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Optimization of Mediterranean building design using genetic algorithms

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Abstract

While it is possible to check the energy performance of a given building by means of several available methods, the inverse problem of determining the optimum configuration given a desired performance is more difficult to solve. In the Mediterranean region this problem is more complex due to the following two reasons: the air-conditioning load is as important as the heating load, and the energy needs depend on a high number of architectural parameters which have different, even contradictory, effects on summer and winter loads. In this paper we present an optimization algorithm that couples pseudo-random optimization techniques, the genetic algorithms (GA), with a simplified tool for building thermal evaluation (CHEOPS) for the purpose of minimizing the energy consumption of Mediterranean buildings. Since increasing the energy performance usually requires the use of special devices resulting in a high construction cost, we also propose to use GA for the purpose of economical optimization.

Keywords: Energy optimization; Cooling and heating load; Mediterranean building; Genetic algorithms

1. Introduction

The energy performance of a building depends on a high number of parameters. It is determined by its response as a complete system to the outdoor environment and the indoor conditions. Improved levels of performance require the coherent application of measures which altogether optimize the performance of the complete building system. Given the number of individual attributes that have to be combined to make a single building, the number of possible designs is very large, and determining the most efficient one is a complex problem.

Optimization of building energy performance is more complex in the case of Mediterranean buildings. While in some cold European regions only heating energy consumption is usually considered, the Mediterranean climate makes it essential to consider both heating and cooling energy uses. Varying some parameters of the building over their ranges of practical values can have opposite effects on heating and cooling energy consumptions. It is evident, for example, that an insulated building envelope helps in reducing the heating demand. But in summer, the outdoor night temperature being generally lower than the required indoor temperature, uninsulated but high thermal capacity walls allow for the evacuation of the heat stored in the building during the day, leading to the reduction of air-conditioning need. One important question is raised: what is the wall composition that leads to the lowest energy consumption in both seasons? The answer is not straightforward.

In order to optimize the energy performance of the building, D.A. Coley and S. Schukat proposed in [1] to use genetic algorithms (GA) coupled with a dynamic thermal model, but they considered only the need for heating energy. In the present paper, we propose to use these techniques to find the appropriate trade-offs in the Mediterranean context, i.e. minimize the sum of heating and cooling loads, which we shall try to compute in a simplified way in order to be able to quickly evaluate numerous solutions.

Since special measures are required to reduce the energy loads of the building, we also propose to use genetic algorithms in the economic optimization of the Mediterranean buildings. We aim to minimize the building global monetary cost, including the construction investments, purchase price and maintenance costs of the heating and air-conditioning systems, as well as the cost of the total energy consumption through the life cycle of the building.

The main characteristics of the two sided problem are: a large multi-dimensional space to be searched, a range of different

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Nomenclature

A	surface of the building (m^2)
C	cooling load (Wh)
C_{ea}	energy operating cost (TND)
$C_{eq,cool}$	purchasing and installation cost of the cooling equipments (TND)
$C_{eq,heat}$	purchasing and installation cost of the heating equipments (TND)
C_{global}	global monetary cost (TND)
C_{maint}	preventive maintenance cost (TND)
C_{ea}^{cool}	cooling energy cost (TND)
C_{ea}^{heat}	heating energy cost (TND)
DH_C	degree-hours corresponding to a cooling load during the hot season (°C h)
DH_h	degree-hours corresponding to a heating load during the cold season (°C h)
F	solar fraction
Fe_1	solar factor
H	heating load (Wh)
i_{elec}	increase rate of electricity price (%)
i_{gas}	increase rate of gas price (%)
I	basis investment (TND)
I_{const}	construction investment (TND)
L_1	length of the south facade (m)
L_c	losses through the dynamic system during cooling season (Wh)
L_h	losses through the dynamic system during heating season (Wh)
$L_{ref,c}$	reference cooling load (Wh)
$L_{ref,h}$	reference heating load (Wh)
N	populations size
Q_{eff}	effective gains (Wh)
Q_g	gross free gains (Wh)
Q_u	useful gains (Wh)
S	solar overheating factor
V	volume of the building (m^3)
V_i	fraction of the glazed surface on the facade i (%)

variable types and a non-linear objective function. The results presented in this paper demonstrate that using genetic algorithms to solve such problems is a good alternative that allows us to identify not only the best design, but a set of good solutions.

