ISSN: 2319-5967
ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
Volume 4, Issue 4, July 2015

Winter thermal multi-objective optimization: a simulation case study

Marco Camponeschi, Alessandro Fonti, Fabio Leccese, Gabriele Comodi, Maurizio Grossoni, Stefano Pizzuti

***Abstract*—In this work we propose a new approach based on multi-objective optimization combined with simulation tools in order to improve the building thermal energy performance during winter by keeping into account gas consumption and user comfort. In particular different scenarios have been investigated and results showed that there is a nearly 20% potential of energy saving. Experimentation has been carried out by simulating a real building and comparisons refer to the real settings applied to it.**

***Index Terms*— energy saving, Pareto optimization, energy management systems, demand side, demand response.**

I. INTRODUCTION

The building sector is the largest user of energy and CO_2 emitter in the European Union (EU) and is responsible for about 40% of the EU's total final energy consumption and CO_2 emissions. As a consequence, the cornerstone of the European energy policy has an explicit orientation to the conservation and rational use of energy in buildings as the energy performance of building directive (EPBD) 2002/91/EC and its recast (EPBD) 2010/31/EU indicate [1,2]. The EPBD's main objective is to promote the cost-effective improvement of the overall energy performance of buildings. In Europe, member states have set an energy savings target of 20% by 2020 and 27% by 2030, mainly through energy efficiency measures. A number of methodologies for optimizing real-time performance, automated fault detection and isolation were developed in IEA-Annex 25 [3]. Moreover, amongst worldwide scale organizations, the International Organization for Standardization (ISO), the European Committee for Standardization (CEN) and the International Energy Agency (IEA) have complementary provided strategic and operational directions towards the implementation of energy efficiency improvements in buildings [4]. The "conventional" measures that can be employed to improve energy performance in buildings can be classified in those that immediately relate to the building envelope i.e., the constructional elements, and those that relate to the operation of energy systems used for heating, cooling, ventilation, hot water supply, etc. [5-6]. Apart from "conventional" type measures, energy management techniques combined with innovative environmental technologies and advanced materials and systems may, if properly applied, affect drastically the process of saving energy in the building sector so as in other sectors [7-9]. A critical aspect in the design but also in the operational phase of a building, when renovation or retrofit actions are needed, is the evaluation and adjustment of the alternative measures based on a set of criteria such as energy consumption, environmental performance, investment cost, operational cost, indoor environment quality, security, social factors, etc. [5]. In some cases, the aforementioned criteria are competitive by themselves or interrelate in a non-linear way, making the problem of reaching a globally optimal solution generally infeasible; researching for such optimal solution is usually attempted via two main approaches. According to the former, an energy analysis of the building under study is carried out, and several alternative scenarios, predefined by a building expert, are developed and evaluated [10]. These specific scenarios, which may vary according to the features of the buildings, (type, use, climatic conditions,…), are pinpointed by the building experts and evaluated mainly through simulation [11-16]. The selection of the alternative scenarios, energy efficiency measures and actions is, thus, largely based on the building expert's experience. The second approach includes decision supporting techniques, such as multicriteria-based decision making methods and new approaches evolved combining simulation with notions and concepts originating from the scientific area of multi-objective optimization [17-20]. In the last area studies addressing optimization in building science mainly focus on the optimization of multi-scale systems ranging from the construction element [21], through the building envelope and HVAC systems [22-25], to building design [26,27]. In this scenario the proposed work deals with building efficient energy management through a decision support system based on Pareto front multi-objective optimization combined with simulation tools. In particular, the goal is to provide the day-ahead optimal thermal settings by keeping simultaneously into account gas consumption and occupant comfort.

