OPT-*i*
An International Conference on
Engineering and Applied Sciences Optimization
M. Papadrakakis, M.G. Karlaftis, N.D. Lagaros (eds.)
Kos Island, Greece, 4-6 June 2014

LIFE CYCLE ANALYSIS OF A STEEL BUILDING

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Keywords: whole-life cost optimization of steel building, KENAK, structural optimization, energy performance optimization

Abstract. The present study tries to couple structural optimization problems for building frames, with that of energy efficiency optimization. The objective function of the problem takes into account the following parameters: heat capacity, wall and window insulation profile, window sizes, losses due to ventilation, boiler and air conditioning system sizing, sizing of steel cross-sections as well as parameters related to the life cycle of the building. Modeling is based on acceptable from national and European regulations procedures. Optimization is solved using evolutionary algorithms. The optimization problem is implemented on a steel building (10x15 m), in Chania, Greece. This is a first attempt to combine Life Cycle Cost and Optimization with classical Structural Optimization for steel structures. Depending on the requirements from the users of the building further evaluation using building energy management system (BEMS) for the intelligent operation and management of heating, ventilation and air-conditioning (HVAC) may be performed.

1 INTRODUCTION AND FORMULATION OF THE PROBLEM

The total life cycle cost of a specific system, and in particular of a structure, depends on the system's most critical components. The most important parameters that are usually examined in life cycle cost problems are following:

1. Construction costs
2. Maintenance costs
3. Operation costs
4. Remaining cost at the end of the structure's expected life cycle.

The formula below is a generalized approach for a system's total life cycle cost:

$$LCC = C + PV_{RECURRING} - PV_{RESIDUAL\text{-}VALUE}$$

LCC is the total life cycle cost.
C is the Year 0 construction cost.
$PV_{RECURRING}$ is the present value of all recurring costs (utilities, maintenance costs, replacements, service costs etc.).
$PV_{RESIDUAL\text{-}VALUE}$ is the present value of the residual value at the end of the examined life cycle period.

In order for the life cycle cost of a specific building to be minimized, it is important to determine -during its design and construction stage- the subsystems that affect its life cycle cost with the view of taking optimal design decisions.

In general, the following subsystems have a considerable impact on the life cycle cost of a specific building:

- Building Envelope (insulation profiles, shading systems, glazing, roofing etc.)
- Mechanical and Energy Systems (use of photovoltaic panels or alternative sources of energy, ventilation systems, water distribution systems)
- Structural Systems (selection of appropriate frame materials, sizing of the frame components)
- Sitting (landscaping and irrigation-related design decisions).
- Electrical Systems (lighting sources and control, distribution)

For typical cases of buildings in Greece, practical experience as well as data derived from statutory sources in building construction cost analysis studies, have shown that the most critical subsystems that affect its total whole life cost are those related to its structural and energy performance.

These subsystems, also interact with one another as the building frame affects its energy performance and the insulation plays a role on the frame's structural design loads. Furthermore, the other subsystems such as the water distribution systems, landscaping options, electrical systems constitute an optimization problem that can be examined separately.

Apart from that, it is also necessary to consider the average life cycle of above mentioned subsystems in order to predict any potential replacements that may occur during the examined life cycle period. According to various sources (Technical Chamber of Greece, Stanford university, CIBSE), the average life cycle of the examined building components is as follows:

- Structural steel or reinforced concrete: 80 years (lifetime)
- Building Exteriors, Doors, and Windows: 80 years (lifetime)
- EPS insulation profiles: 100 years (lifetime)
- Mineral wool insulation profiles: 50 years
- HVAC systems: 15-20 years

2 METHODOLOGY

In terms of their contribution to total life cycle cost of typical building, the most important subsystems are the structural systems and the systems related to the energy design of a building. These ones can also be optimized from the early stages of the design of a building.

In order to test the capacity of a software to optimize these subsystems, it was decided to develop an algorithm unifying the structural and energy performance optimization of a building. This algorithm would also be one of the first published attempts to optimize the energy performance of buildings according to KENAK; the recent Greek code for the energy design of buildings.