2. The energy consumption problem

In cold countries there is not a real need for summer air-conditioning except where internal gains are high such as concert halls or opera houses. Therefore, in [1] the fictitious load of air-conditioning due to the possible overheating was introduced in the objective function in the form of penalty. Our situation being different, in the present work, the objective function is taken as being the sum of the heating and air-conditioning energy loads.

2.1. Simplified evaluation tool

Some anterior studies [3] have shown the increased importance of the dynamic behavior of the building envelope in the Tunisian context, and more widely in the Mediterranean one. In the absence of free gains (solar and internal gains) the heating need is uniquely due to the losses through the dynamic system, noted L_h, which result from the difference between the indoor and the outdoor temperatures. This load is partly satisfied by the useful gain Q_u which is a fraction of the gross free gains Q_g that contributes to increasing the indoor temperature until the set point. The heating needs H are then given by:

$$H = L_h - Q_u \tag{1}$$

The gross free gains Q_g are the sum of the internal free gains and the whole amount of solar gains received by the building envelope. The fraction of useful provisions depends on the importance of the crude provisions in comparison with losses, on the discrepancy schedule between heat losses and solar provisions, as well as on building inertia.

All the same, the air-conditioning load C is given by:

$$C = L_c + Q_{eff} \tag{2}$$

with L_c being the air-conditioning load for the dynamic system in the absence of solar provisions and Q_{eff} the effective gain or part of free gains that induce air-conditioning needs [2]. This amount is generally lower than the gross free gains.

Determining the dynamic-mode loads as well as the useful and effective provisions necessitates the use of a tool for energy assessment. There are two classes of tools used for building energy evaluation: the dynamic simulation tools based on physical principles and models, and the simplified procedures. The first ones provide accurate and detailed results but running a simulation takes generally several minutes, and the preparation of the input data several hours or days.

In order to find the optimal design of a building, we have to compare the energy performance of a large number of configurations, which needs the computation of the heating and cooling loads for each of them. In the optimization approach proposed in the present study, we use the simplified procedures that are more straightforward and easier.

The chosen tool is the simplified method CHEOPS developed by N. Ghrab-Morcos [2]. It has the important advantages of:

- Being well adapted to the Mediterranean climatic conditions,
- Allowing for the calculation of both cooling and heating loads using approximately the same method,
- Requiring little expertise.

Using simple correlations, this tool allows for determining the dynamic losses on the basis of those computed for permanent state:

$$L_h = a \times DH_h \tag{3}$$

$$L_c = d \times DH_c + e \times DH_c^2 \tag{4}$$

DH_h: degree-hours corresponding to a heating load during the cold season; DH_c: degree-hours corresponding to a cooling load during the hot season; and a, d and e: the correlation factors.

The useful and effective gains are calculated on the basis of the gross free gains due to the internal provisions and the solar radiation absorbed by the building envelope:

$$Q_u = F \times L_{ref,h} \tag{5}$$

$$Q_{eff} = S \times L_{reff,c} \tag{6}$$

$L_{ref,h}$: a reference heating load; $L_{ref,c}$: a reference cooling load; and F and S are, respectively, the solar fraction of the heating season and the solar overheating factor for the cooling season. They are related to the normalized gross free gains of the two seasons by the means of correlations determined on the basis of a large number of detailed simulations. More details can be found in [2].

2.2. Design variables

The losses across the envelope and the gross free gains depend on the lateral surface of the building, the type of used partitions as well as glazed surfaces on each of the façades. The shape and the dimensions of the solar protections have direct impact on the amount of the solar free gains received by the glazed areas. We have defined a set of possible configurations, by combining different cases of these design variables, taken inside reasonable values. The resulting set of configurations defines the space of research of our problem.

2.2.1. Cell-test geometry

While keeping a constant volume, we can vary the dimensions of the building envelope and its shape. As the present work is a first approach of the optimization problem, we consider a simple cell-test having a rectangular shape with a fixed volume $V = 108\ m^3$. The length of the south (or north) facade, is denoted by L_1. To obtain several designs with different dimensions, we kept the floor area constant ($A = 36\ m^2$) and let L_1 vary to take the following values: 1, 2, 3, 4, 6, 9, 12, 18 or 36 m.

2.2.2. Composition of walls and floors

For the opaque partitions, we consider the most commonly used solutions in the Tunisian dwellings. We consider two different types of roofing (one insulated, the other not) and five kinds of walls of different inertia and levels of insulation.

