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Building optimization and control algorithms implemented in existing BEMS using a web based energy management and control system

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ABSTRACT

The aim of the present paper is to analyze a building optimization and control (BOC) algorithm which is implemented in the existing building energy management system (BEMS) of the Saint George Hospital in Chania, Greece. The developed algorithm consists of predicted models for outdoor/indoor air temperature using artificial neural networks, multi-step optimization using genetic algorithms and Real Time control using fuzzy techniques. The algorithm is developed in Matlab™ environment and is implemented to the existing BEMS of the Hospital, using a specialized web-based energy management and control system (Web-EMCS). The implementation of the BOC algorithm is realized by developing a ".net assembly" code, which interconnects the Web-EMCS with the existing conventional hospital's BEMS, without the need of Matlab™. The annual primary energy efficiency achieved is almost 36%.

1. Introduction & state of the art

Hospitals consume high amounts of energy due to their 24/7 operation and increased electric power requirement for specialized heating/cooling equipment, in order to provide the required comfort level and indoor air quality.

The comfort level of a hospital ward in Malaysia, has been assessed by Azizpour et al. [1]. Based on measurements of PMV and subjective measurements collected using questionnaires, the comfort level in several areas of the hospital is estimated. Based on their measurements, most of the rooms achieve the required thermal comfort.

Another study concerning comfort level has been performed by Giridharan et al. [2] in the UK, involving indoor air temperature measurements in a ward of the Glenfield hospital. The measurements indicate that indoor air temperature is above the comfort level. Furthermore, using a validated simulation model, light touch interventions (controlled fans, horizontal shades and reduction of internal gains) are proposed to control the overheating by 2050.

An energy audit of hospitals has been presented by Balaras et al. [3] based on the air change rate measurement of operating rooms. Furthermore, Argiriou et al. [4] performed an audit in offices and hospitals which identified indoor air quality problems, due to outdoor air pollution, verified with local measurements of specific pollutants. Moreover, Santamouris et al. [5] have performed energy audits on 30 hospital buildings. An analysis of the energy consumption of Greek Hospitals has been performed by Sofronis and Markogiannakis [6]. Based on their energy analysis in 10 hospitals, the 56% of the hospitals consume 200–400 kW h/m^2. The reduction of energy consumption in hospitals is also mandated by the increase of the energy price [7].

A review of the hospitals' energy saving techniques is presented by Kolokotsa et al [8]. Based on the above review, a significant number of hospitals are turning to the installation of renewable energy sources and advanced energy efficient technologies (photovoltaic, trigeneration and geothermal systems) to reduce their dependency on fossil fuels.

A study on the effect of envelope changes in hospitals has been performed by Ascione et al. [9]. Increased insulation, installation of low-emissive windows, external blinds, replacement of windows and replacement of HVAC systems was among the scenarios which were tested in the Day-hospital "G. Pascale" in Naples, Italy. The proposed energy efficiency measures led to a 50% reduction of primary energy.

Other techniques such as solar cooling are also proposed [10]. The Department of Energy of USA [11] recommends various techniques to reduce the energy consumption of hospitals' services and envelope. Set-back strategies are also tested aiming to reduce the energy consumption of the HVAC.

On the other hand, digital controllers can be used to implement either logic control rules, or On–Off or PID control in buildings'

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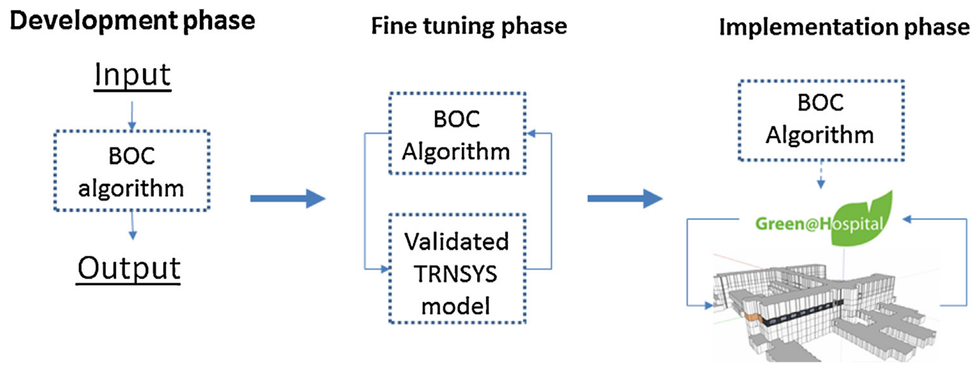


Fig. 1. Steps towards the implementation of the BOC algorithms in the Web-EMCS.

services [12,13]. The advancement of control technologies has led to the use of fuzzy logic and artificial neural networks (ANNs) in various BEMS for the control of their HVAC systems [14–18]. Predictive control techniques are also applied [19–22]. Prívara et al. [23] proposed a methodology for selecting the most appropriate model for predictive control, conducting performance evaluation on a TRNSYS model. Dynamic models, such as TRNSYS type, are also used for the evaluation of energy saving techniques in HVAC systems, such as heat pumps with heat recovery as presented by Gustafsson et al. [24]. Finally, optimization techniques, such as dynamic programming [25,26], multi-objective optimization [27,28] and simulation assisted multi-criteria analysis [29] are proposed in order to deal with the complexity of contemporary HVAC systems. Weather forecast is critical for the predictive optimization techniques because it affects the operation of the HVAC systems, as described by Oldewurtel et al. [30]. Oldewurtel et al. combine the prediction of weather forecast with local measurements and through a Kalman filtering procedure, a more accurate weather prediction is fed to the model of the building.

Advanced technologies have been applied to minimize the energy demand of the hospitals' HVAC systems. For example, a run-around membrane energy exchanger (RAMEE) was proposed by Rasouli et al. [31] to transfer moisture and energy between exhaust and ventilation air streams. Simulation results indicated that the energy saving potential was 60% for heating in cold climates and 15–20% in hot climates. Moreover, Huang et al. [32] presented an energy management and control strategy for a HVAC system, which reduces the energy consumption by 17%. A review of intelligent HVAC systems implemented in hospitals has been performed by Reijula et al. [33]. In their research, the optimization and energy conservation techniques for HVAC systems in hospitals are presented. Ursu et al. [34,35] developed an advanced neuro-fuzzy strategy to control the HVAC system (flow rate of air and the flow rate of chilled/heated water in the coil). The developed controller maintained indoor air temperature, while relative humidity or outdoor temperature increased by 10%.

To this end, the aim of the present study is to develop a BOC algorithm which can be integrated in existing conventional hospitals' BEMS. The development of the BOC algorithm is presented in Section 3. The fine-tuning process is described in Section 4, the implementation of the BOC algorithm in the existing BEMS of Saint George Hospital (SGH) is described in Section 5, while the energy efficiency achieved and the implementation results are described in Section 6. Conclusions are incorporated in Section 7.