At first, a market research took place in an attempt to discover average, real-life cost figures of the subsystems that would be used in the algorithm. The market research took into consideration the costs of the following building components:

- Metallic wall or roof panels.
- EPS or mineral wool insulation of various thicknesses.
- A+++ or A energy class air-conditioning systems.
- Structural steel cost per kg.
- Double and triple-glazed aluminum windows (with regular or low-e values).

In order to save computational time and unify parameters that have an impact on each and correlate the energy performance parameters with the resultant cost, curve-fitting and multiple linear regression has been used. The cost functions below are some of the ones that were used in the algorithms and they are demonstrated in order for the reader to be able to understand the logic behind that idea:

*costwindowseast = (218.376 - 38.931*Uwineast + 47.888*ggl)*Awineast*
costinsulationwallwest = (5.603 Uwwest^-1.21)*Awwest (mineral wool)*
*costAC = -3461.45 + 172.5595*Ptherm + 190.222*SEER + 674.565*SCOP (A energy class air conditioning systems)*

The correlation results revealed (basing any judgment on the computed R-squared values of the cost functions that were produced through multiple linear regression), a relatively high degree of correlation implying a logical relationship between cost and critical energy perfor-

mance parameters. Furthermore, the following scenarios are examined, for a life cycle period of 10 or 30 years:
Scenario 1:
-Mineral wool insulation profiles with A energy class A/C as HVAC system.
Scenario 2:
-EPS insulation profiles with A energy class A/C as HVAC system.
Scenario 3:
-EPS insulation profiles with A+++ energy class A/C as HVAC system.

3 OPTIMIZATION PROCEDURE

After a finite element analysis, the building frame components were optimized along with the following subsystems:

- Characteristic dimensions of the steel frame cross-sections (b, d, tw, tf).
- U-values of floor (it is assumed that the building floor has a reinforced concrete slab (of 20 cm thickness) and below that a u-value results from the optimization procedure).
- U-values of walls (each orientation was examined separately).
- U-value of roof.
- Area of windows (south elevation).
- Area of windows (all other elevations; each orientation was examined separately).
- ggl value.
- Power of heating system.
- Power of cooling system.
- SCOP
- SEER

4 CONSTRAINTS

The algorithm that was developed took into account the following constraints:

- Lower and upper limits were imposed on all the characteristic dimensions of the steel frame cross-sections (b, d, tw, tf).
- Stress constraints were also imposed on the steel frame cross-sections.
- The power of the heating system should be greater than the result of following formula, that is used for the sizing of heating systems by the Greek specifications.

$$P\ thermal\ system > 2.5xU_m xAx\Delta T$$

- The same should apply for the air conditioning system, whose power (in kilowatts) must be sufficient for the most adverse day of the summer (21st of July).
- All the components of the building envelope should have acceptable lower and upper limits of u values. Therefore:

1. U-values of walls:

$$0.20 < U_{walls} < 0.60$$

2. U-value of the floor:

$$0.20 < U_{floor} < 1.20$$

3. U-value of the roof:

$$0.20 < U_{roof} < 0.50$$

- The overall average u value of the building, should be lower than what is required by the relevant specification (KENAK).
- The window u-values should be realistic and therefore they should not be lower than what can be encountered in the market.
- The seasonal coefficients SCOP for the heating system and SEER for the air-conditioning system should represent the upper and lower limits that are encountered in the Greek market.
- The total window area in the main elevation (therefore, the south oriented elevation with an acceptable deviation equal to plus or minus 30 degrees ($\pm 30^o$)) of the building should be sufficiently big. Despite the fact that this consideration is generally a choice dependent on the architectural designer, for the current building it was decided that 45% of the total window area should have south orientation.

- The total area of the building windows should ensure sufficient natural illumination and ventilation. According to the Greek building codes, this area should represent at least 10% of the total area of the building.

- The ggl values (hence, g values multiplied by 0.75; therefore reduced due to the contribution of the window frame that was considered to approximately occupy 25% of their total area) of windows should have a value between 0.29 and 0.55.

