × 2.00	3937.50	18202.80
V-40	40	67	12.00	6.00 × 2.00	4500.00	20803.20

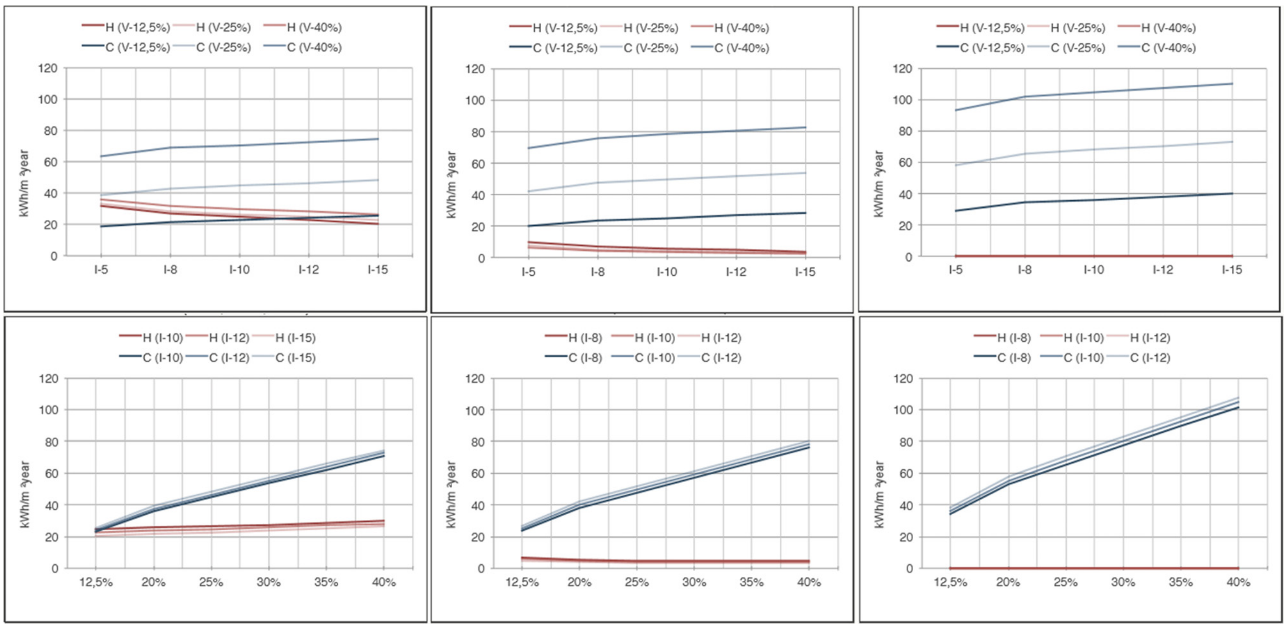

Fig. 4. Energy demand for the X-lam envelope system showing the variation related to the parametric variables (insulation layer thickness and glazed surface) in Milan (left column), Rome (centre column), Palermo (right column).

Table 6
Data about climate conditions considered for the calculation.

Data	Milan	Rome	Palermo
Location	North	Centre	South
Weather station	Linate	Fiumicino	Punta Raisi
Latitude	45.43°N	41.08°N	38.18°N
Longitude	9.28°E	12.23°E	13.01°E
Altitude	103 m	3 m	21 m
Climate zone	E	D	B
Degree days	2404	1415	751
Heating season	15/10–15/04	1/11–15/04	1/12–31/03
Threshold for Irradiation	–	X	X

is 1/8 of the floor useful surface) as 12.5% of the floor area corresponding to 20.8% of the south façade [56,57].

The dimensions of the window in the different envelope configurations for the parametric calculation are summarized in Table 5.

3.3. Climate conditions

The test rooms are calculated in three representative climate zones in Italy a) temperate continental northern climate in Milan (MI); b) Mediterranean climate in centre in Rome (RM) and c) seaside hot southern climate in Palermo (PA). Heating and cooling seasonal parameters are specified by the national regulation [58] and the allowed primary energy consumption is related to envelope compactness (S/V ratio) and Degree Days (Table 6).

The Degree Days data commonly define how much is warm or cold the climate is and how much the demand for heating and cooling related to the variable parameters discussed in Section 4 should be. In Fig. 4 an example of energy demand result is provided for one technological solution adopted in the three locations showing the need of custom technological solutions to address a significant energy saving in the national territory: the lower demand for heat-ing is evident in Palermo (PA). Moreover, it is worthy to note that in Milan (MI) the registered solar radiation [59] is lower than the current regulation threshold of 290 W/m^2 and thus virtually the required values of surface mass or periodic thermal transmittance for the envelope are not mandatory. Nevertheless in the parametric analysis is significant as the glazed surface would widens and the insulation layer would augments then the cooling demand in refur-bished envelope solutions worsens seriously (see Fig. 4 in Section 4.3) [60,61].

4. Multicriteria analysis

The evaluation criteria for the application suitability of the technological optioneering in the three climate zones are listed below:

1. Energy demand for winter and summer;
2. Primary energy calculated considering the use of a GSHP;
3. Embodied energy in the materials of the envelope technologies of the test room [62,63];
4. Energy Running Cost (indoor comfort conditions 20 °C in winter; 26 °C summer) [64];
5. Investment costs and extra-cost to enhance the insulation layer thickness of the opaque envelope components [65].

Table 7
Embodied energy (EE) for the materials used in the technological stratifications.