2. Description of methodology

The methodology followed for the specific research is divided in three phases (Fig. 1):

1. *The development phase:* In the development phase the BOC algorithm is designed in the Matlab^{TM} environment, setting the available inputs and the selected outputs. During the development phase, the architecture of the BOC is established and the sub-systems are trained based on the available data.
2. *The fine tuning phase:* Throughout the fine tuning phase, the BOC algorithm is coupled with a validated TRNSYS model in order to evaluate its performance using a dynamic building model [36].
3. *The implementation phase:* During this phase, the BOC algorithm is connected to the existing conventional BEMS of the Saint George hospital in Chania, through a specialized Web-EMCS platform, described in Section 5.2. The BOC input and output variables are connected to sensors and actuators respectively.

3. Development of the BOC algorithm

The BOC algorithm consists of three parts:

1. The identification and prediction of indoor and outdoor temperatures using ANN.
2. The controller based on fuzzy techniques, which is developed to maintain the operation of the HVAC at the desired level.
3. A genetic based optimization algorithm which performs multi-step optimization, in order to minimize the energy consumption and to maintain the comfort level for a predictive horizon of 8 h.

3.1. Prediction of outdoor and indoor air temperature

The developed methodology, i.e. the identification algorithm for the outdoor temperature prediction is depicted in Fig. 2. The algorithm reads the latest available meteorological data, trains the ANN and predicts the outdoor air temperature. The ANN uses 5 inputs (outdoor air temperature, total horizontal radiation, wind speed, relative humidity and time of the day measured in min) to predict the outdoor air temperature for 8 h ahead. The input data are normalized and a recurrent ANN (Elman) is used. The ANN is re-trained every 24 h to adjust to the latest measurements.

The identification algorithm is developed using Matlab^{TM} environment. The performance indicators used for the evaluation of the identification algorithm are the R-squared and root mean square error (RMSE). The prediction of the outdoor air temperature for a predicted horizon of 8 h can be seen in the regression plot (Fig. 3a). The values of *R*-squared and RMSE confirm the quality of the developed identification algorithm. Furthermore, an example of outdoor temperature prediction for 8 h ahead is depicted in Fig. 3b.

The prediction of outdoor air temperature is used as input to the prediction of indoor conditions, employing ANN. Identification algorithms are also developed for the prediction of indoor temperature, as defined in methodology description (Section 2). This algorithm predicts the indoor air temperature of the next time step

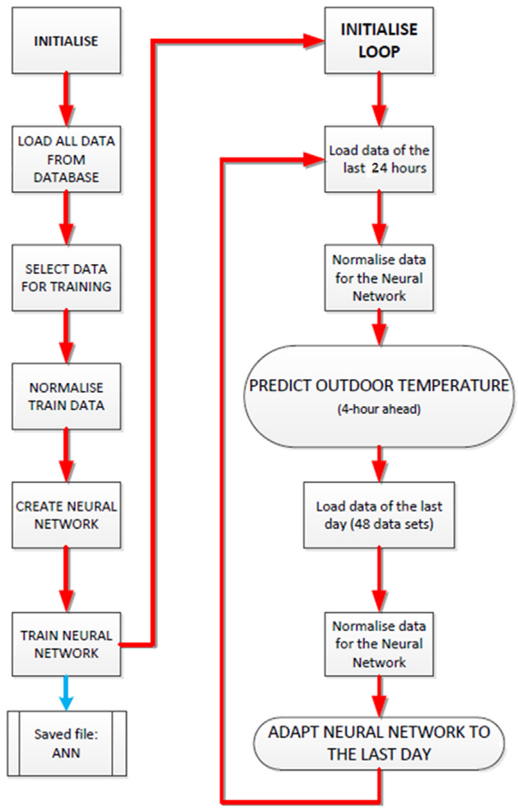


Fig. 2. Methodology followed for the prediction of outdoor air temperature.

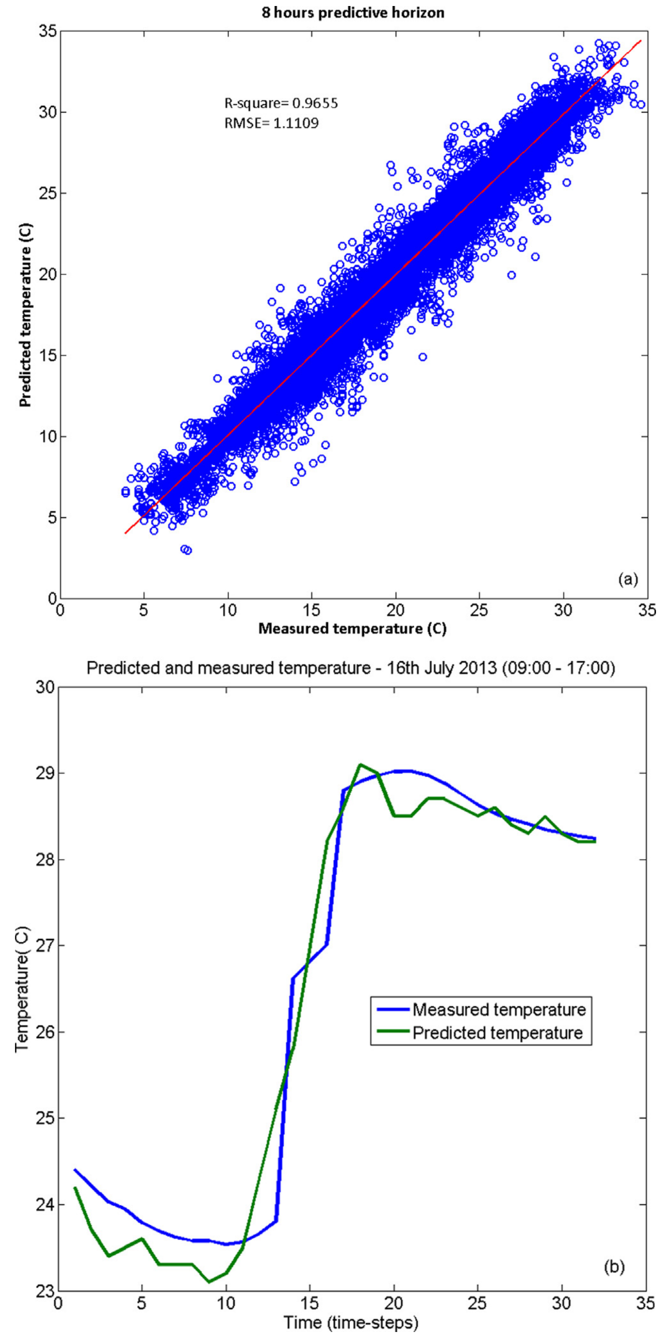


Fig. 3. (a) Regression plot showing measured temperature and predicted (8 h predictive horizon); (b) example of prediction of measured temperature.