Each of the four façades of the building is provided with a glazed surface, whose area is a variable fraction V_i of the facade ($i = 1 \ldots 4$ is the facade index). In order to limit the research domain of the problem, we let this variable take one of the following discrete values: 0.08; 0.2; 0.4; 0.6 or 0.8. We also use simple or double glazings that differ by their transmission coefficients and their loss coefficients.

2.2.3. Solar protections

For the Mediterranean climate, an efficient solar protection should allow for minimizing the cooling load without excessive increase in the heating load. This means that the shadowed portion of the glazed area should be as large as possible in summer and as low as possible in winter. Knowledge of the shaded part is necessary to compute the gross solar gains.

Table 1
Set of the considered solar protection devices

Orientation	South					East/west		North		
$N°$	1	2	3	4	5	1	2	1	2	3
Fe_1 winter	0.9	1	0.9	0.8	0.7	0.8	0.9	1	0.9	0.8
Fe_1 summer	0.8	0.8	0.7	0.6	0.5	0.6	0.7	1	0.9	0.8

The development of the simplified tool CHEOPS [4] included consideration of the effect of different shadowing devices. The solar factors Fe_1 are defined as the ratios of the received solar radiation in the presence of the shadowing device over the radiation that would be received in its absence. Their average values over both the heating and the cooling seasons have been calculated for different overhangs and shadowing devices.

Referring to this work, we selected five configurations that will be tested on the south facade, two configurations for the east and west façades and three others for the north one. All these devices correspond to an Fe_1 factor with a high value in winter and a reduced one in summer (Table 1).

With such a set of parameters, the number of feasible solutions reaches 13,500,000. In addition to the large dimension of the research domain, the considered problem is characterized by a non-linear objective function and discrete variables of different natures. For these reasons, we shall use genetic algorithms which are known to be efficient for the resolution of such combinatorial problems.

3. The optimization algorithm

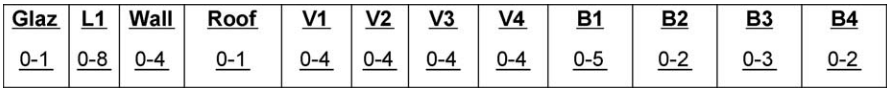
3.1. Genetic algorithms

Genetic algorithms have proved their efficiency in dealing with different energy optimization problems such as the optimization of building thermal design and control [5–7] and solar hot water systems [8] as well as the design of thermally comfortable buildings [1] and the control of artificial lights [9].

These techniques belong to a class of probabilistic search methods that strike a remarkable balance between exploration and exploitation of the search space.

Genetic algorithms are initiated by selecting a population of randomly generated solutions for the considered problem. They move from one generation of solutions to another by evolving new solutions using the objective evaluation, selection, crossover and mutation operators. In general, genetic algorithms work with the solutions being represented by a code, rather than the initial variables. Typically, a solution is represented with a string of bits (also called chromosome). Each bit position is called gene, and the values that each gene can take are called alleles [10].

A basic genetic algorithm has three main operators that are carried out at every iteration:



Glaz	L1	Wall	Roof	V1	V2	V3	V4	B1	B2	B3	B4
0-1	0-8	0-4	0-1	0-4	0-4	0-4	0-4	0-5	0-2	0-3	0-2

Fig. 1. Used encoding.

- Reproduction: chromosomes or solutions of the current generation are copied to the next one with some probability based on the value they achieve for the objective function which is also called fitness.
- Crossover: randomly selected pairs of chromosomes are mated creating new ones that will be inserted in the next generation.
- Mutation: it is an occasional random alteration of the allele of a gene.

While the selection operator for reproduction is useful for creating a new generation that is globally better than the preceding one, crossover brings diversity to the population by handling the genes of the created chromosomes and mutation introduces the necessary hazard to an efficient exploration of the research space. It makes the algorithm likely to reach all the points of research space.

Before developing a genetic algorithm, we must choose the encoding that will be used to represent an eventual solution of the problem by a chromosome where the value of each variable is represented by one or several genes. The quality of the developed algorithm depends essentially on the adopted encoding strategy and its adequacy to the used crossover and mutation operators, while respecting the nature of variables and the constraints of the problem.

3.2. The developed algorithm

In this work, a genetic algorithm was developed in order to provide a method for obtaining a set of optimal architectural configurations. It has the basic structure of genetic algorithm developed by Goldberg [10]: choosing an encoding strategy, initializing the algorithm by randomly generating the first population, and then at each iteration creating from the current population another one of a globally better quality, evaluated on the basis of the objective function value calculated here with CHEOPS. The algorithm converges when the objective function of the best solution has the very same value during several consecutive iterations.