Construction materials	EE [MJ/kg]	Insulation materials	EE [MJ/kg]
Stone block	45.00	Wood fibre	13.04
Brick with raw earth	5.33	Rock wool	8.65
Solid brick	35.99	Polistirene expanded	10.09
Semi-tubular brick	33.00	Polistirene extruded	17.80
Hollow brick	25.00	**Finishing materials**	**EE [MJ/kg]**
Hollow brick with pores	34.00	Plasterboard	6.10
Double masonry brick	22.00	Floor	7.30
Hollow masonry	30.00	Screed for heating/coolng systems	0.81
Concrete blocks	8.53	**Structural materials**	**EE [MJ/m^2]**
Cellular concrete blocks	19.22	Steel profiles U shape 5 × 5 cm	43.50
Reinforced concrete	60.21	Steel profiles U shape 5 × 8 cm	69.60
Cement mix with brick	56.3	Steel profiles U shape 5 × 10 cm	87.00
Glued laminated timber	7.80	Steel profiles U shape 5 × 12 cm	104.40
X-lam system	135.00	Steel profiles U shape 5 × 15 cm	130.50
Acquapanel (OSB)	11.96	Laminated timber beam 5 × 15 cm	990.00

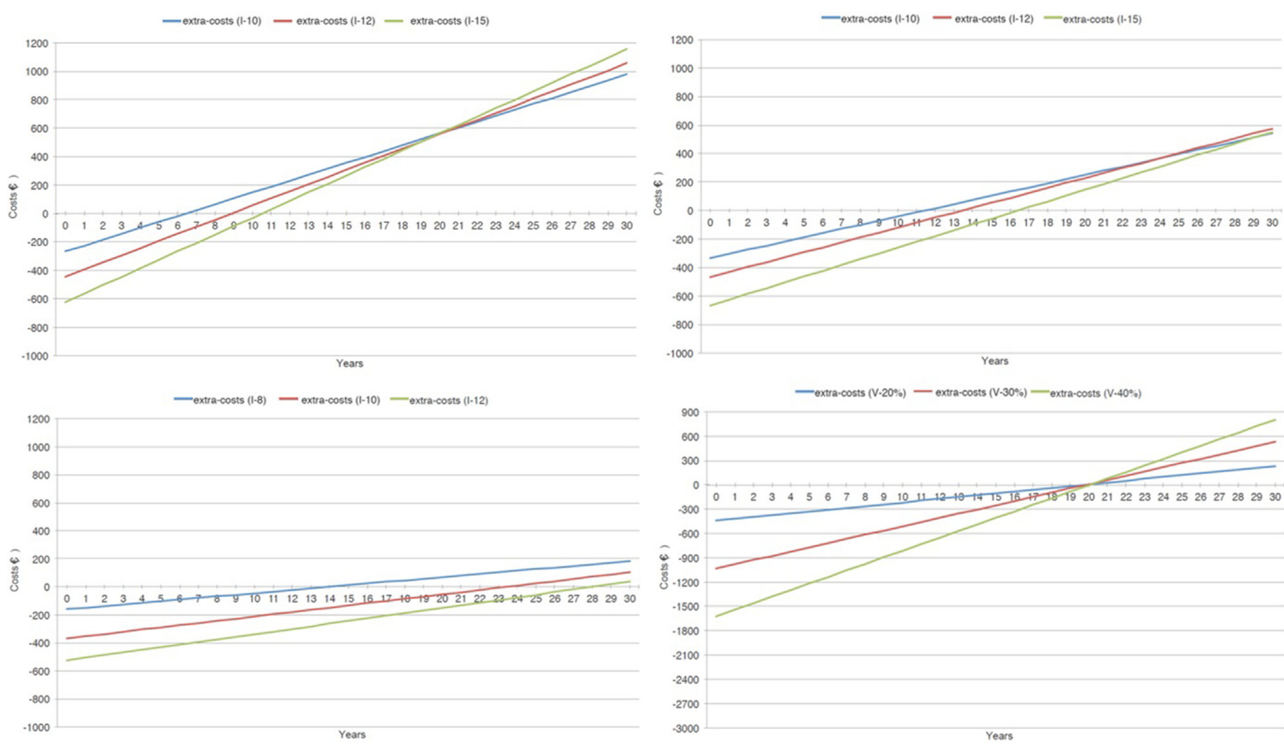

Fig. 5. Extra cost economic evaluation based on Discounted Payback Period: a) Location: Milan, glazed surface 40%, technological solutions: CV-BP/SFV-L/SC-L, variable: insulation layer thickness; b) Location: Rome, glazed surface 40%, technological solutions: CV-BC/SFV-VA/SC-CA, variable: insulation layer thickness; Location: Palermo, glazed surface 40%, technological solutions: CV-SA/SVF-A/SC-A, variable: insulation layer thickness; Location: Palermo, insulation layer thickness 8 cm, technological solutions: CV-XL1/SF-PCA/SC-XL, variable: glazed surface.

4.1. Thermal simulation setting

The running set up assumed for the thermal zone is a standard residential schedule defining the main thermal characteristics of the test room. The schedule of the occupants' activity level, the internal gains and ventilation rate are fixed. The equipment has a power density equal to 4 W/m^2 and the air changes are set to 0.3 vol per hour. The thermal zone is equipped with a ground source heat pump thermal system with an average seasonal efficiency of 4 [66] complying the national regulation requirements. A simplified value of the system efficiency has been adopted accordingly with the analytical goals. The heat pump uses the electricity coming from the national grid (i.e. conversion factor equal to 2.18) according with the heating period specified by the national law [58] related to climate zones (E, D, B) as shown in Table 6.

4.2. Embodied energy data

The embodied energy data come from existing databases as the materials used in the envelope technologies have not specific EPDs. The increased importance of the energy in the production phase stems by the efficiency promoted in the last 15 years in the run-ning energy costs and if a 30% of embodied energy can be ascribed to traditional buildings the percentage increase significantly for NZEB [67,68]. Thus, it will become increasingly imperative to calculate a global energy calculation taking into account the energy for materials production, transportation, and substitution for maintenance and disposal to address the Life Cycle Zero Energy Buildings (LCZEB) [69]. The energy-saving strategies prove to be effective considering the energy balance of the entire life cycle of the building. Massive constructions, commonly adopted in temperate and Mediterranean countries, use concrete, brick or blocks of various materials, how-