(15 min), based on the current conditions ($T_{in(k+1|k)}$). The output of the algorithm is used as an input for the next time-step prediction. The algorithm is predicting the indoor temperature for 8 h ahead. The parameters of the specific algorithm are tabulated in Table 1.

The ANN is trained using real data collected from the Saint George hospital, where the overall system is integrated. The data collection started on the 17th of May 2013. An example of the comparison between the predictive values of indoor temperature and the measured ones, for one day in July 2013 (02/07/2013), are illustrated in Fig. 4.

By extracting the R-squared = 0.97 and RMSE = 1.11 K of the measured and the predicted indoor temperature, it is noted that the developed identification algorithm predicts the indoor thermal conditions with increased accuracy.

Table 1
Properties of the predictive algorithm for indoor air temperature.

Parameter	Description
Architecture of identification algorithm	Artificial neural network
Topology of identification algorithm	Elman neural network
Construction of the model	Grey box
Number of inputs	5
Inputs	Indoor temperature Time (minutes of day) Convective transfer of windows HVAC's coil operation HVAC's fan consumption
Number of outputs	1
Output	Indoor temperature T_in ($k+1|k$)
Number of hidden layers	3
Size of hidden layers	[353]
Performance function/indicator	"Mean square error"
Predictive horizon	1 step (15 min)

3.2. Control algorithms based on fuzzy techniques

The developed controller for the HVAC system is depicted in Fig. 5. The controller's operation depends on the measured indoor temperature. The controller is based on a fuzzy architecture. The characteristics of the control algorithm including inputs/outputs are tabulated in Table 2.

The membership functions for the fuzzification of input are plotted in Fig. 6, while the de-fuzzification functions can be seen in Fig. 7. The applied fuzzy rules are tabulated in Table 3.

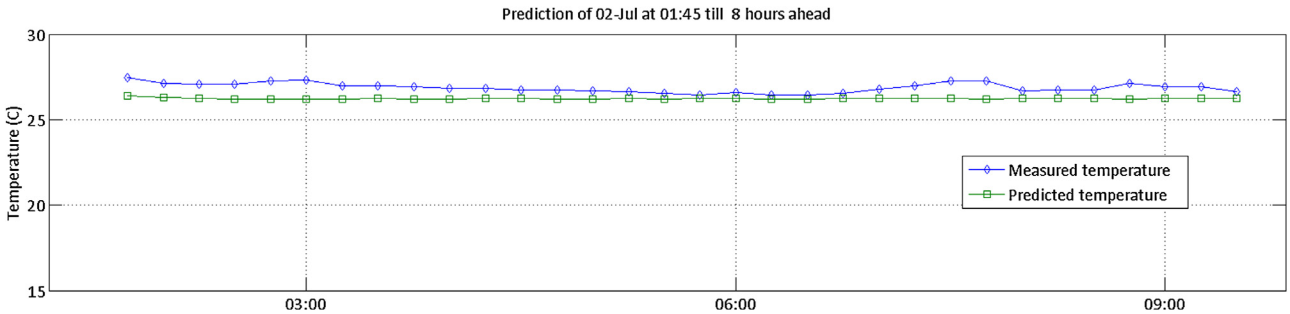


Fig. 4. Comparison of measured and predicted indoor temperatures for a predictive horizon of 8 h.

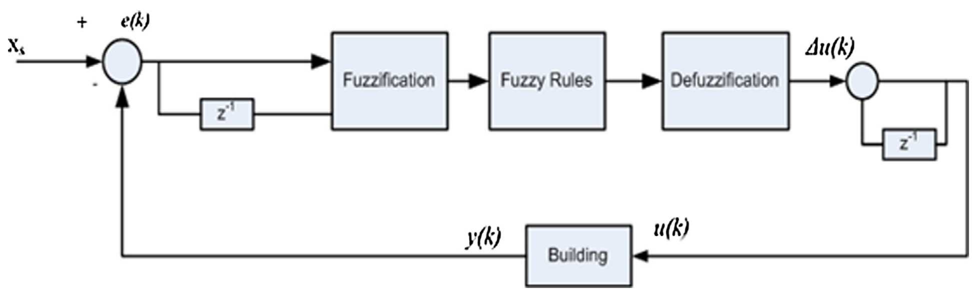


Fig. 5. The fuzzy control system.

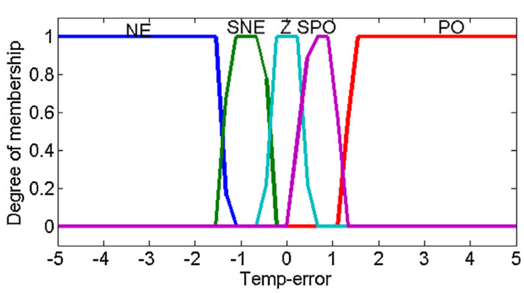


Fig. 6. Fuzzification membership function of the developed controller.

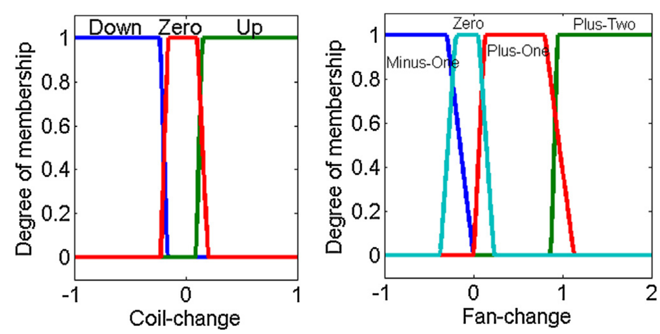


Fig. 7. De-fuzzification parameters of the developed controller.

3.3. Optimization techniques

The aim of the optimization algorithm is to provide the set-points for a period of 8 h ahead for the various hospital rooms, taking into consideration the identification algorithms' outputs (as described in Section 3.1). The optimization procedure requires an objective function to evaluate the performance of the various possible future set-points. Therefore, the optimization algorithm is designed such as to minimize an objective function based on a set of pre-defined constrains.

$$\text{Obj}F = \min\left(\sum_{1}^{32} \text{cost of operating the HVAC} + \text{error of temperature}\right)$$

s.t.

$$x_i \times x_{i+32} > 0$$

$$0 < x_i : x_{32} < 1$$

$$0 < x_{33} : x_{64} < \text{HVAC's fan max power}$$

Table 2
Characteristics of the developed controller.

Type of fuzzy controller	'Mamdani'	
No of inputs	1: Error between current and indoor temperature set-point	
No of outputs	2: Change of HVAC's coil & change of HVAC's fan speed	
Fuzzification membership functions	5 (see Fig. 6)	
De-fuzzification membership functions	5 (see Fig. 7)	
Fuzzy controller parameters	AndMethod: min' ImpMethod: min' DefuzzMethod:'lom'	OrMethod: max' AggMethod: max'

Table 3
Fuzzy rules of the developed controller.

