Multi-Objective Decision Making Optimization of a Residential Net Zero Energy Building in Cold Climate

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Abstract— **the challenge in Zero energy building (ZEB) design is to find the best combination of design strategies that would face the energy performance problems of a particular building. This paper outlines the methodology and the cost-effectiveness potential for optimizing the design of net-zero energy building (NZEB) in a cold climate region in Lebanon; Cedars. Specifically, the non-sorting genetic algorithm (NSGA-II) is chosen in order to minimize thermal, electrical demands and life cycle cost (LCC) while reaching the net zero energy balance; and thus getting the Pareto-front. A ranking decision making technique (ELECTRE III) is applied to the Pareto-front so as to obtain one optimal solution. A wide range of energy efficiency measures are investigated, besides solar energy systems are employed to produce required electricity and hot water for domestic purposes. The results clearly indicate that, for designing a residential NZEB in cold climate, it is essential to minimize the space thermal load through a building envelope with high thermal performance. Envelop high level of insulation is an essential step to decrease the high heating demand. Building thermal loads are decreased by 33.19%. Moreover the LCC is decreased by 31.09%.**

Keywords— Optimization; Decision making;Passive stategies; Life cycle cost; Net Zero Energy Building; Renewable energy systems

I. INTRODUCTION

Globally, buildings' energy demand is estimated to keep increasing in the next decades. By the end of 2014, buildings (residential, commercial and public) represented about 49% of the world's electricity consumption, where the residential sector accounts for 27% of the total electrical use [1].

Nowadays, a new approach is suggested to limit energy consumption and pollution emissions in buildings; Net Zero Energy Building (NZEB) [2].

Building optimization is an effective technique to evaluate design choices and to get the perfect solution for a specific intention expressed as objective functions under several constraints [4]. Multi-objective optimization (MOO) results are sets of non-dominated solutions called Pareto optimal solutions represented as a Pareto frontier [5]. Once the Pareto frontier is obtained, here comes the importance of the multi-criterion decision-making (MCDM) process in order to select the final optimal solution among all available possibilities.

In this paper, cost-effective design options for a prototypical residential NZEB in Cedars, a cold climate region in Lebanon, is investigated. First, the base case design conditions, RE systems, and simulation results are described. Then, optimization problem of a wide range of design and operating measures is presented; including wall and roof insulation levels, windows glazing type, window to wall ratio (WWR) in eastern and western facades, cooling and heating set points, PV and SC systems sizing. The optimization is formulated and carried out using "MOBO", a Multi-Objective Building Optimization tool introduced by Palonen et al. (2013) [6]. Besides, in order to obtain a unique solution, the ELECTRE III (Elimination and Choice Expressing the Reality) MCDM technique, developed by Roy [7] is employed. Finally, a set of recommendations is outlined in order to improve the performance design of ZEBs in cold climate.

II. RESIDENTIAL BUILDING DESCRIPTION

The optimized building is composed of three floors. Each floor is 205 m^2, consisting of two apartments: A & B, housing a family of four respectively. Building shape, dimensions, orientation and openings are presented in the plan view of Figure I.

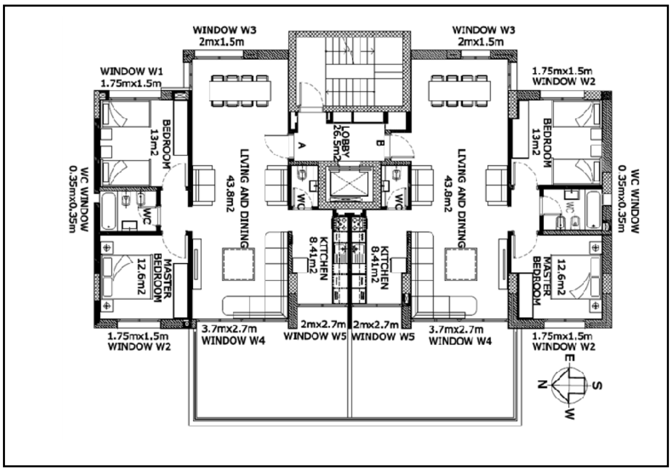

FIGURE I PLAN VIEW OF BUILDING'S TYPICAL FLOORS (WITH TWO APARTMENTS A AND B)

Eastern and western windows are shaded with opaque roller blinds. Furthermore, cooling loads are covered by air source heat pumps, characterized by a coefficient of performance (COP) equal to 2.9. Heating loads are covered by a natural gas condensing boiler (Efficiency=98.3%). Systems set points in bedrooms, living rooms and kitchens (cooling only) are set respectively at 24 ˚C for cooling and 20 ˚C for heating during occupied hours. However, during unoccupied hours, both cooling and heating systems are turned off. The desired relative humidity is set at 50 %. The building is considered as tight, so the infiltration rate is equal to 0.38 ACH [8].

III. Building renewable energy (RE) systems and simulation

A. Maintaining the Solar domestic hot water system characteristics

In order to cover domestic hot water demands, a flat plate direct active solar domestic hot water system (SDHW) with auxiliary heater inside the tank, located on the house roof, is chosen. The SDHW system is composed of 15 solar collectors (SC) connected in series of total area equal to 31.35 m^2. Collectors are south oriented; their slope is approximately equal to the local latitude of Cedars.