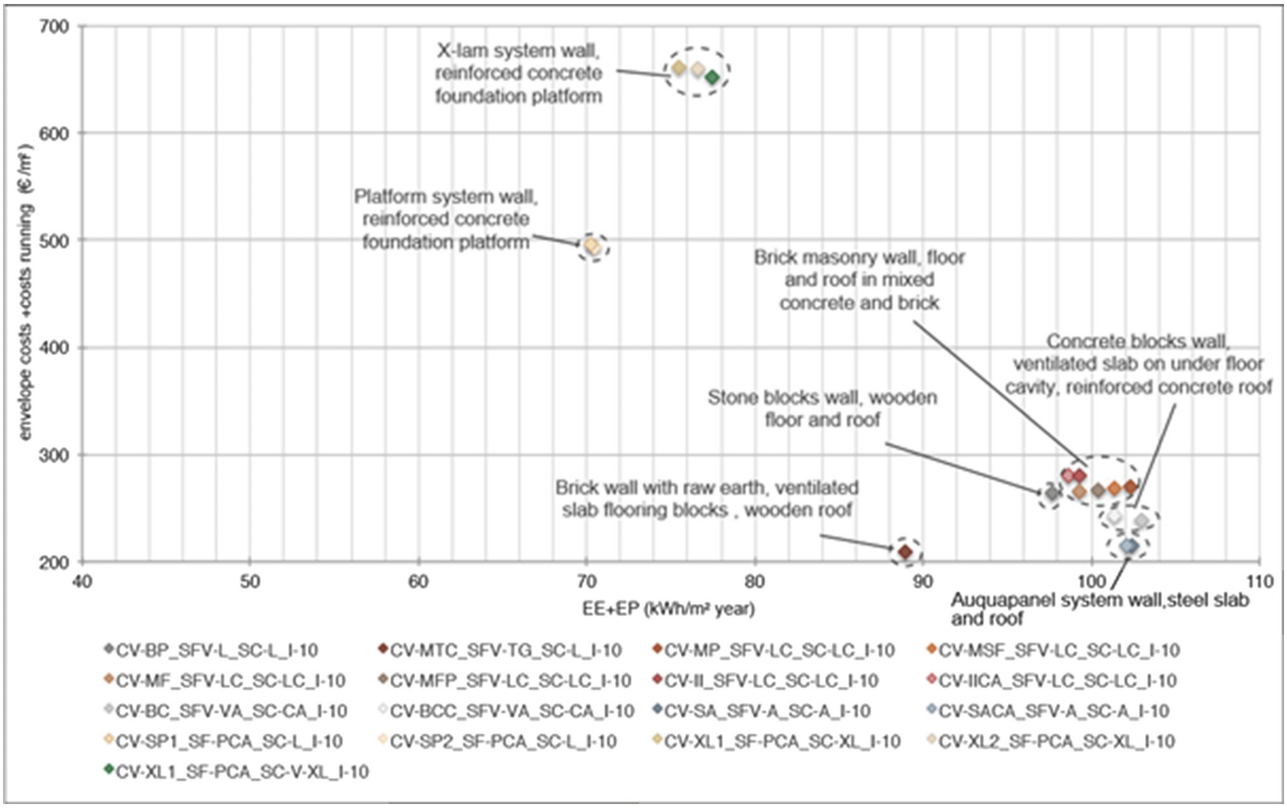

Fig. 6. Cost optimal diagram considering energy (EP+EE) and investment and running costs (site: Milan, V-12.5).

ever they have high embodied energy. On the contrary, wooden construction systems used for solutions based on structure and cladding systems have a reduced embodied energy in the life cycle and often they are embraced in regions from cold to temperate climate, since the wood is natural material subjected to few operations in the production phase. The embodied energy assumed in the calculation for the materials considered in the analysis are resumed in Table 7.

4.3. Economic parameters

The economic evaluation is based on the cost of the technologies and the extra investment cost to enhance the insulation layer comparing the thickness variation and the widening of the test room's window. The extra investment cost is measured comparing the parametric variables with the baseline i.e. the test rooms with insulation layer of 5 cm (I-5) for all vertical and horizontal envelope technologies and 12.5% of glazed surface referred to the floor area (V-12.5%).

Starting from the envelope investment costs for improving the baseline the NPV (Net Present Value) is estimated as shown in Eq. (1):

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1+r)^t} \quad (1)$$

where:

t is the duration of the investment project;

C_t is the cash flow at time t;

r is the rate of return.

The methodology defines the upright discounted at the expected rate of return of net flows generated by the project, which expresses the profitability of the investment project. The NPV is the sum of the cash flows related to the entire investment period, discounted the year of estimation. The net cash flow in the investment period is calculated using the public net electricity to feed the heat pump and it has an initial cost of 0.16 €/kWh and an increase cost rate of 0.04 €/kWh; these values are estimated considering the entire duration of the investment together with the extra-consumption of energy.

Finally, the DPP (Discounted Payback Period) is used to determine the profitability of the investment project. Unlike the NPV analysis, which provides the overall value of the project, the DPP provides the number of years to equalize the initial investment. Future cash flows are considered and discounted at the time zero, according with the following Eq. (2):

$$DPP = \sum_{t=0}^{n} \left[1 + \frac{C_t}{(1+C_i)^t} \right] \quad (2)$$

where:

C_i is the investment costs referred of the envelope solutions. t, C_t are defined in Eq. (1).

The DPP is calculated with an interest rate of 0.04 and with the data coming from the NPV. The profitability of investment in 30 years and the period of time required to pay off the investment costs (Fig. 5) have been estimated [70].

5. Results and discussion

The methodology adopted in the research enables the contemporary evaluation of the different criteria introduced into the multicriteria framework aiming at compare on a techno-economical systematization the proposed envelope technologies optioneering as possible strategies for energy retrofitting towards NZEB goal. The results of the specific analyses on heating demand, cooling demand, EE, Investment costs, running costs and primary