Input	Output	
Temp. difference from set-point	HVAC's coil change	HVAC's fan change
NE	Up	Plus-two
SNE	Up	Plus-one
ZERO	Zero	Zero
SPO	Zero	Minus-one
PO	Down	Minus-two

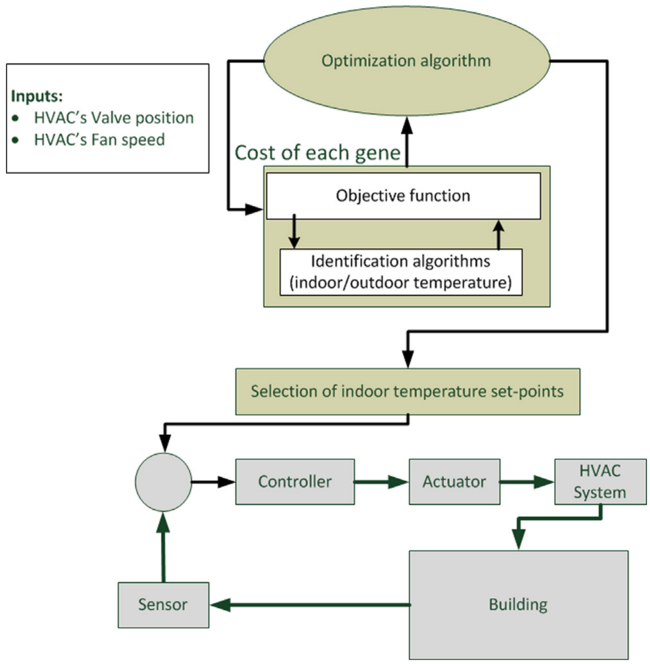


Fig. 8. Structure of the optimization algorithm for the paediatric department in SGH.

The optimization technique is developed using genetic algorithms, which are of adaptive search and optimization type algorithms, which work by mimicking the principles of natural genetics [25,37]. The optimization process uses 64 variables, 32 of which are used for the operation of the hospitals' HVAC fan coils, while the rest are used for the HVAC fans' speed. These variables are provided as input to the identification algorithm for indoor temperature prediction for a predictive horizon of 8 h described in Section 3.1. The structure of the optimization algorithm is presented in Fig. 8. The output of the optimization algorithm is provided as input to the controller described in Section 3.2.

Fig. 8 displays the operation of the developed multi-step optimization algorithm. The selected inputs of the genetic algorithm are evaluated using the objective function and the output returns to the genetic algorithm. The parameters of the optimization algorithm are described in Table 4.

Table 4
Parameters of optimization algorithm for SGH—Paediatric department.

No.	Parameter	Value
1	Mutation function	Mutation adapt feasible
3	Use parallel	Always
4	Population size	20
5	Generations	300
6	Tolerance of function	10^{-20}

4. Fine-tuning of BOC algorithm

The fine-tuning of the BOC algorithm is performed by its interconnection with a validated building model, developed in TRNSYS environment. The building model (Fig. 11) includes all the three selected hospital rooms with their HVAC system. The characteristics of the simulated building are depicted in Fig. 9. Furthermore, the available measurements collected from the HVAC systems are schematically presented in Fig. 10.

The TRNSYS model is validated and fine-tuned using the collected measurements from the rooms. The comparison of measured and predicted indoor temperature values are illustrated in Fig. 12.

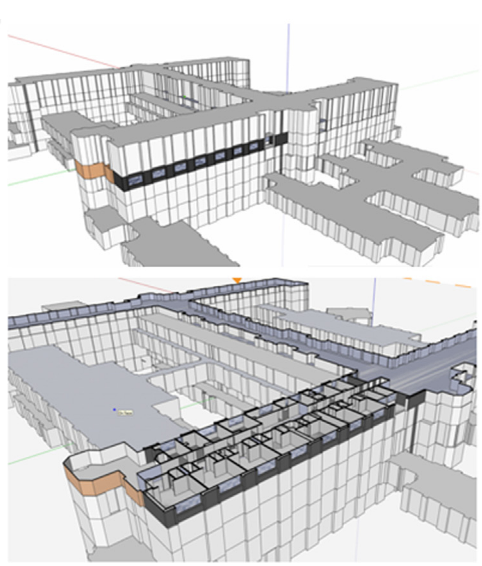
The differences between measured and predicted values can be attributed to the casual gains of the building, as well as to disturbances caused by the building users. After the validation of the TRNSYS model, the BOC algorithm running in Matlab™ environment is coupled with the TRNSYS model, using Type 155. In more detail, the TRNSYS model sends data related to indoor/outdoor air temperature and the BOC algorithm sends the selected operation conditions of the HVACs.

During the fine-tuning procedure, the response of the BOC algorithm is evaluated connecting it to the dynamic building model developed using TRNSYS (Fig. 13).

Indoor temperature set-point is increased from 19 °C to 23.5 °C. During the "transient state", the fan coil operates continuously trying to reach 23.5 °C. During the "steady state", the BOC algorithm maintains indoor air temperature at 23.5 °C, although outdoor air temperature is decreased.

5. Implementation of the BOC algorithm in the hospital's BEMS

The implementation of the BOC algorithm is performed through a Web-EMCS, which is described in Section 5.2. The framework of



Characteristics of the building (Saint George Hospital)	
General information	
Location	Chania, Crete, Greece
Building type	Hospital
Floors	7 (2 underground floors, 2nd floor for HVAC systems)
Surface area	49 400 m^2
Operation hours	24 hours 365 days
Orientation	NW
Building Envelope	
Walls	3 layer (concrete, insulation and drywall lining inside)
Roof	3 layer (concrete, insulation and gravel on the top)
Windows	Double glazing windows
Building services	
Cooling system	Central chillers with cooling tower
Heating system	Central boilers with efficiency
Ventilation system	Air handling Units with pre-condition of fresh air

Fig. 9. Characteristics of Saint George Hospital Building.