B. Base case demands simulation

Buildings different demands, i.e. electrical, thermal and hot water are simulated using TRNSYS software. The obtained buildings' total annual electrical loads are 61.57 KWh/y.m2. Whereas, heating and cooling loads are 89.63 KWh/y.m2and 14.42KWh/y.m2 respectively.

C. Photovoltaic system characteristics

In order to generate electricity, a photovoltaic (PV) array composed of mono-crystalline silicon modules is used. The array is south oriented and sloped at Cedars local latitude. After the necessary analytical calculation [9], results yield to 90 PV modules (15 in series, and 6 in parallel). The building exploits the utility power grid for storage, delivering energy to the grid when the PV system produces more energy than the building uses and draws from the grid when the PV system produces less energy than the building needs.

D. Base case electrical and economic simulation results

After integrating the analytically sized PV system in different models, the annual electric balances, i.e. consumption, generation, and electric flows are summarized in Table I. Besides, the obtained life cycle cost (LCC) for a life period of 20 years and an annual discount rate of 5% is 181180 \$ (294.60 \$/m^2). It can be noticed that over 40% of building loads are covered by PV system. The Zero energy balance is attained but with a high amount of "Gains" which represent a loss in terms of cost. The next objective will be to minimize this difference in order to save capital cost of PV. It is better to find the just necessary required size.

Table I Summary of electrical balaces

Description	PV system output (Before inverter)	Supplied from PV to the building	Supplied from PV to the grid
Value (MWh)	61.53	15.26	44.42
Description	Total building load	Supplied from Grid to the building	Gains "Load-generated by PV"
Value (MWh)	37.87	22.6	-21.81

IV. Formulation of the optimization problem and decision making procedure

A. Objective functions and decision variables

In general, the electrical consumption is given by equation (1):

$$\text{Electrical consumption} = \text{consumption of (cooling+ heating + appliances+ lighting+ SDHW)} \quad (1)$$

However, consumption from cooling and heating can be minimized by minimizing the thermal demand. Furthermore, consumption from appliances and lighting is not concerned in this study, although it is recommended to use energy star appliances and adequate lighting to maintain visual comfort and at the same time save electricity. Hence, in this study there are four objective functions to be minimized:

f1=min ("Auxiliary electric heater + Pump" consumptions)
f2=min (Thermal demand)
f3=min (Difference between load and generation)
f4=min (LCC)

Table II provides the list of building passive and RE systems decision variables. Furthermore, the implementation costs of different design options are derived from [10], [11], [12], [13] and [14].The optimization problem is constrained by the following condition: the average predicted mean vote (PMV) of the whole building must remain between its acceptable bounds |PMV|≤ 0.5.

Table II Description and different options of decision variables used in the optimization problem

Description	Type	Values	Step
External walls insulation thickness (cm)	D	1,3,5,7,10	-
Roof insulation thickness (cm)	D	1,3,5,7,10	-
Type of double glazing: Krypton or Argon, U-value (W/m^2.K)	D	0.86, 1.4	-
Cooling set point (˚C)	D	24, 25, 26	-
Heating set point (˚C)	D	19, 20	-
Number of solar collectors in series	C	1 to 20	1
SDHW pump flow rate (Kg/h)	C	50 to 120	5
Number of solar panels in series	C	1 to 20	1
Number of solar panels in parallel	C	1 to 40	1
Width window bedroom (m)	C	1 to 2	0.25
Width window master bedroom (m)	C	1 to 2	0.25
Width window Living and dining, w3, (m)	C	1 to 3	0.25
Width window Living and dining, w4, (m)	C	1 to 3.7	0.25
Width window Kitchen, (m)	C	1 to 2	0.25

D: discrete, C: continuous

B. *Building optimization tool, Algorithm and Pareto-front*

In this study, the optimization is conducted using TRNSYS coupled with MOBO. The non-sorting genetic algorithm (NSGA-II), developed by Deb et al. [15], is adopted. The used parameters' setting of NSGA are as follows: Population size = 40, Generation number = 25, Crossover probability= 70%, Mutation probability= 2%[16]. The MOO results are graphically represented in Figure II. However, in the present work the four-objective optimization generates a four-dimensional (4D) problem space, projected in a bi-dimensional (2D) graph.