II. SIMULATION

A real office building located at ENEA (Casaccia Research Centre, Rome, Italy) was considered as a case study (see Fig. 1). The building was built between 1970 and 1972 and it is composed of three floors and a heating plant in the basement. There are 41 offices of different size with a floor area ranging from 14 to 36 m^2, 2 EDP rooms each of about 20 m^2, 4 Laboratories, 1 Control Room and 2 Meeting Rooms. Each office room has from 1 up to 2 occupants. Each room and laboratory is equipped with fan-coils with on-off fan speed controlled by a room thermostat with hysteresis. The heating plant consists of a traditional natural gas boiler. The building is equipped with an advanced monitoring system aimed at collecting data about both external and internal ambient conditions, electrical and thermal energy consumption. In order to simulate the variables of interest, a MATLAB Simulink simulator based on HAMBASE model [28,29] was developed. In particular, the building was divided into 15 different zones according to different thermal behavior depending to solar radiation exposure. Therefore a zone consists of a group of rooms with about the same indoor ambient conditions and the same climate control policy. As a consequence of this assumption, thermostat behavior in the same zone was assumed equal.

Fig. 1 F40 Building.

The final model of F40 building consisted of 15 thermally homogeneous zones (Fig. 2).

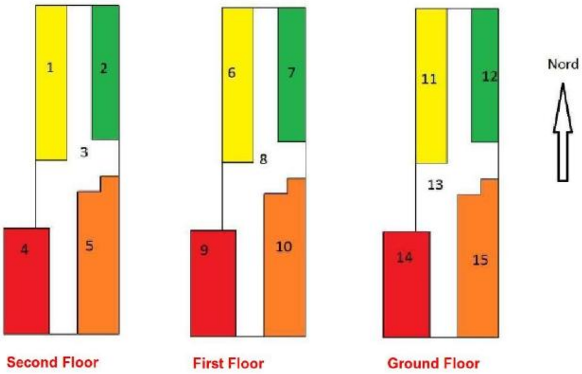

Fig. 2 Partitioning of F40 building zones for simulation.

Three of them (white zone in Figure 2) correspond to corridors and are not provided with heating system. For each zone, the thermal model output includes radiant temperature, air temperature and relative humidity. From those variables, the PPD can be computed using PMV model. Among those taken from the building model, there are four variables, that were set to their typical values - metabolism (70 [Wm^{-2}]), external work (0 [Wm^{-2}]), clothing (1 [−]), and air velocity (0.1 [ms^{-1}]).

The gas consumption, m_{gas}, was calculated according to eq.1, as the thermal energy provided to the building (distribution system losses included), $E_{th\_building}$, divided by the boiler efficiency, η_{th_boiler}, which is a function of its thermal load (Figure 3); in each time step of simulation, thermal load is calculated as the ratio between the actual thermal power provided by the boiler and its nominal thermal power.

$$m_{gas} = \frac{E_{th\_building}}{\eta_{th\_boiler}} \tag{1}$$

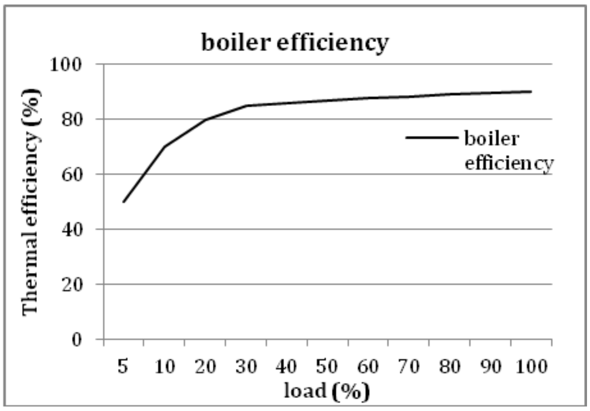

Fig. 3 Boiler efficiency as a function of thermal load.

Fan-coils were modelled with the ε-NTU method which allows to calculate the heat provided to the zones and the outlet water temperatures once known zone air temperatures, fan-coil inlet water flows and fan speed. The simulator is used to generate data from which the occupant comfort can be evaluated the main inputs being the indoor temperature set points and external meteorological data.

III. EXPERIMENTATION

The control variables have been discretized as follows:

- TSP : from 17 to 22.5 with step 0.5
- SWT = from 30 to 80 with step 1

Giving rise to 12x51=612 total possible combinations of the control variables.

As first experimentation we explored the entire search space simulating the whole winter season in order to perform some preliminary analysis and to get some reference for the effectiveness of the optimization algorithm. In fig. 4 it is reported the graphical result of this experimentation (which took 12 days of computation). In the graph each of the 612 points corresponds to a different combination of the control variables giving as result some PPD and energy consumption.