Since the problem variables are discrete and of different types, we opted for real encoding in order to represent the solutions by a chromosome of twelve genes, as shown on Fig. 1. Every gene can take a value between zero and a maximum value that depends on the range of the variable considered.

For the selection process, rather than the basic approach called the wheel selection, we use an improved one, known as the elitism approach. It consists of copying the best elements of the current population and inserting them into the following generation. It is then impossible for the best element of the new generation to be worse than the one obtained in the preceding iterations. The performances of the algorithm are then greatly improved.

The traditional operator of mutation is replaced by the immigration procedure [11]. Instead of altering the value of one or several genes, we randomly regenerate a reduced number of new individuals. This reduces the probability of converging to local optimum. It also should be noted that the developed algorithm uses the strategy of the ‘‘populations without doubles’’ which consists in inserting the new created chromosomes in the new generation only when they are different from those already reproduced. This strategy makes the algorithm converge more rapidly.

4. Results and analysis

Genetic algorithms are pseudo-random techniques. Therefore, the speed and efficiency of the developed algorithm will depend on the population size and the maximum number of iterations that have to be done before convergence. Several tests carried out in [12] have shown that operating on a population of a large size ($N > 200$) and with a maximum number of 1000 iterations, gives good results. While varying the initial population, the algorithm converges towards all of the same solution and the running time never exceeds few seconds. It can be considered as efficient and robust.

The optimal solution given by the algorithm is represented on Fig. 2. It is of a rectangular shape with the principal facade being 9 m of length; the south and north façades are longer than the east and west ones. It’s profitable to use insulated roofing and walls as well as double glazing. While the glazed surface has to be maximized on the south facade ($V_1 = 80\%$), the others façades must be provided with small windows as far as possible ($V_i = 80\%$). The best solar protections are those having the winter solar average factor very close to one.

This configuration corresponds to an annual energy load of 7×10^6 kJ. It’s considered to be a good energy saving solution since the annual energy load exceeds 20×10^6 kJ/year for some of the configurations in the same context.

The good quality of this configuration is easy to justify. The efficiency of the used design parameters can be explained by the means of the physical phenomena occurring on the building. Nevertheless, varying some parameters value has opposite effects on increasing the useful free gains and reducing the heat loss.

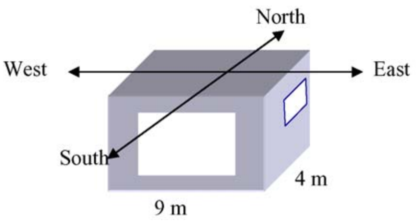


Fig. 2. Optimal solution for energy consumption.

It is, for example, clear that having a large southern facade is beneficial because it is the most sunny in winter and the least in summer. But it is not interesting to have a building with a large lateral surface because it increases the heat loss through the envelope. The compromise is obtained with a 9 m long facade. With nor insulated walls, the energy consumption of the same configuration (9 m south facade with $V_1 = 80\%$, and $V_i = 8\%$ for the other façades) is 19×10^6 kJ/year. This consumption is reduced to 18×10^6 kJ/year if the glazed surface on both east and west façades is maximized. This confirms the fact that the optimal value of a one design parameter depends on the global configuration of the building.

In [12] we used the developed algorithm to determine the optimal building design in different Tunisian climatic regions. The result was the same except for the north–west region where the climate is relatively cold; it was found that it is better to use buildings of compact shape.

5. The economic problem

Minimizing the energy consumption of a building requires the use of special devices and measures (such as insulated walls and solar protections) that bring about an extra investment cost not necessarily offset by the achieved reduction in energy consumption. Hence, in the following, we shall be interested in optimizing the economic performance of the Mediterranean buildings, based on the evaluation of the global monetary cost.

5.1. Objective function

We shall work on the research space considered for the energy problem (see Section 2). But the objective function of the economic problem is defined as:

$$\text{Min}\, C_{\text{global}} = I + C_{\text{maint}} + C_{\text{ea}} \tag{7}$$

With:

- I: the initial investment which includes construction costs I_{const} and purchasing and installation costs of the heating and air-conditioning equipments, respectively, $C_{\text{eq,heat}}$ and $C_{\text{eq,cool}}$,
- C_{maint}: the preventive maintenance cost that is proportional to the purchase price:

  $$C_{\text{maint}} = Y \times C_{\text{eq}} \tag{8}$$

  where Y is a multiplier factor that takes into account the conversion to current value and the increase in the maintenance cost.
- C_{ea}: the energy operating cost, i.e. the expenditures due to the heating $C_{\text{ea}}^{\text{heat}}$ and cooling $C_{\text{ea}}^{\text{cool}}$ energy consumptions during the life cycle of the building.