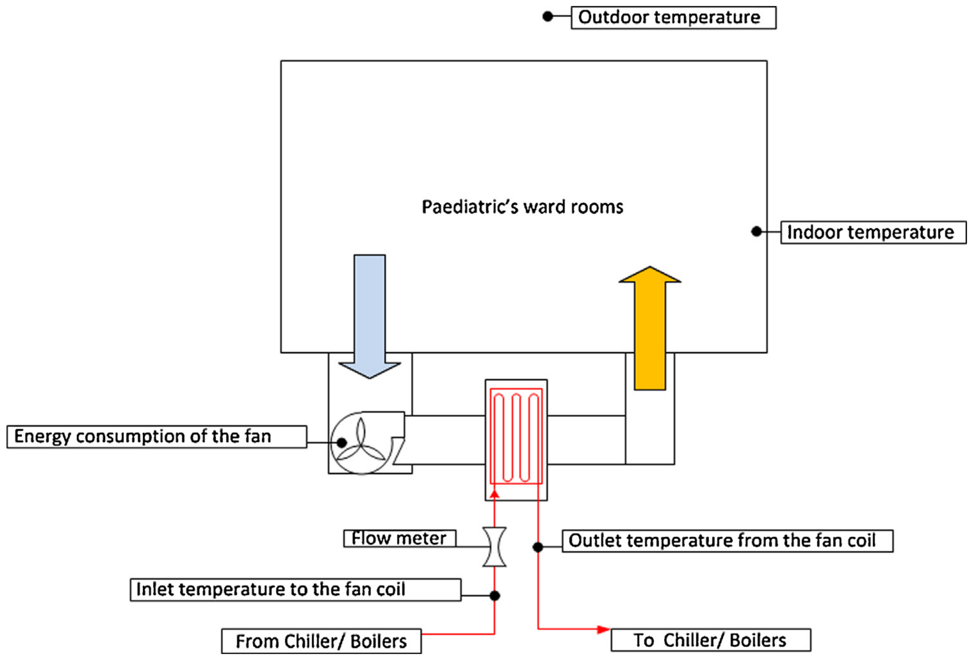


Fig. 10. Schematic description of the available inputs/outputs of the HVAC in SGH.

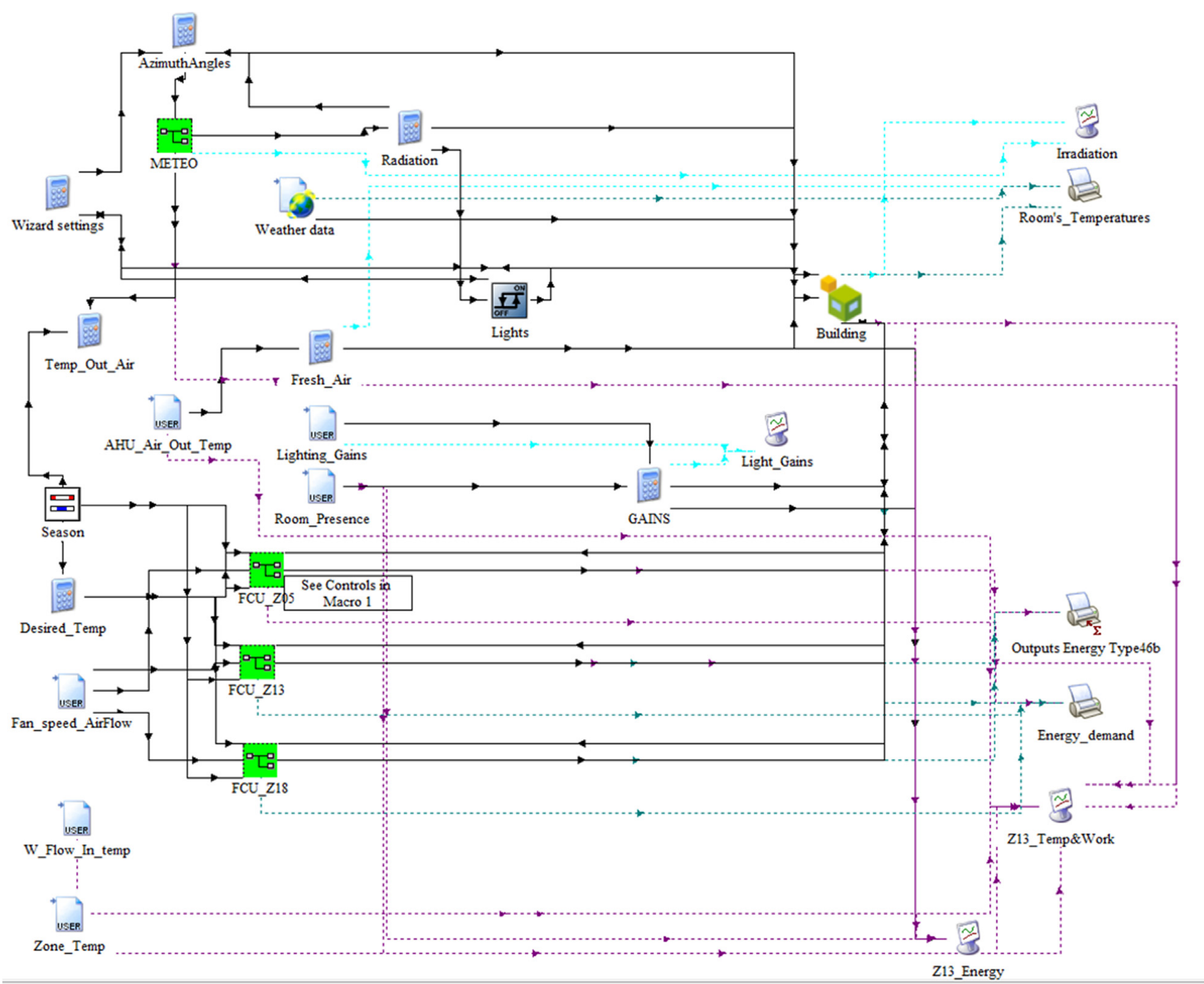


Fig. 11. Schematic of the developed TRNSYS model for simulating the operation of the 3 selected rooms.

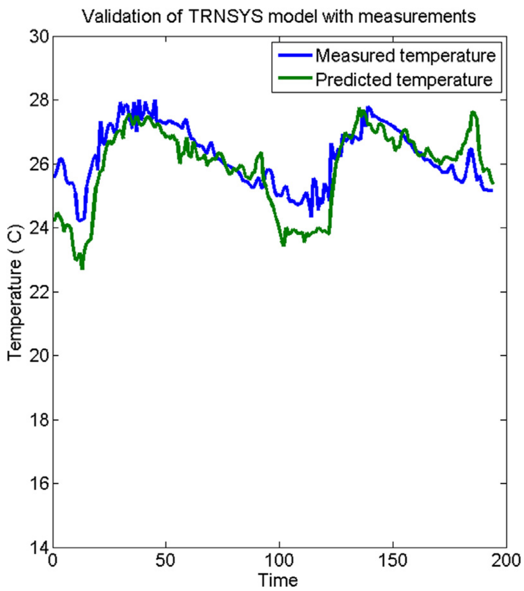


Fig. 12. Comparison of simulated and measured indoor temperature in the Doctor's office.

the Web-EMCS is based on Microsoft's .net v3.5. The algorithm is transformed to .net assembly language, using the deploy toolbox of Matlab™. The whole structure is depicted in Fig. 14.

5.1. Installation of infrastructure

The developed BOC algorithm is evaluated in Saint George Hospital, Chania Crete. For this research, monitoring equipment and actuators for the fan coils and artificial lights has been installed in selected rooms of the paediatric department of SGH. The installed equipment and connection diagram are illustrated in Table 5 and Fig. 15, respectively.