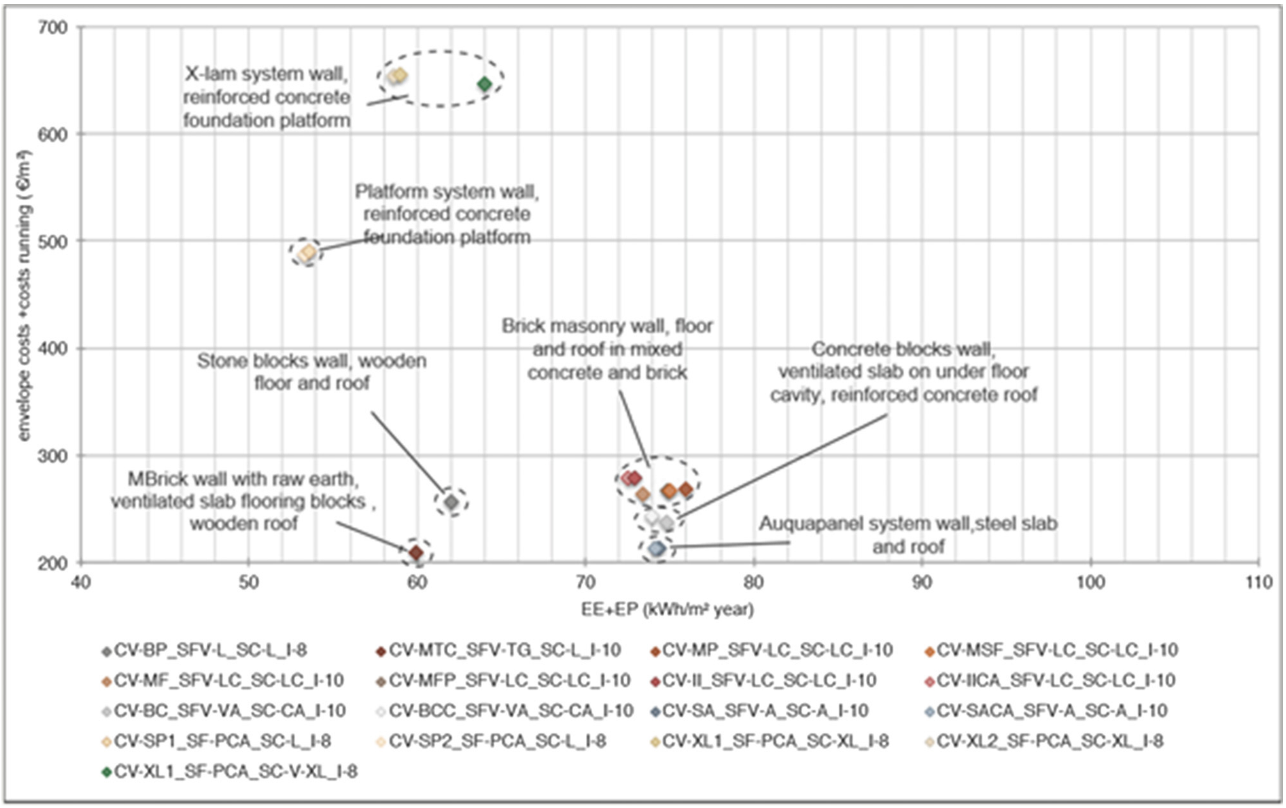

Fig. 7. Cost optimal diagram considering energy (EP+EE) and investment and running costs (site: Rome, V-12.5).

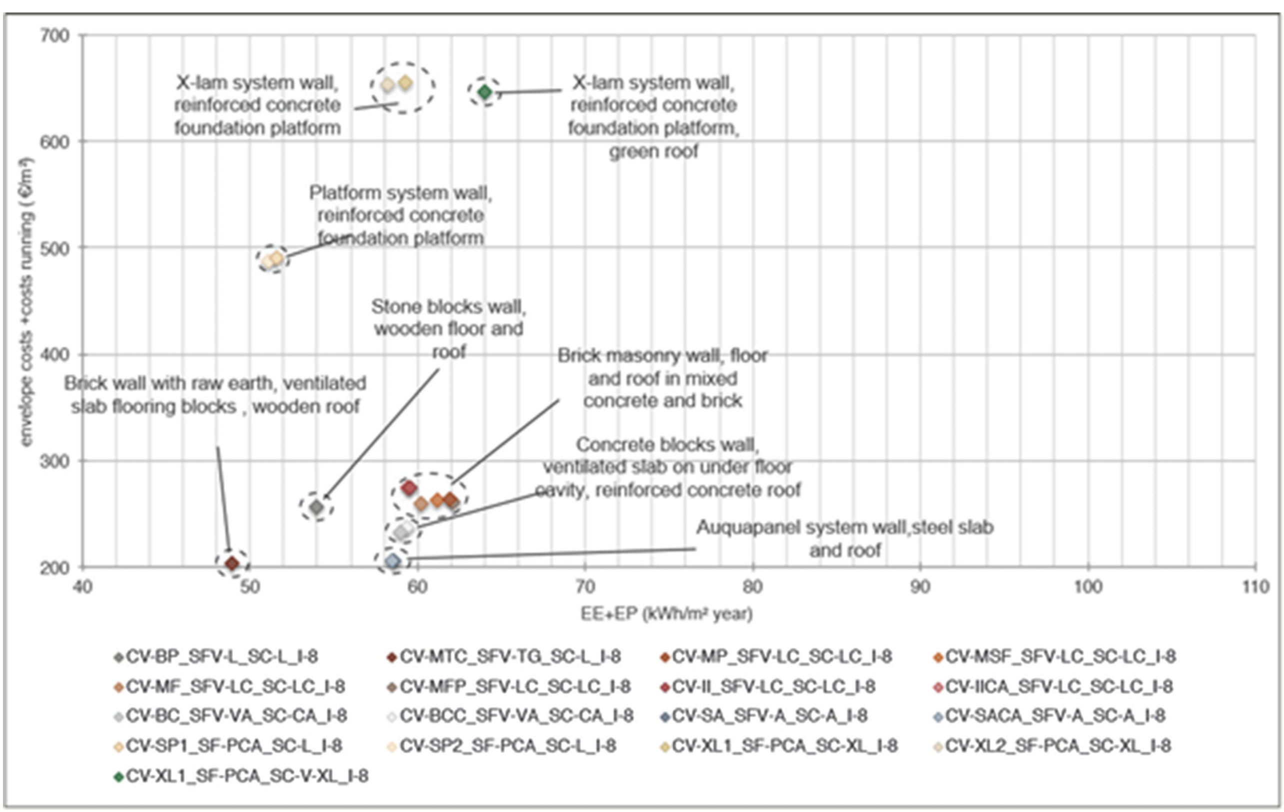

Fig. 8. Cost optimal diagram considering energy (EP+EE) and investment and running costs (site: Palermo, V-12.5).