The first analysis is to understand if the current real building settings are at least within the theoretical set of optimal solutions (Pareto front) and the answer was negative. Indeed, the combination TSP=21°C , SWT=65°C was not on the Pareto front having PPD=6.1% and a seasonal consumption of 8419 m^3. The optimal solution with the same comfort level (PPD=6.1%) is provided by shifting on the left up to the border (indicated by the red arrow) where there is the optimal solution with TSP=21.5 and SWT=52 which has a consumption of 7821 m^3, thus saving about 5% of thermal energy without affecting the current comfort level.

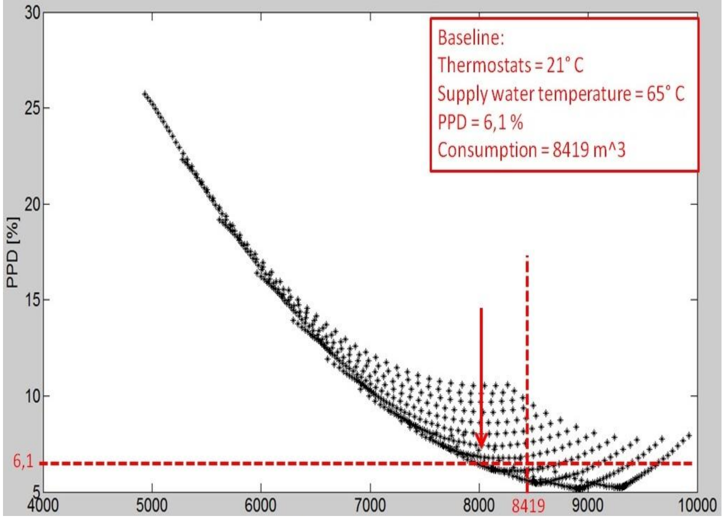

Fig. 4 Seasonal exhaustive search.

The next step is to apply the optimization algorithm to scenario 1 (seasonal). Table 1 reports the settings for the NSGA-II that we found out after tuning pre-processing. It is important to point out that for this experimentation we employed only ¼ of all the possible combination with a remarkable saving of computational time.

TABLE I. NSGA-II SETTINGS

POPULATION	10
SELECTION	TOURNAMENT
CROSSOVER	SINGOLE POINT RATE=0,8
MUTATION	UNIFORM RATE=1/612
FITNESS EVALUATIONS	150 (1/4 OF THE TOTAL)

In Fig. 5 we report the result compared to the theoretical Pareto front given by the exhaustive search of the previous stage. First of all, it is possible to notice that the solutions provided by the algorithm (filled blue points) are very close to the theoretical case.

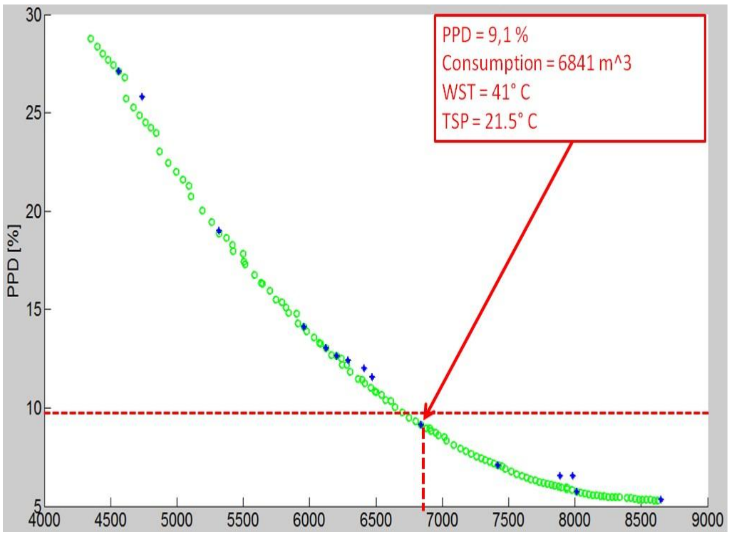

Fig.5 Comparison of the multi-objective seasonal optimization with the theoretical Pareto front

Then, if we chose the best solution right below PPD=10% (which is given as the maximum acceptable discomfort by many EU countries) we can get a remarkable energy saving with respect to the given baseline. In fact, the potential saving given by 8419-6841 m^3 which is around 18%.

