A hierarchical optimization methodology for the cost optimal design of low energy buildings in Cyprus

ANDREAS KANARACHOS, GEORGETTE KANARACHOS, STRATIS KANARACHOS
Frederick Research Center
7, Y. Frederickou Str., Pallouriotisa, Nicosia 1036
CYPRUS
eng.ka@frederick.ac.cy http://www.frederick.ac.cy

Abstract: In view of the needs for energy minimization in the buildings sector, the design of cost optimal low energy buildings (LEB) in the Mediterranean area is of significant interest. The measures available to accomplish this task include the use of latest building technology and the customization of the design (climate, owner’s needs and requirements, user behavior, etc). The goals include the minimization of the annual primary energy consumption/carbon dioxide emissions and of the costs. Both measures and goals constitute in general a multi-objective optimization problem, for which numerous methods, including mathematical optimization methods, have been proposed in the past. This paper proposes a new optimization method for the design of low energy buildings based on Hierarchical Optimization (HO). The method uses technical and financial information of building components available in Cyprus organized in an excel database CyLEBd, which feeds CyLEBs, a building performance simulation (BPS) tool. A case example illustrates how the method enables the design optimization of low energy buildings in Cyprus, implying that the method could be easily adjusted for other Mediterranean climates. This research has been financed by the Research Promotion Foundation of Cyprus.

Key-Words: Low energy buildings, Hierarchical optimization, Energy and costs minimization, Cyprus

1 Introduction
The design of cost optimal low or very low energy building implies the choice and combination of operational and aesthetic factors (e.g. climate, building use, owner requirements, shape, orientation, size, etc.) with passive (e.g. building envelop materials, insulation, roofing materials, finishing materials, window types, etc.) and active system components (e.g. heating, air conditioning, cooling, ventilation, alternative energy sources, building management systems, etc.). The numerous design parameters and the design goals, such as minimization of the annual primary energy consumption/carbon dioxide emissions and of the costs, constitute a multi-parameter and multi-objective optimization problem.

For the solution of this problem several methods have been proposed in the past. These methods are mainly based on multivariate analysis of data and on mathematical optimization methods, e.g. [2-11]. In engineering practice these methodologies are many times exceeded and complemented by professional skills, knowledge and experience. Building performance simulation (BPS) tools, which incorporate the most significant building design parameters and maximize the reliability of future building performance predictions, are also used.

However, the complexity of the task reveals the need for further or additional methods, which take into account the differences in climate, local architecture, local costs, owner’s needs, as well as the necessary cooperation of architects, engineers (civil, mechanical, etc.) and contractors. These further methods should avoid mathematization, consort with engineering knowledge and practice and minimize design iterations.

This paper proposes a new optimization method for the design of low and very energy buildings based on Hierarchical Optimization (HO). HO was initiated by J. Bracken and J.M. McGill [12-13]. The activities in the field have ever grown lively, both in terms of theoretical developments and terms of the diversity of the applications.

The HO method is in our case based (and uses) technical and financial information of building components available in Cyprus. This information is organized and managed in an excel database CyLEBd, which feeds CyLEBs, a building performance simulation (BPS) tool. A case example illustrates how the method enables the design
optimization of low energy buildings in Cyprus, implying that the method could be easily adjusted for other Mediterranean climates.

2 Hierarchical Optimization

2.1 Hierarchical Levels

Hierarchical optimization is concerned with decision making problems that involve multiple decision makers, ordered within a hierarchical structure. The higher order decision makers strongly influence the decisions of those with a lower rank. The most well-known case, described by the so-called “Stackelberg game”, is the one in which decision makers of two different ranks are involved. This is the bilevel Optimization case.

Newly, a general model for hierarchical optimization has been proposed [16] on the basis that searching methods solve optimization problems by navigating on the surface of a possibly rugged landscape, which is the optimization function. This kind of navigation is not very effective because the property of the landscape at different resolutions can be very different. Therefore the model emphasizes the possibility to provide a basis for resolution control and smoothing of the search space and to introduce continuous memory into search.

Considering the above theoretical basis an analysis of the design problem of low energy buildings was performed. The following main parameter groups or decision makers have been identified:

(a) Operational parameters (climate, building use, owner requirements, etc.)
(b) Aesthetic/geometrical parameters (building shape, orientation, size, transparent and opaque elements, etc.)
(c) Passive building parameters (building envelop, materials, insulation, roofing materials, finishing materials, window types, etc.), classified in Database-c.
(d) Active building parameters (heating, air conditioning, cooling, ventilation, alternative energy sources), classified in Database-d.
(e) Building control and management systems (BCMS), classified in Database-e.

In view of the fact that the parameters (a)-(b) are more or less of unclassified type and that the technical and financial information for the parameters (c)-(e) can be gathered and managed in appropriate Databases (see above), the optimization problem can be split into hierarchical levels and formulated as follows:

2.1.1 Hierarchical Optimization Level 1 (HOL1)

In the HOL1 the performance/costs optimization will be performed with constant (for HOL1 already defined and not varying) parameters (c)-(e). The free decision parameters are the decision makers (a)-(b).

