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Research paper

Multi-Objective Optimization of a Family House Performance and Forecast of its Energy Needs by 2100

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Abstract

This paper describes a general multi-objective optimization approach of the energy performance of buildings using genetic algorithms, and the forecast of future energy needs according to the IPCC climate change scenarios. To this end, the energy performance of a family house is optimized and the optimal solution is studied in a future context marked by global warming and rise of temperatures.

Keywords: *Building simulation; Climate change; Genetic algorithms; Optimization; MOBO*

1. Introduction

2018 Climate Change Performance Index (CCPI) results place Morocco as the third most efficient country in the world in the field of fighting the climate change, thanks to its low emissions level and its ambitious greenhouse gas emissions reduction target by 2030 [1].
Thermal design of buildings is done under precise climatic conditions, using energy simulation tools and recent year's weather data (Tm2, Tm3 files…). These buildings often have a lifetime of a century. Nowadays, the impacts of global warming are wide spreading, making it mandatory to take into account their repercussions on the design of buildings.
In the scope of this work, we will choose and optimize the performance of a building model in the environment of Settat, using a multi-objective method: energetic (reduction of heating & cooling needs) and economic (additional investment cost), by means of genetic algorithms. We thereafter forecast the performance of the optimal solution in the future context (until the year 2100), by way of the climate change scenarios of the Intergovernmental Panel on Climate Change (IPCC).

2. Materials and Methods

2.1. Weather data and climate change scenarios

The climatic zone of the study is Settat, a Moroccan city located between the national capital Rabat and Marrakech (33,0°N, -7,6°E & 385m).
According to the Moroccan thermal regulation for buildings (RTCM), Settat is located within the zone of Agadir (Zone 1), and is bordering the climatic zones of Marrakech (Zone 5) and Fez (Zone 3) [2].
Weather data used in this article are generated by Meteonorm7 software. Meteonorm includes three IPCC (Intergovernmental Panel on Climate Change) scenarios [3]:

- B1 (low, global 2°C warming until 2100) : Optimistic scenario;
- A1B (middle, 3°C warming until 2100);
- A2 (high, 3.5°C warming until 2100) : Pessimistic scenario;

2.2 Heating and cooling degree-days forecast

Heating (HDD) / cooling (CDD) degree-days are a measure of how much (in degrees), and for how long (in days), outside air temperature was lower/higher than a specific "base temperature" (or "balance point"). They are used for calculations relating to the energy consumption required to heat/to cool buildings.
HDD & CDD can be calculated using the equations (1) and (2):

$$HDD = \sum_{k=1}^{365} \frac{1}{24} \sum_{i=1}^{24} (18 - Ti) \quad (1)$$

$$CDD = \sum_{k=1}^{365} \frac{1}{24} \sum_{i=1}^{24} (Ti - 21) \quad (2)$$

18°C and 21°C are the set-point temperatures for the calculation of HDD and CDD respectively [3] and Ti is the outside temperature of the hour i. During calculation, we do not retain negative values.

We below calculate heating and cooling degree-days according to the three scenarios of the IPCC, for the years 2020, 2040, 2060, 2080 and 2100 (figures 1 and 2).