5 THE MODEL

The building that was used in the simulation is a single-storey steel building located on Chania, Crete. A plan view of the building -which has a 10x15 m rectangular shape- is shown below:

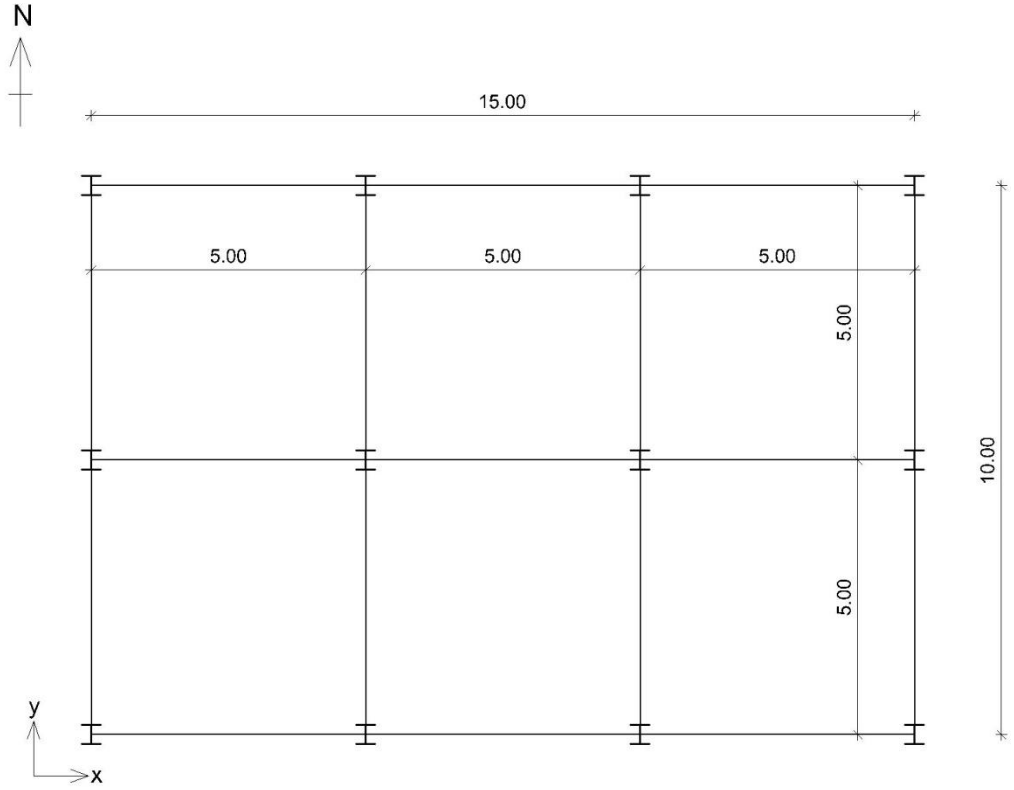

Figure 1: Simplified plan view of the building.

At first it was assumed that the building will be used as an office building and this influenced the considerations that were used in the calculations (thermal or cooling loads generated by the theoretical population of building users, minimum required ventilation, characteristic electrical appliances expected to be used in the building).

Apart from that, the following data were used for the optimization of energy design of the building:

- The thermal bridges were calculated with the use of the approximate standardized values of the national standards.

- The outer and inner walls are made of metallic panels and their color is grey.

- The solar gains during the winter period (October to May) are not taken into account in the calculation of the total thermal load. The opposite however, applies for the summer period (May to October). The solar gains were calculated with the use of the approximate standardized values of the national standards for the specific geographic location.
- Loads on the steel frame: 20.94 kN/m (middle span along x-x axis, mineral wool scenario).
- Loads on the steel frame: 10.24 kN/m (side spans along x-x axis, mineral wool scenario).
- Loads on the steel frame: 20.48 kN/m (middle spans along y-y axis, mineral wool scenario).
- Loads on the steel frame: 10.24 kN/m (side spans along y-y axis, mineral wool scenario).
- Loads on the steel frame: 18.76 kN/m (middle span along x-x axis, EPS scenarios).
- Loads on the steel frame: 9.38 kN/m (side spans along x-x axis, EPS scenarios).
- Loads on the steel frame: 18.76 kN/m (middle spans along y-y axis, EPS scenarios).
- Loads on the steel frame: 9.38 kN/m (side spans along y-y axis, EPS scenarios).
- Base temperature inside the building = 25 ^{o}C.
- Heating Degree days (Geographic location: Chania) = 2215.
- Cooling degree days (Geographic location: Chania) = 218.
- Uniform building height = 3 m.
- Examined life cycle period in years: 10 & 30 years
- Coefficient accounting for the electricity cost in Euros/kWh = 0.012269.
- Illumination load per square meter: 0.05 kWh/m^2.