For the design analysis and optimization the building performance software CyLEBs is used. The CyLEBs tool allows a continuous (e.g. time step 60 sec) time simulation. The heart of CyLEBs is a 3R2C thermal model for the building shell (including roof and floor), thus enabling the simulation of an outer and/or between and/or inner insulated building shell. This covers typical alternatives of a LEB design. In addition the environmental climate issues and the user’s possible requirements (e.g. continuous or discontinuous heating/cooling operation) and behavior are incorporated in the software. Finally a building management system (BMS) including the use of controllers has been included. Thus CyLEBs allows a detailed analysis of the buildings thermal performance.

The inputs of CyLEBs are the unclassified (a)-(b) and the classified parameters (c) and (e). These are used for the computation of the thermal losses and of the necessary heating-cooling loads, rsvp. of the thermal needs of the building.

The above analysis/optimization is performed for typical weather scenarios and user requirements (control of heating, ventilation and cooling, etc.).

The data in Database-e is classified according to a cost criterion (low⇒high prices) for a single controlled thermal zone. The cost criterion includes hard-, software (sensors, actuators, CPU, software) and installation costs. The Database-e contains “ready to buy” BCMS components and it mirrors the state of the art at the local market.

2.1.2 Hierarchical Optimization Level 2 (HOL2)

In HOL2 a “local” optimization is performed concerning the passive building shell (frontage) components. In our proposed methodology Database-c allows the classification of its passive building shell components according to the classification criterion “C”:

\[ C_{Database-c} = w_{21} \cdot Phys + w_{22} \cdot Fin = Min \]  

(1)

\( w_{21} \) and \( w_{22} \) are weights chosen by the user. \( Phys \) represents the physical properties of the passive components (e.g. thermal transmittance \( U \), conversed heat capacity \( 1/C_{th} \) or a combination of both) and \( Fin \) the component cost. The Database-c contains the “ready to buy” passive components and mirrors the state of the art at the local market.
Through this splitting of the optimization problem in hierarchical levels and the introduction of local optimization loops, the parameters (c) are decoupled from the other parameters and the optimization problem can be solved in a much easier way.

2.1.3 Hierarchical Optimization Level 3 (HOL3)
In HOL3 another “local” optimization is performed concerning the active building components. In our proposed methodology Database\(_d\) allows the classification of its active building components according to the classification criterion “C”:

\[
C_{\text{Database-}d} = w_{31} \cdot \text{Phys} + w_{32} \cdot \text{Fin} = \text{Min}
\]  

(2)

\(w_{31}\) and \(w_{32}\) are weights chosen by the user. \(\text{Phys}\) corresponds to physical properties (e.g. degree of efficiency \(\eta\) per KW) and \(\text{Fin}\) to component cost. The Database\(_d\) contains “ready to buy” active components and it mirrors the state of the art at the local market.

The HOL3 is of lower rank than HOL1 and HOL2. It has only to cover the already optimized thermal needs/loads of the building.

Again, through this splitting of the optimization problem in hierarchical levels and the introduction of local optimization loops, the parameters (d) are decoupled from the other parameters and the optimization problem can be solved in a much easier way.

2.2 Design Process with HOL
Let us now assume that the architect or design engineer (ADE) starts the design of a LEB following the proposed hierarchical optimization method with the information already classified in the Database\(_c\), \(_d\) and \(_e\).

2.2.1 BCMS
With respect to BCMS an initial choice are room thermostats (Fig.1). Room thermostats have, as one may see from Database\(_e\), the best ratio performance to cost.

Fig.1 Room thermostats for heating and/or cooling. Room thermostats can cover a wide range of different heating, ventilation, and cooling applications while addressing individual customer needs. Time programs can adjust the room temperature to the desired comfort level at predefined times. The thermostats provide a wide choice of easy-to-set energy saving functions that help reduce energy consumption, like self-learning PID control, set point limitation, vacation function, or fan control. They can also be connected to external sensors or contact switches such as window contacts. All of these functions offer an efficient, convenient way to set the right temperature in every room. This means that the building can be easily divided in independent thermal zones.

2.2.2 Passive Building Components
With respect to passive building components, an initial choice is a double insulated wall consisting of 5 cm thick outer EPS insulation, 18-20 cm thick inner massive concrete or bricks wall and 5 cm thick inner EPS insulation (Fig.2). This corresponds to \(U\) and \(C\) values of \(U \approx 0.3\) W/[m\(^2\)K] and \(C \approx 0.88\) J/[gK].

Through such a type of wall thermal bridges are eliminated and the thermal mass of the building is increased to the highest possible level. In addition the absorption of radiation from the walls is practically set to zero.
static body. Thus, small openings of the building shell are from the standpoint of thermal losses and costs advantageous. On the other hand they may be not advantageous from the standpoints of lighting, thermal gains in the winter and increased ventilation. This makes further investigations necessary.