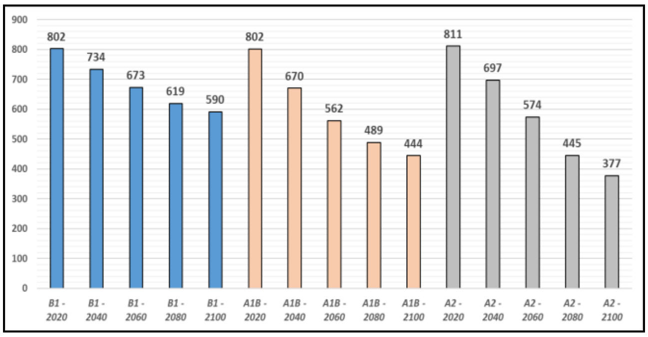

Fig. 1: Heating degree-days

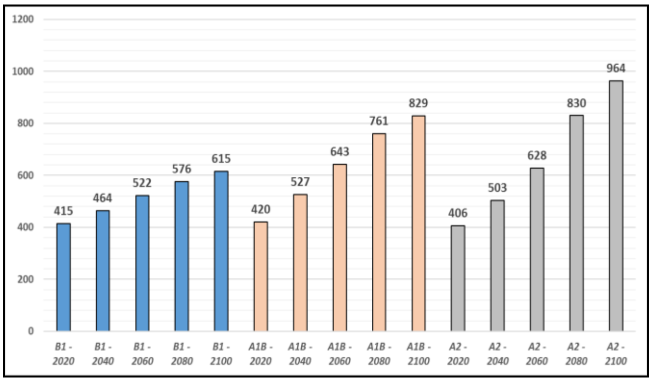

Fig. 2: Cooling degree-days

Thus, A2 scenario presents a reduction of 54% of HDD (from 2020 to 2100), against 45% and 26% for A1b and B1 scenarios respectively (figure 1).
Therefore, A2 scenario displays a CDD rise of 137% (from 2020 to 2100), and of 97% and 48% for A1b and B1 scenarios respectively (figure 2).
Consequently, it is crucial to take into account the climate change in thermal design of buildings. In fact, today's high thermal comfort building might be uncomfortable in the years to come.

2.3 Building model

The selected building for this study is a family house with a net surface of 81m² (9m x 9m x 2,7m), composed of two bedrooms, a living room, a kitchen, a hall and a bathroom and occupied by five people. TRNSYS type 56 (multi-zone building) makes it possible to study the six thermal zones of our building.
We set the total percentage of windows to 15%, uniformly split between the building frontages (3.25m² per window). We use simple glazing (U = 5.74 W/m².K / g = 0.87) / Double-glazing (U = 2.95 W/ m².K / g = 0.777) or double-glazing with argon gap (U = 1.43 W/ m².K / g = 0.596) windows. External shading devices are used when the external temperature exceeds the heating temperature set point of the RTCM (21°C) [2].
Radiation and temperature data cover respectively the periods 1991-2010 and 2000-2009.
The floor is in contact with the soil. The vertical distribution of temperature was modeled by Kasuda [4]. He demonstrated that the temperature of the soil is function of time and depth below surface.

Fig. 3: Building model

Table 1: Walls properties

	Materials	Width
External walls	Brick	10 cm
	Insulation	Variable
	Brick	10 cm
Roof	Filler slab	16 cm
	Insulation	Variable
Internal walls	Plaster Insulation Plaster	Variable
Floor	Reinforced concrete slab	20 cm
	Insulation	Variable

We selected the design variables below for the study:

- External walls thermal insulation (U-value from 0.383 to 2.381 W/m².K) ;
- Roof thermal insulation (U-value from 0.247 to 3.076 W/m².K) ;
- Floor thermal insulation (U-value from 0.249 to 3.445 W/m².K) ;
- Windows type : Simple / Double / Double Argon gap glazing ;
- Building orientation (0 à 360°) ;

The parameters above were used to elaborate the RTCM [2];

- Internal walls thermal insulation (U-value from 0.3 to 3.233 W/m².K);
- Air infiltration (from 0.2 to 1.15 Vol/h) ;
- Absorption coefficient of external walls (0.35 à 0.7) ;
- Absorption coefficient of the roof (0.35 to 0.7).

3. Optimization Results

3.1. Single objective optimization

3.1.1. Energetic optimization

In this paragraph, we will optimize the heating and cooling needs of the six thermal zones of the model building. In figure 4, X and Y-axis show the simulation number and the annual energy needs (heating and cooling) in kWh respectively;

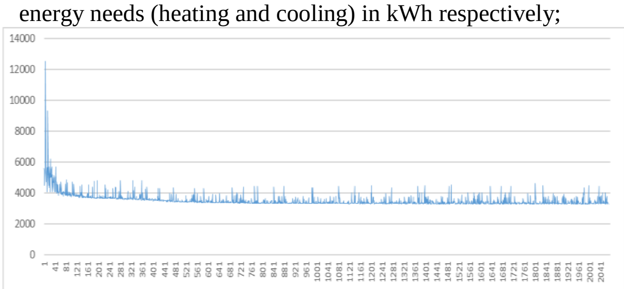

Fig. 4: Energy needs optimization

The optimal combination (3312 kWh) is:

Table 2: Optimal combination of design variables

External walls insulation (U-value)	1.389 W/m².K
Absorption coefficient of external walls	0.35
Internal walls insulation (U-value)	3.233 W/m².K
Roof insulation (U-value)	0.247 W/m².K
Absorption coefficient of the roof	0.35
Floor insulation (U-value)	0.249 W/m².K
East-facing window	Double glazing with argon gap
South-facing window	Simple glazing
West-facing window	Double glazing with argon gap
North-facing window	Double glazing with argon gap
Building orientation	84.6°
Air infiltration	0.56 Vol/h

We notice that the optimal configuration requires solely a low insulation of external walls and no insulation of internal walls while using high efficient windows (except for the south-facing windows to bring heat in winter) and light painting colors of external walls and roof.
However, it is recommended for this building to insulate the roof and the floor to avoid the losses with the ground and the outside via the roof.
The optimal configuration positions the kitchen and the bathroom on the northern frontage of the building.

3.1.2. Economic optimization

The economic and financial analysis constitutes a key element for the evaluation of a construction project or rehabilitation of a building.
We will study the additional investment cost related to the reinforcement of the thermal insulation (roof, floor, external and internal walls) and the glazing type used (simple/double/double with argon gap);
The economic single objective optimization converges in a quick processing time, with no insulation and the use of single glazing in all the frontages. These combinations give a high-energy consumption (around 15300 kWh). Thus, a multicriterion optimization should be used to meet a compromise between both energetic and economic objectives.

3.2. Multi-objective optimization

3.2.1. Methodology

Multi-objective optimization can be defined as the process of simultaneously optimizing two or more conflicting objectives. It calls mathematical algorithms for the decision-aid and decision-making.
We carry out a coupling of the TRNSYS software with MOBO optimization tool, developed by the Technical Research Centre of Finland [5].
To perform the multi-objective optimizations, we will use the genetic algorithms (in specific the non-dominated sorting genetic algorithm NSGA-II) [6]. These algorithms reflect the process of natural selection where the fittest individuals are selected for reproduction in order to produce offspring of the next generation [7].

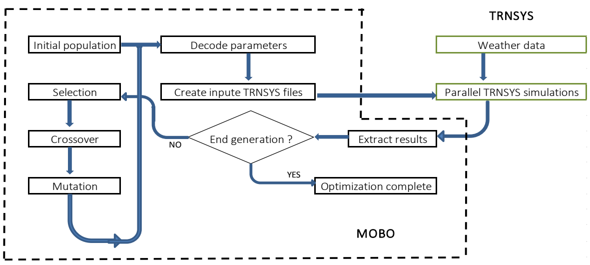

Fig. 5: TRNSYS/MOBO coupling process

3.2.2. Multi-objective optimization results

We will optimize in this paragraph the energy needs and the additional investment cost for the design variables;
We analyze the results using the Pareto-based analysis method.
X-axis refers to energy needs in kWh and Y-axis to additional investment cost (Moroccan Dirham);

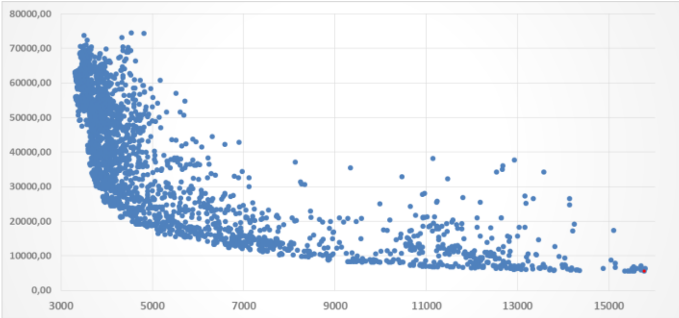

Fig. 6: Multi-objective with NSGA-II and Pareto Front

We compare these results with those obtained by the algorithm of random-search. This algorithm generates randomly in each iteration a new sample (figure 7).
In our case study for an equal number of simulations, genetic algorithms give better results of the optimization problem.
We notice that for the combinations in the Pareto front, the recommendations of the single-objective optimization about design variables still valid.