In accordance with the national specifications, it was also taken into account that the office building is used 29.66% of the time during a year. The maintenance rates for the building are considered to be equal to 1% of its initial value (therefore, unaffected by inflation rates) per year, with a start point five years after its construction. As regards the HVAC systems, the maintenance rate is considered to be equal to 2% of their initial value (unaffected by inflation rates) per year. An inflation rate with a constant value equal to 3% per year, is also taken into account in the calculation of the cost of their replacement at the end of their life cycle (20 years).

As regards the heating and cooling costs, it is also possible to use the predicted UPV values of the electricity costs 30 years after the construction of the building, however only predicted values from countries such as the USA, can be found.

The objective function is the sum of the cost of the following subsystems:

*total cost = cost of insulation + Heating cost*Number of years + Cooling cost*Number of years + cost of frame + cost of A/C system + cost of windows + cost of roof + cost of walls + HVAC maintenance + general building maintenance + cost of the floor slab*

The constraints incorporated in the objective function describing the total life cycle cost through the use of conditional penalty functions whose violation would result in very high cost values.

6 NUMERICAL RESULTS

The optimization problem is possible to be solved with the use of simulated annealing and genetic algorithms and the first method seems to constantly produce better results. The use of Sequential Quadratic Programming is also possible but at times it requires either some degree of relaxation on the constraints or segregation of the optimization procedure in gradual steps.

The energy performance optimization results that were produced by running several scenarios for a life cycle period of 10 or 30 years, are shown in the appendix.

As regards the optimized cross-sections of the frame components (Scenario 1):

- Middle span beams: IPE 240.
- Side span beams: IPE 200.
- Corner columns: HEB 140.
- Middle columns of the west and east elevation: IPE 300
- Middle columns of the north and south elevation: IPE 300.
- Interior columns: IPE 360.

The optimized cross-sections of the frame components for the scenarios 2 & 3, are as follows:

- Middle span beams: IPE 240.
- Side span beams: IPE 200.
- Corner columns: IPE 100.
- Middle columns of the west and east elevation: IPE 100.
- Middle columns of the north and south elevation: IPE 100.
- Interior columns: IPE 120.

An interpretation of the results can lead to the following conclusions:

- It seems to be a cost-effective decision to use window panes with very low g values. Nevertheless, for the examined life cycle periods of the building the triple glazed window profiles with low g values, in no case constituted the optimal alternative. The area occupied by the windows is every time dependent on the optimization calculations.

- The floor generally seems to be the least important component to insulate and the roof the most important to insulate. Furthermore, the optimal insulation thickness of the walls slightly increases with the increase of the examined life cycle period.

- Subsystems with a high degree of homogeneity (e.g. A+++ or A energy class A/C systems and insulation profiles where the thickness of -merely one- specific material needs to be optimized) can be correlated with energy performance parameters through multiple linear regression, attaining very high R-squared values. This can save considerable computational time.

- The optimization program naturally selects larger -within reason- window areas on the south elevation. It seems that it may be a redundant constraint to place a lower bound on the window area of the south elevation.

- The heating and cooling requirements of the office building can be covered with a typical 12000 btu, A/C system. The comparison of the market prices for the current building showed that an A energy class A/C system is by 67% a cheaper alternative in comparison with an A+++ energy class A/C system. It should be born in mind that the algorithms also consider replacement of the HVAC system 20 years after the building construction.