  These are calculated on the basis of the annual energy loads for heating H and cooling C, taking into account the increase in the gas price for heating and in electricity cost for air-conditioning as well as discounting future expenses.

  With two values for the increase rate of gas price ($i_{\text{gas}} = 0.2\%$ and $i_{\text{gas}} = 8.2\%$) and of electricity cost ($i_{\text{elec}} = 1.4\%$ and $i_{\text{elec}} = 3.5\%$), four different economic scenarios were considered.

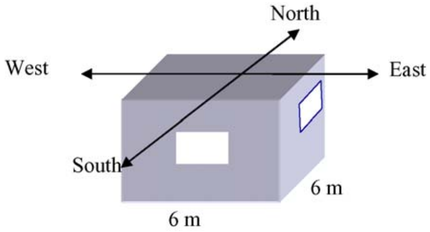


Fig. 3. Economic optimal solution.

Thus, the global monetary cost to minimize is:

$$C_{\text{global}} = I_{\text{const}} + (1 + Y) \times (C_{\text{eq,heat}} + C_{\text{eq,cool}}) + C_{\text{ea}}^{\text{heat}} + C_{\text{ea}}^{\text{cool}} \tag{9}$$

The heating and cooling equipments were dimensioned on the basis of the peak loads in steady state, i.e. those occurring for the most severe outdoor conditions.

5.2. Results

In order to solve the economic problem, we use the developed algorithm described in Section 3.2 while considering the global monetary cost as a selection criterion (fitness).

The obtained optimal configuration, represented on Fig. 3, is of a more compact shape than the best configuration for the energy problem, with insulated partitions, small glazy surfaces and without solar protections. The number of glazing for windows depends on the economical scenario considered: with a low rise in the gas price, it is optimal to use simple glazing; the higher the fuel price is, the more it is profitable to use double glazing.

Compared to the optimal solution for energy savings, this configuration ensures to carry out a monetary gain of 18% but the energy load is 32% higher.

The compact form corresponds to a minimal lateral surface. Hence, the losses through the building envelope are reduced. On the other hand, the solar provisions, which are profitable in winter, are also reduced and the night refreshment, desirable in summer, is limited, leading to an increase in the global energy load. This increase is balanced out by the reduction of the construction investment justifying the benefit of the compact form.

The large windows and the solar protections have proved to be too expensive and their additional cost cannot be compensated by the increase (respectively decrease) of the crude solar provisions profitable in winter (respectively summer).

6. Conclusion

The energy problem presented in this paper is particularly interesting. While it is relatively easy to find the best characteristics of a building under winter or summer conditions separately, tackling the two problems simultaneously is more complex. There is a trade-off that has to be done between the two seasons requirements.

We have developed an optimization algorithm coupling the genetic algorithms' techniques to the thermal assessment simplified tool for Mediterranean buildings CHEOPS. This algorithm is used to identify the best configurations from both energetic and economic points of view. It proved its effectiveness by determining the most adequate architectural design to the considered climate and under the fixed objectives in only a few seconds. This is due to the fact that genetic algorithms represent a simple and very efficient approach for the solution of non-linear combinatorial optimization problems. Although GA find good solutions without exploring the whole space of research, yet they need the evaluation of a large number of building configurations. This was made possible with the help of CHEOPS which is a simplified evaluation tool, requiring little time to compute results of a good accuracy. Actually, the correlations embedded in the tool have been developed on the basis of the results of a very large number of cases, simulated with detailed tools, allowing the dynamic aspects to be represented in CHEOPS.

The algorithm presents also the big advantage of converging not only toward the best solution but toward a set of configurations all of a high quality and diverse enough to allow the user to choose the most adequate one to his personal considerations that are not necessarily quantifiable. The fact that the required result is a set of very good solutions (and not the best one) means that a good evaluation accuracy is sufficient.

This is why the use of CHEOPS is satisfactory and coherent with the heuristic approach of GA, detailed evaluation methods with very high accuracy being useless in this case.

The obtained results show that the best solutions for saving energy and saving money are quite different. It is possible to combine the two problems and then carry out a multi-objective optimization approach. It will also be interesting to expand the presented algorithm to the case of more complex and varied buildings so as to provide the designers with a powerful new design tool.

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