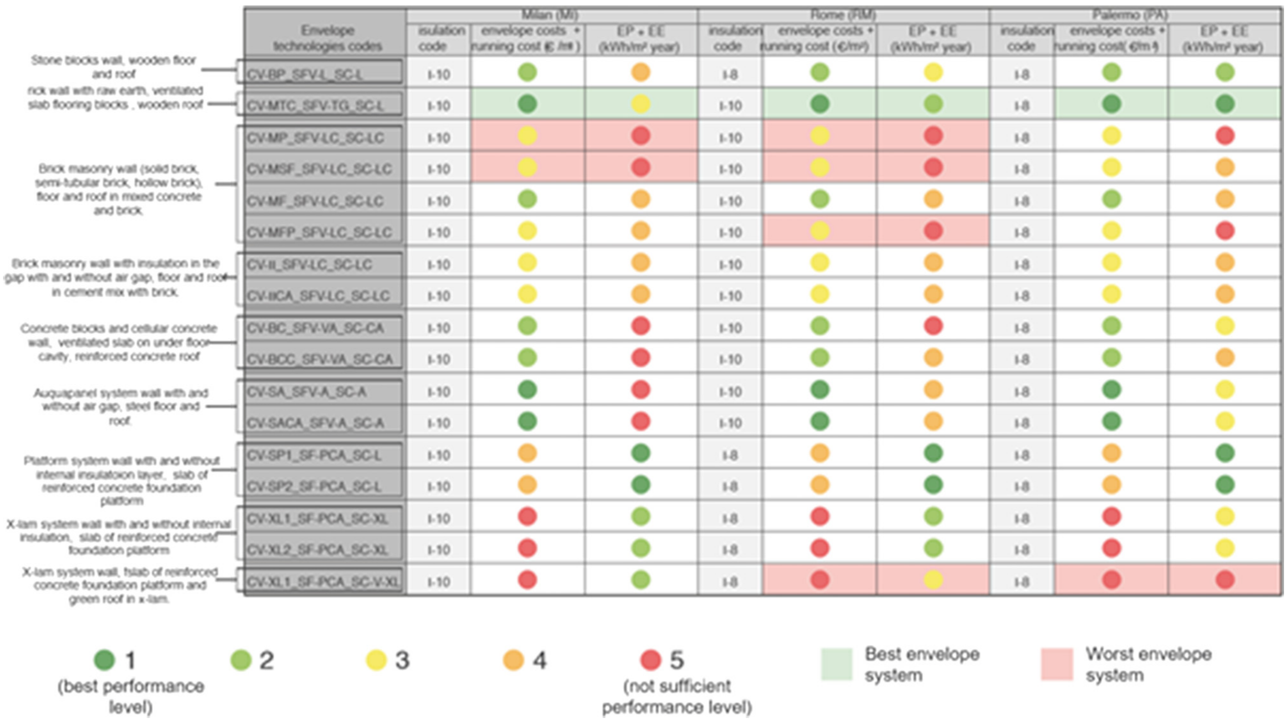

Fig. 9. Synoptic table about suitability of the different technologies in the three climate conditions.

energy are represented in the following diagrams reported for the 12.5% of glazed surface referred to the floor area.

In Fig. 6–8 the synoptic diagrams synthetize the energy, economic and environmental comparison between the tested tech-nologies for the climate of Milan, Rome and Palermo. On the x-axis is reported the primary energy (heating in winter period and cool-ing in summer period) and the embodied energy (kWh/ m^2 year) while the y-axis shows the investment costs for additional thermal insulation layer and the associated running costs (€ /m^2). Hence, it is possible to evaluate which envelope configuration can be branded as predominantly appropriate in the climate zones of Milan (MI). Roma (RM) and Palermo (PA) according to the mul-ticriteria evaluation framework.

In Milan and Rome the best options include vertical walls Plat-form system with interior insulation/foundation slab of reinforced concrete/wooden roof and the vertical platform system/foundation slab of reinforced concrete/wooden roof.

In Palermo, together with the two platform systems also the ver-tical envelope system in earth brick/ventilated foundation blocks on legs/wooden roof can be suggested as particularly advantageous.

From the point of view of the costs and the annual running cost, the most suitable in the three locations are those solutions with vertical walls in raw earth bricks/ventilated foundation blocks on legs/f wooden roof. Also Aquapanel wall system/ventilated foun-dation slab steel/steel roof and the vertical Aquapanel wall with air gap/ventilated foundation steel floor/steel roof represent highly suitable solutions. However, in Milan, a stronger energy reduction can be pursued with X-lam systems and Platform systems never-theless the cost is more than double in comparison with brick wall with raw earth and ventilated floor with blocks and wooden roof. This latter solution has an energy parameter a 13% higher than the light technological solutions but the cost is one third. Furthermore, in Rome the energy saving is comparable for the three solution and the cost criterion results even more relevant. The technolog-ical solution with brick and concrete blocks and the Acquapanel have an energy saving which is 16% less that the X-lam and Plat-form systems but the cost is, also in these cases, between one half and one third. In Palermo, where the climate is warmer the energy saving that can be achieved with brick wall with raw earth, venti-lated slab floor blocks and wooden roof is a 19% higher than with X-lam and Platform systems because of the thermal mass effect which is more significant for the energy efficiency of the building. The energy parameter of X-lam and Platform systems is comparable with brick and concrete blocks and Aquapanel technological solu-tions. The KPI of energy efficiency is a 17–18% lower for Acquapanel system with steel slab and roof, in comparison with brick with raw earth, ventilated slab floor blocks and wooden roof. The cost is com-parable and, thus, the solutions could be suitable options related to possible technological constrains and compatibility in case of addi-tion of existing volumes. Therefore, the less suitable technologies in all the three locations, results those with vertical walls in X-lam sys-tems/ foundation slab of reinforced concrete platform/x-lam roof slab, walls in x-lam systems without internal insulation/foundation slab of reinforced concrete platform/roof slab in the x-lam and ver-tical wall X-lam/foundation slab of reinforced concrete/green roof with x-lam system. This is due to the higher cost; however, a sig-nificant difference can be reported between the two systems. The cost KPI is a 23% higher for X-lam system than for Platform sys-tem and the difference with the lower cost technologies (brick with raw earth and Acquapanel) is 60% for Platform system and 70% for X-lam system which is not an irrelevant difference when technical-economic evaluation is promoted.