- The figure below displays several well-known upper limits of building energy consumption levels. Level 1 is an approximate figure for current acceptable consumption levels for buildings in Germany, level 2 stands for the Minergie practice followed by Switzerland, levels 3 & 4 are regarded as low energy consumption levels and buildings whose energy consumption is below 15 kWh/m^2 are classified as passivhaus. The results showed that 10 years after the construction of the building the optimal level is around 32 kWh/m^2, but 30 years after the construction of the building it escalates to slightly above 30 kWh/m^2.

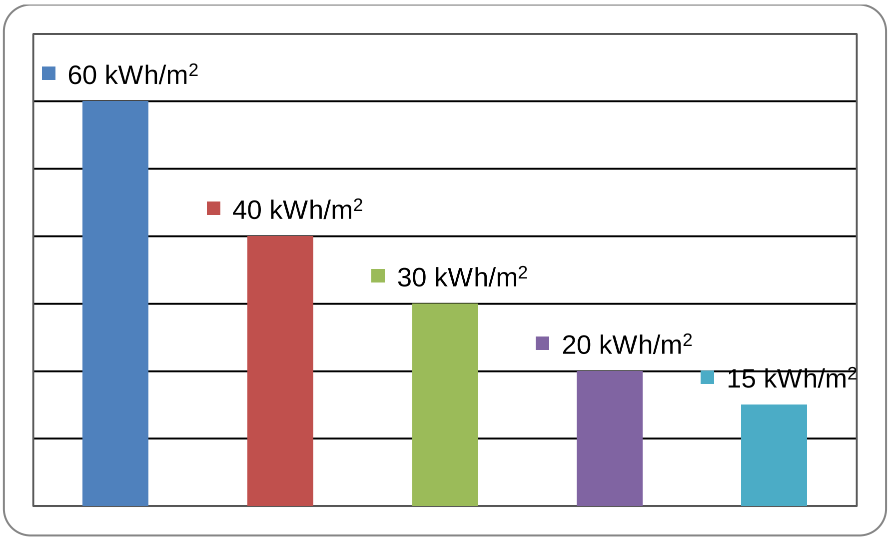

Figure 2: Well-known building energy consumption levels.

7 CONCLUSIONS AND FUTURE EXTENSIONS

A life cycle analysis of a steel building has been performed that takes into account energy considerations for both construction and material costs, as well as energy consumption during usage of the structure. In this sense structural and energy optimization are combined and solved with practical global optimization algorithms. It must be emphasized that the complexity of the model restricts the applicability of classical numerical optimization algorithms.

By using the proposed model an optimal design of a new steel structure that takes into account its energy consumption during its whole life cycle can be attempted.

In a reverse engineering setting, the cost functions proposed here can be used for the evaluation of several alternative design scenarios.

Since almost all involved quantities are contaminated with uncertainties, extension of the proposed method using fuzzy variables and fuzzy optimization seems to be reasonable. This extension remains open for further investigation.

ACKNOWLEDGMENTS

This research has been co-financed by the European Union (European Social Fund – ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF) – Research Funding Program: **ARCHIMEDES III.** Investing in knowledge society through the European Social Fund.

REFERENCES

[1] P.D. Bourkas, Applications of building services in typical and industrial buildings, pp. 214-233, 1998.

[2] F.Y. Cheng & K. Z. Truman, *Structural optimization: Dynamic and seismic applications*, Spon Press, pp. 351-359, 2010.

[3] Current German Energy Saving Regulations for Buildings, http://leap-eu.org/assets/dynamic/training_weeks/1/Theme%201%20%20Current%20German%20energy%20Saving%20Regulations%20for%20Buildings20120723111711.pdf .

[4] D.N. Kaziolas, I. Zygomalas, G.E. Stavroulakis, D. Emmanouloudis, C.C. Baniotopoulos "Evolution of Environmental Sustainability for Timber and Steel Construction", in, A. Hakansson, M. Höjer, R.J. Howlett, L.C. Jain (Editors), *Sustainability in Energy and Buildings, Proceedings of the 4th International Conference in Sustainability in Energy and Buildings (SEB΄12), Smart Innovation, Systems and Technologies*, Vol. 22, pp. 24-33, 2013.