The room sensors are connected to the FX07 controller (Fig. 16) which is directly connected to the hospital's BEMS framework. Furthermore, the controller addresses the commands to the HVAC of each room. All data from the sensors are collected by the Web-EMCS and are also fed to the BOC algorithm. The outputs of the BOC algorithm are forwarded to the BEMS of SGH, through the Metalink software which uses macros to read/write the necessary parameters.

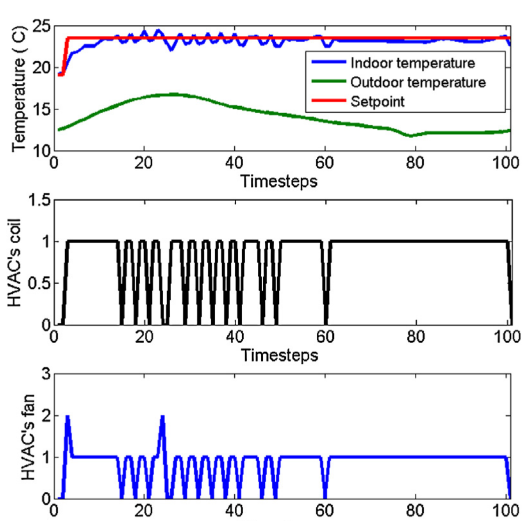


Fig. 13. Evaluation of BOC algorithm's transient and steady state by its connection to the dynamic building model.

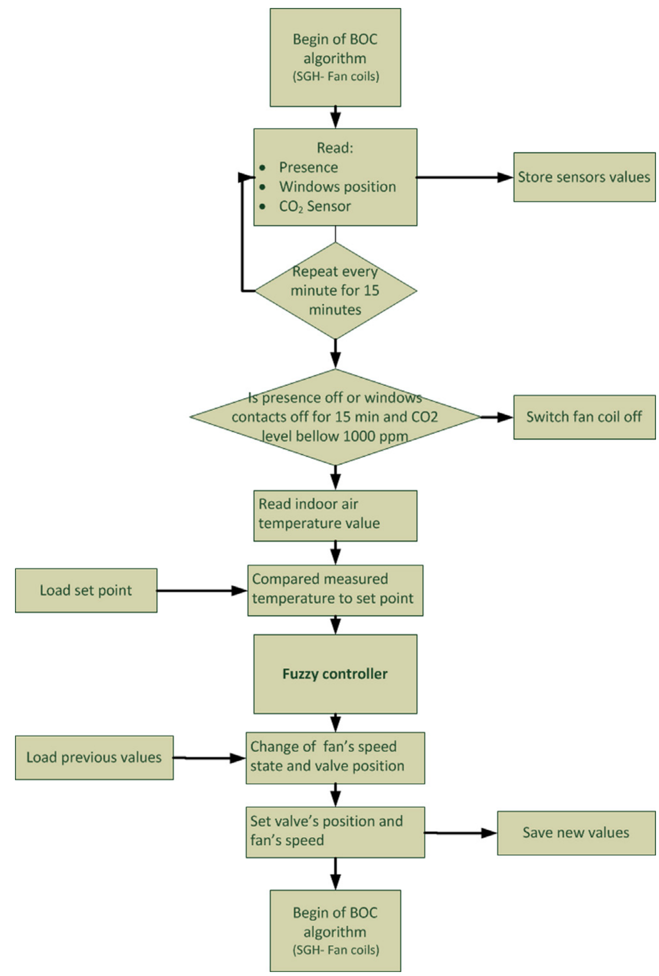


Fig. 14. Structure of the BOC algorithm for the HVAC of the paediatric department.

5.2. The Web-EMCS

The Web-EMCS is a platform developed to interact with hospitals' authorized personnel for the operation of the implemented systems. It can override the existing BEMS and sends the BOC algorithms' commands to the various subsystems. The Web-EMCS contains 3 interfaces, which are addressed to the various users:

1. A graphical user interface for the hospital's technical department, which displays the current readings from the installed sub-systems.

Table 5
Equipment installed in the selected rooms in SGH.

No	Equipment	Description	Quantity	Network
1	Energy meter	Kamstrup 382 Generation L	3	Lon
2	Thermal meter	Kamstrup MULTICAL 602	3	Lon
3	Internet server	Ilon server	1	Lon
4	Controller	FX07 terminal unit field controller	3	N1 & N2 Metasys
5	Nose sensor	EE80-2CTF3	3	Analog 0–10 V
6	Presence/light sensor	Thermokolon MDS	3	Analog 0–10 V
7	Window contacts	Magnetic contacts	6	Analog 0–10 V

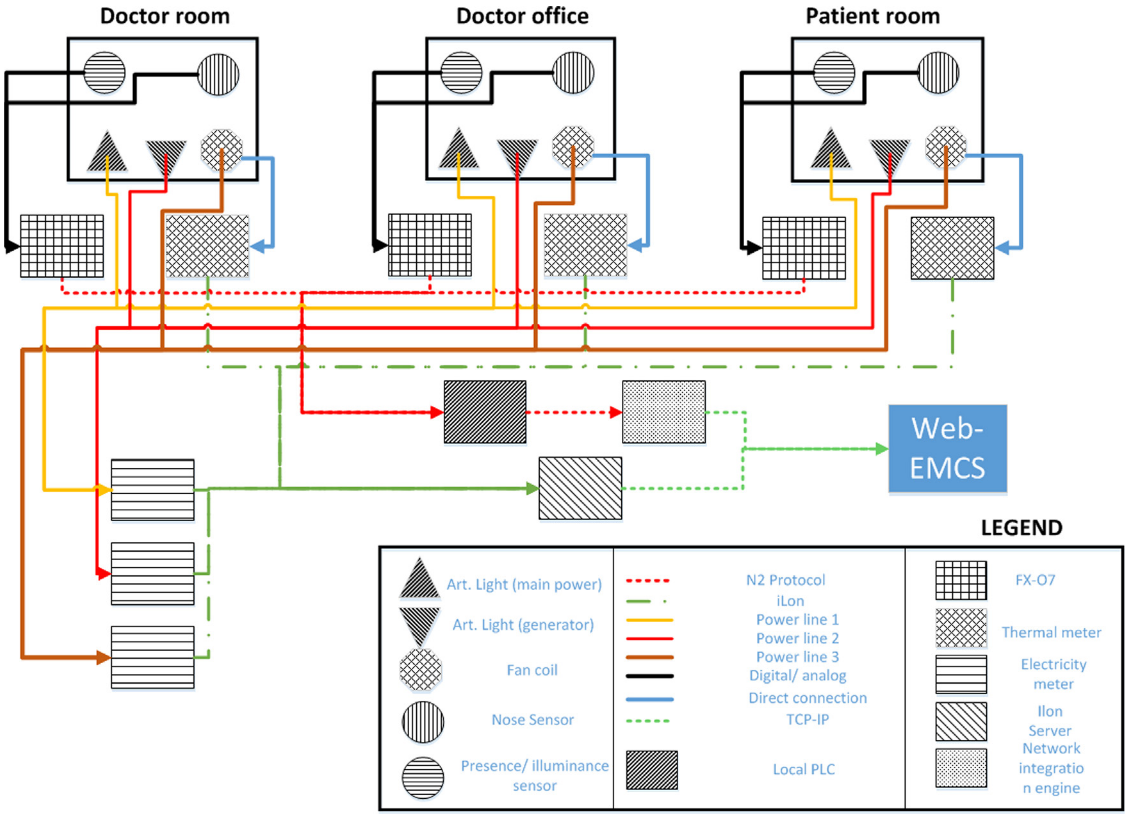


Fig. 15. Connection diagram of the installed equipment in SGH.