The provided solution is similar to the one of Fig. 5, the difference is the TSP is lower meaning that the comfort level in the rooms is achieved more slowly than in the other case. One problem with this approach is that the PPD is calculated as an average over the whole season and it means that there are days where the PPD can be higher than 10%. In particular we found out PPD>10% for 70% of the days and this cannot be considered acceptable. Therefore we elaborated scenario 2 which concerns the day-by-day optimization.

In fFig. 6 there is as example of one daily Pareto front compared to the theoretical one. In this scenario the strategy to pick up the solution from the given front is the same and consists of choosing, every day, the one with PPD closest to 10%, in this way it is guaranteed that there is no day above the PPD threshold of 10% as demonstrated by the fact that the highest PPD achieved throughout the whole winter season is 9.8%.

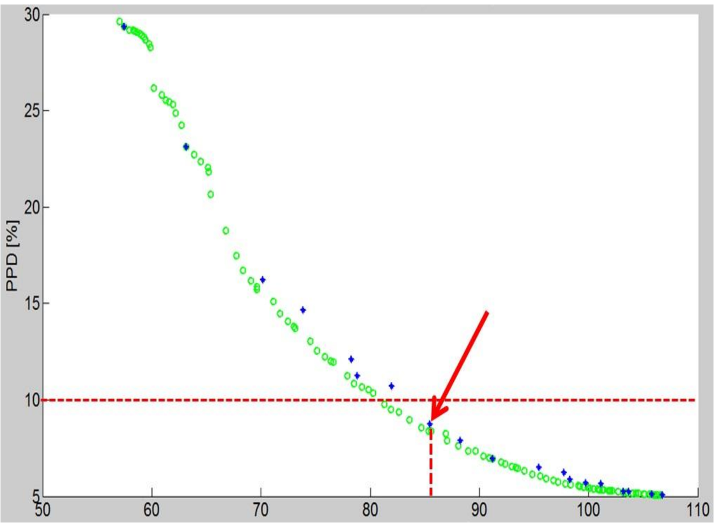

Fig.6 Comparison of one multi-objective daily optimization with the theoretical Pareto front.

In table 2 it is reported a comparison of all the results.

TABLE II. SUMMARY OF OPTIMIZATION RESULTS IN THE WHOLE WINTER SEASON

	Baseline: Exhaustive search (seasonal)	Scenario 1 (seasonal)	Scenario 2 (daily)	
WST [°C]	65	52	41	--
TSP [°C]	21	21,5	21,5	--
AVERAGE PPD [%]	6,1	6,1	9,1 (73% >10)	8,9 (max = 9,8)
GAS CONSUMPTION [m^3]	8419	7821	6841	6801
ENERGY SAVING [m^3]	-	420	1578	1618
ENERGY SAVING [%]	-	5	18,7	19,2

From this table we can see that starting from the baseline solution adopted in the real building there is an interesting potential for thermal energy saving and gas consumption reduction. In fact, with a little increase of discomfort it is possible to achieve high rates of energy saving (near 20%) through a day-by-day multi-objective optimization.

IV. CONCLUSION

In this work we proposed a new approach based on multi-objective optimization combined with simulation tools in order to improve the building thermal energy performance during winter by keeping into account gas consumption and occupant comfort. Results were carried out by simulating the behavior of a real building during the whole winter season. In particular different scenarios were investigated and results showed that there is a nearly 20% potential of energy saving with little increase of user discomfort through a day-by-day multi-objective optimization.

The main drawback of the proposed approach is computational time since each fitness evaluation corresponds to a simulator call, therefore as future work fitness approximation methods will be investigated in order to reduce computational time. Moreover, the electrical consumption of the devices related to conditioning will be added, a summer study will be carried out and finally the proposed system will be implemented on a real building in order to test the multi-objective optimization proposed.

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