[5] *European national strategies to move towards very low energy buildings*, Danish Building Research Institute, Aalborg University, March 2008.

[6] I. Zygomalas, D.N. Kaziolas, G.E. Stavroulakis, C.C. Baniotopoulos, "Life Cycle Assessment of a Steel-Framed Residential Building", in B.H.V. Topping, P. Iványi, (Editors), *"Proceedings of the Fourteenth International Conference on Civil, Structural and Environmental Engineering Computing"*, Civil-Comp Press, Stirlingshire, UK, Paper 152, 2013. doi:10.4203/ccp.102.152.

[7] *Minergie building energy design criteria*, http://www.minergie.ch/standard_minergie.html .

[8] Stanford University: *Land and Buildings, Guidelines for life cycle cost analysis,* October 2005.

[9] *Passive house certification criteria*, http://www.passreg.eu/index.php?page_id=305 .

[10] Technical Chamber of Greece, T.O.T.E.E. 20701-1/2010 & T.O.T.E.E. 20701-2/2010, July 2010.

[11] Technical Chamber of Greece, T.O.T.E.E. 20701-3/2010, April 2012.

[12] Toke R. Nielsen, *Optimization of buildings with respect to energy and indoor environment*, pp. 26-103, 2002.

APPENDIX

Table with results supporting Figure 2.

SCENARIO 1																			
	U_{floor}	SCOP	ggl	$A_{winouth}$	$A_{wimorth}$	$A_{wineast}$	$A_{winwest}$	U_{roof}	$U_{wall\ south}$	$U_{wall north}$	$U_{wall east}$	$U_{wall\ west}$	$U_{win\ south}$	$U_{win\ north}$	$U_{\ vin\ east}$	$U_{winwest}$	Power of HVAC system	SEER	Time Period
1	0,991	3,600	0,291	11,054	4,348	0,500	0,525	0,500	0,591	0,600	0,592	0,600	3,399	2,849	2,448	3,036	4,385	3,202	30 years
2	1,196	3,603	0,290	7,783	4,174	0,500	2,546	0,500	0,600	0,600	0,600	0,600	3,400	2,745	3,052	3,386	4,723	3,200	10 years
Optimal Energy consumption level: Below Level 2																			
SCENARIO 2																			
	U_{floor}	SCOP	ggl	$A_{winouth}$	$A_{wimorth}$	$A_{wineast}$	$A_{winwest}$	U_{roof}	$U_{wall\ south}$	$U_{wall north}$	$U_{wall east}$	$U_{wall\ west}$	$U_{win\ south}$	$U_{win\ north}$	$U_{\ vin\ east}$	$U_{winwest}$	Power of HVAC system	SEER	Time Period
1	1,186	3,600	0,290	9,045	4,019	0,531	1,406	0,500	0,566	0,600	0,600	0,600	3,400	3,106	3,029	3,400	4,714	3,202	30 years
2	1,141	3,600	0,291	9,304	4,712	0,500	0,500	0,500	0,599	0,600	0,600	0,600	3,399	2,644	3,051	3,353	4,614	3,201	10 years
Optimal Energy consumption level: Below Level 2																			
SCENARIO 3																			
	U_{floor}	SCOP	ggl	$A_{winouth}$	$A_{wimorth}$	$A_{wineast}$	$A_{winwest}$	U_{roof}	$U_{wall\ south}$	$U_{wall north}$	$U_{wall east}$	$U_{wall\ west}$	$U_{win\ south}$	$U_{win\ north}$	$U_{\ vin\ east}$	$U_{winwest}$	Power of HVAC system	SEER	Time Period
1	0,900	5,100	0,290	10,372	3,620	0,500	1,328	0,500	0,581	0,594	0,599	0,572	3,400	2,747	2,552	3,315	2,952	8,330	30 years
2	1,068	5,100	0,341	6,991	4,771	0,500	3,193	0,500	0,597	0,600	0,600	0,597	3,399	2,672	3,004	3,400	3,170	8,145	10 years
Optimal Energy consumption level: Below Level 2																			