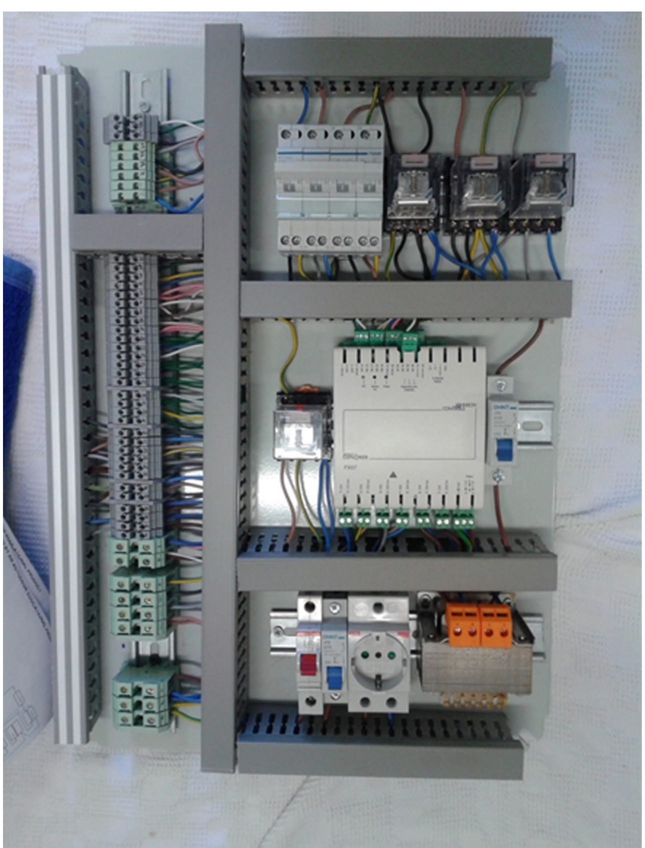


Fig. 16. The FX07 controller with the actuators (relays) of each room.

2. A dashboard (Fig. 17) which is used for the analysis of the system over a specific time period, along with real time visualization for selected parameters. Furthermore, authorized personnel can operate the systems remotely, if necessary.
3. A board with widgets which displays information to non-technical personnel in real time.

Furthermore, for safety reasons, override features are implemented which can be activated to manually control the Web-EMCS by the various users.

6. Results and discussion

6.1. Indoor comfort in Saint George Hospital

The indoor and outdoor thermal conditions of the patients' and doctors' rooms in the paediatric department of the SGH, are depicted in Figs. 18 and 19, respectively. The specific diagrams display the operation of the BOC and Web-EMCS for a 2 h period, during the afternoon of a typical summer day. It is observed that the indoor temperature is maintained close to 26 °C when there is presence in the rooms, even if the outdoor temperature reaches almost 32 °C. The HVAC is turned on following the presence detection. Furthermore, when the doctors leave their room (Fig. 19), the HVAC is turned off after 7 min, in order, not only to reduce the energy waste, but also to avoid continuous on and off due to occupancy oscillations. Moreover, the patients can override the BOC via the Web-EMCS override programing option. With a careful inspection of Fig. 18 at 16:10, although there is presence in the patients' room, the HVAC is turned off by overriding the system. In all cases, either users' thermal comfort is satisfied by the BOC via the Web-EMCS or the users select to override and set their own preferred thermal conditions.

Fig. 17. The graphical user interface of the Web-EMCS for the technical department of SGH.

6.2. *Assessment of the energy efficiency*

The energy efficiency is assessed using the TRNYS model, described in Section 4. Running an annual simulation of the TRNSYS model, coupled with Matlab^{TM} and comparing it to the current operation of the system, the results of primary energy for heating and cooling are tabulated in Table 6.

The reduction of the energy consumption for heating by 62.1 kW h/m^2, is three times higher compared to the increase of the energy consumption for cooling. Thus, an overall energy efficiency improvement of 36%, on yearly basis, is achieved.

The significant decrease of the energy consumption for heating is attributed to the fact that the indoor temperature using the BOC algorithm is maintained around 20 °C, avoiding overshootings, which causes increase of energy waste (Fig. 20). Therefore, indoor air temperature is maintained at 20 °C, thus consuming less energy, because the BOC algorithm prevents the operation of the HVAC when temperature exceeds the 20 °C.

The increase of the annual primary energy consumption for cooling is justified by the increase of comfort level in the rooms. In Fig. 21, it can be seen that the energy demand for cooling is increased, however indoor temperature doesn't exceed 26 °C, which signifies that indoor comfort is maintained. On the other hand, the simulation based on the systems' operation without the BOC and Web-EMCS, indicates that indoor air temperature exceeds 26 °C very frequently.

The overall energy savings of almost 40 kW h/m^2 is achieved by using the BOC algorithm for controlling the HVAC systems via

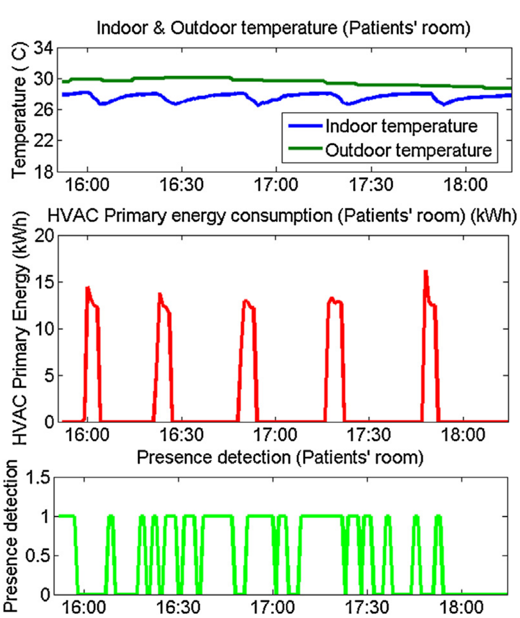


Fig. 18. Collected measurements from the Web-EMCS (Patients' room) implementing the BOC algorithm.