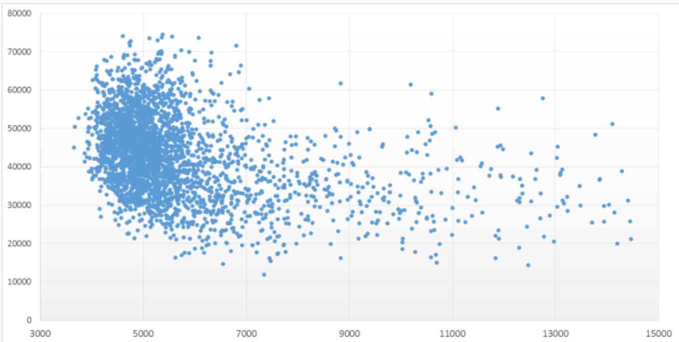

Fig. 7: Multi-objective with random search algorithm

4. Energy Consumption Forecast

We will forecast in this paragraph the future energy needs of the building model, within the configuration of the optimal alternative in 2020, 2040, 2060, 2080 and 2100 using the optimistic scenario (B1) and the pessimistic scenario (A2) of the IPCC.

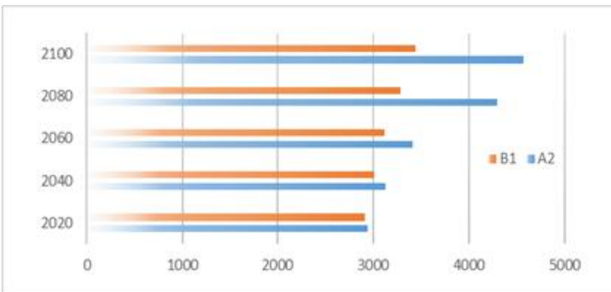

Fig. 8: Energy needs forecast

We notice a significant rise of the energy needs for the A2 scenario and a moderated increase for the B1 scenario. Figures 9 and 10 make a zoom on the heating and cooling needs separately;

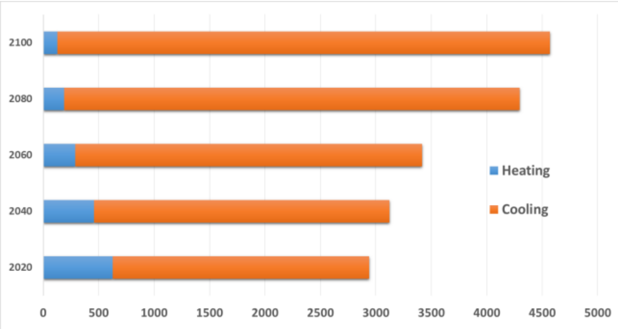

Fig. 9: Heating & Cooling needs forecast – A2 scenario

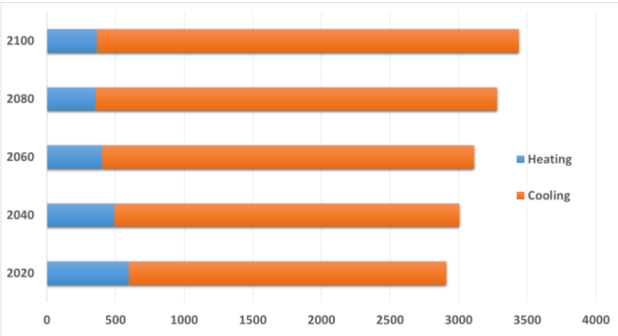

Fig. 10: Heating & Cooling needs forecast – B1 scenario

We note a significant increase of the cooling needs between 2020 and 2100 (about 92% for the A2 scenario and 33% for the B1 scenario), as for the generic results of the degree-days method. On the other hand, the heating needs decrease until passing very close to zero for the A2 scenario.
A special attention is thus to bring to thermal summer comfort while designing high-energy efficiency buildings in Settat area.

5. Conclusion

This paper describes a general approach of optimization of the energy performance of buildings.
This method is based on the coupling of the optimization tool MOBO, comprising many algorithms (genetic algorithms, random search algorithm…) with TRNSYS software, thus allowing to carry out single-objective (energy needs) or multi-objective optimizations (energetic and economic optimization) helping engineers in decision-making.
The most energy efficient solution was therefore studied in the future context (until the end of the current century), and presents a significant increase in cooling needs. Engineers must then study finely the summer thermal comfort of buildings and propose solutions to lower the air-conditioning needs, in order to face the impacts of the global warming of the planet.

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