The suitability of the different technological options is resumed in Fig. 9 where a synoptic table is provided. The table shows a grad-uation of technological opportunity of the envelope optioneering for each test room with the different levels of insulation thick-ness and size of the glazed south exposed surface. In this way, a simplified guideline for technological refurbishment of the enve-lope is eased by the multicriteria framework to enable an informed decision making process and possibly a future autonomization of the choices into a technological basket that could be populated by in real-time updated information about embodied energy, costs and climate variations. The parametric automatic calculation of the different parameters and the possibility to implement a synoptic matrix of and interrelated criteria and interferences could endorse transparency in the choices and in the public contracts. The cost optimal analysis of the technological options is going to be implemented into digital common data environment where the materials and thus the components are correlated to their attributes and BIM methodologies are the main framework for this scenario. The energy driver encourages a more efficient built environment, empowers a control of energy cost in the life cycle of the building, and optimizes the choices for the asset management.

The performance scale ranges from 1 (best performance level) to 5 (not sufficient performance level). The technologies are briefly labelled to get the meaning of the reference codes used to describe of the technological systems (as defined in Table 1 and Table 2).

6. Conclusions

The research aims at underline the methodology to include in a synthetic evaluation energy, environmental and economic parameters in a multicriteria framework, which can be a synthetic and efficient decision support for technological optioneering. The possible outcome are synoptic tables where envelope technologies for refurbishment are compared on the basis of the parametric analyses performed on the test room in three representative climate zones of the national territory (i.e. Milan, Rome and Palermo) to define how to change materials, configuration and components synergy related to natural flows of energy and materials. The performance scale is defined by the technology costs and annual running cost to maintain the comfort conditions in the fixed periods of the year complying with energy laws, embodied energy and primary annual energy for the running phase. The EU Directive introduces the cost optimal criterion to identify the most suitable technological solutions based on energy efficiency and economic optimization. However, the present study introduces a further step that is included in the most advanced ongoing researches: the definition of energy, environmental and economic KPIs in the life cycle and thus considering energy and cost during the different phases of the building. The proposed methodology interrelates the information about the KPIs to define a performance approach to the technological evaluation. This is based on energy and economic parameters considering the energy in the construction and running phase; the disposal phase is not included and can be an additional focus in the future development of the work, and the economic factor that is composed by the investment cost and energy management. In this way it is possible to accomplish a comprehensively evaluation of potential application of the envelope technologies based on a multicriteria framework. As example in the coldest climate considered the traditional envelope technologies (e.g. brick, concrete blocks, stone) are a 21% less efficient but a 57% cheaper compared to advanced wood envelope technologies; in the central Italy climate the raw earth technology allows the same energy result of X-lam wood systems reducing the cost of 69% and in the warmer climate the results show that traditional massive technologies have the same energy result of advanced wooden systems with a reducing the cost of about 57%, while raw earth technology furthermore is more efficient in energy saving (9% less than an average value for platform and X-lam systems). The use of dynamic simulation and parametric computational tools is required when big amount of data and configurations have to be rapidly calculated and simultaneously compared with high accuracy of the results. The adopted workflow and tools allows customizing the output variables and enabling the parallel variation of the three main AEC parameters. A further additional step could be to enable an automation of the workflow into digital environments the can connect the building energy model (BEM) to introduce the KPIs into a BIM model for design optioneering and outline the optimal solution through genetic algorithms.

Acknowledgements

The authors would like to mention and acknowledge Eng. Massimiliano Manfren for the useful and enlightening discussion on suitable tools about parametric analysis and cost-optimal evaluation. Special thanks and rewards go to Arch. Lorenzo Ciuffi for the fundamental data crunching work and analyses of the technological solutions used to conceive the test rooms. Finally, thanks to Eng. Michela Buzzetti for the support during the development of the economic calculation set up.

References

[1] D. Gerber, F. Flager, Teaching design optioneering: a method for multidisciplinary design optimization, ASCE Conf. Proc. 416 (41182) (2011) 109.

[2] B. Givoni, Comfort, climate analysis and building design guidelines, Energy Build. 18 (1) (1992) 11–23.

[3] Directive 2010/31/EU of The European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). L 153/13 Official Journal of the European Union 18.6.2010.

[4] A.J. Marszal, P. Heiselberg, J.S. Bourrelle, E. Musall, K. Voss, I. Sartori, A. Napolitano, Zero Energy Building–A review of definitions and calculation methodologies, Energy Build. 43 (4) (2011) 971–979.

[5] J. Kurnitski, A. Saari, T. Kalamees, M. Vuolle, J. Niemelä, T. Tark, Cost optimal and nearly zero (nZEB) energy performance calculations for residential buildings with REHVA definition for nZEB national implementation, Energy Build. 43 (11) (2011) 3279–3288.

[6] M. Kapsalaki, V. Leal, M. Santamouris, A methodology for economic efficient design of Net Zero Energy Buildings, Energy Build. 55 (2012) 765–778.

[7] S.B. Sadineni, S. Madala, R.F. Boehm, Passive building energy savings: a review of building envelope components, Renew. Sustain. Energy Rev. 15 (8) (2011) 3617–3631.

[8] M.M. Sesana, G. Salvalai, Overview on life cycle methodologies and economic feasibility for nZEBs, Build. Environ. 67 (2013) 211–216.

[9] E. Naboni, Y. Zhang, A. Maccarini, E. Hirsch, D. Lezzi, Extending the use of parametric simulation in practice through a cloud based online service, BPSA-Conference of International Building Performance Simulation Association (2013).

[10] M.S. Al-Homoud, Computer-aided building energy analysis techniques, Build. Environ. 36 (4) (2001) 421–433.

[11] S. Greco, B. Matarazzo, R. Slowinski, Rough sets theory for multicriteria decision analysis, Eur. J. Oper. Res. 129 (1) (2001) 1–47.

[12] B. Lehmann, D. Gyalistras, M. Gwerder, K. Wirth, S. Carl, Intermediate complexity model for model predictive control of integrated room automation, Energy Build. 58 (2013) 250–262.

[13] R. Evins, A review of computational optimisation methods applied to sustainable building design, Renew. Sustain. Energy Rev. 22 (2013) 230–245.

[14] M. Ferrara, E. Fabrizio, J. Virgone, M. Filippi, A simulation-based optimization method for cost-optimal analysis of nearly Zero Energy Buildings, Energy Build. 84 (2014) 442–457.

[15] S. Attia, M. Hamdy, W. O'Brien, S. Carlucci, Assessing gaps and needs for integrating building performance optimization tools in net zero energy buildings design, Energy Build. 60 (2013) 110–124.

[16] L.C. Tagliabue, G.M. Di Giuda, V. Villa, E. De Angelis, E. De Angelis, Parametric Assessment of Energy, Environmental and Economic Performances Of Building Envelope Technologies, Colloqui. A T.e, 12–15 October 2016, Matera, Italy, 2016.

[17] I. Garcia Kerdan, R.M. Raslan, P. Ruyssevelt, Parametric study and simulation-based exergy optimization for energy retrofits in buildings, in: 28th International Conference on Efficiency, Cost, Optimization Simulation & Environmental Impact of Energy Systems (ECOS), Pau, France, 30 Jun 2015–03 July 2015, 2015.

[18] I. Iqbal, M.S. Al-Homoud, Parametric analysis of alternative energy conservation measures in an office building in hot and humid climate, Build. Environ. 42 (5) (2007) 2166–2177.

[19] S.P. Corgnati, E. Fabrizio, M. Filippi, V. Monetti, Reference buildings for cost optimal analysis: method of definition and application, Appl. Energy 102 (2013) 983–993.

[20] E. Arbizzani, P. Civiero, General overview of the problems, needs and solutions in the Italian urban building envelopes, in: M. Almeida, G. Hadjmichael, E. Melgaard, L.G.W.A. Verhoef (Eds.), Improving the Quality of the Existing Urban Building Envelopes–Needs, 3, 2007, pp. 69–79.

[21] G. John, D. Clements-Croome, G. Jeronimidis, Sustainable building solutions: a review of lessons from the natural world, Build. Environ. 40 (3) (2005) 319–328.

[22] I.Z. Bribián, A.V. Capilla, A.A. Usón, Life cycle assessment of building materials: comparative analysis of energy and environmental impacts and evaluation of

the eco-efficiency improvement potential, Build. Environ. 46 (5) (2011) 1133–1140.
[23] C. Thormark, A low energy building in a life cycle—its embodied energy, energy need for operation and recycling potential, Build. Environ. 37 (4) (2002) 429–435.
[24] P. de Wilde, G. Augenbroe, M. van der Voorden, Design analysis integration: supporting the selection of energy saving building components, Build. Environ. 37 (8) (2002) 807–816.
[25] Y. Heo, R. Choudhary, G.A. Augenbroe, Calibration of building energy models for retrofit analysis under uncertainty, Energy Build. 47 (2012) 550–560.
[26] H. Herring, R. Roy, Technological innovation energy efficient design and the rebound effect, Technovation 27 (4) (2007) 194–203.
[27] Oxman, R. performance-based design: current practices and research issues, Int. J. Architect. Comput. 6 (1) (2008) 1–17.
[28] H. Masuda, D. Claridge, Estimation of Building Parameters Using Simplified Energy Balance Model and Metered Whole Building Energy Use, 2012.
[29] D.B. Crawley, L.K. Lawrie, F.C. Winkelmann, W.F. Buhl, Y.J. Huang, C.O. Pedersen, J. Glazer, EnergyPlus: creating a new-generation building energy simulation program, Energy Build. 33 (4) (2001) 319–331.
[30] Y. Zhang, I. Ivan Korolija, Performing complex parametric simulations with jEPlus, in: SET2010-9th International Conference on Sustainable Energy Technologies, Shanghai, China. 24–27 August, 2010.
[31] L.C. Tagliabue, M. Manfren, A.L.C. Ciribini, E. De Angelis, Probabilistic behavioural modelling in building performance simulation –the Brescia eLUX lab, Energy Build. 128 (2016) 119–131.
[32] K.J. Lomas, H. Eppel, Sensitivity analysis techniques for building thermal simulation programs, Energy Build. 19 (1) (1992) 21–44.
[33] Z. Yang, B. Becerik-Gerber, A model calibration framework for simultaneous multi-level building energy simulation, Appl. Energy 149 (2015) 415–431.
[34] A. Alcon, Embodied Energy and CO_2 coefficients for NZ building materials, in: Centre for Building Performance Research, Victoria University of Wellington, Wellington, 2001.
[35] G. Hammond, J. Craig, Inventory of Carbon & Energy (ICE). Version 1.6 Department of Mechanical Engineering. Bath (UK), University of Bath, 2006.
[36] I. Ballarini, V. Corrado, Application of energy rating methods to the existing building stock: analysis of some residential buildings in Turin, Energy Build. 41 (7) (2009) 790–800.
[37] A. Pasquinelli, L.C. Tagliabue, G.M. Di Giuda, V. Villa, E. De Angelis, A.L.C. Ciribini, Cognitive adaptive urban systems for the living built environment, 2nd Annual International Conference on Urban Planning and Property Development (UPPD 2016) (2016), http://dx.doi.org/10.5176/0000-0000_UPPD.43.
[38] L.C. Tagliabue, M. Manfren, Sustainability Indicators for Buildings: Network Analysis and Visualization. Sustainable Built Environment (SBE) Regional Conference Expanding Boundaries: Systems Thinking for the Built Environment, Zurich, June 15–17, 2016.
[39] A. Schlueter, F. Thesseling, Building information model based energy/exergy performance assessment in early design stages, Autom. Constr. 18 (2) (2009) 153–163.
[40] T. Uygunoğlu, A. Keçebaş, LCC analysis for energy-saving in residential buildings with different types of construction masonry blocks, Energy Build. 43 (9) (2011) 2077–2085.
[41] D.M. 26/06/2015 – Applicazione delle metodologie di calcolo delle prestazioni energetiche e definizione delle prescrizioni e dei requisiti minimi degli edifici.
[42] A. Bolattürk, Determination of optimum insulation thickness for building walls with respect to various fuels and climate zones in Turkey, Appl. Therm. Eng. 26 (11) (2006) 1301–1309.
[43] S. Attia, E. Gratia, A. De Herde, J.L. Hensen, Simulation-based decision support tool for early stages of zero-energy building design, Energy Build. 49 (2012) 2–15.
[44] R.H. Crawford, G.J. Treloar, R.J. Fuller, M. Bazilian, Life-cycle energy analysis of building integrated photovoltaic systems (BiPVs) with heat recovery unit, Renew. Sustain. Energy Rev. 10 (6) (2006) 559–575.
[45] W. Tian, A review of sensitivity analysis methods in building energy analysis, Renew. Sustain. Energy Rev. 20 (2013) 411–419.
[46] G.C. Rodríguez, A.C. Andrés, F.D. Muñoz, J.M.C. López, Y. Zhang, Uncertainties and sensitivity analysis in building energy simulation using macroparameters, Energy Build. 67 (2013) 79–87.
[47] G.M. Di Giuda, V. Villa, E. De Angelis, P. Piantanida, L.C. Tagliabue, E. De Angelis, Progressive Energy Retrofit for the educational building stock in a Smart City, in: IEEE Second International Smart Cities Conference (ISC2 2016), Improving the Citizens Quality of Life, 12-15 September 2016, Trento, Italy, 2016.
[48] E. De Angelis, A.L.C. Ciribini, L.C. Tagliabue, M. Paneroni, The brescia smart campus demonstrator. Renovation toward a zero energy classroom building, Procedia Eng. 118 (2015) 735–743.
[49] L. Tronchin, M. Manfren, L.C. Tagliabue, Multi-scale analysis and optimization of building energy performance–Lessons learned from case studies, Sustain. Cities Soc. 27 (2016) 296–306.
[50] A.J. Marszal, P. Heiselberg, Life cycle cost analysis of a multi-storey residential net zero energy building in Denmark, Energy 36 (9) (2011) 5600–5609.
[51] S.C. Hui, Low energy building design in high density urban cities, Renew. Energy 24 (3) (2001) 627–640.
[52] D. Holzer, R. Hough, M. Burry, Parametric design and structural optimisation for early design exploration, Int. J. Archit. Comput. 5 (4) (2007) 625–643.
[53] E. De Angelis, Matteo Fiori, T. Poli, Le Pareti Perimetrali Opache, Maggioli Editore, 2011.
[54] D.J. Sailor, A green roof model for building energy simulation programs, Energy Build. 40 (8) (2008) 1466–1478.
[55] L. Aye, T. Ngo, R.H. Crawford, R. Gammampila, P. Mendis, Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules, Energy Build. 47 (2012) 159–168.
[56] Pratt, K.B., Bosworth, D.E., A Method for the Design and Analysis of Parametric Building Energy Models. Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association, Sydney, 14–16 November.
[57] A. Mohammadpour, M. Mottahedi, S.S. Amiri, S. Asadi, D. Riley, A. Shafaghat, Parametric analysis of building elements on building energy use, Jurnal Teknologi (Sci. Eng.) 74 (4) (2015) 79–83.
[58] D.P.R. 26/08/1993. n. 412. Regolamento recante norme per la progettazione. l'installazione. l'esercizio e la manutenzione degli impianti termici degli edifici ai fini del contenimento dei consumi di energia. in attuazione dell'art. 4. comma 4. della L. 9gennaio 1991. n. 10. Pubblicato nella Gazz. Uff. 14 ottobre 1993. n. 242. S.O.
[59] D.B. Belzer, M.J. Scott, R.D. Sands, Climate change impacts on US commercial building energy consumption: an analysis using sample survey data, Energy Sources 18 (2) (1996) 177–201.
[60] E. Musall, T. Weiss, A. Lenoir, K. Voss, F. Garde, M. Donn, Net Zero energy solar buildings: an overview and analysis on worldwide building projects, EuroSun Conference (2010).
[61] J. Pfafferott, S. Herkel, M. Jäschke, Design of passive cooling by night ventilation: evaluation of a parametric model and building simulation with measurements, Energy Build. 35 (11) (2003) 1129–1143.
[62] G. Verbeeck, H. Hens, Life cycle inventory of buildings: a contribution analysis, Build. Environ. 45 (4) (2010) 964–967.
[63] J.A. Alcorn, G. Baird, Use of a hybrid energy analysis method for evaluating the embodied energy of building materials, Renew. Energy 8 (1) (1996) 319–322.
[64] A.A. Chowdhury, M.G. Rasul, M.M.K. Khan, Thermal-comfort analysis and simulation for various low-energy cooling-technologies applied to an office building in a subtropical climate, Appl. Energy 85 (6) (2008) 449–462.
[65] S. Fuller, Life-cycle cost analysis (LCCA), in: National Institute of Building Sciences, An Authoritative Source of Innovative Solutions for the Built Environment, 2010 (1090).
[66] L.C. Tagliabue, M. Maistrello, M. Fattor, Technical and cost-optimal evaluation of thermal plants for energy retrofitting of a residential building, Energy Procedia 50 (2014) 597–602.
[67] R. Fay, G. Treloar, U. Iyer-Raniga, Life-cycle energy analysis of buildings: a case study, Build. Res. Inf. 28 (1) (2000) 31–41.
[68] L.F. Cabeza, L. Rincón, V. Vilari ño, G. Pérez, A. Castell, Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: a review, Renew. Sustain. Energy Rev. 29 (2014) 394–416.
[69] Y. Dutil, D. Rousse, G. Quesada, Sustainable buildings: an ever evolving target, Sustainability 3 (2) (2011) 443–464.
[70] L. Lu, H.X. Yang, Environmental payback time analysis of a roof-mounted building-integrated photovoltaic (BIPV) system in Hong Kong, Appl. Energy 87 (12) (2010) 3625–3631.