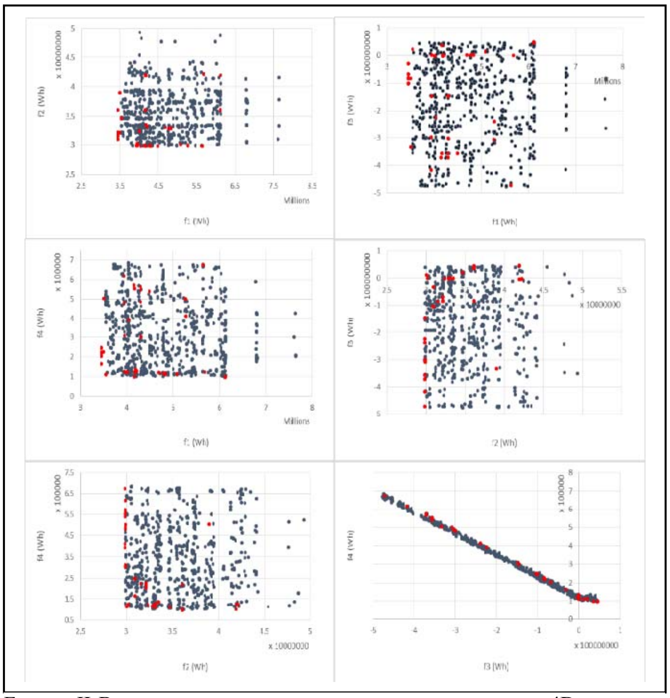

FIGURE II BI-DIMENSIONAL PROJECTIONS OF THE ANALYZED 4D-PROBLEM SPACE (BLUE: BUILDING VARIANTS, RED: PARETO FRONT)

C. *Decision making and sensitivity analysis*

This research employs the ELECTRE III method in order to classify the Pareto front solutions and to choose the most adequate one for each region. Indifference, preference and veto thresholds of ELECTRE III are assigned respectively as follows: 5%, 10% and 30% relative to the average of each objective function's value for the Pareto front points. The relative weight of each objective function is assigned using the Analytical Hierarchy Process (AHP), proposed by Saaty [17].The best solutions after ELECTRE III ranking are shown in Table III, all together with the difference between the ideal case and the base case. It is noticed that SDHW electric consumption is reduced by 17.91%, thermal energy consumption is decreased by33.19% through optimal passive designs compared to the base case, and LCC is reduced by 31.09%. Moreover, the difference between load and generation is decrease to -0.33 MWh instead of -21.82MWh which represent an advantage in terms of initial investment costs of PV system.

TABLE III DIFFERENCES BETWEEN THE BEST SOLUTION BY ELECTRE III AND THE BASE CASE

	f1 (MWh)	f2 (MWh)	f3 (MWh)	f4 (1000$)
Best solution	3.94	30.19	-0.33	124.84
Base case value	4.80	45.19	-21.82	181.18
% difference	17.91	33.19	-98.48	31.09

D. *Results and discussion*

Table IV lists NZEBs parameters consequent of the decision making phase. The results clearly indicate that there is a significant potential to improve the energy performance of residential buildings in cold climate of Cedars by using proven passive strategies.

It can be noticed that the necessity to insulate building envelope components is found to be very important, walls and roof insulation is increased up to 10 cm instead of 5 cm and 1cm respectively. Windows U-value is decreased to 0.86 W/m2.K instead of 1.4W/m2.K in order to decrease cold thermal flow from outside to inside the building. Moreover, the optimal WWR in eastern and western façades must guarantee the necessary heat gain from day time's solar radiation. WWR in eastern and western façades are decreased to 21.87% and 35.15% respectively. Optimal cooling and heating set points are modified to 25˚C and 19˚C respectively in a way to decrease the thermal loads; the occupants comfort is not affected since the PMV is considered as a constraint.

TABLE IV SUMMARY OF THE OPTIMAL BUILDING DESIGN OPTIONS IN EACH REGION

	Walls insulation	Roof insulation	Windows U-value	Cooling set point	Heating set point
Unit	(cm)	(cm)	($W/m^2.K$)	(˚C)	(˚C)
Base case	5	1	1.4	24	20
Optimal case	10	10	0.86	25	19
	Solar collectors	**Pump flow**	**Number PV**	**Eastern WWR**	**Western WWR**
Unit	-	(Kg/h)	-	(%)	(%)
Base case	15	70	90	23.43	59.46
Optimal case	8	115	72	21.87	35.15

V. CONCLUSION

The challenge in ZEB design is to find the best combination of design strategies that would face the energy performance problems of a particular building.

In this study, an energy simulation and optimization programs (TRNSYS and MOBO) coupled with a ranking decision making technique (ELECTRE III) are utilized to evaluate the most cost-effective passive strategies and RE systems sizes that should be implemented to achieve a NZE design for a classic residential building located in cold climate of Cedars. In the optimization analysis, a wide range of design and operating measures are considered including wall and roof insulation levels, windows glazing type, WWR in eastern and western facades, cooling and heating set points, PV and SC systems sizing.

The optimum design parameters and their corresponding objective functions shows that the annual thermal load and LCC can be decreased by 33.19% and 31.09% respectively, compared to the baseline model. Envelop high level of insulation is an essential step to decrease the high heating demands. Besides, WWR of about 21% and 35% respectively on eastern and western facades are sufficient to collect the necessary solar radiation and to avoid the excessive outside low temperature.

Future studies may be extended to other passive design parameters, energy efficient systems, and RE systems as well as other objective functions such as the life cycle assessment impact. In addition, the simulation-based sensitivity and uncertainty analyses of the decision maker preferences and design parameters are interesting topics for the future research works.

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