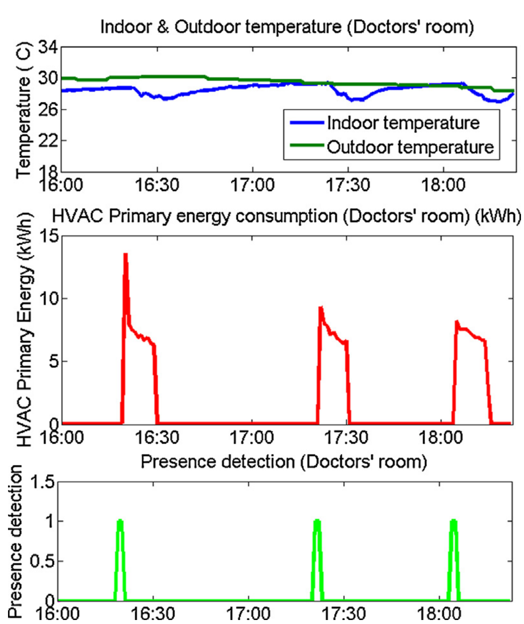


Fig. 19. Collected measurements from the Web-EMCS (Doctors' room) implementing the BOC algorithm.

Table 6
Annual energy saving potential comparing the operation of the HVAC based on users' with and the operation of the developed BOC algorithm.

	Annual heating energy consumption (primary) (kW h/m^2)	Annual cooling energy consumption (primary) (kW h/m^2)	Annual primary energy consumption (kW h/m^2)
Existing conditions	91.0	19.5	110.5
BOC algorithm	28.9	42.0	70.9
% Energy savings	−68.2%	115.7%	−35.8%

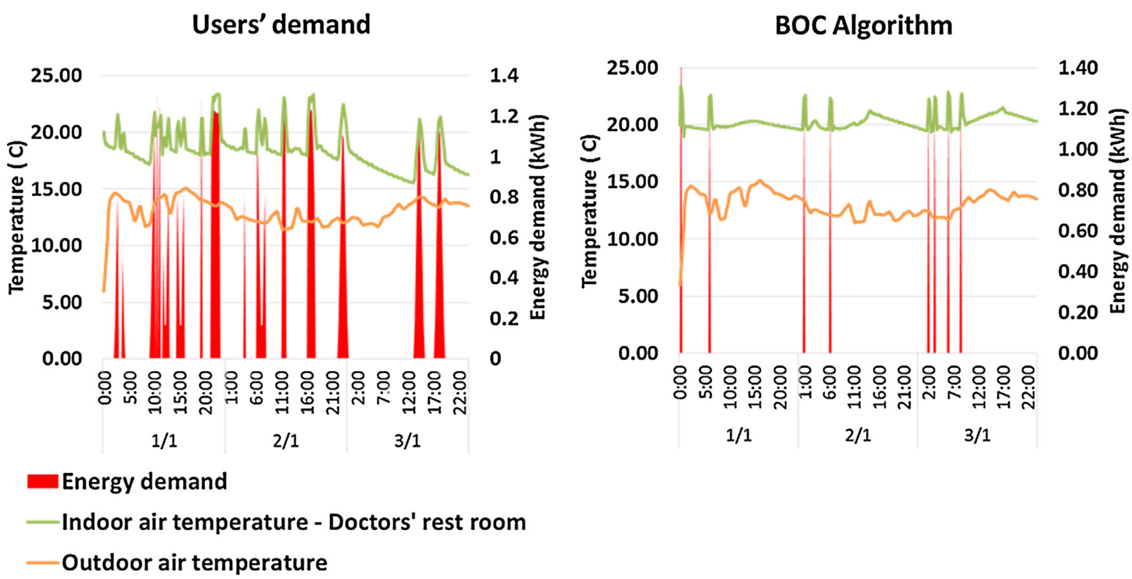


Fig. 20. Comparison of indoor air temperature and energy consumption under the same external condition using the BOC algorithm and using an operation based on users demand—heating period.

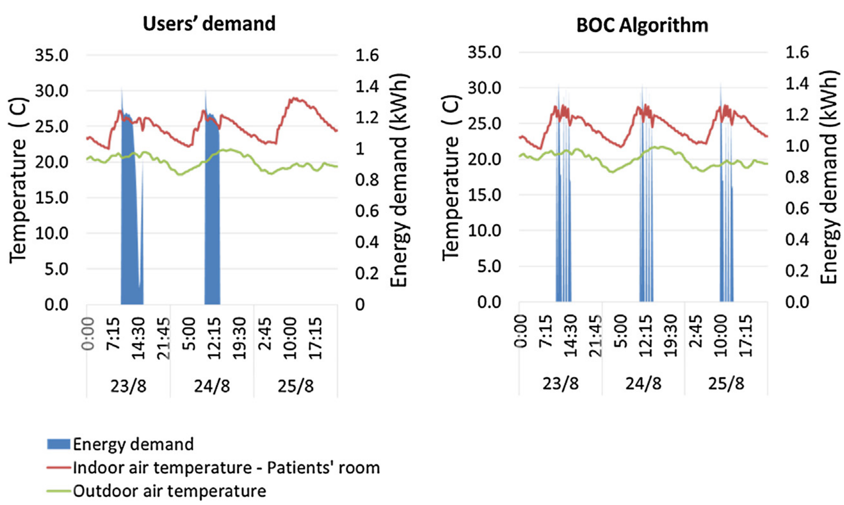


Fig. 21. Comparison of indoor air temperature and energy consumption under the same external condition using the BOC algorithm and using an operation based on users demand—cooling period.

the Web-EMCS. In addition, the thermal comfort of the personnel/patients in Saint George Hospital is significantly improved.

7. Conclusions

The proposed BOC algorithm implemented in a Web-EMCS is integrated to the existing BEMS of Saint George Hospital in Chania, Greece, after the completion of the aforementioned phases (development, fine-tuning, and implementation).

The identification algorithms, developed as part of the multi-step optimization, are evaluated using actual measurements. The operation of the fuzzy controller, during the fine-tuning phase, is tested using a TRNSYS model validated with measurements collected on-site. The energy saving potential is estimated by the TRNSYS model at 36%. The developed optimization algorithm computes the most suitable temperature set-point for the next hour, which is then sent to the real time controller for comparison with the input value from the indoor temperature sensor.

A ".net" based plugin especially developed for the Web-EMCS quite satisfactorily displays the results from the operation of the BOC algorithm, such as the energy saving and the preservation of thermal comfort. It remains to the future investigations to further verify and fine-tune the operation of the BOC algorithms in other spaces and hospital facilities.

Acknowledgements

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at http://dx.doi.org/10.1016/j.enbuild.2014.10.083.

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