Finally, with respect to the roof and floor construction a number of alternatives exist, which have to be individually evaluated. For example, insulated roof towards outside or upper floor or insulated floor towards a lower apartment, a non heated cellar (with or without insulation), towards soil (with or without border insulation) or towards outside air.

2.2.3 Analysis of Thermal Zones

The thermal analysis of a LEB is split in the analysis of its individual thermal zones. As already stated this is performed using CyLEBs, which allows the continuous (per minute) time-simulation of the building’s performance and the incorporation of trustworthy and realistic scenarios concerning thermal needs, environment (air and earth data, see Fig.3-5) and bioclimatic measures. Assumptions, such as constant air changes per hour (ACH) during winter and summer over 24 hours/day in order to compute the thermal needs of a building, are not considered and not accepted for the present analysis.

3 Optimization Procedures

3.1 A Possible Optimization Strategy

In view of the above mentioned many and different scenarios for the thermal analysis of a LEB it is necessary to build up an overall optimization strategy.

In this context, the introduction of HOL allows certainly (and this is very important) the reduction of the number of the decision parameters and the introduction of a discrete type optimization through the classification of the information in the Databases-c, -d and –e. This greatly facilitates the optimization as, for example, the next candidate solution for the passive building components of the LEB will be the Nr.2, Nr.3, etc. according to the specific sorting performed by the specific criteria-weights within the Database-c.

In view of the target to design a LEB which can compete financially with a conventional building, the overall optimization strategy to be followed is to counterbalance the additional costs for control and insulation by costs savings coming from the reduced HVAC installation.

If, in this conjunction, the windows of the LEB are kept the same with the windows of a conventional building (double glazing without heat protection) no additional costs arise from this passive component. The only additional cost is the double insulation. This cost can be counterbalanced by the savings of the HVAC installation. The basic reason is that the mass of the building shell between the double insulation does not participate directly in
the temperature control procedure, but only the building mass within the thermal zone (e.g. plaster, furniture, movables). This is generally a small a part of the mass of the building shell, leading therefore to smaller HVAC installation costs.

3.2 User Behavior
In many cases, user behavior is of significant importance. If a LEB is designed to be controlled, then the user must be streamlined with the suggested controls and should not intervene with them.

In the following a 12m x 9m x 3m residential LEB situated in Nicosia, Cyprus is analyzed using the Building Performance Simulation (BPS) software CyLEBs. The main characteristics of the building are displayed in Fig.5.

Characteristic results for a typical day in July in Nicosia using CyLEBs are displayed in Fig.6-8:

- In Fig. 6 the BPS results for constant ACH=0.5 are displayed. The room temperature $T_{Room}$ starts at 30°C, reaches 36.7°C and goes down to 28.1°C at the end of the day (24h time period). This reduction of the temperature is due to the assumed contact of the floor with the earth and also to the assumed earth temperature of 20°C. As a result the floor temperature $T_{Floor}$ is also reduced.

- In Fig. 7 the BPS results for variable ACH (night ventilation ACH=0.5 between 24h and 7h in the morning and reduced day ventilation ACH=0.17) are displayed. The room temperature $T_{Room}$ starts at 30°C, reaches 32.5°C and drops at 24.5°C at the end of the day (24h time period). This bigger reduction of $T_{Room}$ is due additionally to the bioclimatic measure of night ventilation.

- In Fig. 8 the BPS results for false variable ACH (day ventilation ACH=0.5 and reduced night ventilation ACH=0.25 set by user and caused by fear of thieves) are displayed. The room temperature $T_{Room}$ starts at 30°C, reaches 40.4°C and drops to 31.7°C.
4 Conclusion
This paper proposes a new optimization method for the design of cost optimal low energy buildings based on Hierarchical Optimization. The method uses technical and financial information of building components available in Cyprus and organized in an excel database CyLEBd, to feed CyLEBs, a building performance simulation (BPS) tool.

The advantages of this method are (i) a significant reduction of the number of the decision parameters and (ii) the introduction of a discrete type optimization through the classification of the information in the Databases-c, -d and -e. This greatly facilitates the optimization as, e.g. the next candidate solution for the passive building components of the LEB will be the Nr.2, Nr.3, etc. of the corresponding Database-c, always according to the chosen classification criterion.

Finally the CyLEB software seems to be a valuable supporting tool to the architect or design engineer, which greatly facilitates the design of LEB and supports him also with respect to decisions that have to be taken for the aesthetic and operational issues.

Acknowledgments
The results presented in this paper are part the work performed for the research project “Development of a Database and of Software for the Design and Construction of Low Energy Buildings in Cyprus” which is co-funded, through the Research Promotion Foundation, by the Republic of Cyprus and the European Regional Development fund of the EU.

References: