Technical University of Crete

School of environmental engineering

"ENVIRONMENTAL ENGINEERING"

<u>Ph.D. Thesis</u>

"Development and application of smart algorithms for control and management in buildings, towards zero energy buildings."

Sotiris Papantoniou

CHANIA July 2015

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Air Handling Unit	AHU
Artificial Neural Networks	ANN
Building energy management system	BEMS
Building Integrated Photovoltaic	BIPV
Building optimization and control	BOC
Genetic algorithms	GA
Graphics Performance Unit	GPU
Heating ventilation and cooling	HVAC
Heating ventilation and cooling and lighting and Renewable energy sources	HVAC +L +RES
Information and communication technologies	ICT
Information technologies	IT
Proportional Integral Derivative	PID
Predicted Mean Vote	PMV
Power Usage effectiveness	PUE
Renewable energy sources	RES
Variable speed drive	VSD
Zero energy building	ZEB

Περίληψη

Ο στόχος της παρούσας διδακτορικής διατριβής είναι η παρουσίαση της ανάπτυξης και ενσωμάτωσης σύγχρονων αλγορίθμων ελέγχου και βελτιστοποίησης σε κτίρια οι οποίοι: (1) διασφαλίζουν την άνεση των χρηστών, (2) μειώνουν την κατανάλωση ενέργειας των κτιρίων, (3) ενσωματώνουν και διαχειρίζονται την παραγωγή ενέργειας από ΑΠΕ, (4) μπορούν να ενσωματωθούν σε υπάρχοντα συστήματα διαχείρισης ενέργειας κτιρίων και (5) συμβάλουν στην μετατροπή ενός κτιρίου σε κτίριο μηδενικής ενεργειακής κατανάλωσης.

Τα κύρια χαρακτηριστικά των αλγορίθμων ελέγχου και βελτιστοποίησης οι οποίοι αναπτύχθηκαν είναι:

- Η ενσωμάτωση προβλεπτικών αλγορίθμων για εξωτερικές και εσωτερικές συνθήκες που συμβάλουν στον υπολογισμό της ενεργειακής συμπεριφοράς των συστημάτων θέρμανσης ψύξης και αερισμού.
- Η χρήση αλγορίθμων βελτιστοποίησης οι οποίοι υπολογίζουν την βέλτιστη χρήση των συστημάτων θέρμανσης ψύξης και αερισμού για τα επόμενα χρονικά βήματα.
- Η εφαρμογή κλειστών βρόγχων ελέγχου οι οποίοι ελαχιστοποιούν την διαφορά μεταξύ των επιθυμητών και πραγματικών τιμών.
- Ο συνδυασμός των υπολογισμών από το σύστημα βελτιστοποίησης και την ανθρώπινη παρέμβαση, όταν αυτή χρειάζεται, έτσι ώστε πιθανό σφάλμα σε ένα από τα υποσυστήματα δεν θα επηρεάζει το σύνολο του αλγορίθμου βελτιστοποίησης.

Τα διαφορετικά υποσυστήματα που ενσωματώνονται στους αλγόριθμους ελέγχου και βελτιστοποίησης είναι:

- Υποσύστημα κλειστού βρόγχου για τη διασφάλιση της άνεσης και της μείωσης των απωλειών ενέργειας λόγω σπατάλης.
- Υποσύστημα πρόβλεψης της εξωτερικής θερμοκρασίας, διότι αυτή επηρεάζει τη θερμική άνεση του κτηρίου, καθώς και της κατανάλωσης των συστημάτων θέρμανσης ψύξης και αερισμού.

- Υποσύστημα πρόβλεψης της εσωτερικής θερμοκρασίας το οποίο αξιοποιεί την πρόβλεψη της εξωτερικής θερμοκρασίας και την κατάσταση λειτουργίας των συστημάτων θέρμανσης ψύξης και αερισμού.
- Υποσύστημα αλγορίθμου βελτιστοποίησης που υπολογίζει τη ρύθμιση του θερμοστάτη για τα επόμενα χρονικά βήματα.
- Υποσύστημα παράκαμψης για τα παραπάνω υποσυστήματα, ώστε προσωπικό του κτιρίου, με χρήση κωδικού πρόσβασης και κατάλληλη εκπαίδευση να μπορεί να ενεργοποιεί/ απενεργοποιεί εξ' αποστάσεως τα κλιματιστικά και τα φώτα.

Αναπτύχθηκαν κατάλληλα μοντέλα προσομοίωσης της θερμικής και της οπτικής συμπεριφοράς του κτιρίου, τα οποία επικυρώθηκαν με μετρήσεις πεδίου. Τα θερμικά μοντέλα χρησιμοποιούνται για την αρχική αξιολόγηση της ετήσιας κατανάλωσης των κτιρίων καθώς και την θερμική άνεση των ενοίκων. Τα θερμικά μοντέλα συνδέονται με τους αλγόριθμους ελέγχου. Επιπλέον, τα επικυρωμένα θερμικά μοντέλα αξιοποιούνται για την επιβεβαίωση της συμπεριφοράς των αλγορίθμων ελέγχου κλειστού βρόγχου και για την εκτίμηση της ετήσιας εξοικονόμησης ενέργειας. Τα θερμικά μοντέλα ενσωματώνουν την γεωμετρία των κτηρίων, τα κατασκευαστικά χαρακτηριστικά τους καθώς και τα εσωτερικά κέρδη. Τα αποτελέσματα των θερμικών μοντέλων υποδεικνύουν την κατεύθυνση που πρέπει να ακολουθήσουν οι αλγόριθμοι ελέγχου ώστε να μετατραπεί ένα ενεργοβόρο κτήριο σε κτήριο μηδενικής ενεργειακής κατανάλωσης.

Σχεδιάστηκαν ευφυείς αλγόριθμοι ελέγχου για τις κλιματιστικές μονάδες και τα τεχνητά φώτα και ρυθμίστηκαν κατάλληλα με στόχο να συμβάλλουν στη διατήρηση της θερμικής άνεσης και στη μείωση των ενεργειακών απωλειών λόγω σπατάλης ενέργειας. Οι αλγόριθμοι ελέγχου αξιοποιούν τη γνώση των διαχειριστών του συστήματος συντάσσοντας κανόνες, ενώ οι υπόλοιπες παράμετροι προσαρμόζονται εύκολα. Η συμβολή των αλγορίθμων ελέγχου στη μείωση της εξοικονόμησης ενέργειας συμβάλει στη μετατροπή του κοινού κτιρίου σε κτίριο μηδενικής ενεργειακής κατανάλωσης (zero energy building).

Αναπτύχθηκαν καινοτόμοι προβλεπτικοί αλγόριθμοι για την εκ προοιμίου εκτίμηση της συμπεριφοράς των συστημάτων θέρμανσης ψύξης και αερισμού. Οι προβλεπτικοί αλγόριθμοι εκτιμούν τις εσωτερικές και εξωτερικές συνθήκες. Η εκ των προτέρων γνώση, βοηθάει στην ανάπτυξη δράσεων που μπορούν να μειώσουν τη μέγιστη ζήτηση ισχύος σε συγκεκριμένες ώρες την μέρα. Με τον τρόπο αυτό μειώνεται η εξάρτηση του κτιρίου από το ηλεκτρικό δίκτυο.

Επιπλέον, αναπτύχθηκαν εξελικτικοί αλγόριθμοι βασισμένοι στην γενετική εξέλιξη, ώστε να επιλεχθεί η πιο «συμφέρουσα» λύση για την χρήση των συστημάτων θέρμανσης και ψύξης για τις επόμενες ώρες. Η έξοδος των γενετικών αλγορίθμων μειώνει το συνολικό κόστος χρήσης των κλιματιστικών μονάδων, ενώ παράλληλα διασφαλίζει τη θερμική άνεση. Τέλος, οι αλγόριθμοι βελτιστοποίησης μπορούν επιπλέον να λαμβάνουν υπόψη την παραγωγή από ανανεώσιμες πηγές ενέργειας, ώστε να μετακινούν την μέγιστη ζήτηση ενέργειας όταν οι ΑΠΕ παράγουν την μέγιστη δυνατή ισχύ. Έτσι μειώνεται η μέγιστη ζήτηση ισχύος από τον πάροχο και το κτήριο τείνει προς την μηδενική ενεργειακή κατανάλωση.

Οι προτεινόμενοι αλγόριθμοι ελέγχου και βελτιστοποίησης ενσωματώθηκαν στα υπάρχοντα συστήματα διαχείρισης ενέργειας δύο επιλεγμένων Νοσοκομείων (Νοσοκομείο των Χανίων και Νοσοκομείο της Ανκόνα, Ιταλία). Η εξοικονόμηση ενέργειας που επιτεύχθηκε από τη χρήση τους στο Νοσοκομείο των Χανίων είναι 57 % και 55 % για θέρμανση/ψύξη και ηλεκτρικό φωτισμό, ενώ για το Νοσοκομείο της Ανκόνα προέκυψε εξοικονόμηση 75 % για φωτισμό .

Η παρούσα εργασία παρουσιάζει ένα ολοκληρωμένο και καινοτόμο σύστημα βελτιστοποίησης και ελέγχου το οποίο μπορεί να ενσωματωθεί είτε σε υπάρχοντα συστήματα διαχείρισης ενέργειας ή σε νέα και μπορεί να μεγιστοποιήσει την εξοικονόμηση ενέργειας. Η χρήση των αλγορίθμων ελέγχου και βελτιστοποίησης έδειξε ότι επιτυγχάνεται σημαντική εξοικονόμηση ενέργειας χωρίς να υποβαθμίζεται η άνεση (θερμική και οπτική) των ασθενών και των ιατρών. Ένα σημαντικό χαρακτηριστικό των νέων αλγορίθμων είναι η δυνατότητα πρόσβασης και παρακολούθησης της συμπεριφοράς τους εξ αποστάσεως μέσω της διαδικτυακής πλατφόρμας Web-Energy Management Control Systems (EMCS).

Abstract

The scope of the present doctoral thesis is to develop and integrate building optimization and control algorithms which: (1) safeguard the comfort of occupants, (2) reduce the energy consumption of the HVAC equipment, (3) embody and manage the energy production from RES, (4) can be integrated in existing and new BEMS and (5) facilitate the transformation of any building towards a zero energy building. The main characteristics of the developed BOC algorithms are to:

- Integrate predictive models for outdoor and indoor conditions to facilitate calculation of the performance of the HVAC systems.
- Incorporate optimization algorithms which predict the optimum operation of the HVAC systems in the near future.
- Apply close loop control which minimizes the difference between the set-points and the actual values.
- Combine the calculations from the optimization with human interference, when required, in order to guarantee that potential failure of a subsystem is not affecting the whole BOC structure.

The different sub-systems which compose the BOC algorithms are:

- ✓ A closed loop control algorithm for safeguarding the comfort conditions and reduce the energy consumption from waste energy.
- ✓ A predictive algorithm for outdoor conditions which affect the buildings' fabric and the operation of the HVAC systems
- ✓ A predictive algorithm for indoor conditions which estimate the indoor conditions under the predicted outdoor conditions and the use of the HVAC system
- ✓ An optimization algorithm which sets the set-point of the AHU for the near future in order to exploit the thermal mass of the buildings' fabric.
- ✓ An override sequence which bypasses all the system and allows authorized/trained personnel to send commands directly to the HVAC and artificial lights.

Thermal and lighting models of hospital facilities are developed and validated with collected measurements. The thermal models are used to preliminary estimate

energy requirements of buildings and the comfort of occupants. Furthermore, the thermal modes are used for the fine-tuning of the control algorithms and the estimation of their energy efficiency potential. The thermal models incorporate the geometry of the buildings, the construction characteristics and the internal gains. The thermal models are connected with the BOC algorithms development software. The thermal models point the direction the developed algorithms should follow to transform the energy consuming buildings to zero energy ones.

Advanced control algorithms for AHU and artificial lights are designed and fine-tuned to safeguard the comfort level and reduce the energy losses from wasted energy. The control algorithms use the knowledge from the users in the form of rules and their parameters are easily fine-tuned, if required. The reduction of the energy losses contribute to the target of zero energy buildings.

Innovative identification algorithms are developed in order to estimate in advance the conditions of the facilities in order to adjust the usage of the HVAC equipment. The identification algorithms predict indoor and outdoor conditions. The a priori knowledge assists the definition of plans which can reduce the energy consumption of the next hours of operation, reducing the power demand for specific hours of the day.

Furthermore, optimization algorithms using genetic techniques are used to select the most “profitable” operation of the HVAC system in the next hours. The solution selected from the optimization algorithm minimizes the operational cost of the HVAC system over the next hours while the comfort level can be maintained. The optimization algorithms can integrate additional energy efficiency technologies such as RES and swift the loads when RES provide power.

The BOC algorithms are integrated in specific facilities of the two Hospitals (Hospital of Chania and Hospital of Ancona, Italy) and the energy efficiency are calculated at 57% and 55% for the Air handling Units and the artificial lights respectively for the hospital of Chania and 75 % for the artificial lights in the hospital of Ancona.

The present thesis provides a completed innovative optimization and control system which can be applied to existing BEMS or new ones in order to maximize the energy efficiency of the systems. The optimization and control system has achieved significant energy efficiency in both pilot hospitals, without compromising the comfort (visual or thermal) of patients. Another significant advantage the new control algorithms is the ability to be accessed and monitored from distance by means of a Web-EMCS internet platform.

--------------------------------------Chapter 1--

INTRODUCTION AND STATE OF THE ART

1 Introduction and state of the art

1.1 Energy consumption in buildings

Environmental, economic and policy reasons mandate the reduction of the energy consumption in buildings. The increase of CO_2 level in the atmosphere, the elimination of fossil fuels and the stability of the energy grids are among the causes which imply the reduction of energy consumption in the building's sector. Energy consumption in buildings measures at 40% of the worldwide energy consumption (Pérez-Lombard et al., 2008).

Energy efficiency in buildings can be achieved using either passive or active energy efficiency techniques. Passive energy efficiency techniques, such as wall/ roof insulation or fenestrations with low-e glass and window frames with low U-value contribute significantly in the reduction of energy consumption for heating and cooling. Although passive energy efficiency techniques reduce energy losses from the fabric of the buildings, energy consumption can also be reduced by adjusting the internal gains, which directly affect energy consumption. Moreover, during the summer period, when cooling is mostly required, the surplus internal gains increase indoor temperature, which is directly related to the cooling loads.

Furthermore, the increased energy consumption of buildings affects its surrounding micro-climate increasing outdoor air temperature by removing the excess heat from the building to the environment. The urban heat island phenomenon has been identified by many researchers in cities due to the increased level of human activity. Studies by Kolokotsa et al. (Kolokotsa et al., 2009b) and Maragkogiannis et al (Maragkogiannis et al., 2013) have identified the urban heat island phenomenon using collected measurements and simulation results respectively.

Urban heat island effect can be estimated by the prediction of the outdoor air temperature. Gobakis et al. (Gobakis et al., 2011) developed a neural network for predicting outdoor air temperature for the city of Athens during the summer period.

By predicting outdoor air temperature energy efficiency techniques can be applied by using optimization techniques which minimize the energy consumption of the HVAC system over a predictive horizon. As can be seen in Figure 1- 1, outdoor temperature prediction can be used as input to indoor conditions predictive algorithms (Papantoniou et al., 2012).

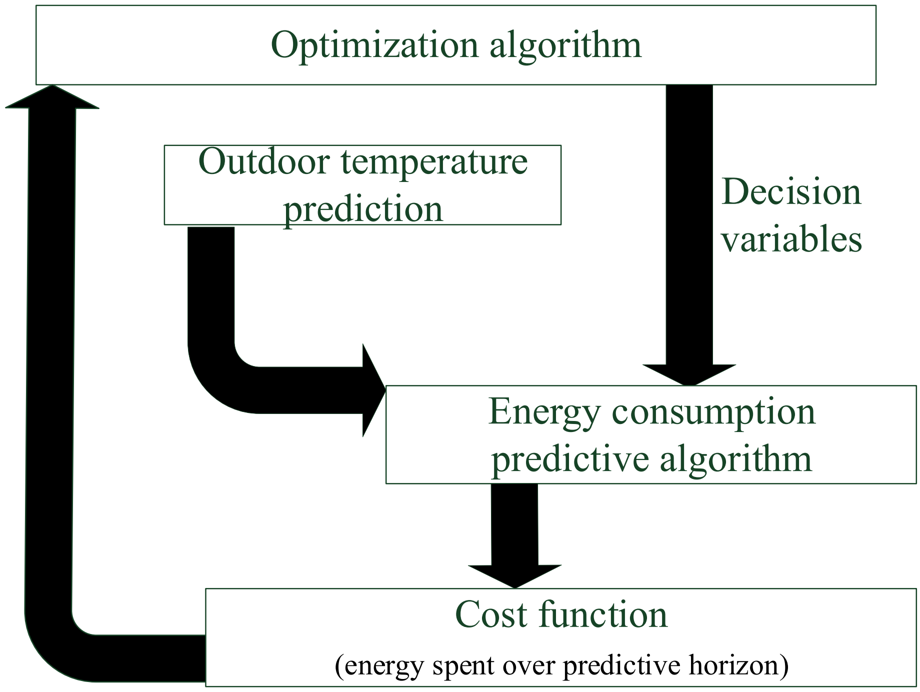


Figure 1- 1: Application of an optimization algorithm for minimizing energy consumption over a defined predictive horizon

The optimization algorithm reduces the energy consumption over a pre-defined predictive horizon by shifting the energy requirements of the buildings (Kolokotsa et al., 2011). Thus, the reduced operation of the HVAC systems when outdoor air temperature is maximum during summer increases the energy efficiency potential and affects the micro-climate of the city.

The improvement of HVAC systems energy efficiency can assist in the achievement of ZEB. Marszal and Heiselberg (Marszal and Heiselberg, 2009) review the literature concerning the definition of ZEB and they separate according to Torcelline et al. (Torcellini et al., 2006) ZEB into different categories according to the approach.

A **net zero site energy** building produces in annual base the same energy it consumes. A **net zero source energy** building produces the same primary energy it consumes during a year, while a **net zero energy cost** building has a budget balance concerning the money paid to utility companies related to the money gained from energy provided to the grid. Finally **net zero energy emission** buildings provide balance in annual base concerning the CO_2 emissions of the house comparing to CO_2 emissions saved from the use of RES.

1.2 Energy consumption of hospitals

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

The comfort level of a hospital ward in Malaysia, has been assessed by Azizpour et al (Azizpour et al., 2013). Based on measurements of PMV and subjective measurements collected by the use of 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 (Giridharan et al., 2013) in the UK, involving indoor air temperature measurements in a ward of the Glenfield hospital. The measurements indicate that indoor air temperature is above comfort level. Furthermore, using a validated simulation model, light touch interventions (controlled fans, horizontal shades and reduction of internal gains) are proposed to control overheating by 2050.

An energy audit of hospitals has been presented by Balaras et al (Balaras et al., 2007) based on the air change rate measurement of operating rooms. Furthermore, Argiriou et al (Argiriou and Asimakopoulos, 1994) 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 (Santamouris et al., 1994b) have performed energy audits on 30 hospital buildings. An analysis of the energy consumption of Greek Hospitals has been performed by Sofronis and Markogiannakis (Sofronis and Markogiannakis, 2000). Based on their energy analysis in 10 hospitals, 56% of the hospitals consume 200–400 kWh/m^2. The reduction of energy consumption in hospitals is also mandated by the increase of the energy price (Sullivan, 2013).

Among the most common internal gains existing in buildings, is the use of artificial lighting. Artificial lighting in buildings used for offices consume a significant amount of worldwide energy compared to the total building's energy consumption as presented by Santamouris et al. (Santamouris et al., 1994a) and Lam et al. (Lam et al., 2003) affecting the cooling loads of buildings as reported by Franzetti et al. (Franzetti et al., 2004). According to Santamouris's research artificial lights consume 10% of total energy consumption based on measurements in buildings in Greece. Current artificial light systems use fluorescent lamps. Before the mandatory installation of fluorescent light bulbs throughout Europe (Commission, 2009), most buildings used incandescent light bulbs which were very inefficient. Lately, LED luminaire with proper driving circuitry, adjust indoor illuminance to comfort levels. The adjustment of illuminance to the minimum required level compared to the maximum capacity of the light fixtures generates energy efficiency potential.

The efficiency of such energy efficiency techniques is also affected by the behaviour of the occupants which may reduce the energy efficiency potential. On the other hand, new systems such as smart controllers can adjust the artificial light level based on data collected from illuminance sensors and occupancy detectors. A smart controller may also be adjusted to the needs of the occupants if during the pre-commissioning period the manual-control used by the occupants has been measured and analysed as presented by Reinhart (Reinhart, 2001), Reinhart and Voss (Reinhart and Voss, 2003). Nevertheless, when designing smart controllers for optimum and energy efficient operation of building services, the existence of an advanced and integrated simulation environment is very important.

1.3 Passive energy efficiency techniques towards zero energy buildings/ hospitals and RES towards zero energy buildings

A building's fabric exchanges energy between the indoor and outdoor environment. The energy exchange can be useful only when it is required by the occupants. Energy exchange from opaque and transparent surfaces needs to be reduced. Different techniques have been applied in recent years for reducing the energy demands due to losses from a buildings' fabric. Fabric losses occur from surfaces which come into contact with the outdoor environment. Technologies focus on the reduction or the control of the energy transfer.

Innovative coatings have been evaluated in buildings fabrics which significantly reduce the cooling loads which are dominant in the southern countries of Europe.

Kolokotsa et al. (Kolokotsa et al., 2012a) have tested the effect of a cool layer on the outer upper shell of a building in Heraklion, Greece and have measured a significant reduction of outdoor surface temperature.

Comparison between cool roof and green roof energy performance has been performed by Pappa Athina (Pappa, 2014). In a typical house construction the reduction of the HVAC loads have been evaluated using Energy Plus simulation software. The simulation results demonstrate that the green roofs reduce both heating and cooling loads while the cool materials only reduce the cooling loads.

A different approach for reducing the energy transfer from outer upper shell has been tested by Spanaki et al (Spanaki et al., 2014, 2012). A roof pond has been created to absorb the higher indoor temperature during the day and emit it during night. The proposed pond roof has decreased the energy heat transfer from outdoor to indoor during summer period contributing to the reduction of the cooling loads.

For reducing the cooling and heating loads of office buildings Papadaki et al. (Papadaki et al., 2013) tested a double façade glazing combined to interior or exterior shades. The double skin façade has reduced the annual energy consumption of heating and cooling based on simulated results using a validated thermal model developed on EnergyPlus.

Energy efficiency techniques have been applied in houses which consume minimum energy for heating and cooling (Wang et al., 2009). Calculation of the loads has been performed by using Energy Plus simulation software and for the modelling of HVAC systems TRNSYS v16 is used.

Buildings' energy demand can be reduced by applying passive energy efficiency techniques. Ieronimakis (Ieronimakis, 2013) has demonstrated through simulation that a typical house energy performance can be upgraded significantly by applying insulation layers to the fabric.

In order to achieve zero energy building the usage of RES is vital. RES cover the minimized energy requirements of the buildings which can be off-grid with a storage system or on-grid by exchanging energy with the existing power grid.

The requirements of fabric upgrades of an office building towards a net zero energy building has been estimated by Pyloudi et at (Pyloudi et al., 2014). The required changes in the fabric of the building and the installation of RES (PV-plants and vertical wind generators) have been estimated using TRNSYS software for the fabric while HOMER software has dimensioned the RES.

1.4 Applied control and management techniques in zero energy buildings

A review of the hospital energy efficiency techniques is presented by Kolokotsa et al (Kolokotsa et al., 2012b). 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, tri-generation and geothermal systems) to reduce their dependency on fossil fuels.

Table 1- 1: Energy consumption of hospitals and method for reducing it (Kolokotsa et al 2014)

N.	Country	Description of building	Audit results	Suggested technologies	Comments
1	Greece	30 health care buildings	Annual average energy total energy consumption is 407 kWh/m^2 in hospitals and 275 kWh/m^2 in clinics	Increase efficiency of production and distribution of heating system. Night ventilation, ceiling fans, external shades, fluorescent lamps	Energy for heating can be reduced by 15% and 11% for hospitals and clinics respectively. Cooling needs can be reduced by 68 to 58% respectively. Electricity for lighting can be reduced up to 50%.
2	Greece	30 air-conditioned and natural ventilated buildings in Athens part of them are hospitals	Sick building syndrome, increased levels of some pollutants. Values are related to the outdoor environment	No technologies are suggested	Sick building syndrome is a very critical problem for hospital buildings
3	Netherlands	No description is available	No audit was performed	Optimization of HVAC system	Economic profits or Primary energy efficiency can be achieved depending on the Scenario of Optimization
4	Greece	20 operation rooms in 10 Hellenic Hospitals	Measured temperature: 14 to 29 ^{o}C Relative Humidity 13 to 80% ARCH: 3.2 to 58.	Variable air Volume system, Sensible heat and energy recovery	

5	Portugal	No description is available	Energy efficient technologies were constrained due to lack of information, budget limitations and personnel behaviour	No technologies are suggested	Energy efficient measures could be provided by energy services companies
6	Malaysia	No description is available	234 kWh/m^2 energy consumption. Most of the energy was used for lighting and medical equipment	Replacement of old motors with high efficiency new motors	New motors can contribute 20-60% energy efficiency.
7	Poland	715-bed University Hospital, 690-bed Provincial Hospital	Domestic heat water consumption constant throughout the year for both hospitals,	Partial use of Renewable energy sources to cover domestic heat water demand.	
8	Mexico	General Hospital	Diesel is mainly used for energy consumption	Pinch technology	Savings 38 % of thermal power used at present. 60 % of thermal power demand is low enthalpy and renewable energy sources can be used to cover it
9	Poland (Bydgoszcz)		Incinerator for medical waste combustion	High load of the incinerator increases efficiency, Efficiency is decreased with time due to dirt at the incineration area	600-800 kW of usable energy can be produced from 100 kg medical waste, heat can be used to save energy from gas boilers.
10	New Zealand	120 beds	Doubled direct use geothermal heating system since 1977	Data acquisition (flow rate, temperature, heat exchange)	Calculate energy produced and consumed

11	Italy	No description is available	Oil is used to satisfy electrical needs in Italian Hospitals	Fuel cells for electricity production and heat recovery for thermal requirements	Fuel cells can cover 70 % of the electrical need and 2,975 MWh of thermal energy requirements
12	Italy	No description is available	Electricity is provided from the grid and heat from gas-fired boilers	Trigeneration technology: 1) Fuel cells and photovoltaic cells for electricity needs and 2) cogeneration for heat production, Solar collectors can be used especially in summer to cover peak loads. Absorption chillers increase efficiency even more	Increased capital cost, high efficiency system, insurmountable economic market barrier. Externalities should be examined
13	Brazil	20 Complete energy diagnoses in Hospitals	Energy consumption depends on the size of hospital and the services provided.	Gas fired cogeneration in Brazilian Hospitals	Total savings are estimated at 71,616 MWh/month for all the hospitals
14	Spain	80,000 m^2 more than 1,000 beds	No audit was performed	Cogeneration from diesel engines and gas turbines, and trigeneration with cold water production	Primary used energy loss is reduced from 60% to 15 and 20 %
15	Slovenia	No description is available	No audit was performed	Trigeneration system: 3 MW gas fuelled engine for electrical power. Cogeneration for heating, and absorption chiller for cooling. Ice storage for peak cooling loads	Trigeneration system can be profitable, payback period is low, COP is increased using absorption chillers
16	Greece	1,250 m2	No audit was performed	Solar cooling system: 179 solar collectors, 70 kW absorption chiller	Increased capital cost, increased environmental savings

17	Belgium	No description is available	81 % of total cooling energy and 22 % of heating used by direct use of groundwater		Primary energy consumption 71 % lower than reference installation with gas-fire boiler 1,280 tons of CO_2 saved in 3 years

A study on the effect of envelope changes in hospitals has been performed by Ascione et al (Ascione et al., 2013). Increased insulation, installation of low-emissive windows, external blinds, replacement of windows and replacement of HVAC systems were 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.

The Department of Energy USA (Energy, 2009) recommends various techniques for the reduction of energy consumption in hospital’ services and fabric. Set-back strategies are also tested aiming to reduce the energy consumption of the HVAC.

1.4.1 Applied control techniques for Air handling Units

Control algorithms can be used to implement either logic control rules, or On-Off or PID control in buildings services (Panke, 2002)(Dounis and Caraiscos, 2009). 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 (Alasha’ary et al., 2009; Karatasou et al., 2006; Preglej et al., 2014; Ruano et al., 2006). Predictive control techniques are also applied (Álvarez et al., 2013; Bălan et al., 2011; Kolokotsa et al., 2009a; Yuan and Perez, 2006). Privara et al (Prívara et al., 2012) proposed a methodology for selecting the most appropriate model for predictive control, conducting performance evaluation on a TRNSYS model. Dynamic models, such as the TRNSYS software, are also used for the evaluation of energy efficiency techniques in HVAC systems, such as heat pumps with heat recovery as presented by Gustafsson et al (Gustafsson et al., 2014). Finally, optimization techniques, such as dynamic programming (Avci et al., 2013; Caldas and Norford, 2003), multi-objective optimization (Diakaki et al., 2008; Kolokotsa and Diakaki, 2009) and simulation assisted multi-criteria analysis (Roy, 1996) are proposed in order to deal with the complexity of contemporary HVAC systems. Weather forecast is critical for the characteristics of the predictive optimization techniques because it affects the operation of the HVAC systems, as described by Oldewurtel et al (Oldewurtel et al., 2012). Oldewurtel et al combine the prediction of the weather forecast by 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 energy demand in hospital HVAC systems. For example, a Run-Around Membrane Energy Exchanger (RAMEE) was proposed by Rasouli et al (Rasouli et al., 2010) to transfer moisture and energy between exhaust and ventilation air streams. Simulation results indicated that the energy efficiency potential reached 60% for heating in cold climates and 15-20% in hot climates. Moreover, Huang et al (Huang et al., 2006) presented an energy management and control strategy for a HVAC system, which reduces energy consumption by 17%. A review of intelligent HVAC systems implemented in hospitals has been performed by Reijula et al (Reijula et al., 2013). In their research, the optimization and energy conservation techniques for HVAC systems in hospitals are presented. Ursu et al (Ursu et al., 2013) 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%.

Solar cooling techniques have been applied by Tsoutsos et al ((Tsoutsos et al., 2010) in a hospital building using TRNSYS simulation software to evaluate the performance of the system and the potential payback period has been estimated less than 7 years.

1.4.2 Applied control techniques for artificial lights

The issue of energy efficiency from artificial lights, maximizing the benefits from natural daylight has been raised by many researchers. The initially developed controllers were switching artificial lights on/ off based on the indoor illuminance level (Knight, 1998). As Knight mentioned in his research, “Mark 1” model could only adjust the illuminance set point of 500 lux, preventing the user to set a different set point based on the usage of each workstation.

Communication between sensors and actuators may be wired or wireless. An example of a wireless on/ off controller is designed and applied by Kumaar et al. (Nippun Kumaar et al., 2010) saving 14.4 kWh per month, which is 20% of the energy consumption of artificial lights. In this installation, wireless sensors located in the various areas of a room switch artificial lights on and off sending signals to a wireless actuator located next to the light fixture.

Apart from the on an off systems, more sophisticated controllers can be used especially for light systems that integrate dimmers. A wireless control system is designed and tested by Wen and Agogino (Wen and Agogino, 2010). According to their research if a photo sensor and a controller is located above each workstation, energy efficiency can reach 60.8% considering a specific occupancy profile for an office, compared to the initial state where all the lights where switched on and off simultaneously. The advantage of this control system compared to the previous one is the capability to dim artificial lights separately. Another comparison between automated on/ off systems and fully dimmable systems has been presented by Frattari et al. (Frattari et al., 2009). According to their research, a fully dimmable system can save up to 68 %, during autumn and up to 43 % during the winter months, while an automated on and off system saves 56% and 20 % respectively. Dimmable controllers are also available on the market and have been tested to measure their energy efficiency. Knight (Knight, 1998) has tested 2 products available on the market and has found that a controller with higher dimming capabilities can save more energy even during the night since it can adjust the provided illuminance level to the required set point.

Lighting controllers can be combined with other daylight harvesting techniques such as light shelves. Raphael (Raphael, 2011) developed a control which combines the movement of light-shelves with the proper dimming of the artificial lights improving the performance of the system and saving 12% compared to that of a steady light-fixture.

Furthermore, automated control of light fixtures can be combined with other parameters such as indoor air quality and thermal comfort to achieve an overall optimization of the building's energy consumption while guarantying indoor conditions inside buildings as described by Dounis et al. (Dounis et al., 2011) based on simulation results and D. Kolokotsa et al. (Kolokotsa et al., 2009a) based on real measurements. Another approach for artificial lights control is presented by Kurian et al. (C.P. Kurian et al. 2008) combining the control of the artificial lights with a separate control for the venetian blinds in order to maximize daylight harvesting and minimize visualization problems. Based on the research, energy efficiency potential depending on the orientation of the windows and the floor level varies from 21 % to 60 %. The development of the fuzzy control for dimming the artificial lights has been presented by Kurian et al. (C.P Kurian et al. 2005) and its application including the achieved results has also been published by Colaco et al. (Colaco et al., 2012) Although fuzzy technology has been developed since 1965 its application is continuously increasing. Their main advantage is the users' knowledge inserted in the controller in the form of rules. Another advantage of fuzzy technology is its adaptability for actual measurements using ANFIS (Adaptive Neuro Fuzzy Inference System) (Jang, 1993) architecture, in which the fuzzification and de-fuzzification parameters are updated based on measurements collected on-site.

An automated controller can also be combined with a fault detection system in order to inform the energy managers that a sensor might have sent some fault measurements. Such a fault detection system has been developed by D. Kolokotsa et al. (Kolokotsa et al., 2005) showing remarkable results despite its simplicity.

1.5 Problem statement

Hospitals consume significant energy amounts throughout the day in order to provide the required comfort conditions to patients in their wards. Hospital buildings are also energy inefficient because their HVAC and lighting equipment is outdated with limited control potentials. Moreover existing BEMS of the hospitals is mostly used for the monitoring of crucial parameters of specific wards (Emergency ward, surgery rooms etc). All the aforementioned conditions affect the energy consumption of the hospitals.

Based on the state of the art previously described, techniques for reducing the energy consumption of hospitals have been presented for individual systems applying passive energy efficiency techniques or integrating RES. Moreover control algorithms have been applied for individual HVAC systems of other types of buildings (houses and offices) in order to reduce their energy consumption.

Although all the above technologies for controlling individual systems have been applied, the successful integration of HVAC, lighting systems (L) and renewable energy sources (RES) is still under consideration. In addition, change of weather conditions affect the behavior of an operational building including the consumption of the HVAC +L + RES. Moreover during the operational phase of a building the various subsystems' performance cannot be a priori ascertained due to unpredictable user actions that adversely affect energy efficiency such as:

- Unnecessary operation of the lighting or the HVAC systems
- Opening and closing of windows
- Setting of the setback temperature too high or too low

In real time operation of a hospital building which aims to perform as a nearly zero energy building, a coupling mechanism of the energy production and energy requirements may yield significant benefits since it will manage to:

- Provide the required comfort requirements using advanced control techniques.
- The overall energy production from different subsystems can be maximized by suitable optimization techniques.
- Extreme weather conditions can be met annually with suitable control and/ or override actions.

Based on the aforementioned points, this thesis addresses the development and integration of control and energy management algorithms into hospital buildings under operational conditions.

This thesis provides the methodology to reduce the energy consumption using ICT on the available HVAC + L+ RES systems of hospital buildings in order to assist their upgrade from typical energy consuming buildings into ZEB.

1.6 Innovation of the research

The innovation of this research is:

- The development of control algorithms for HVAC and artificial light systems which can be applied in different installations.
- The formation of identification algorithms for predicting indoor/ outdoor conditions which can be used for reducing the energy demand over a predictive horizon, and can be applied in hospital rooms with different usage and different properties (orientation, schedule of usage, internal gains etc.)
- The design of optimization algorithms, to use the values of the identification algorithms to calculate the optimized performance of HVAC systems over a predefined predictive horizon of 8 hours..

- The integration of the aforesaid contemporary control and energy management algorithms in hospital building through their existing BEMS or in new installations, through a Web-EMCS to improve their performance and the whole hospital energy efficiency towards a zero energy hospital state.

1.7 Short presentation of the work

In this thesis, the process for reducing the energy consumption of buildings is exploited as presented in Figure 1- 2. The performed work is separated in phases starting with the energy audit of existing hospitals (Phase 1), proceeding with the development of control and management algorithms (Phase 2) and development of integration techniques for RES (Phase 3). In the 4^{th} phase the developed control and management algorithms as well as the RES are integrated in the existing BEMS of the hospital buildings and system is implemented in the actual Hospital to transform it into a zero energy building. Phase 2, is illustrated in Figure 1- 3, while phases 3, 4 and 5 are plotted in Figure 1- 4.

The followed methodology in order to reach the objective is illustrated in Figure 1- 5.

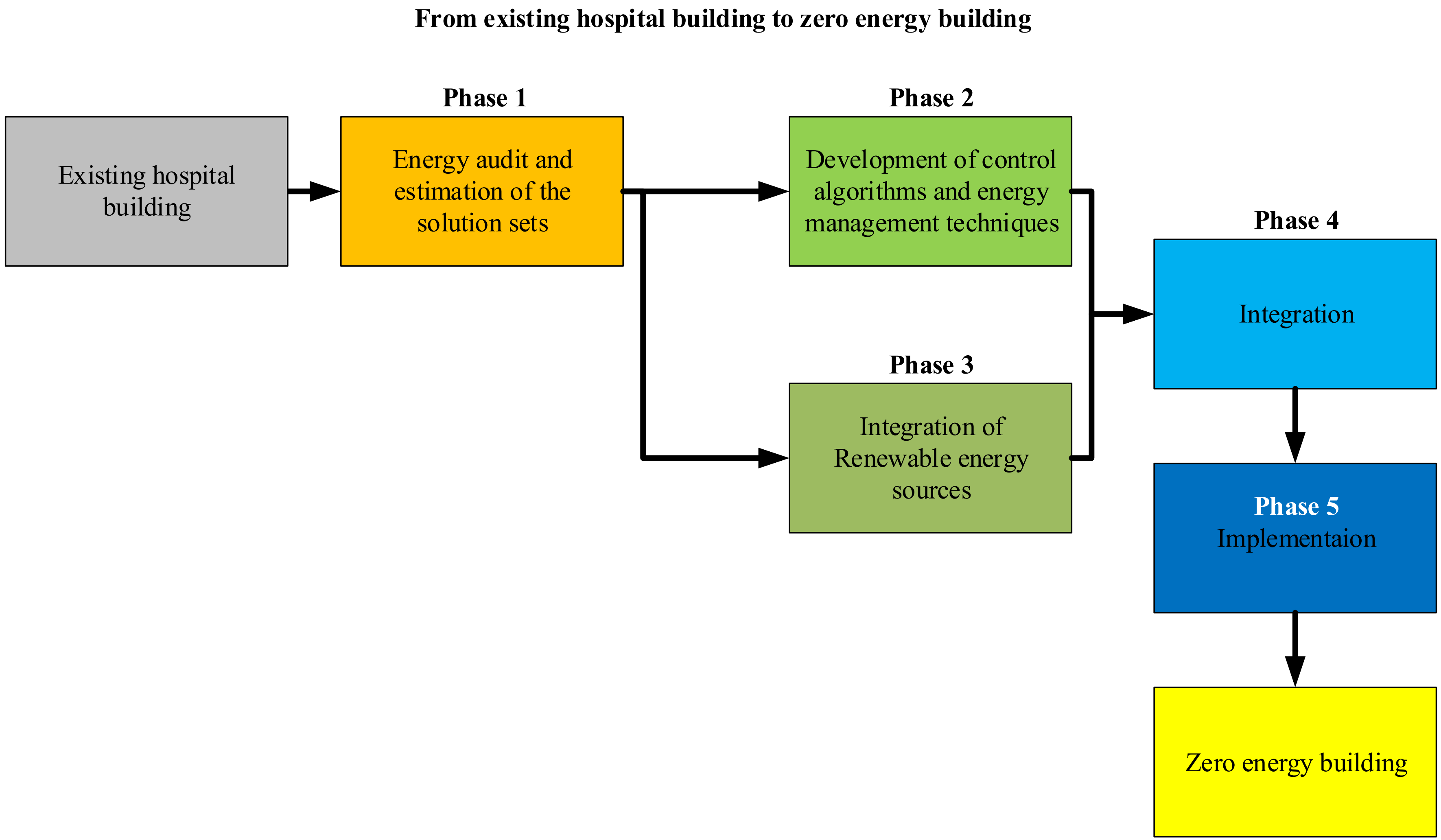


Figure 1- 2: Followed steps from existing energy consuming hospital buildings to zero energy buildings

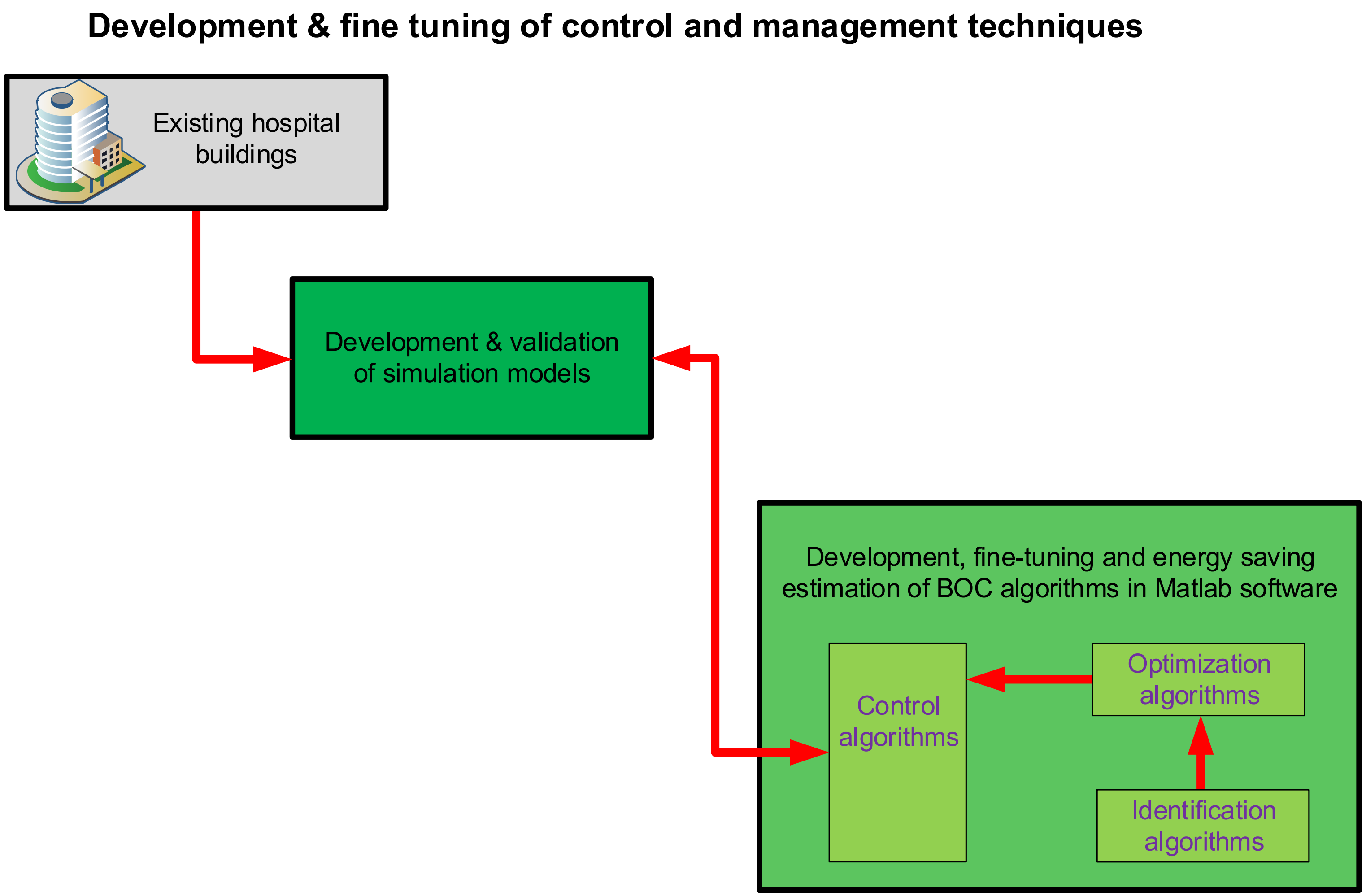


Figure 1- 3: Development and fine tuning of contemporary control and management techniques

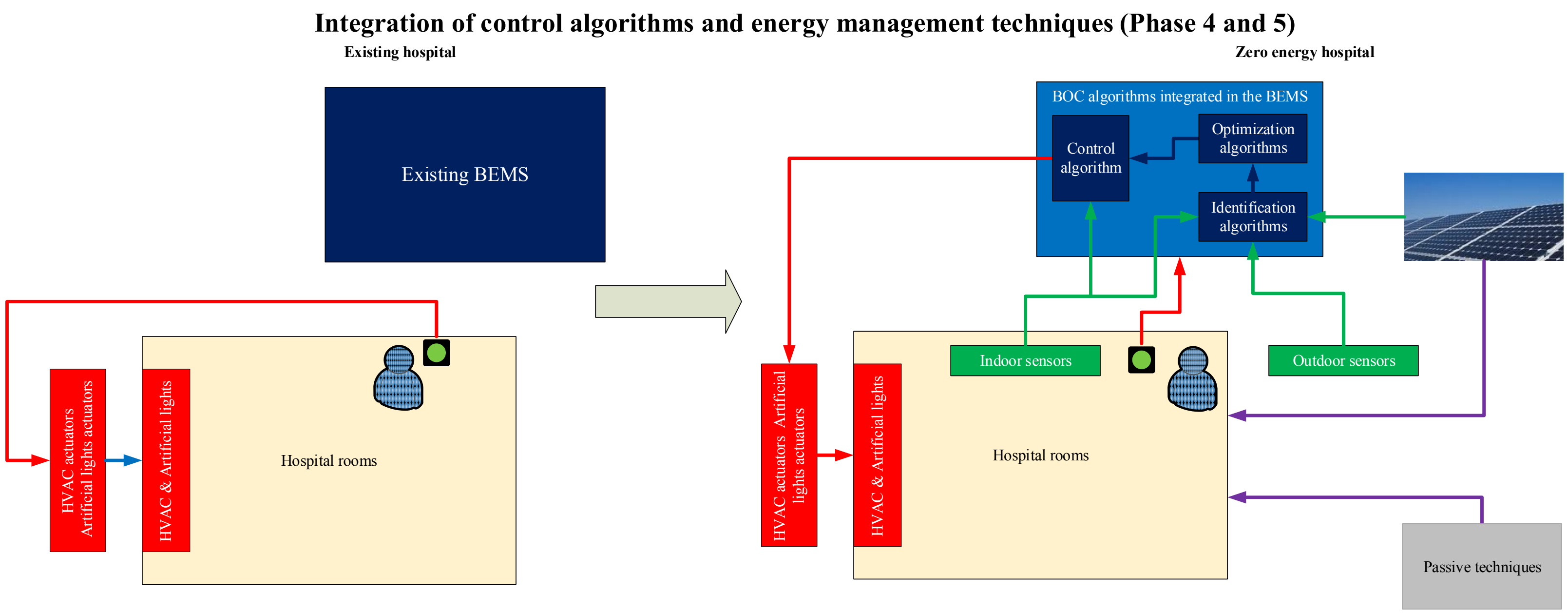


Figure 1- 4: From existing hospitals' rooms and their operations to zero energy hospitals

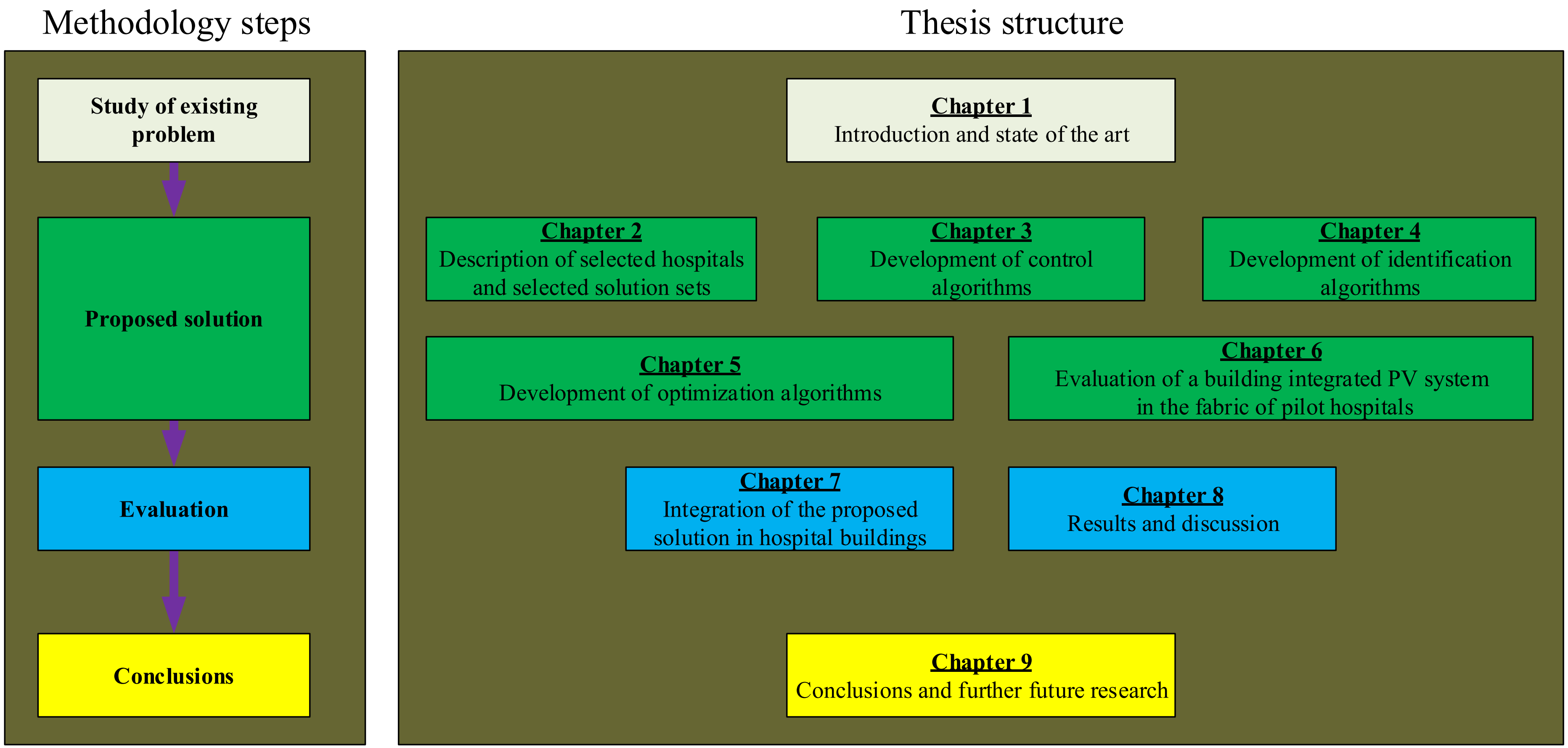


Figure 1- 5: Methodology followed for the research

In Chapter 2, the selected hospital buildings are described and the solution sets are presented. Moreover in Chapter 2 validated thermal and lighting models using dedicated software are presented. The models are used for the estimation of the annual energy consumption of the selected solution sets before the use of BOC algorithms.

Chapter 3 incorporates the developed closed loop control algorithms and their connection with the developed models of Chapter 2. The developed closed loop control algorithms are fine-tuned demonstrating their capabilities to adjust the operation of the selected systems (art. Lights & Air handling units) and the energy annual saving potential is estimated.

In Chapter 4, identification algorithms are developed for predicting indoor and outdoor conditions of selected areas. Artificial neural networks are trained and evaluated with acquired measurements to predict up to 8 hours the conditions of the HVAC systems.

In Chapter 5, optimization algorithms are established for selecting the operation of HVAC systems in advance. The optimization algorithms use the information provided by the artificial neural network of Chapter 4 and minimise the overall energy consumption of the HVAC systems during the next 8 hours, while safeguard the comfort of the occupants.

In Chapter 6, the potential energy efficiency from the integration of PV as shades in the hospital rooms are exploited in order to identify their energy contribution in the required energy of the hospital. Furthermore, the energy prediction of the PV can be estimated with the use of artificial neural networks and can be combined with the optimization algorithms shift load the energy demand.

In Chapter 7 the integration of the control algorithms and the optimization process in the field controllers is described presenting the required updates in the control algorithms in order to integrate them into the existing BEMS.

In Chapter 8 the results of the integration are analysed. The performance of the control algorithms is presented and the annual energy efficiency potential is calculated. Finally, in Chapter 9 conclusions and suggestions for further future research is presented.

--------------------------------------Chapter 2 ---

DESCRIPTION OF SELECTED HOSPITALS AND SELECTED SOLUTION SETS

2 Description of selected hospitals and selected solution sets

The aim of the present Chapter is to describe the selected hospitals and the audit procedure based on the methodology outlined in Figure 1- 5. Based on the audit procedure a set of energy efficiency solutions is defined. The solutions for each hospital are described in the following paragraphs. For each solution set, a simulation model is developed and validated using the measurements accumulated during the audit and monitoring period.

2.1 Description of the pilot hospitals and the related solution sets

2.1.1 Hospital of Ancona and the related solution sets

The first selected hospital (Azienda Ospedaliero Universitaria Ospedali Riuniti Umberto I, G.M. Lancisi , G. Salesi of Ancona) is a university hospital (Figure 2- 1). It was formed by the union of 3 hospitals. It is the biggest regional hospital and it belongs to the National Health Service In the hospital of Ancona, 3 areas are selected to improve their energy performance using control and optimization algorithms.

For the areas selected, energy audit has been performed collecting questionnaires and measurements related to the comfort level of patients and personnel. Compared to the typical energy audit procedures the attention was mainly focused on Building Management Systems and Automation. The main tool used for collecting information about building automation is the standard CEN UNI EN 15232:2012, “Energy performance of buildings – Impact of Building Automation, Controls and Building Management”. In parallel with the audit, questionnaires have been distributed at the selected areas to understand their opinion on the selected solution sets.

In total 20 people were interview. The answers vary from 0 (not satisfied) to 7 (fully satisfied). The results of the interview is tabulated in Table 2- 1.

Table 2- 1: Analysis of the collected questionnaires in Ancona hospital concerning artificial lights

Question	**Mean vote doctors**	**St. deviation doctors**	**Mean vote nurses**	**St. deviation nurses**
There is enough artificial light in the rooms	4.5	1.9	5.7	2.1

There is enough daylight in the rooms	3.1	2.5	3.5	2.1
Overall, how satisfied are you with the visual comfort of the lighting (e.g., glare, reflections, contrast)?	3.4	1.8	4.5	2.0
I am aware of the control capabilities of the system	2.8	1.5	3.8	1.8
I know how to adjust the system	2.4	1.7	4.2	1.8

From the open questions it has been identified that personnel and patients wanted to exploit more the available daylight.

In parallel energy measuring equipment has been installed to measure the energy consumption of these areas. Acquired measurements are used for the development of the baseline model.

Figure 2- 1: Aerial view of Ancona Hospital

The solution sets for improving the energy efficiency for the specific hospital are:

- Artificial lights
- Data centre

2.1.1.1 Artificial lights

This solution set is selected because the artificial lights consume significant amounts of energy (14 %) comparing to the total energy consumption of the hospitals as presented by Kolokotsa et al (Kolokotsa et al 2014) In the Oncology and Haematology departments (located on the 2^{nd} floor), the existing artificial lighting system used fluorescent artificial lights for the visual comfort of personnel and patients alike. The artificial lights were controlled by the users at will, contributing to the energy losses when the lights were left on during their absence or when daylight was sufficient. The selected solution set is to update the existing lighting structure with new ones using dimmable led fixtures as in the Dali protocol and implement advanced control algorithms to consider the indoor illuminance level and presence. The upgrade of the artificial lights combined with the development of the control algorithms reduces significantly the energy consumption.

In the Oncology department the selected rooms are presented in Figure 2- 2. The selected rooms are modelled using collected data (plants, art. Lights properties illuminance values etc.) from the performed audit. Table 2- 2 tabulates the names of the selected rooms and the required illuminance level that should be maintained based on EN 12464.1 2002: "European Standard for Interior Lighting".

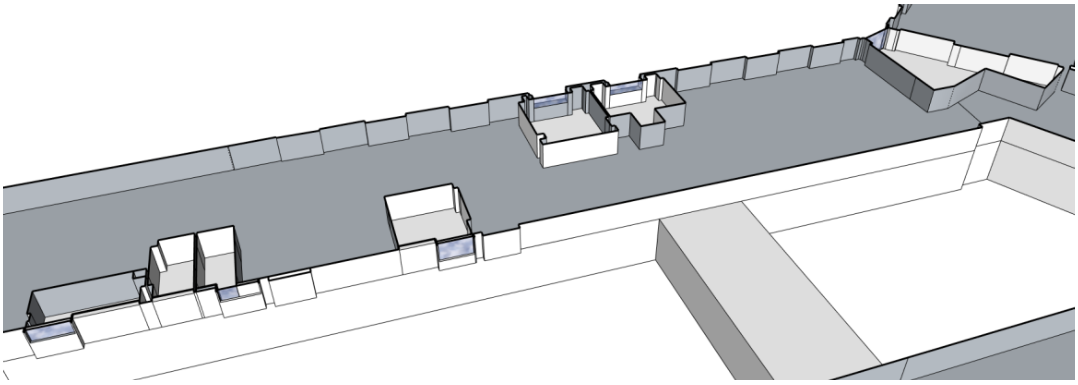


Figure 2- 2: Representation of the selected rooms of the oncology department

Table 2- 2: Names of the selected rooms and the required illuminance level (lux)

Selected room	Required illuminance level
Archives	200 lux
Nurses' room	500 lux
Doctors' room	500 lux
Patients' room	500 lux
Patients' wait room	500 lux
Visitors' wait room	500 lux

Similarly in the haematology department of the same hospital 3 rooms were selected for the application of the same improvement in the artificial lights and the implementation of control algorithms. The rooms of the haematology department are illustrated in Figure 2- 3.

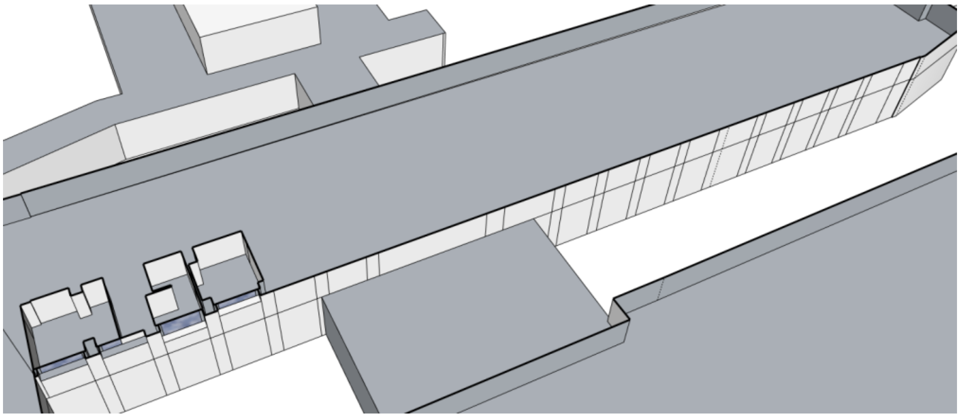


Figure 2- 3: Illustration of the selected rooms in the haematology department

Table 2- 3 tabulates the names of the selected rooms and the required illuminance level that should be maintained based on EN 12464.1 2002: "European Standard for Interior Lighting".

Table 2- 3: Names of the selected rooms and the required illuminance level (lux)

Selected room	Required illuminance level
Archives	200 lux
Nurses' room	500 lux
Doctors' room	500 lux

2.1.1.2 Data centre

Furthermore, the data centre of the Ancona hospital (Figure 2- 4) is selected as a solution set. The specific data centre is considered as a state of the art energy efficient data centre with a small PUE factor (PUE = 1.6). The selection is based on the possibility to further improve its energy performance through control and optimization of the HVAC system which provides cooled water on the internal system. This solution set has already integrated all the required sensors and actuators and the available measurements are store in databases since 2011.

The objective is to reduce the energy consumption due to non IT load by increasing the PUE value (Avelar et al., 2012). The cooling of the data centre is based only on the operation of the chillers. The proposed solution is to use the dry chillers when outdoor conditions allow the cooling of the system using outdoor air.

Figure 2- 4: Image of the data centre of Ancona

The cooling system of the data centre (Figure 2- 5) has two chillers which feed on cold water from the main manifold. A variable speed drive pump (with backup pump) guarantees correct water flow from the main manifold to the computer room air conditioning units. The chillers are water condensed; the condensing heat is then dissipated by two dry coolers for each chiller. The dry coolers can be used both as condensing unit and in free cooling configuration: when the external temperature is below a Set Point value, a bypass valve excludes the chillers in order to cool the water of the main manifold directly with the dry cooler switching off the chillers and avoiding the energy consumption due to the chillers compressors. In respect to the pumps, two twin pumps circulate water from each couple of dry coolers to the heat exchanger. VSD controlled twin pumps have been chosen to ensure the highest level of efficiency and reliability. Another pump controls the flow from the heat exchanger to the main manifold. Two more VSD controlled pumps (one working and the other uses as backup) guarantee the requested amount of water from the chillers to the main manifold and from the main manifold to the Computer Room Air Conditioning System, throughout 24 hours daily.

In respect to the valves, two three-way valves are used to switch from active cooling to free cooling mode. Four two-ways valves are used to enable the four dry coolers.

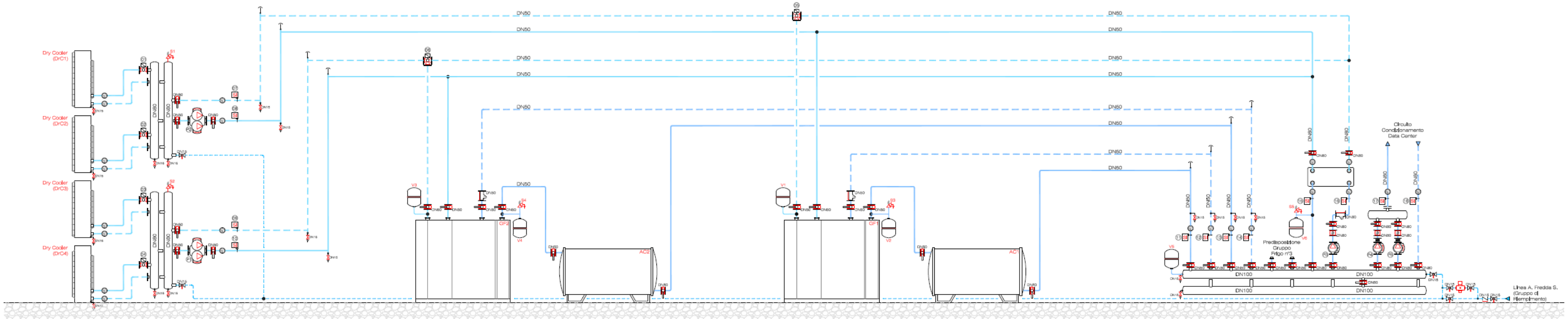


Figure 2- 5: Schematic diagram of Ancona Hospital data centre's cooling system

2.1.2 Hospital of Chania and the related solution sets

Chania Hospital (Figure 2- 6) is an active treatment hospital. The building was constructed during the period 1997-2000 and first operated in 2000. The total conditioned area is 50.992,54 m^2. The hospital operates on a 24/7 basis.

Figure 2- 6: View of SGH

For the areas selected, energy audit has been performed collecting questionnaires and measurements related to the comfort level of patients and personnel. Compared to the typical energy audit procedures the attention was mainly focused on Building Management Systems and Automation. The main tool used for collecting information about building automation is the standard CEN UNI EN 15232:2012, "Energy performance of buildings – Impact of Building Automation, Controls and Building Management". In parallel with the audit, questionnaires have distributed at the selected areas to understand their opinion on the selected solution sets.

In total 31 clinicians were interview. The answers vary from 0 (not satisfied) to 7 (fully satisfied). The results of the interview is tabulated in Table 2- 4 for artificial lights and in Table 2- 5 for HVAC systems.

Table 2- 4: Analysis of the collected questionnaires in Chania hospital concerning artificial lights

Question	Mean vote doctors	St. deviation doctors	Mean vote nurses	St. deviation nurses
There is enough artificial light in the rooms	5.7	1.5	5.1	2.1
There is enough daylight in the rooms	6.0	1.3	6.0	1.6
Overall, how satisfied are you with the visual comfort of the lighting (e.g., glare, reflections, contrast)?	4.8	1.6	5.2	1.7
I am aware of the control capabilities of the system	4.3	1.5	4.2	1.9
I know how to adjust the system	4.1	1.8	4.2	1.9

Table 2- 5: Analysis of the collected questionnaires in Chania hospital concerning HVAC

Question	Mean vote doctors	St. deviation doctors	Mean vote nurses	St. deviation nurses
General thermal comfort in your room	3.8	1.2	3.7	1.4
Overall, how satisfied are you with the temperature in your room?	5.1	1.6	4.1	1.0
How stable is the room temperature during the day?	4.0	1.9	3.6	1.7
Air humidity in your room	3.9	0.6	3.7	0.7
Air odour's in your room	4.8	1.5	4.6	1.8
Overall perception of air quality in your room	5.6	1.2	4.3	1.6
I am aware of the control capabilities of the system	4.6	1.4	3.7	1.5
I know how to adjust the system	2.6	1.5	2.3	1.5
Overall, I can sufficiently control the environmental conditions in the rooms	2.3	1.5	2.0	1.1

In parallel energy measuring equipment has been installed to measure the energy consumption of these areas. Acquired measurements are used for the development of the baseline model.

In the paediatric department of Saint George Hospital, 3 rooms were selected to improve the performance of the air handling units and the artificial lights. The rooms of the paediatric department are selected because the current department of Chania Hospital represents the typical construction in the hospital. Furthermore, the paediatric department is located above the HVAC room (2nd floor of the hospital) and the communication with the central BEMS is easier. The solution sets selected for the specific hospital are:

- The air handling units
- The artificial lights

Currently both systems are controlled by the users at will. The control algorithms will change the operation of the air handling units and the artificial lights based on indoor conditions and the optimization algorithms will estimate the set-point of the air handling units for the next 8 hours.

2.1.2.1 Air handling units

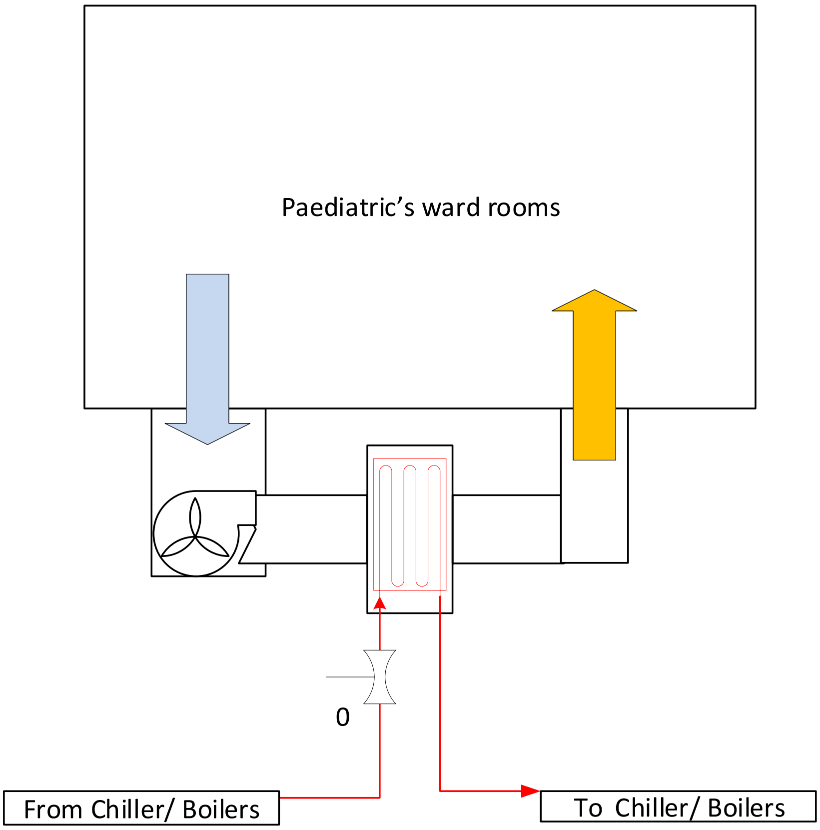


Figure 2- 7: Schematic of the air handling units of the paediatric department

The air handling units use the coolant fluid from the central heating/ cooling system of the hospital. A valve allows or prevents the fluid from entering the coil and a fan transfers the heat from the fluid to the air stream in heating mode, or absorbs heat in the cooling mode. In terms of the system set up and operation, a centralized air handling unit provides conditioned fresh air to the zones (all at the same conditions of temperature and relative humidity), while the main heating and cooling plant (which is not included in the model) provides either hot or cold water (depending on the season, it is a 2-pipe system) to the individual air handling unit located in each room. These individual AHU can adapt to the space conditioning requirements of the individual rooms.

The occupants currently use a rotating thermostat and can select the speed of the AHU. Furthermore, the user can switch the AHU on/ off.

2.1.2.2 Artificial lights

The artificial lights of the hospital of Chania are used based on the users' requirements. On/off switches change the operation of the artificial lights. As mentioned before, 3 rooms are selected in the paediatric department. In all the selected rooms, 2 light fixtures operate based on different circuits and they are connected to central power line and the generator line respectively. For the specific solution set the operation of the artificial lights will be based on readings from an illuminance and a presence sensor located in each room.

2.2 Development of thermal/ lighting models for preliminary evaluation of the control algorithms and fine-tuning of control algorithms

The evaluation of the energy performance of the selected solution sets and the energy efficiency potential requires the development of simulation models for each solution set. Therefore the models developed are:

- Thermal models using TRNSYS 17 software with the integrated TESS libraries.
- Lighting models using the Radiance software and artificial lights technical information from Relux suite.

2.2.1 Description of the models and tools for the simulation procedure

The overall methodology followed for the development of the thermal and lighting models is illustrated in Figure 2- 8.

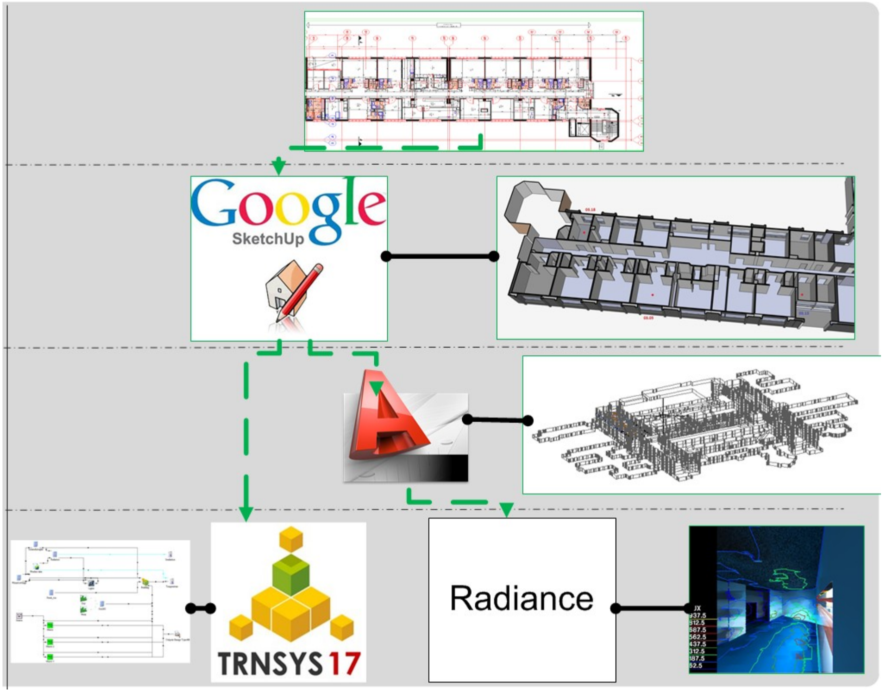


Figure 2- 8: Visual representation of methodology for developing lighting and thermal models

The plans (floor plans, views & sections) are collected in electronic or paper form and are imported to a geometry developed software (Google SketchUp v8). In Google SketchUp, the 3D geometry of the buildings is developed. For the thermal models, the trnsys3d plugin is used for properly exporting the geometry properties in TRNSYS v17. For the lighting models, the geometry is exported in *Drawing eXchange Format (dxf)* format and the exported file is translated into radiance geometry using dxf2rad tool (http://www.schorsch.com/en/download/dxf2rad/). The development of the lighting models for the hospitals of Ancona and Chania is described in Chapter 2.2.2, while the thermal models development is described in Chapter 2.2.3. The tools used are described in the following sections.

2.2.1.1 TRNSYS software

TRNSYS software has been developed 35 years ago, currently on its 17th version, it is used to run thermodynamic equations. It solves the differential equations of mass and energy for each time step which may vary from 1 s to 1 h. TRNSYS software contains sets of equations from specific components of HVAC, RES, Storage and other systems organized in individual files named as types. For further analysis, more types are available from the TESS libraries which contain information for modelling almost every mechanical and electrical system. Extra types are available for specific simulations such as swimming pools, ice storage and air handling units modeled as one component. Moreover TRNSYS provides types for the control of the electromechanical equipment. Types for PID control are available and on/off actuators are implemented. Apart from the available types for control, TRNSYS provides connection with other software for applying control techniques.

Type 56 is used for the simulation of buildings fabric and the energy required to maintain certain indoor conditions. Type 56 considers each room/zone (Figure 2- 9) as one air node which exchanges energy with the environment and the internal gains from the occupants and their equipment.

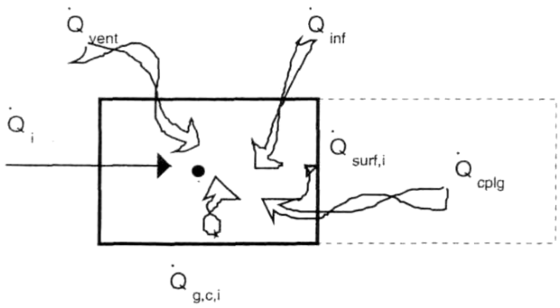


Figure 2- 9: Energy flow of a specific zone in Type 56

Type 56 can be connected with the other types of TRNSYS software and thus estimate the energy provided to the fabric. The main equation that describe the operation of type 56 is:

$$\dot{Q}_i = \dot{Q}_{surf,i} + \dot{Q}_{inf,i} + \dot{Q}_{vent,i} + \dot{Q}_{g,c,i} + \dot{Q}_{cplg,i}$$

Where:

$\dot{Q}_{surf,i}$= convective heat flow from all inside surfaces

$$\dot{Q}_{surf,i} = U_{w,i} \cdot A_{w,\cdot i} \cdot (T_{wall,i} - T_{air})$$

$\dot{Q}_{inf,i}$= infiltration gains (airflow from outside only)

$$Q_{inf,i} = \dot{V} \cdot \rho \cdot C_p \cdot (T_{outside} - T_{air})$$

$\dot{Q}_{vent,i}$= ventilation gains (air flow from a user defined source, like HVAC system)

$$\dot{Q}_{vent,i} = V \cdot \rho \cdot c_{p\cdot} \cdot (\dot{T}_{ventilation,i} - T_{air})$$

$\dot{Q}_{g,c,i}$= internal convective gains (by people, equipment, illumination, radiators, etc.)

$\dot{Q}_{cplg,i}$ = Gains due to (connective) air flow from zone I to boundary condition

$$\dot{Q}_{cplg,i} = V \cdot \rho \cdot c_p \cdot (\dot{T}_{zone,i} - T_{air})$$

Type 753 represents the operation of the fan coil system used in the hospital of Chania. The schematic of the type is illustrated in Figure 2- 10.

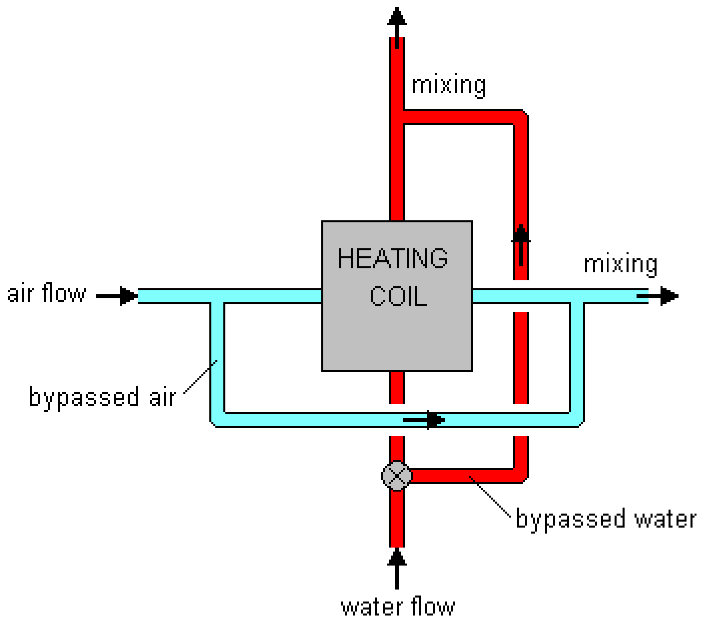


Figure 2- 10: Schematic diagram of Heating/ Cooling coil used in the hospital of Chania simulation model.

The energy transfer from the fluid to the airstream is estimated by the following equation:

$$Q_{fluid} = \dot{m}_{air} \cdot (1 - f_{AirBypass}) \cdot (h_{air,CoilOut} - h_{air,in})$$

m_{air} : Total flow rate of air through the coil (includes bypassed air). [kg/h]

$f_{AirBypass}$: Fraction of air bypassed around the coil (user defined) [0…1]

$h_{air,CoilOut}$: Enthalpy of air exiting the coil before mixing [kJ/kg]

$h_{air,in}$: Enthalpy of air entering the coil [kJ/kg]

Type 666 is used for the simulation of the main chiller of the data centre of Ancona's Hospital. The schematic diagram of type 666 is illustrated in Figure 2- 11

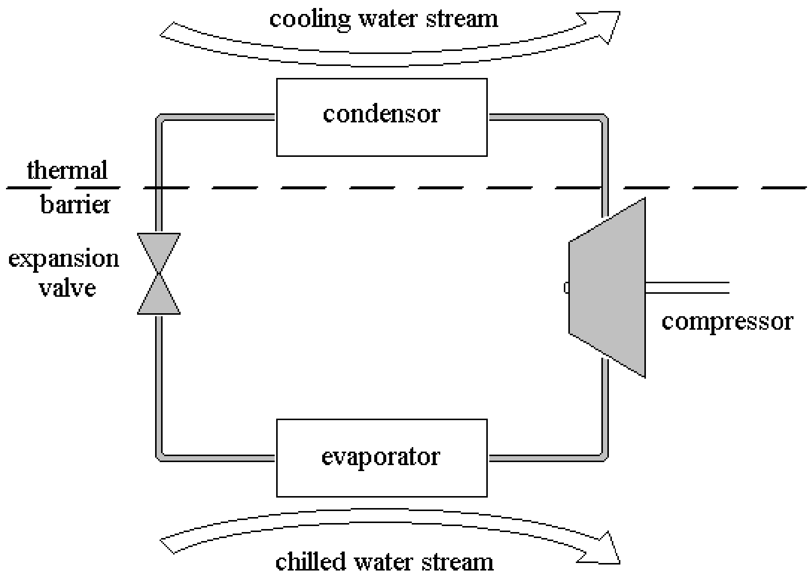


Figure 2- 11: Schematic diagram of a single stage water cooled chiller

The equation which describes the load of the chiller every time-step is

$$Q_{load} = \dot{m}_{chw} \cdot cp_{chw} \cdot \left(T_{chw,in} - T_{chw,set}\right)$$

m_{chw}: Flow rate of fluid entering the chilled fluid stream [kg/h]

cp_{chw}: Specific heat of fluid entering the cooling fluid stream. [kJ/kg·K]

$T_{chw,in}$: Temperature of fluid entering the chilled fluid stream [C]

$T_{chw,out}$: Temperature of fluid exiting the chilled fluid stream [C]

Type 155 is used for exchanging data with Matlab tool during the simulation. Matlab receives the input data makes the necessary calculations and sends the result back to TRNSYS. Data exchange is performed in 2 ways. At first Matlab code can be considered by TRNSYS as a component (type) which needs to exchange information continuously until the TRNSYS model converts into the solution for this time-step. In the second mode Matlab act as a controller which waits for the model to converge and after this point it reads the current state and sends the new command. Thus Matlab works as a field controller would work during the integration.

2.2.1.2 Radiance software

Radiance software is a collection of programs that can do from object modelling to point calculation, rendering, image processing, and display. It uses a hybrid approach of Monte Carlo (stochastic) and deterministic ray tracing techniques to simulate the direct, specular indirect and diffuse indirect illumination components of daylighting. (Shakespeare 2003)The software was created by Greg Ward Larson and was presented in the Siggraph conference in 1994. (Ward 1994) The program takes a scene description with light sources, sun, sky, buildings, rooms, furniture, etc. and produces spectral radiance values which can be collected in a "photo accurate" colour image. (Larson 1991).

When the simulation starts, the software calculates the light reaction between the materials by reading the geometry and the material properties of each surface. By this way it creates an internal database with which for each ray that falls on a surface the surrounding cell's illuminance levels are estimated too. After finishing with the creation of database, the software works for each view to create the image that is desired. Since Radiance is a backwards ray – tracing software, the rays start from the view point towards the direction that is predefined in the view file. When the ray hits a surface that is not a light source, it bounces depending on the characteristics of the material. If the material is purely specular like a mirror for example, the reflection angle is the same with the incident. In the case that the material is not specular, the variety of angles of the reflection is estimated from the characteristics of the material and the specific ones are chosen by the Monte-Carlo approach. The same procedure continues until it reaches a light source or until its bounces exceed the maximum amount of bounds that are set by the user. If it doesn't hit a source the light level of the specific pixel is considered as zero. If it hits a light source during the path that is described above, then the specific pixel reads the value of the light source taking into consideration the reductions due to reflection in every surface from the view point till the light source. The same procedure is repeated for all the pixels of the image that is demanded. The larger the image the larger the amount of pixels required.

2.2.2 Development of the lighting models for the pilot hospitals

The development of Radiance models and the estimation of illuminance level in specific points or the production of photorealistic images requires a specific process of commands which:

- Create the sky dome for the specific time period
- Combing the materials and geometry
- Estimate the illuminance level in selected points
- Produce photorealistic images

The process using the commands of Radiance software is illustrated in Figure 2-12.

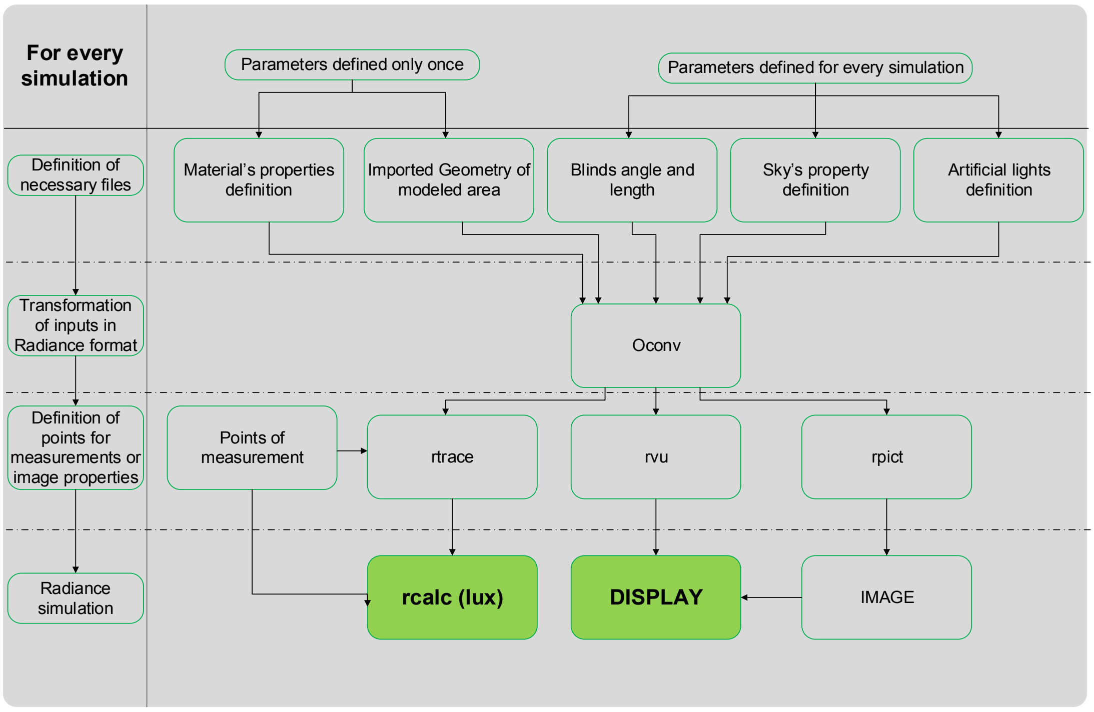


Figure 2- 12: Execution of Radiance commands for estimating indoor illuminance and producing photo-realistic images

Since the fuzzy control algorithm is developed using Matlab and the rooms light simulation is performed using Radiance, an interconnection between MATLAB and Radiance was considered necessary. Radiance software (version 4 in Windows OS), is a joint of several sub-programs running in DOS environment. Matlab tool call each sub-program separately using 'dos' built in function. The sub-programs required to simulate the illuminance level in a point using Radiance software are illustrated in Figure 2- 12.

Simulation of illuminance level in a specific point using Radiance Software is performed calling 'rtrace' sub-program. 'rtrace' command requires a specific type of file which is produced using 'oconv' command. Geometry of a room, materials, and sky properties are converted in a format that Radiance software uses to estimate illuminance level or develop photorealistic images. Outdoor illuminance is simulated using ‘gandaylit’ or ‘gensky’ sub-program.

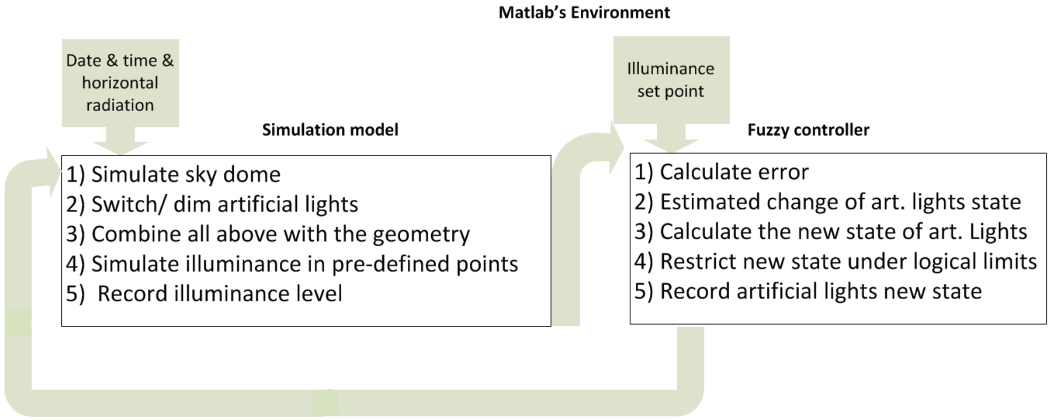


Figure 2- 13: Direct communication between Matlab environment (Fuzzy control algorithm) and Simulation model (Radiance)

The state of the lights is also saved in order to estimate the consumption and savings for the simulation period. The output of the Matlab script is the illuminance level in the pre-selected points of the model. The connection between Matlab and software Radiance can be seen in Figure 2- 13.

2.2.2.1 Lighting model for the hospital of Chania

Prior to the presentation of the developed model and the simulation results for the lighting model of the hospital of Chania it is necessary to present some photographs from the simulations areas to inform the reader. In the top left of Figure 2- 14 an image from Google Earth is used to present a birds-eye view of the hospital, while on the other 3 images of Figure 2- 14 a south-east view of the hospital as designed in Sketch Up is presented showing the detailed simulation in the paediatric department. Finally in the bottom right the selected rooms for testing the solution sets are indicated with red dots.

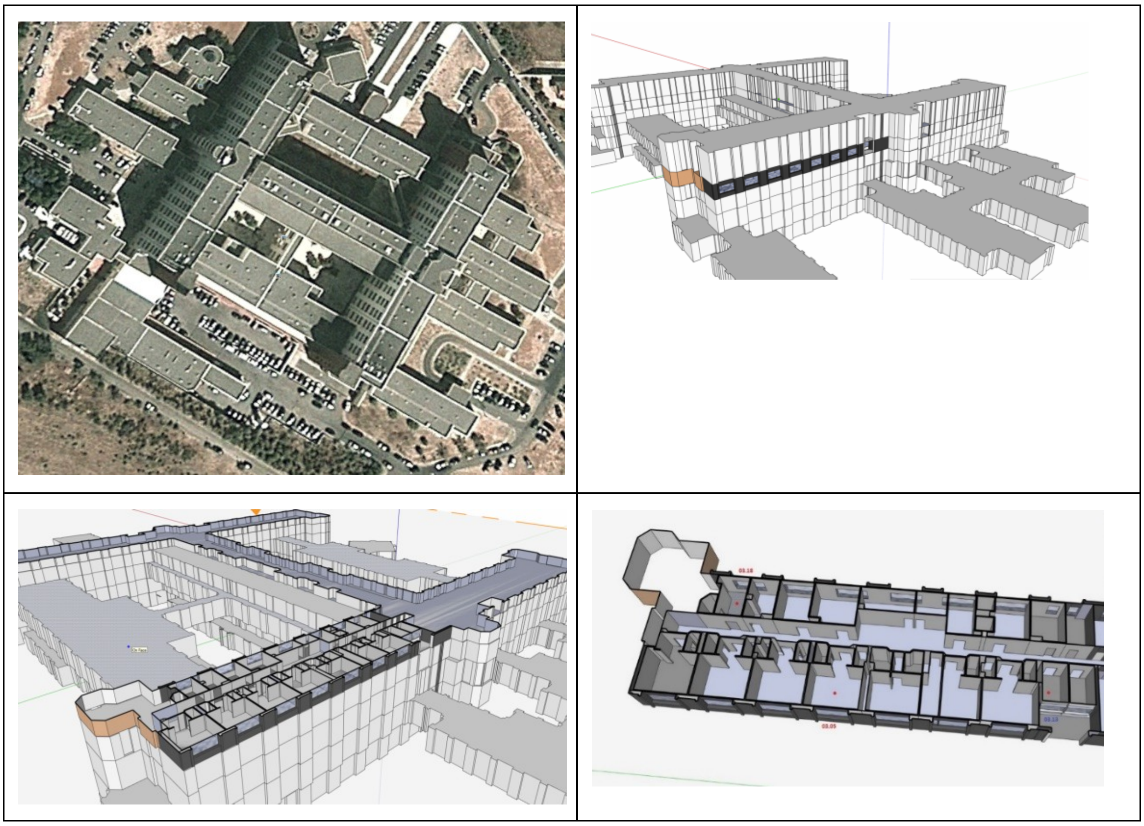


Figure 2- 14: South-East view of Chania Hospital designed in Sketch Up & showing internal walls of paediatric department

Photographs of the specific rooms are presented below. Specifically in Figure 2- 15 the viewer is shown the internal area of the doctors' office as well as the external area.

Figure 2- 15: Internal and outside view outside of the doctor's office in Chania Hospital paediatric department

Some parameters related to the materials lighting properties should be set. These materials' parameters are presented in Table 2- 6.

Table 2- 6: Material's light properties Hospital of Chania

Building's materials name	**Material name**	**Material type**	**Colour properties**		
			Red	**Green**	**Blue**

External walls	“l_external_walls”	Plastic	0.1	0.1	0.1
Internal walls	“l_internal_walls”	Plastic	0.56	0.56	0.57
Internal floor	“l_floor”	Plastic	0	0.32	0.53
Internal doors	“l_doors”	Plastic	0.1	0.5	0.9
Ceiling of the rooms	“l_roof”	Plastic	0.16	0.17	0.18
Windows of the rooms	“l_windows”	Glass	0.8	0.8	0.8
Rest of the hospital’s area	“l_sketchup”	Plastic	0.1	0.1	0.1

In each room, 2 light fixtures are used consuming 36 Watt each. The type of each fixture is: LUMILUX DUO EL-F/R 2x36W. The light distribution of the light fixtures will be used for estimating the combined illuminance level in the rooms (Daylight and artificial).

In order to acquire results from the lighting model a weather file in Energy Plus format (epw) was selected to provide the necessary input concerning the outside conditions. Since annual measurements are not available on-site yet, the pre-mentioned weather file contains annual climatic data representative of the conditions in each area. From the weather file the information used for simulation can be seen in Table 2- 7. It should be noted that the first 9 rows of the sheet are not necessary.

Table 2- 7: Parameters collected from weather file (Soudhour.epw)

Parameter used	Column
Month	2
Day	3
Hour	4
Direct Normal Radiation	13
Diffuse Horizontal Radiation	14

Radiance can produce photorealistic images for every simulation step presenting the light (Daylight and artificial) distribution in the area of interest. It is very difficult to present images for the 3 selected rooms for every hour of simulation. For this reason was selected to present 4 images from the 1st day of the year showing how the illuminance levels vary with time (Figure 2- 16).

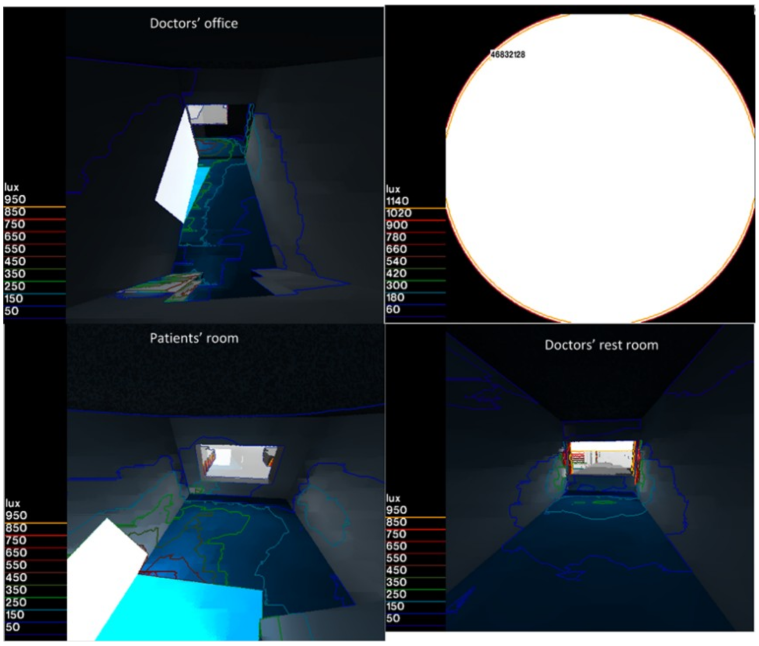


Figure 2- 16: Photorealistic simulation images of the doctors' office showing the illuminance level

2.2.2.2 Lighting model for the hospital of Ancona

An aerial view of the hospital of Ancona can be seen in Figure 2- 17. In order to have proper results in the lighting simulation it is selected to make a good representation of the external geometry of the hospital which shades the areas selected to test the efficiency of the solution sets. A screen-shot of the external geometry of the hospital as it was designed with Google Sketch Up software can be seen in the same figure. The hospital's model is properly oriented according to the sign of North as it was found in the digital drawings handed over the hospital of Ancona.

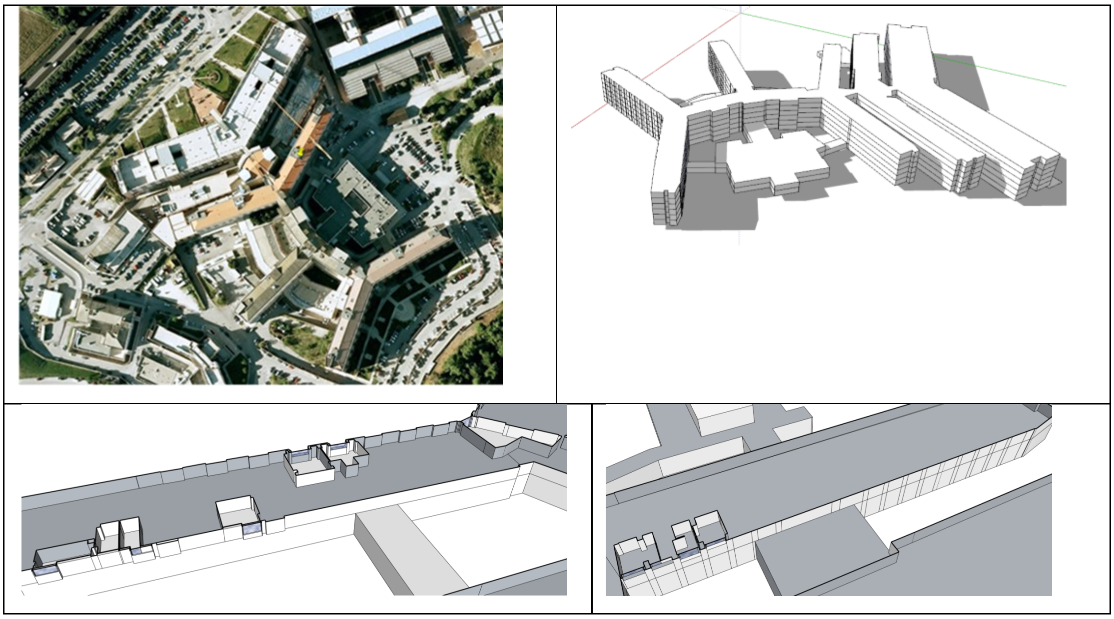


Figure 2- 17: Photograph of Ancona's hospital from Google Earth and View of Ancona's hospital as designed in Google Sketch-Up

Photographs of the rooms of the oncology department can be seen in Figure 2- 18.

Figure 2- 18: Photographs from the oncology department of the Ancona's hospital

The geometry is based on electronic plans and some on site measurements of the rooms. Moreover, external movable shades should be designed but it is possible design directly in the software Radiance in order to benefit from the script commands which allow the programmer to change the angle and the length of the shades without affecting the rest of the geometry, thus reduce the complexity of the model definition procedure.

Some parameters related to the materials' lighting properties should be set. These materials' parameters are presented in Table 2- 8.

Table 2- 8: Material's light properties Hospital of Ancona

Building's materials	**Material name**	**Material type**	**Colour properties**		
			Red	**Green**	**Blue**
Building's floor	1_floor	Plastic	0.281	0.266	0.176
Building's ceiling	1_ceiling	Plastic	0.726	0.706	0.633
Building's internal walls	1_internal_ walls	Plastic	0.726	0.706	0.633
Building's external walls	1_0	Plastic	0.51	0.473	0.412
Building's windows	1_windows	Glass	0.76	0.76	0.76

Artificial lights located in the selected rooms provide necessary lighting when natural daylight is not sufficient and during the night. In the selected rooms of the hospital of Ancona 4 different types of light fixtures are available. According to information available on the electronic plans, 4 different types of artificial lights are available in the rooms. The artificial lights are described based on their wattage in Table 2- 9.

Table 2- 9: Description of Artificial lights and selected lights for modelling

		Luminaire selected for modelling	
Watts per lamp	**N. of lamps**	**Company**	**Type**
18	2	OSRAM	72088 LUMILUX
18	3	OSRAM	Siteco louvre L 3X18W
18	4	OSRAM	DIADEM 4x18 W
36	1	OSRAM	OSRAM ECOPACK DIM 36W

Radiance can produce photorealistic images for every simulation step presenting how light (Daylight and artificial) is distributed in the area of interest. It is very difficult to present images for the selected rooms for every hour of simulation. For this reason it was decided to present 4 images from the 1st day of the year showing how the illuminance levels vary with time. The archives in the Oncology department rooms is selected to present the illuminance levels:

1) During the night with the lights on (02:00)
2) During the day with the lights off (10:00)
3) During the day with the lights off and the external shades deployed (14:00)
4) During the afternoon with the lights on (16:00).

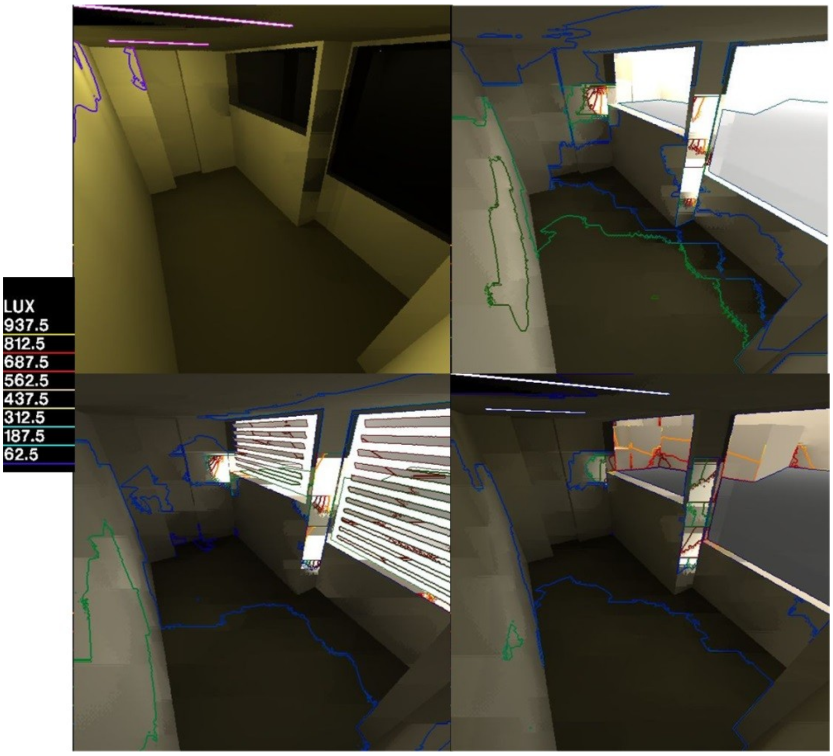


Figure 2- 19: Images from the archives in the Oncology department

2.2.3 Development of the thermal models for the pilot hospitals

The thermal models are developed using TRNSYS software. TRNSYS software estimates the transfer of energy between components (types) and calculates parameters related to the energy consumption of several HVAC systems. Furthermore, TRNSYS contains a specific type for modelling buildings (type 56) which is used for the definition of the geometry and the energy transfer through the fabric. Moreover, type 56, considers the internal gains such as, artificial lights, electronic equipment and occupancy. Using type 56, internal conditions of buildings (ex. temperature, humidity) are calculated.

For the definition of the geometry required by type 56, the available plans provided by the hospitals are used to create the 3D geometry using Google Sketch Up and the plug in (TRNSYS 3D) for exporting the geometry directly to TRNSYS software.

The HVAC equipment provides the thermal comfort required in the rooms and consumes energy (electric, oil or natural gas). Using the proper types of TRNSYS and information collected from the hospitals' equipment, the energy transfer from the modelled HVAC equipment is calculated correctly.

2.2.3.1 Air Handling Unit of Chania Hospital

The geometry of the building component for the AHU model of the hospital of Chania was developed as a simplification of the detailed Sketch Up geometry shown in 2.2.2. As shown in Figure 2- 20, the model includes only the selected areas and the relevant shading elements (i.e., other parts of Chania Hospital building that could provide shading to the selected areas).

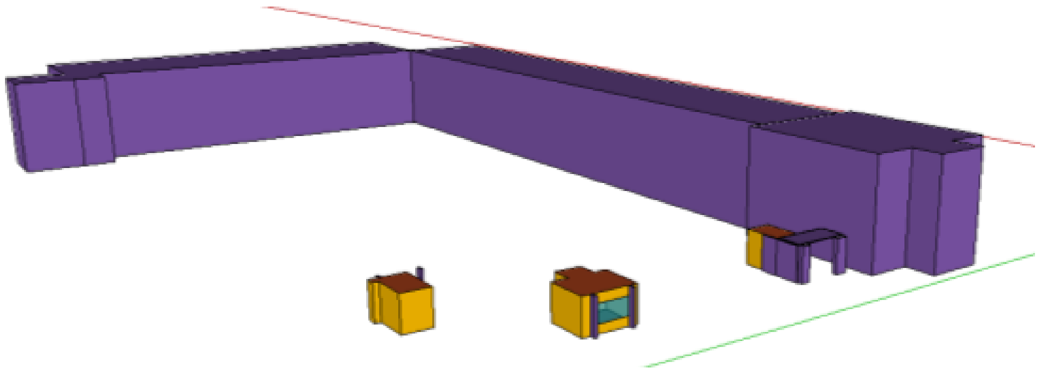


Figure 2- 20: Geometry of the simplified building model in Chania Hospital. Only the selected areas and the relevant shading elements were included in the model

The TRNSYS model includes:

- The building (selected areas), with the corresponding internal gains and heat transfer through walls and windows.
- The ventilation airflow (which would be provided by a centralized AHU).
- The individual AHU in the rooms.

Control of the system as aforementioned is manual. The controlled variables are the temperature set-point and the fan speed. Control of the fan is not continuous, but has 3 discrete steps. Users can independently adjust the temperature set-point and the fan speed at will.

Figure 2- 21 show screenshots of the TRNSYS model (Simulation Studio) corresponding to the ventilation and space conditioning systems for the selected spaces in the Hospital of Chania.

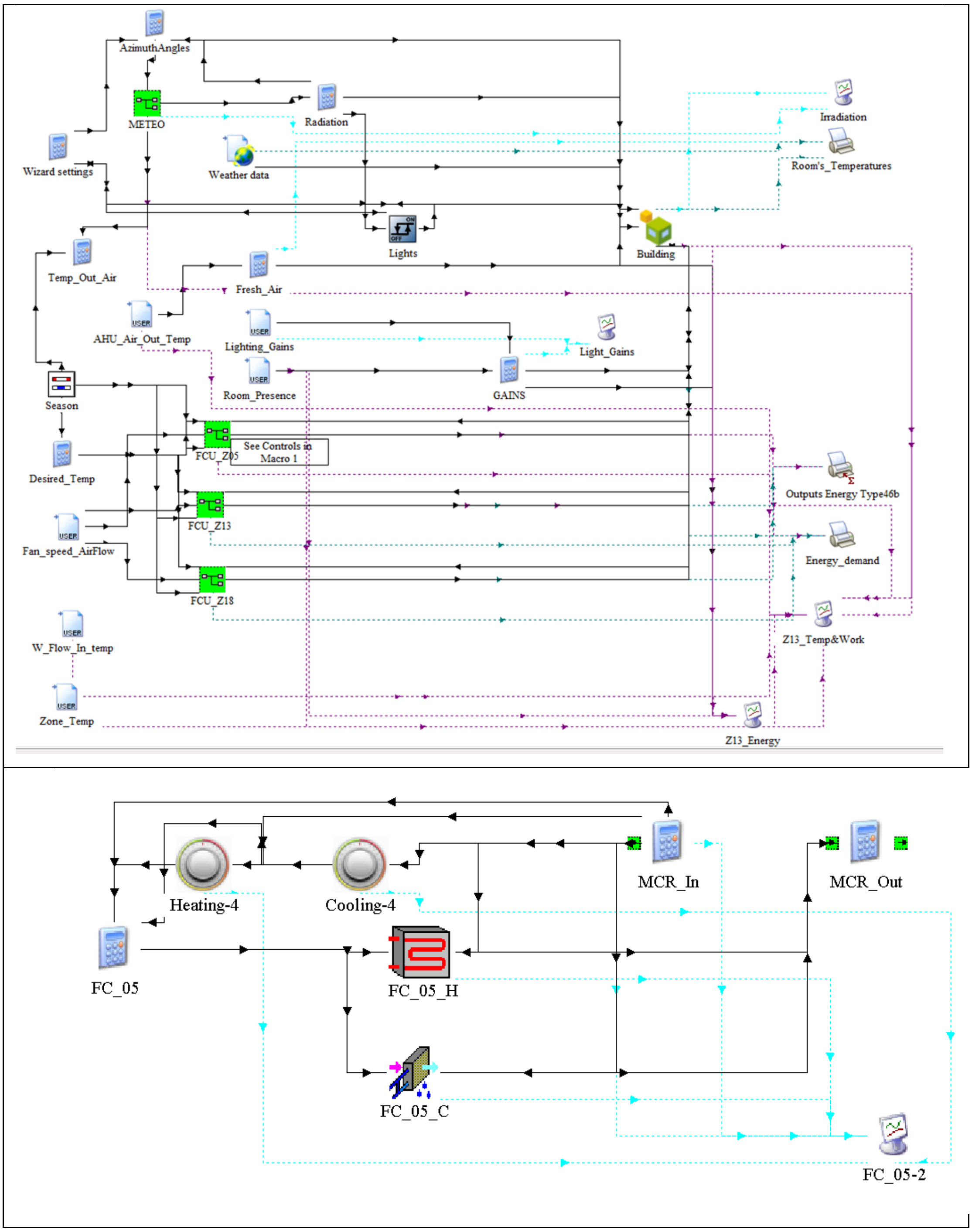


Figure 2- 21: Thermal model of Chania Hospital air handling unit developed in simulation studio (TRNSYS V17)

The AHU control logic implemented in the model is the following:

- Fans run according to a schedule (which is a user input).
- Heating and cooling coil valves open only when it is the right season and the individual room needs conditioning (assessed comparing room temperature vs. set-point).

- Therefore, there is heat transfer (from water to air) to the AHU only when the valves are open and the fans are ON.

The model outputs include:

- Heating and cooling energy use in the individual AHU.
- Temperature and relative humidity in the selected areas.

The weather file is the only external file used in the model. This was obtained from the Meteonorm database ("Software Meteonorm," 2012).

The internal gains in the selected areas (when occupied) were calculated according to the values in Table 2- 10.

Table 2- 10: Internal gains – Assumed values in the selected areas of Hospital of Chania

	Z05	**Z13**	**Z18**
Number of occupants	4	2	1
Occupants gains	W	W	W
Sensible Total	270	135	135
Sensible Convection	176	88	88
Sensible Radiation	95	47	47
Latent	285	142.5	142.5
mw (kg/h)	0.45	0.23	0.23
Equipment gains	W	W	W
Sensible Convection			
Sensible Radiation	100	100	100
Latent			
mw (kg/h)			
TOTAL gains			
Sensible Convection	176	88	88
Sensible Radiation	195	147	147
Latent	285	143	143
mw (kg/h)	0.45	0.23	0.23

2.2.3.2 <u>Data centre Ancona</u>

The data centre in the Hospital of Ancona is a $23m^2$ space that currently houses about 30 kW of IT load. The IT equipment is laid out in the space to allow hot and cold compartments, and is cooled through in row air distribution units. Temperature distribution profiles within the data centre are complex and beyond the scope of this model. Since the focus of the present model is the control of the water side cooling system (i.e., the plant components used to cool off the cooling air rather than the air distribution system itself), a simplified model of the data centre space sufficed for the purposes of the project. Figure 2- 22 shows the basic geometry of the data centre space as modelled.

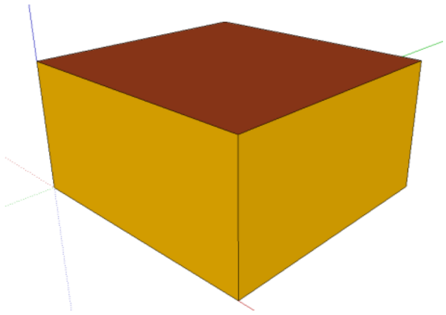


Figure 2- 22: Geometry of the Data Centre room in Ancona Hospital

Figure 2- 23 shows a screenshot of the TRNSYS model.

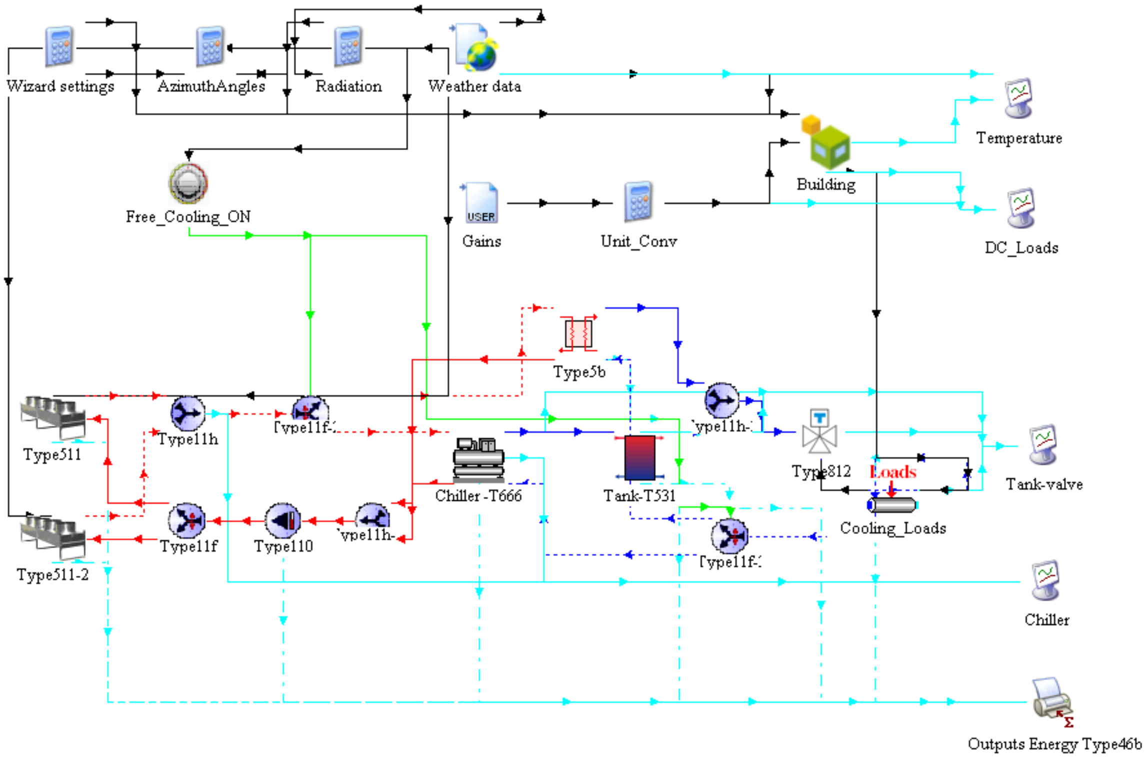


Figure 2- 23: Hospital of Ancona – Data Centre model. TRNSYS Simulation Studio project

The model outputs include:

- Cooling loads of the data centre room.
- Instantaneous real cooling provided by the system – which can be compared vs. instantaneous cooling loads to provide a proxy of "thermal comfort" within the room (load met).

- Energy (electricity) use for cooling: chillers, dry coolers, circulation pumps

The external files used in the model are:

- The weather file, which was obtained from the Meteonorm ("Software Meteonorm," 2012) database.
- The "IT load", which is a table with hourly values of active power used by the IT equipment in the data centre. This file was obtained from actual (real) records in Ancona Hospital. Note that IT is the sole internal gain in the data centre.
- Chiller performance curves: "chiller performance data" (capacity ratio and COP as a function of outlet chilled water temperature and inlet cooling water temperature) and "chiller part load performance data" (fraction of full load power as a function of part load ratio). These files were edited according to the information in the chiller datasheet.

2.3 Monitoring procedure and models' validation

For the validation of the developed models, installation of monitoring equipment is required to collect measurements to compare them with the outputs of the developed models. Furthermore, the installed equipment will be used for collecting data. The collected data from the installed equipment is used as input in the developed models to evaluate their performance.

For the lighting models developed in Radiance software, the evaluation is based on the comparison between measured and simulated indoor illuminance level (lux), under the same external conditions. For the thermal models, their performance will be evaluated comparing measured and simulated indoor air temperature of the rooms.

2.3.1 Installation of monitoring equipment for the validation of the developed models

For the validation of the thermal and lighting models measuring equipment is used to collect data which will be compared to the output of the thermal models. For the data centre of Ancona, all the required monitoring equipment for the operation of the data centre has been installed since 2011 and measurements collected and stored in a SQL databases.

For the validation of the lighting model for the hospital of Ancona, a monitoring equipment was developed and used to collect data from every room. The monitoring equipment for the artificial lights has:

- a light sensor
- an energy meter
- a presence sensor
- a switch recorder

The monitoring equipment is transferred every week to a new room and the data collected and stored in an internal database. The data is then used for the evaluation of the lighting model. The monitoring period for each room is tabulated in Table 2- 11.

Table 2- 11: Monitoring period for each room in the hospital of Ancona

Ward/ Department	Room	Monitoring start date (MDY)	Monitoring end date (MDY)
Haematology	Warehouse	01/18/2013	01/25/2013
	Nurse office	01/25/2013	02/01/2013
	Doctors office	02/01/2013	02/08/2013
Oncology	Visitors waiting room	02/08/2013	02/15/2013
	Nurse office and corridor	02/15/2013	02/22/2013
	Archives (2 rooms)	02/22/2013	03/01/2013
	Ambulatory	03/01/2013	03/08/2013
	Patients waiting room	03/08/2013	03/15/2013
	Day hospital room	03/15/2013	03/22/2013

For the selected rooms in the paediatric department equipment was installed for monitoring the internal conditions within these rooms. Furthermore, the energy consumption of the artificial lights and the AHU was measured using power and thermal meters. The equipment used towards the measurement of the artificial lights consumption and the illuminance level, is described in Table 2- 12

Table 2- 12: Monitoring equipment used for the artificial lights solution set in Chania Hospital

Equipment	Parameter
Thermokolon - MDS Standard1	Illuminance level Occupancy indication
FX07 – Field controller	Art. Lights actuator
Kamstrup 382 Generation L	Energy meter

The collected data is stored in the local BMS of the hospitals' infrastructure and an ftp server.

For the solution set, related to the AHU operation the equipment used is presented in Table 2- 13

Table 2- 13: Equipment installed in the selected rooms in Chania Hospital for the AHUs' solution set

Equipment	Description
Energy Meter	Kamstrup 382 Generation L
Thermal Meter	Kamstrup MULTICAL 602
Internet server	Ilon server
Controller	FX07 Terminal Unit Field Controller
Nose sensor	EE80-2CTF3
Presence/Light sensor	Thermokolon MDS
Window contacts	Magnetic contacts

2.3.2 Validation of models (thermal and lighting) with measurements

In the patients rooms, of the Paediatric department at Chania Hospital, indoor illuminance measurements are compared to the simulation output of the Radiance software under similar external conditions, in order to validate the performance of developed lighting model. The parameters of the comparison are tabulated in Table 2-14.

Table 2- 14: Parameters for the validation process of Chania Hospital for the lighting solution set

Parameters	Values
Period of simulation	29^{th} May 2013 – 31^{st} May 2013
Outdoor Radiation source	Technical University of Crete meteorological station ((Simeonidis, 2012))
Blinds (indoor or outdoor)	Not available
Artificial light's type source	Relux Pro database (IES format)
Artificial lights operating indication	Power demand of artificial lights
Light sensor position information	Position is indicated in the plans of the rooms
Time-step of simulation	15 minutes

The visual comparison (Figure 2- 24) between measured and simulated values indicates the correct performance of the developed Radiance model. Furthermore, the statistical comparison (R^2: 0.9025) verifies its proper performance.

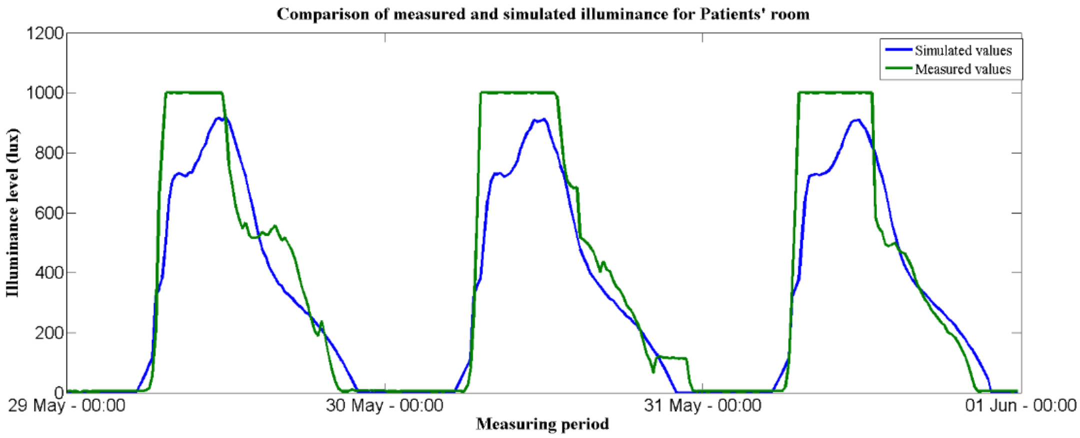


Figure 2- 24: Comparison of measured and simulated illuminance level under the same external conditions

Similarly for the hospital of Ancona, the output of the lighting model is compared to the measured values of the illuminance level under the same external conditions for the Nurses room in the Haematology department. The properties of the comparison are tabulated in Table 2- 15.

Table 2- 15: Parameters for the validation process of Ancona Hospital for the lighting solution set

Parameters	Values
Period of simulation	18th Jan 2013 – 22nd March 2013
Outdoor Radiation source	Loccioni Group premises
Blinds (indoor or outdoor)	Information available from photos
Artificial light's type source	Relux Pro database (IES format)
Artificial lights operating indication	Indication is stored during the measurement
Light sensor position information	Position is estimated from floor-plans
Time-step of simulation	15 minutes

The results (Figure 2- 25) illustrate that the model accurately predicts indoor illuminance level. Using statistical tools the R-square value is calculated at 0.833 and the RMSE at 124.8 lux.

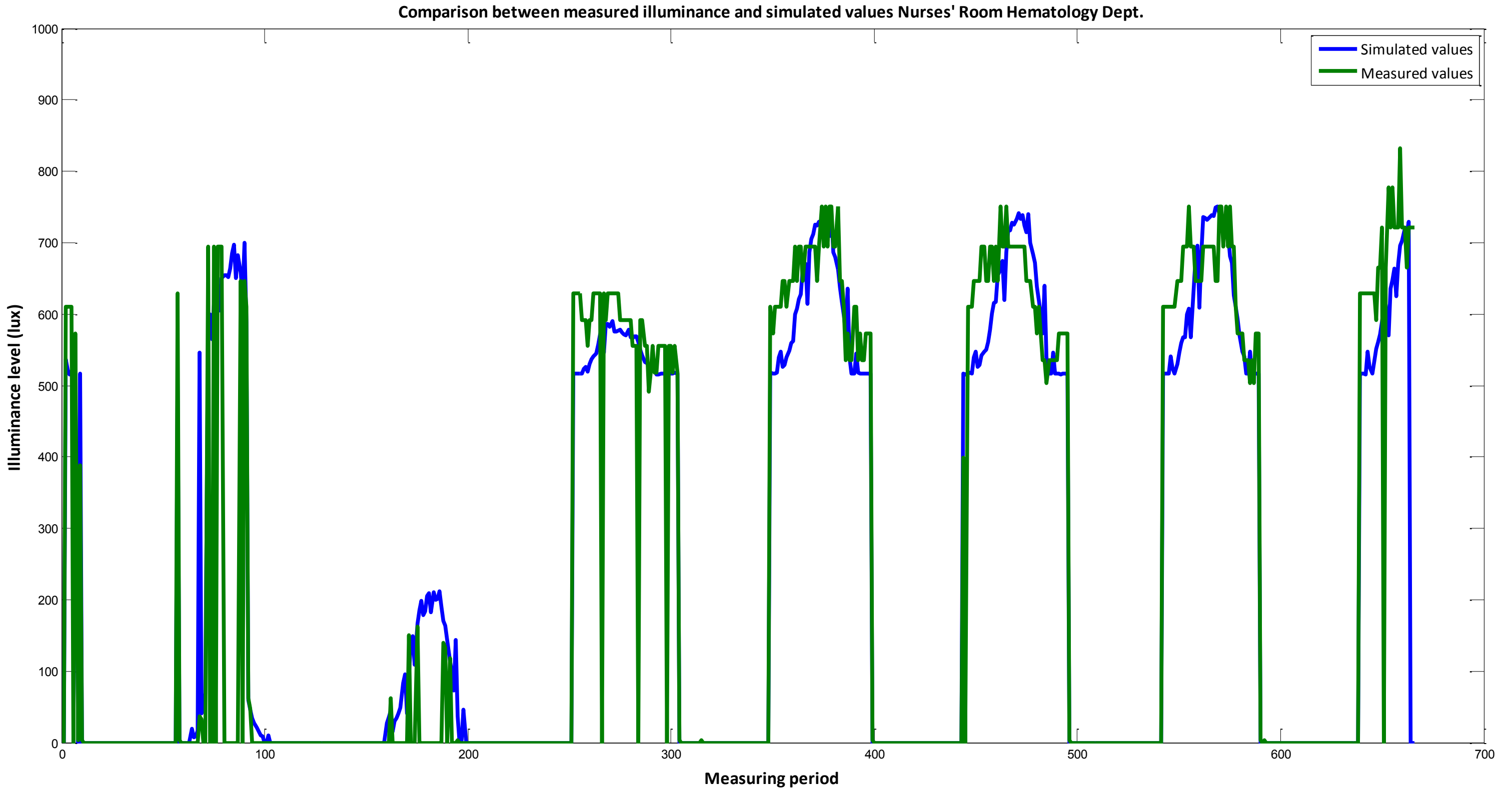


Figure 2- 25: Comparison of simulated and measured values for Haematology Dept.

Similarly, the thermal models are validated comparing their simulated output values and the measurements performed in the modelled areas. Continuing with the thermal model for the hospital of Chania, measurements are collected from the installed equipment and used for comparison with the output of the TRNSYS model. The parameters used are tabulated in Table 2- 16.

Table 2- 16: Parameters for the validation process of Chania Hospital for the AHU in the hospitals rooms

Parameters	Values / source	Model Input /Output
Period of simulation	26th August 2013	
Data collection time-step	15 minutes	
Outdoor Air Temperature	Local BMS	Input
Outdoor Air Relative Humidity	Meteonorm database	Input
Presence of people for each room	Local BMS	Input
Flow in air temperature	Local BMS	Input
Supply Air Temperature	Local BMS	Input
Light heat gains	Local BMS	Input
Supply Air flow rate	Local BMS	Input
Water flow in temperature for each AHU	Local BMS	Input
Room temperature	Local BMS	Output

		comparison

The comparison of measured and simulated values (Figure 2- 26) indicates that the thermal model developed in TRNSYS accurately predicts indoor air temperature considering the operation of the local AHU.

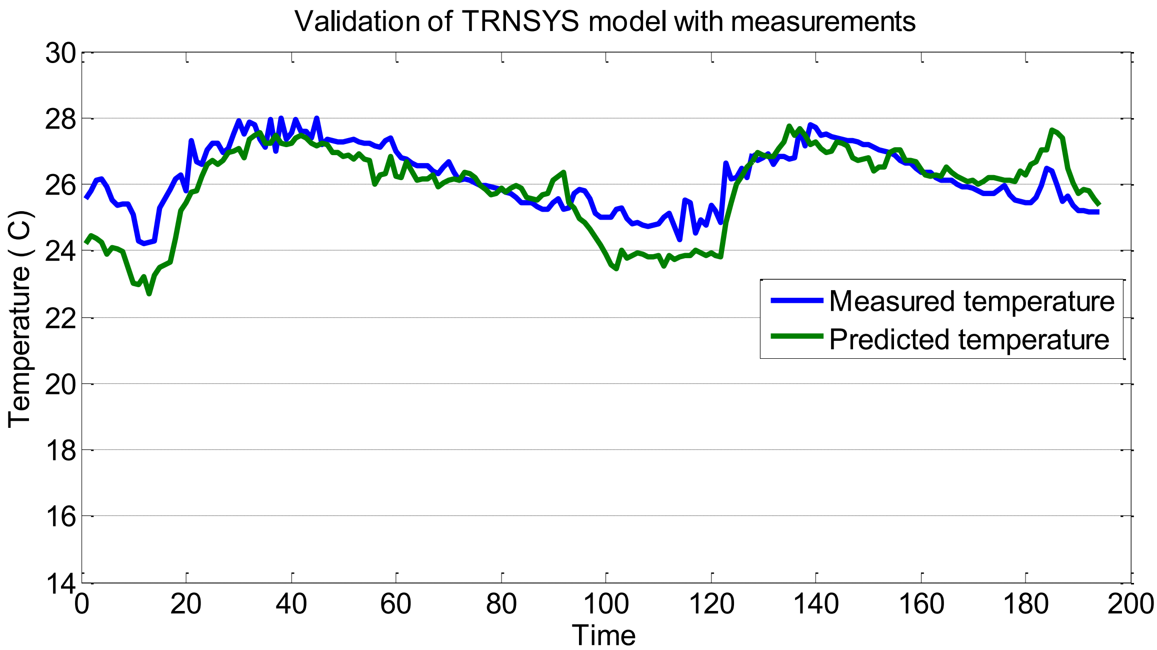


Figure 2- 26: Validation of the developed thermal model for Chania Hospital, Chania - Greece

The validation of the TRNSYS model for the data centre is performed by comparing the monitored temperature in the data centre with the simulated one from the thermal model. The measured data is collected during September 2013 (Table 2-17) and compared as illustrated in Figure 2- 27.

Table 2- 17: Parameters for the validation process of Ancona Hospital for the data centre solution set

Parameters	Values
Period of simulation	September 1-30, 2013
Outdoor Temperature source	Local BMS
Total Electricity use source	Local BMS
Detailed temperature readings in the chiller	Local BMS
Time-step of simulation	15 minutes

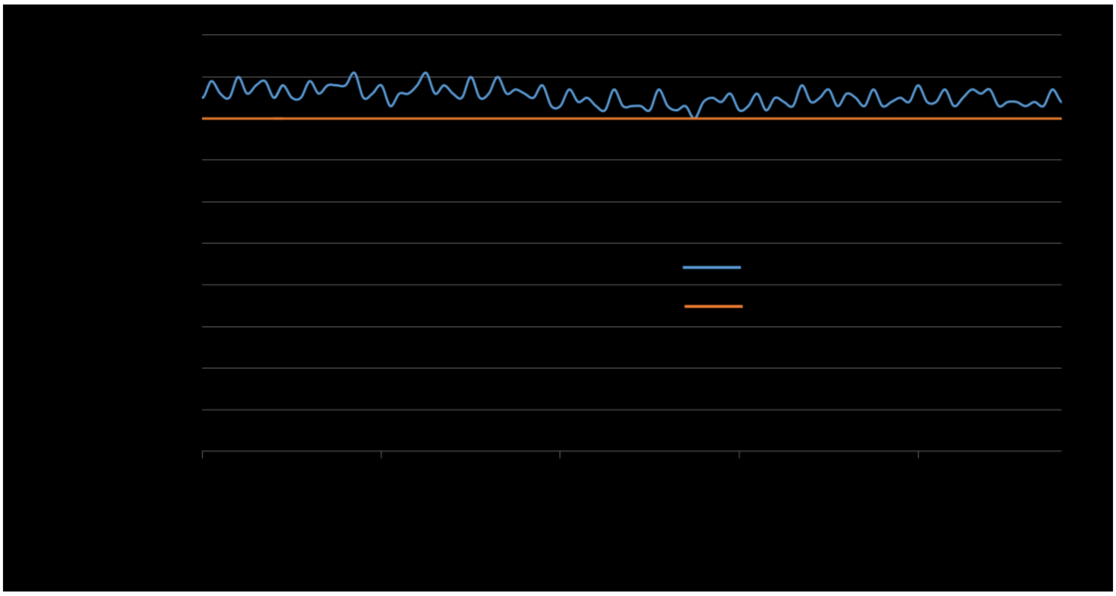


Figure 2- 27: Validation of the thermal model for the data centre of Ancona's hospital

2.4 Estimation of baseline energy consumption

The estimation of the energy consumption of the baseline models is reached by running the developed and validated models for 1 year using the typical meteorological year of each city and then created by using the Meteonorm software.

The thermal models developed using TRNSYS software estimate the energy demands (heating cooling and electricity) and the energy consumption in natural oil or electricity if the related types of TRNSYS are used.

Starting with the air handling units of Chania Hospital data related to the operation of the air handling units from the users is collected as well as data related to their presence and used as input in the model. Running the TRNSYS model, the energy demand for the heating and cooling of the 3 rooms is calculated. The results are plotted on a monthly base in Figure 2- 28.

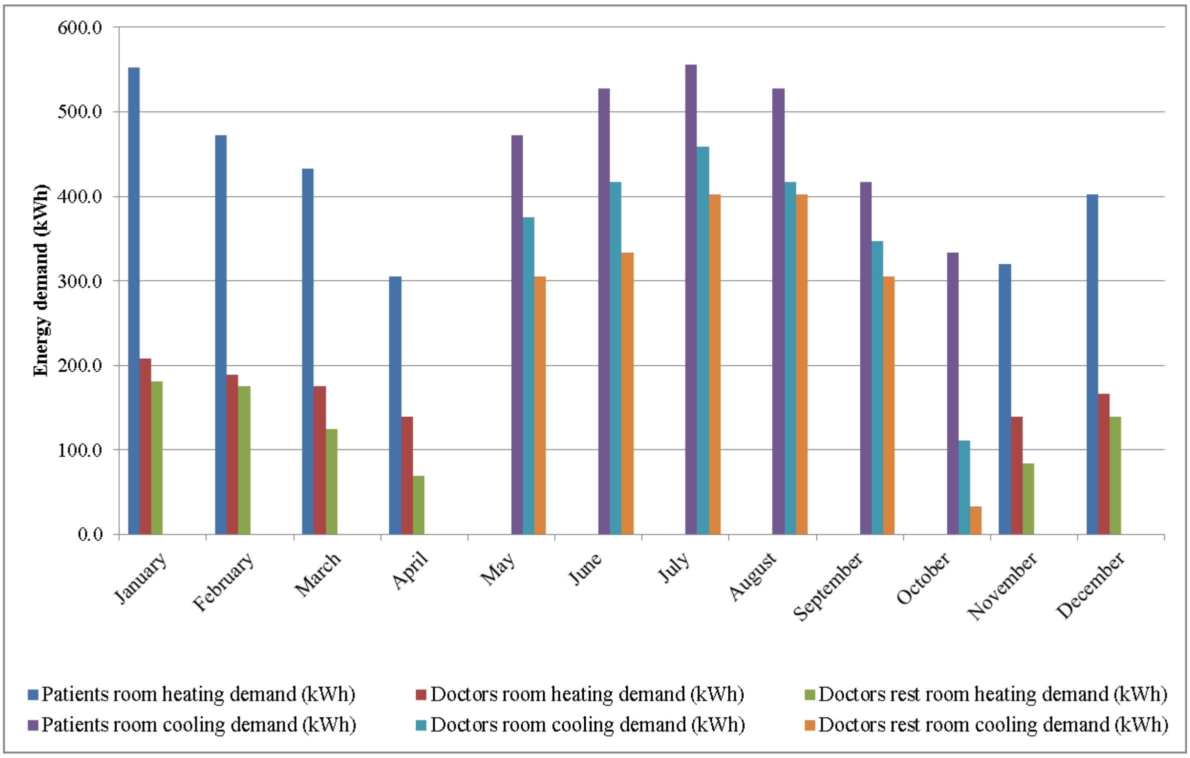


Figure 2- 28: Baseline energy demand for heating and cooling in the 3 selected rooms

The results are converted to energy consumption considering the efficiency of the central cooling system and the boilers of the hospital. The calculations are tabulated in Table 2- 18.

Table 2- 18: Conversion of energy demand to consumption and primary energy

	Energy demand (kWh)	**Energy consumption (kWh)**	**Primary energy**
Heating	3513.5	4085.5	4494.1
Cooling	431	331.5	961.5
Total			5455.5

The estimation of the artificial lights baseline energy is estimated based on the operating hours of the selected rooms which are tabulated in Table 2- 19.

Table 2- 19: Operating hours of the selected rooms in Hospital of Chania

Selected rooms	**Operating hours**
Doctors' office	8:00 – 14:00
Patients' room	00:00 – 24:00
Doctors' rest room	14:00 – 16:00. 23:00 – 07:00

During these hours, the artificial light operate when daylight level is not sufficient, both the artificial lights operate to cover the needs of the rooms. The monthly consumption of the artificial lights for the rooms is illustrated in Figure 2- 29.

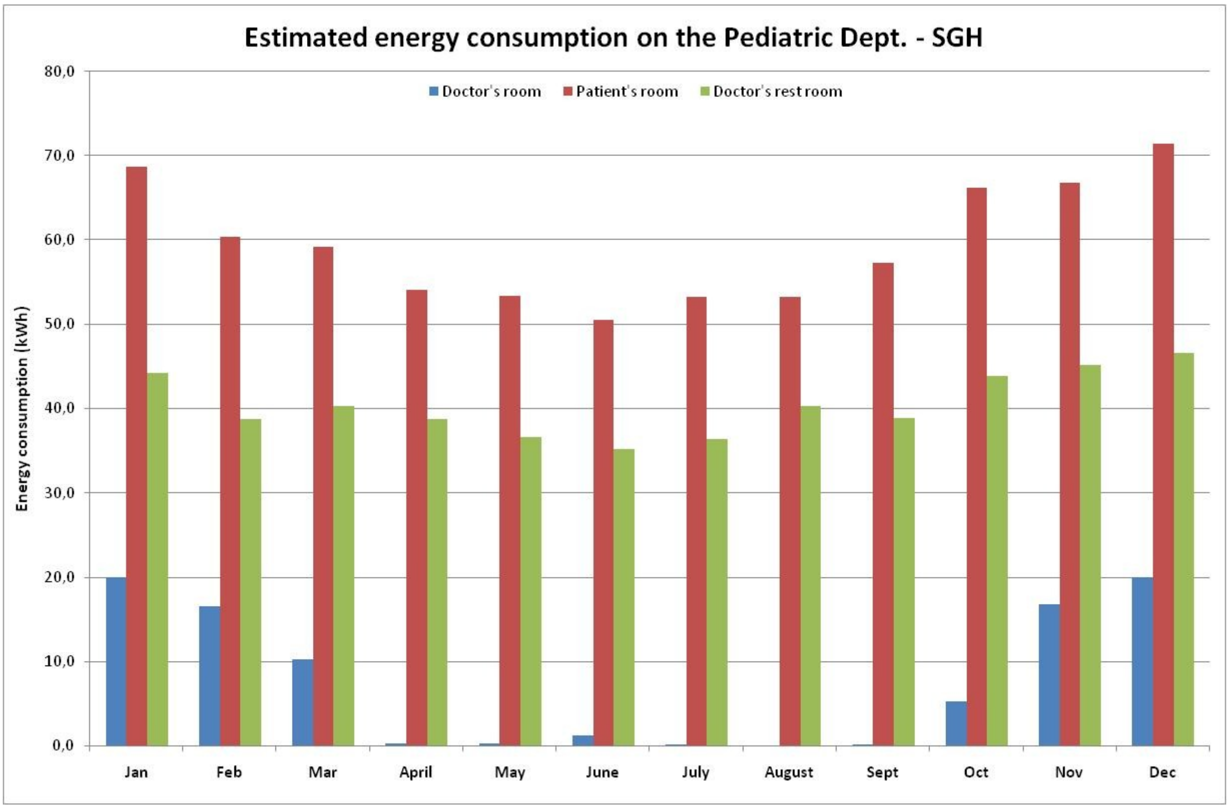


Figure 2- 29: Estimated baseline energy consumption of artificial lights in Chania Hospital

The TRNSYS model for the data centre of Ancona runs for one year and the energy consumption is estimated at 135.4 MWh.

The lighting model for the artificial lights of the selected rooms in the Ancona hospital estimates the operating hours of the artificial lights based on the occupancy schedule the hospital has provided for the operation of the rooms and it is tabulated in Table 2- 20, along with the estimated annual baseline consumption.

Table 2- 20: Estimated annual baseline consumption (kWh) for the selected rooms in Ancona Hospital

Selected rooms of Ancona Hospital	Operating hours	Annual baseline consumption [kWh]
Visitors' waiting room (Oncology Dept.)	7:30 - 19:00	1244.7
Nurse office (Haematology Dept.)	7:30 - 19:00	1030.7
Doctors' office (Haematology Dept.)	7:30 - 19:00	1550.6
Warehouse (Haematology Dept.)	7:30 - 19:00	639.2

Archives- 2 rooms (Oncology Dept.)	7:30 - 19:00	319.2
Ambulatory (Oncology Dept.)	7:30 - 19:00	259.4
Nurse room (Oncology Dept.)	7:30 - 19:00	294.9

------------------------------------Chapter 3 ---

DEVELOPMENT OF CONTROL ALGORITHMS

3 Development of control algorithms

The aim of the present chapter is to describe the development of the control algorithms for the artificial lights and the air handling unit which can be integrated in the field controllers of hospital buildings. This corresponds to Phase 2 of the research methodology depicted in Figure 1- 2. Moreover the energy performance and the efficiency of the control algorithms is estimated after the interconnection with the developed thermal and lighting models of Chapter 2.

3.1 Introduction

A significant element that may contribute to the efficient operation of an energy efficient building is a competent and robust Building Optimization and Control (BO&C) tool that uses building networking inputs and thermal models to evaluate potential scenarios. In this way it takes (almost) real-time decisions for the operation of the building subsystems with the goal of maximizing the selected performance indicators (e.g. primary energy) while retaining building conditions at user-acceptable comfort levels.

Mechanical systems embed control algorithms to adjust their operation based on their users' requirements. Several control algorithms are applied in systems to control parameters such as water, air temperature and air flow. Closed control algorithms are used in systems to adjust the operation comparing to a reference condition (ex. Temperature set-point, Relative humidity set-point or PMV).

The main challenge in the design of control and optimization systems for energy performance of buildings is to find the balance between implementation costs, operation costs, energy consumption, indoor climate quality, user's satisfaction and contribution to sustainable buildings. Intelligently designed buildings are those that involve environmentally responsive design taking into account the surroundings and building usage and involving the selection of appropriate services and control systems to further enhance operation with a view to the reduction of energy consumption and environmental impact over its lifetime. This procedure requires advanced control techniques to establish a balance among:

- User comfort requirements.
- Energy consumption.

- Passive solar design concepts.
- Solar heating and cooling technologies
- Energy production and micro generation.

Various control strategies are used for the regulation of the above. The combined control of active and passive systems, as for example night ventilation for cooling and mechanical cooling or hybrid ventilation, generally requires the use of so called "logic control" implemented by various rules in order to determine which of the passive or active system should be operated.

Many digital control algorithms offer this possibility to implement logic control rules as well as On-Off or PID control(Dounis and Caraiscos, 2009; Levermore, 2000).Modern control systems provide optimized operation of the energy systems while satisfying indoor comfort. Recent technological developments based on artificial intelligence techniques offer several advantages compared with the classical control systems. The use of fuzzy logic and artificial neural networks (ANNs) in various building related applications has been growing significantly over the years (Kalogirou, 2001, 2000; Kolokotsa, 2007).The results have revealed the potential usefulness of the advanced control strategies for the energy management of houses and buildings. Evolutionary computing, namely, genetic algorithms (GA) is employed in buildings since they have proved to be robust and efficient in finding near-optimal solutions to complex problem spaces (Kolokotsa et al., 2002; Kumar et al., 2008). Predictive control techniques are also applied (Kolokotsa et al., 2009a). Finally optimization methods such as dynamic programming (Caldas and Norford, 2003), multi-objective techniques (Diakaki et al., 2008; Kolokotsa and Diakaki, 2009) and simulation assisted multi-criteria analysis (Roy, 1996) are widely adopted due to buildings' non linearity.

The control techniques used for energy management of HVAC can be divided into the following categories tabulated in Table 3- 1.

Table 3- 1: Control Strategies for buildings

Control category	Control strategies
Conventional control	**ON-OFF**
	Proportional Integral Derivative

Control category	Control strategies
	Feedforward control
Advanced control	**Model based predictive control**
	Adaptive control
Intelligent techniques	**Optimal control**
	Fuzzy logic
	Neural network

Based on Table 3- 1 categorization, advanced control for solar architecture includes model based predictive control and adaptive control. Predictive control in buildings, uses a model to estimate and predict the optimum control strategy to be implemented (Figure 3- 1 and Figure 3- 2).

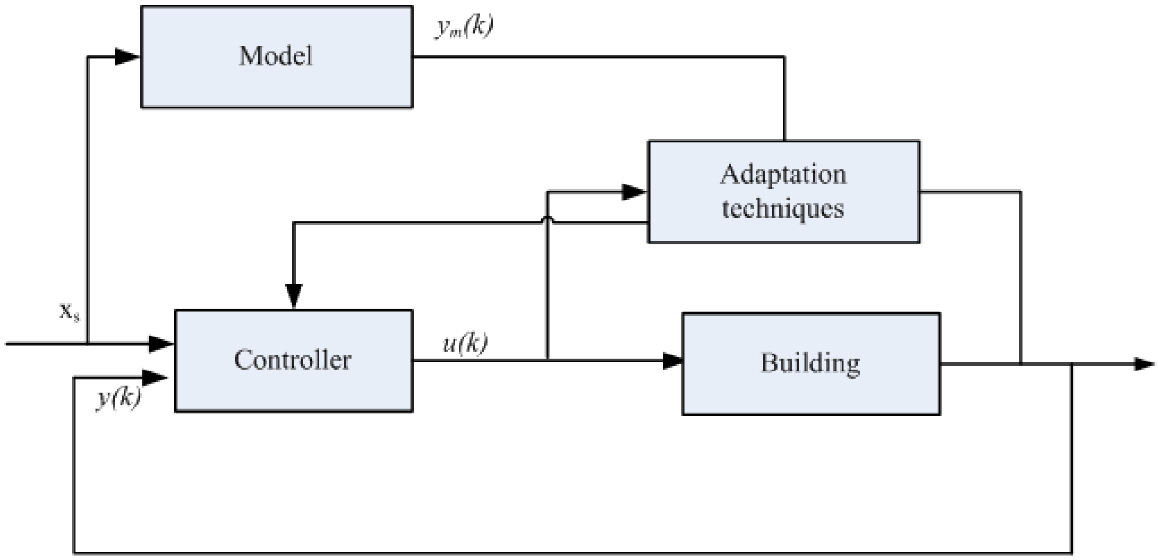


Figure 3- 1: Model based predictive control

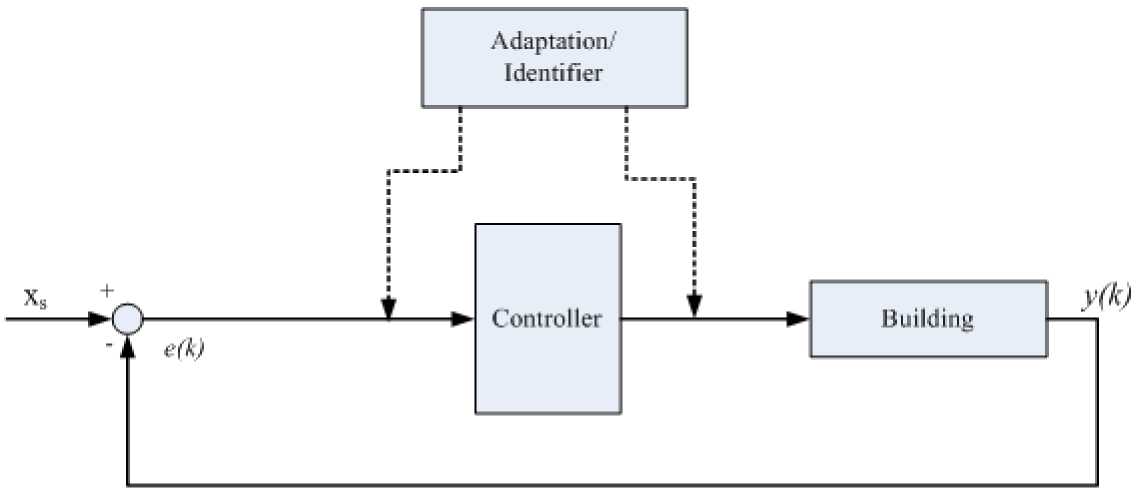


Figure 3- 2: Self-tuning control algorithms

3.2 Control algorithms development using Matlab

The development of control algorithms is performed using Matlab version. 8.3.0.532 (2014a) The specific software is selected due to its connectivity with TRNSYS software (Liu et al., 2013) which is used for the verification of control algorithms performance for systems related to heating, cooling and ventilation after their connection with the TRNSYS models. Furthermore, Matlab software can be connected with Radiance software (Papantoniou et al., 2014b) which is used for the offline verification of the control algorithms for systems related to artificial lights.

Moreover Matlab software can be used for exporting the developed control algorithms in other formats such as ".NET assembly", "C++"," C#" and "exe". Thus it is not required to run the code in a computer with Matlab software installed.

Finally Matlab software can interface with other software such as "energy plus" (Dong et al., 2012), "Ptolemy II" and "building automation BACnet", using **B**uilding **C**ontrols **V**irtual **T**est **B**ed (BCVTB) a software for coupling different software (Nouvel and Alessi, 2012) and hardware applications.

3.3 Control algorithms for artificial lights

Artificial lights cover the lighting requirements of areas. The design and the power of the luminaires is based on standards (EN12461.1 2002: "European Standard for Interior Lighting"). The operation of the luminaires can be either manual with switches operated by the occupants of the rooms, semi-automatic, where the user activates the artificial light and it shuts automatically based on a time delay or a presence detector, or fully automatic where the operation is based on a presence detection sensor and an indoor illuminance sensor.

The developed control algorithm for artificial lights automatically maintains the illuminance level using a presence detector and an indoor illuminance sensor. The structure of the controller is depicted in Figure 3- 3.

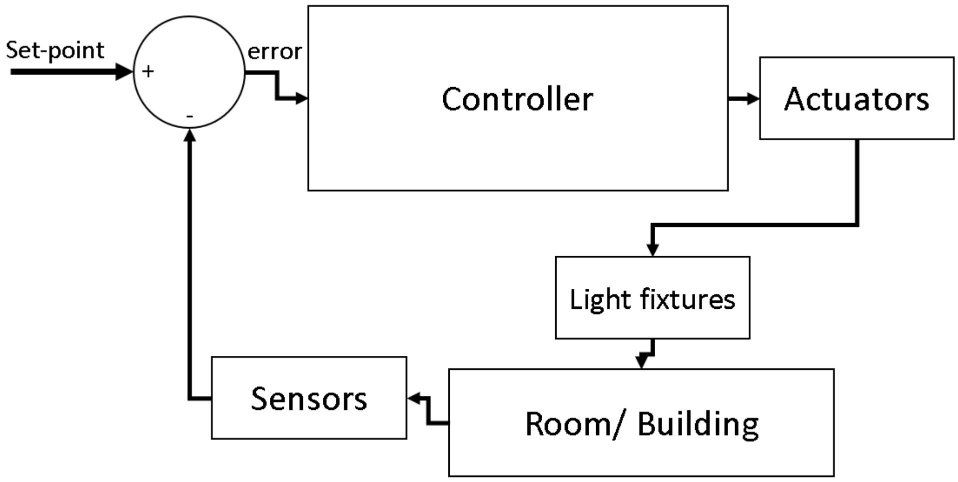


Figure 3- 3: Structure of the developed controller for controlling the artificial lights

The input of the controller (*error*) is the difference between the current illuminance level provided by the illuminance sensor installed in the rooms and the required set point depending on the usage of each room. The output of the controller is linked to the actuators of the light fixtures.

$$error_{illuminance} = Set\ point\ illuminance - measured\ illuminance \qquad (1)$$

The properties of the developed control algorithm are presented in Table 3- 2.

Table 3- 2: Properties of fuzzy control algorithm for artificial lights

Type of fuzzy control algorithm	**'Sugeno'**	
N. of inputs	1: error between current and desired light level	
N. of outputs	1: change in the artificial lights state	
Fuzzification membership functions	5	
	'NE'	-0.7
	'SNE'	-0.3
	'ZERO'	0
	'SPO'	0.3

	'PO'	0.7
Further fuzzy parameters	AndMethod: 'prod'	OrMethod: 'probor'
	ImpMethod: 'prod'	AggMethod: 'sum'
	DefuzzMethod:'wtaver'	

Sugeno architecture is selected because the control algorithm has only one output. On the other hand Mamdami architecture can affect more than 1 output comparing to Sugeno architecture.

The input of the controller ($error_{illuminance}$) is fuzzified using trapezoidal membership functions using the equation bellow.

$$f(x;a.b.c.d) = \begin{Bmatrix} 0 & x \leq a \\ \dfrac{x-a}{b-a} & a \leq x \leq b \\ 1 & b \leq x \leq c \\ \dfrac{d-x}{d-c} & c \leq x \leq d \\ 0 & d \leq x \end{Bmatrix}$$

The membership functions for the fuzzification process are plotted in Figure 3- 4.

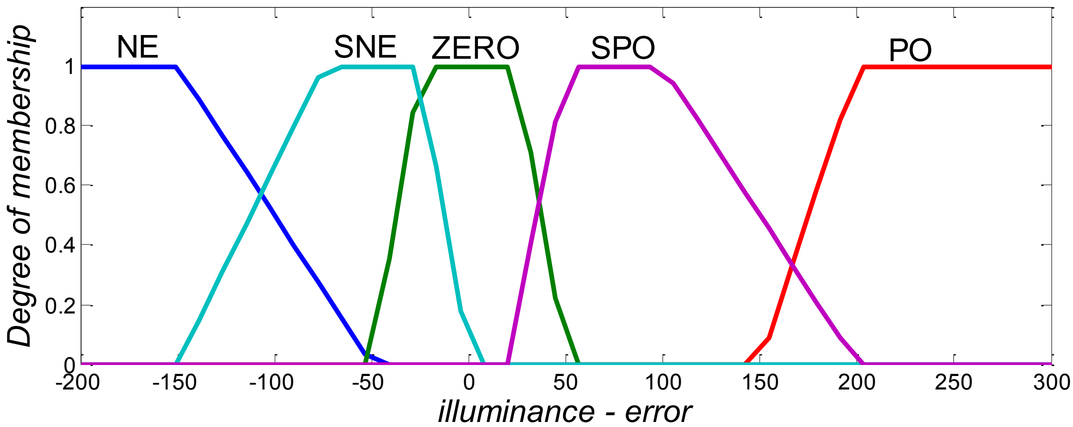


Figure 3- 4: Membership functions for the fuzzification of illuminance error

The membership functions are designed in order to maintain the illuminance level and simultaneously to prevent recurring changes of the artificial lights which will reduce their life expectancy. The rules used in the fuzzy controller are tabulated in Table 3- 3.

Table 3- 3: Embedded rules of the fuzzy controller

Input *Illum. difference from set-point (error)*	**Output** *Art. Lights change*
NE	PO
SNE	SPO
ZERO	ZERO
SPO	SNE
PO	NE

The control algorithms are fine-tuned based on their performance on validated lighting models using Radiance software presented in Chapter 2.

3.3.1 Controlling artificial lights with on/ off installation

The developed fuzzy controller can be implemented to conventional artificial light fixtures with on/ off operation as long as more than one electricity circuits are available. These type of light fixtures are available in Chania hospital (Figure 3- 5).

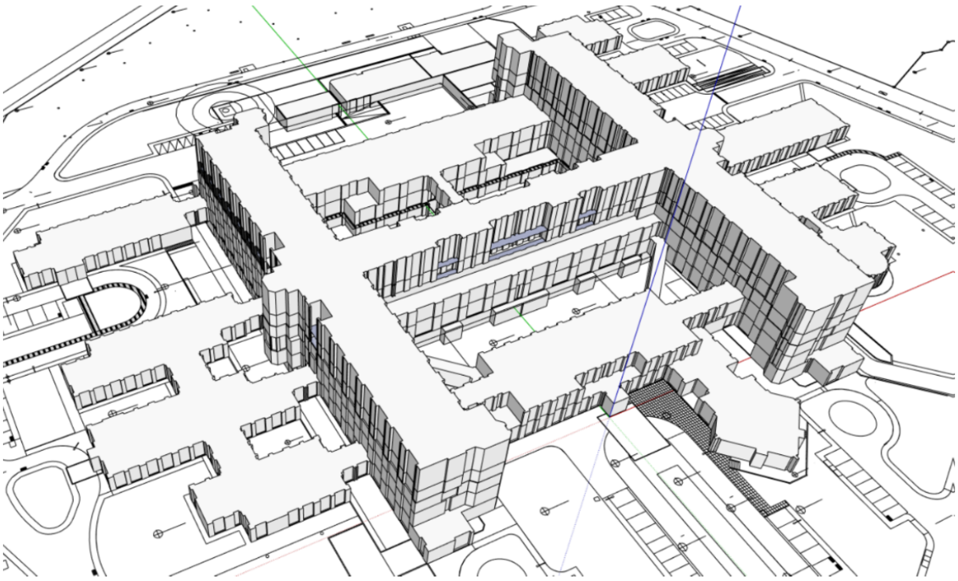


Figure 3- 5: Developed 3D model of the Hospital of Chania

The selected rooms in the paediatric department have on/off switches. The development and the validation of the model is described in Chapter 2.

3.3.1.1 <u>Fine-tuning of control algorithm for artificial lights</u>

The fine tuning of the control algorithm is performed using the validated model of the doctors' room. Doctors occupy this room from 10:00 until 14:00. According to regulations (*EN12461.1 2002: "European Standard for Interior Lighting"*) illuminance level should be 500 lux. The adaptation of the developed control algorithm in the change of set-point (0 lux towards 500 lux) is illustrated in Figure 3- 6.

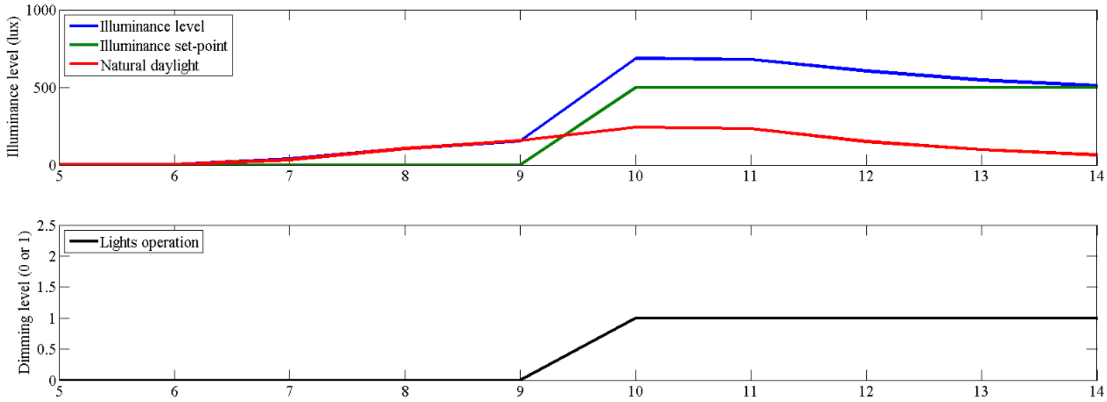


Figure 3- 6: Fine tuning of the developed control algorithm

The controller adjusts the artificial lights' operation and the illuminance level is maintained as required. In order to evaluate the annual performance of the controller with the developed Radiance model, the controller should run from a single function Matlab file (Figure 3- 7) which has the following inputs:

- Name of the room, in order to load previous values
- Current presence indication
- Current illuminance level

The output of the controller is:

- new operation level of the artificial lights

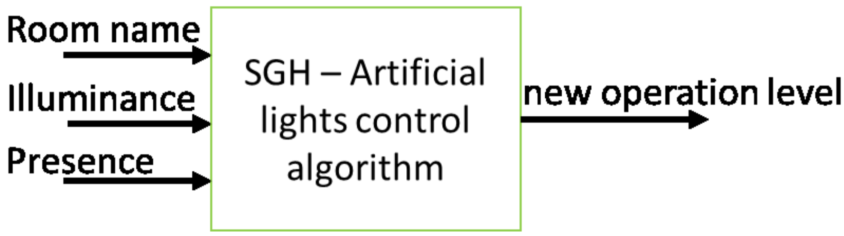


Figure 3- 7: Inputs & outputs for: Chania Hospital – Artificial lights control algorithm

The communication between Radiance software and Matlab is plotted in Figure 3- 8. The work-flow of the controller operating in Matlab environment is illustrated in Figure 3- 9.

Running the Radiance model connected with Matlab annually, the comparison between the automated system (fuzzy controller) and continuous operation of the artificial lights is pictured in Figure 3- 10.

Half of the available artificial fixtures operate, thus reducing their energy consumption while maintaining the required illuminance level. This output demonstrates that under the specific conditions the control algorithms saves energy by allowing only one artificial light to work. The combined luminance from daylight and the artificial light provide the required illuminance level and in parallel save energy.

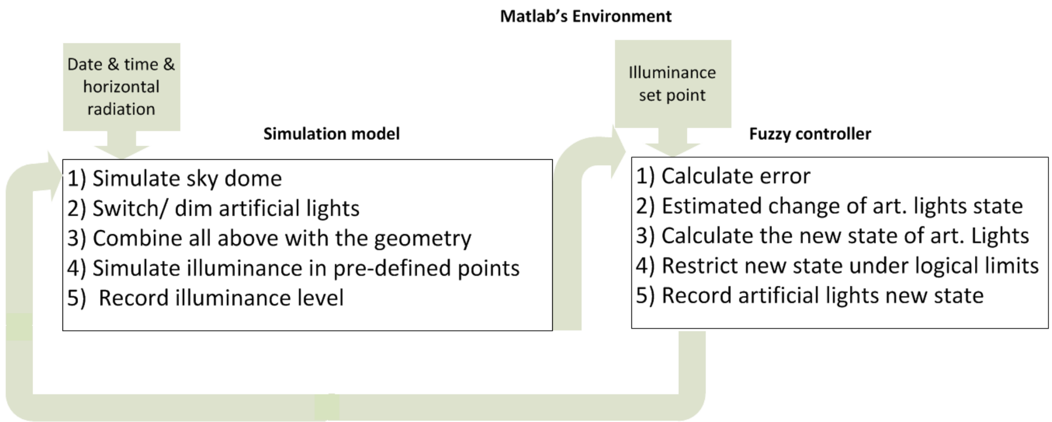


Figure 3- 8: Direct communication between Matlab environment (Fuzzy controller) and Simulation model (Radiance)

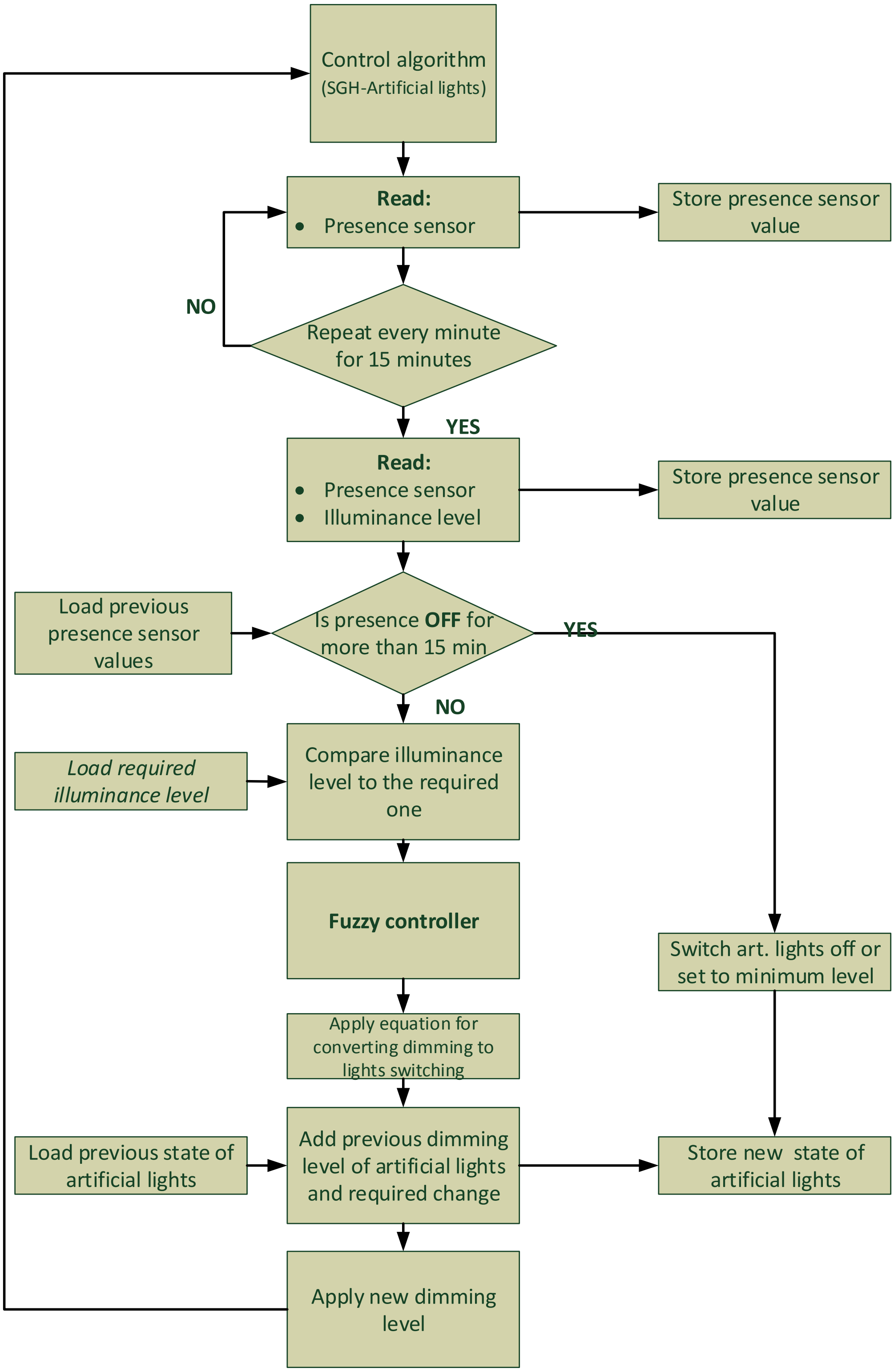


Figure 3- 9: Flowchart of the control algorithm for the artificial lights, in Chania Hospital, Chania

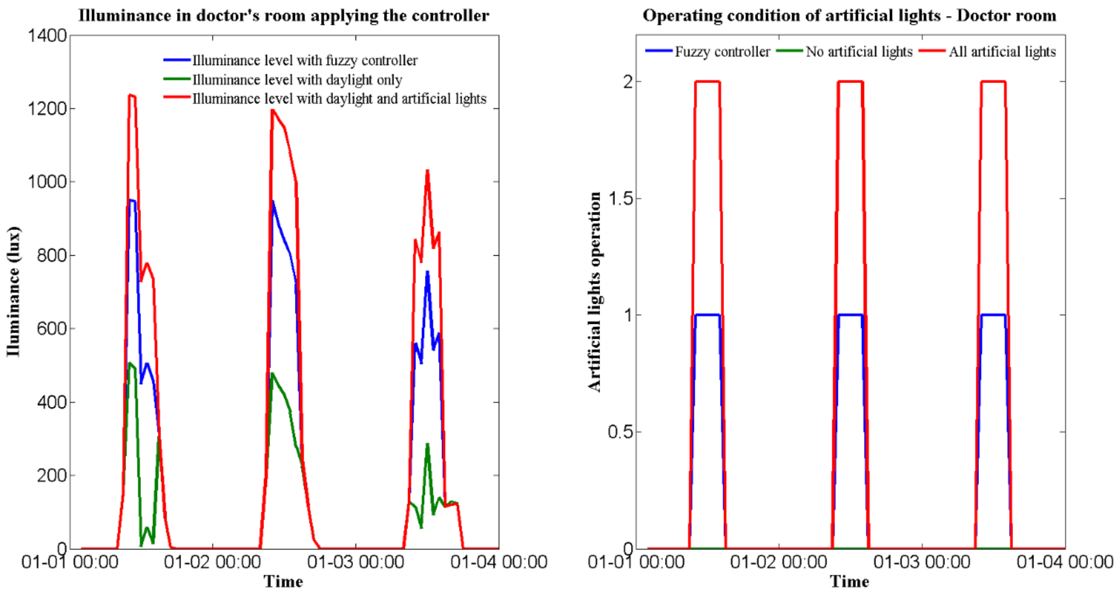


Figure 3- 10: Comparison of illuminance level and artificial lights operation using the control algorithm and the current system in Chania Hospital, Chania

3.3.2 Controlling artificial lights with dimming installation

The developed control algorithm can be implemented in artificial light fixtures with dimming capabilities. The output of the fuzzy controller is addressed to the required change of the dimming level. The output is combined with the previous dimming level and the required dimming level is estimated. The process is illustrated in Figure 3- 13.

Technical properties of the artificial lights set their minimum dimming level (ex. 10%). Furthermore, the rate of dimming level change is also described in their properties (example 10% step of change). The developed control algorithm is fine-tuned using the developed validated lighting model for the Haematology and Oncology department in: "AZIENDA OSPEDALIERO UNIVERSITARIA OSPEDALI RIUNITI Umberto I- G.M. Lancisi – G. Salesi" (Figure 3- 11).

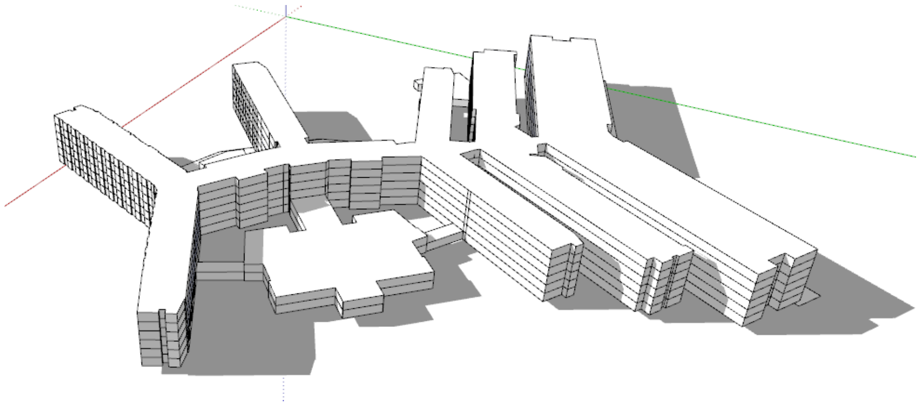


Figure 3- 11: Developed 3D model for the lighting simulation in AZIENDA OSPEDALIERO *UNIVERSITARIA OSPEDALI RIUNITI Umberto I- G.M. Lancisi – G. Salesi*

3.3.2.1 Fine-tuning of control algorithm for artificial lights

The controller adjusts the artificial light level of the selected room based on the measured illuminance level. Figure 3- 12 illustrates the performance of the controller to reach and maintain the required illuminance set-point.

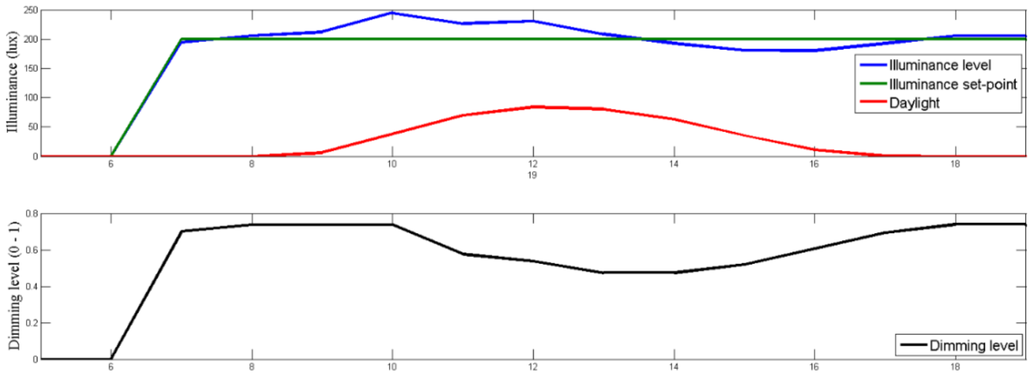


Figure 3- 12: Evaluation of the control algorithms performance to reach and maintain a specific illuminance set-point

Analysing Figure 3- 12 it can be seen that when illuminance set-point changes from 0 lux to 200 lux, the dimming level is increased to reach the set-point. When daylight level increases, the dimming level is reduced because daylight contributes to the illuminance of the specific room.

Running the Radiance model connected with Matlab annually, the comparison between the automated system (fuzzy controller) and continuous operation of the artificial lights is pictured in Figure 3- 13.

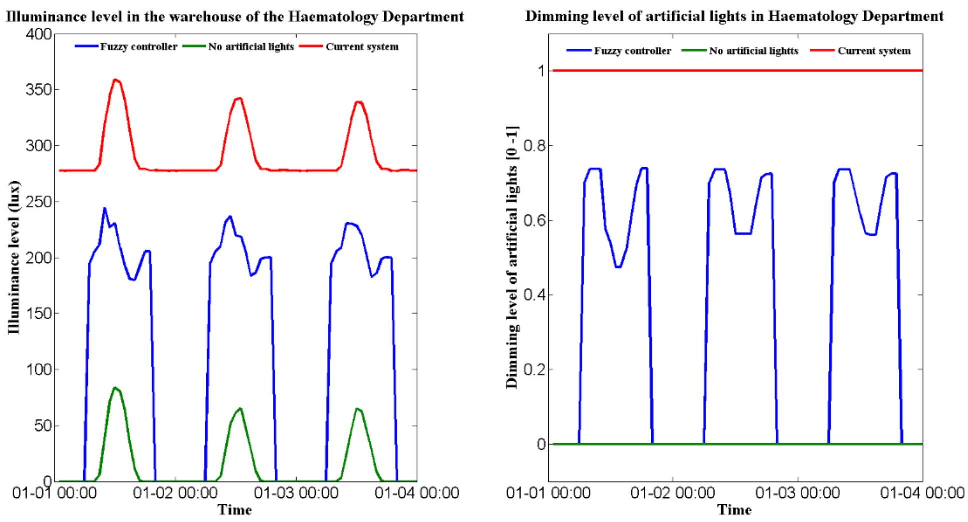


Figure 3- 13: Comparison of illuminance level and artificial lights operation using the control algorithm and the current system in Hospital of Ancona

The energy efficiency potential can be estimated by comparing the dimming level a priori the implementation of the fuzzy control and a posteriori. The difference of the dimming level multiplied by the rated power of the artificial lights provides the reduced power demand and summing the values annually the energy efficiency potential is estimated. The flowchart of the control algorithm running in Matlab is illustrated in Figure 3- 14.

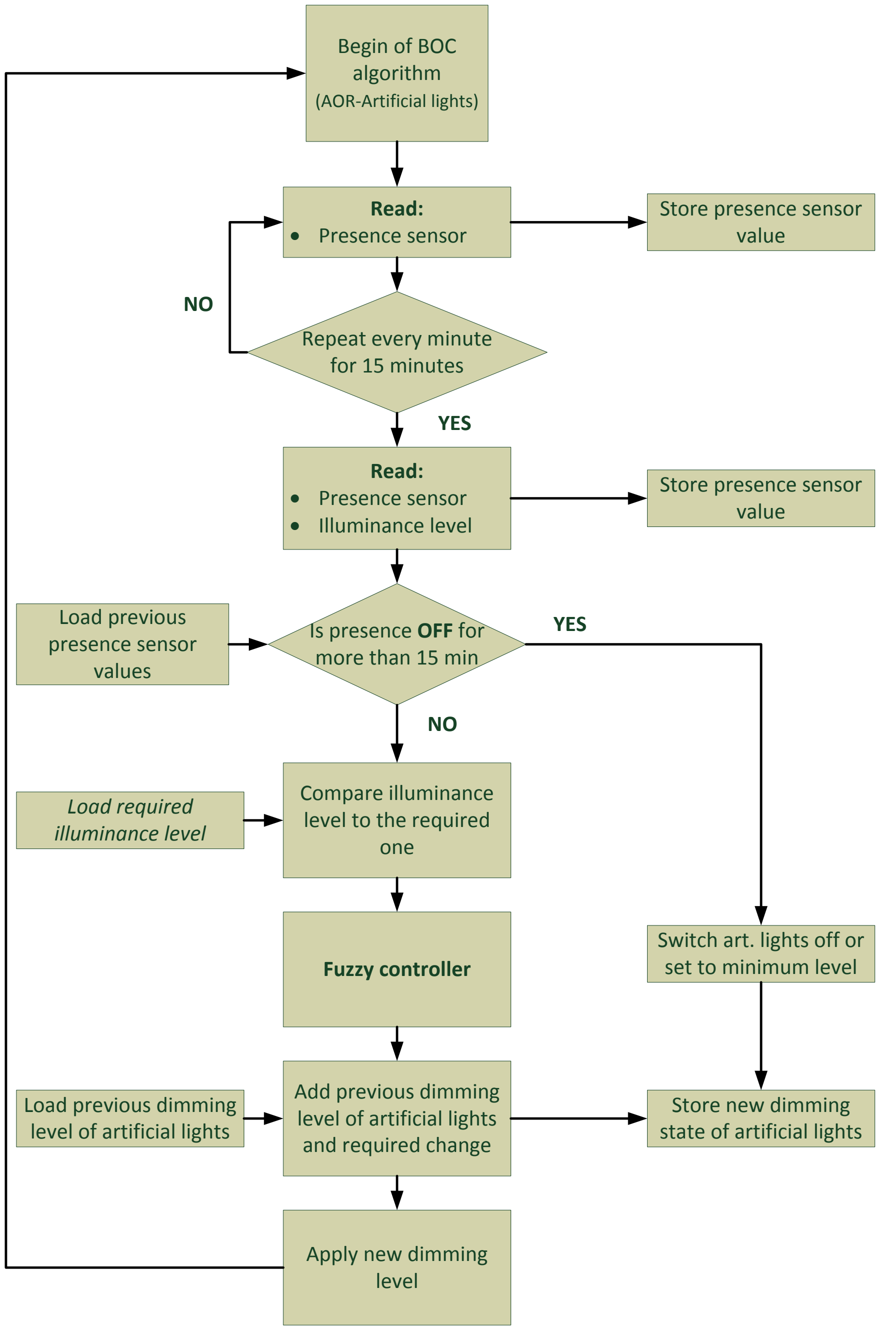


Figure 3- 14: Flowchart of the control algorithm for the artificial lights, in Hospital of Ancona

3.3.2.2 Estimated annual energy efficiency potential applying the developed control algorithm

The energy efficiency potential of the control algorithm is evaluated by comparing the energy consumption of the artificial lights prior and after the usage of the controller. Baseline consumption of the light fixtures for 1 year is calculated at 67.5 kWh considering as baseline consumption operation of both artificial lights when the room is scheduled to be occupied (10:00–14:00) and an illuminance level below 500 lux. Running the model/controller on an annual basis, the energy efficiency potential for the doctors' room has been estimated at 58%.

Similarly in the hospital of Ancona the estimated energy efficiency potential is tabulated in Table 3- 4.

Table 3- 4: Annual baseline consumption of selected and energy efficiency potential by applying the developed control algorithm

Selected rooms of Ancona Hospital	Annual baseline consumption [kWh]	Estimated energy efficiency
Visitors' waiting room (Oncology Dept.)	1244.7	36%
Nurse office (Haematology Dept.)	1030.7	54%
Doctors' office (Haematology Dept.)	1550.6	45%
Warehouse (Haematology Dept.)	639.2	53.1 %
Archives- 2 rooms (Oncology Dept.)	319.2	29 %
Ambulatory (Oncology Dept.)	259.4	11 %
Nurse room (Oncology Dept.)	294.9	17.6

3.4 Control algorithms for air handling units

The air handling units provide thermal comfort in the users by adjusting their operation. The air handling unit contain internal control algorithms which can be either overwritten externally or the user can only adjust the change of temperature set-point. In other systems the users can alter the dampers positions affecting the air stream passing through different coils. Finally other contemporary systems allow the control of humidity level.

In all the aforementioned types of air handling units, the input provided to the controller is the difference between the current temperature measured in a room and the required temperature for each room. The difference is the error which needs to be lessened.

$$error_{temperature} = Temperature\ set_{point} - indoor\ temperature \quad (1)$$

The error is used as input in the developed fuzzy controller. The fuzzification membership functions, trapezoidal form, are designed to maintain temperature at a specific level without adjusting the operation of the air handling units continuously.

The membership function named “ZERO” is responsible for the stability of the systems’ operation. The input membership functions are plotted in *Figure 3- 15*.

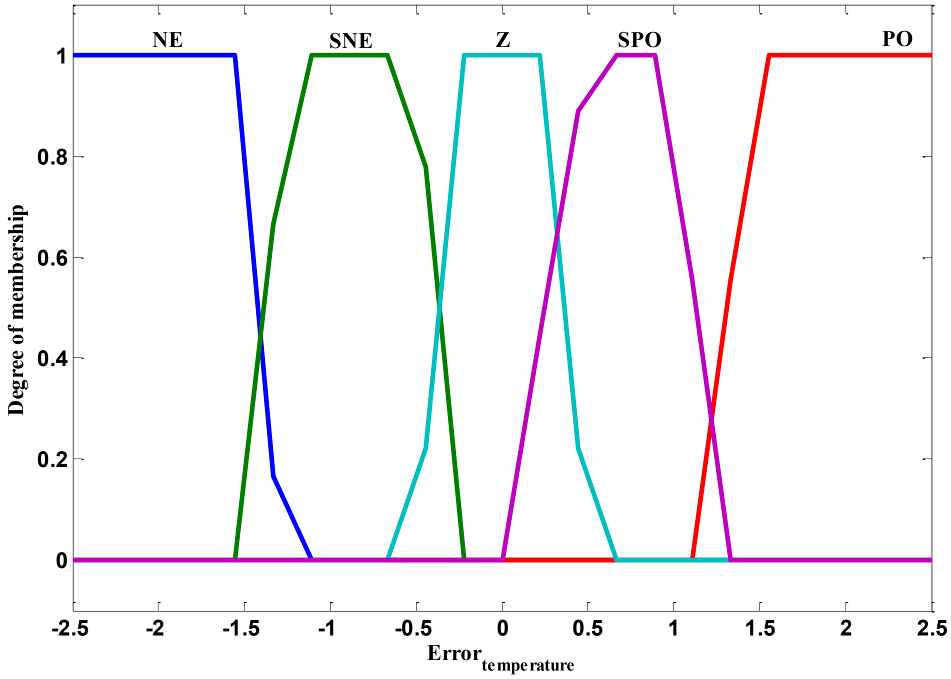


Figure 3- 15: Fuzzification functions for error$_{temperature}$ – Air handling units’ fuzzy controller

The output of the control algorithm affects the operation of the air handling changing the operation of the coil’s valve and fan if possible or the set-point in case the system accepts as input only the temperature set- point.

3.4.1.1 <u>Controlling Air handling units coils valve and fan speed</u>

For the air handling units which allow the external control/ override of the valve and the fan speed the developed controller sends the required operation level. The structure of the controller is presented in *Figure 3- 16*.

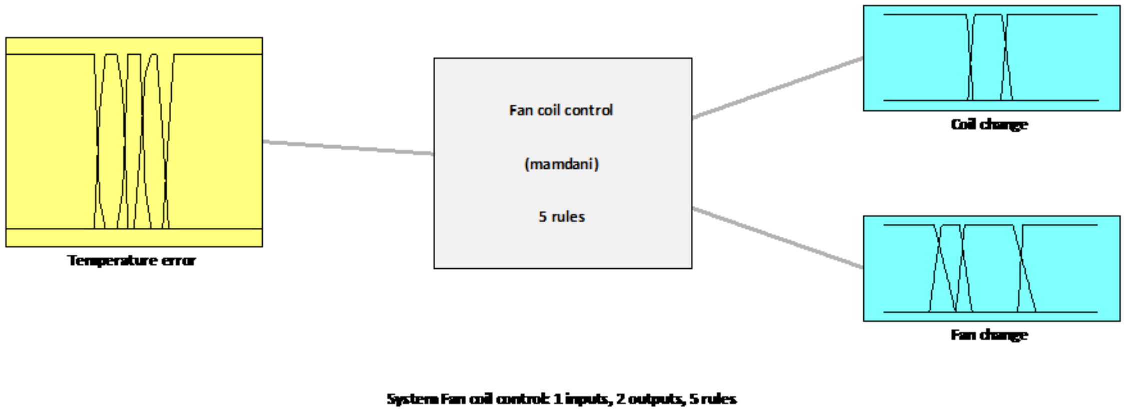


Figure 3- 16: Structure of the developed controller for air handling units with override of fan and coil's valve

The error of temperature is fuzzified using the membership functions presented in *Figure 3- 15*. The properties of the fuzzy controller (*Table 3- 5*) are estimated based on the fine-tuning results.

Table 3- 5: Characteristics of the developed controller

Type of Fuzzy controller	'Mamdami'	
No of inputs	1: error between current and indoor temperature set-point	
No of outputs	2: change of AHU's coil & change of AHU 's fan speed	
Fuzzification membership functions	5	
De-fuzzification membership functions	5	
Fuzzy controller parameters	AndMethod: 'min'	OrMethod: 'max'
	ImpMethod: 'min'	AggMethod: 'max'
	DefuzzMethod:'lom'	

The Mamdami architecture is selected because 2 outputs are affected by the control algorithm and Sugeno architecture cannot control them. In case Sugeno architecture was necessary, 1 control algorithm would have been developed for each output.

The rules included in the fuzzy controller are tabulated in *Table 3- 6*.

Table 3- 6: 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

The de-fuzzification parameters are plotted in Figure 3- 17.

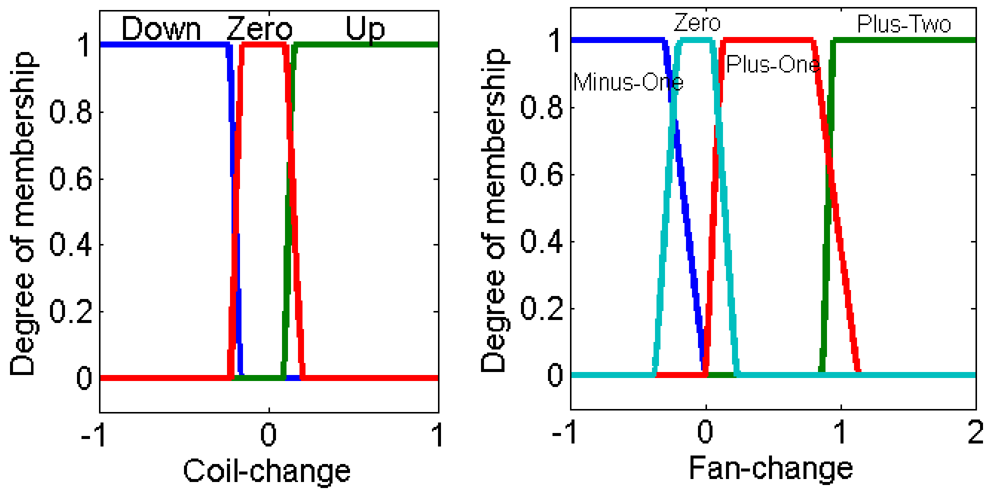
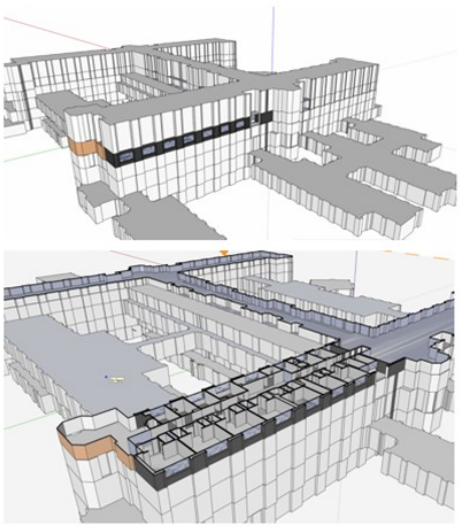


Figure 3- 17: De-fuzzification parameters for controlling coil's and fan's change

The performance of the developed control algorithm to achieve and maintain the required temperature set-point is presented in the fine tuning process.

3.4.1.2 Fine-tuning of control algorithm applied in Air handling units with fan coil and fan speed control

The performance of the developed control algorithm is evaluated connecting it with a validated thermal model developed in TRNSYS environment for selected rooms in the paediatric department of Chania Hospitalin Chania (Figure 3- 18).



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

Figure 3- 18: 3d model and general characteristics of Chania Hospital, Chania – Greece

In Figure 3- 19, the proper operation of the developed controller is verified showing its adaptation on the change of temperature set-point. Moreover the indoor air temperature remains close to the set point regardless the changes of the outdoor temperature. The desired set-point of 24 °C is maintained although the outdoor temperature varies with time.

In order to perform an annual evaluation of the control algorithm connected with the developed thermal model a single function file is created in which the control algorithm is used with the following inputs:

- Name of the room, in order to load previous values
- Current presence indication
- Current temperature level

The output of the controller is:

- new operation level of the fan speed
- new operation level of the coils valve

The flowchart of the control algorithm is illustrated in *Figure 3- 20*.

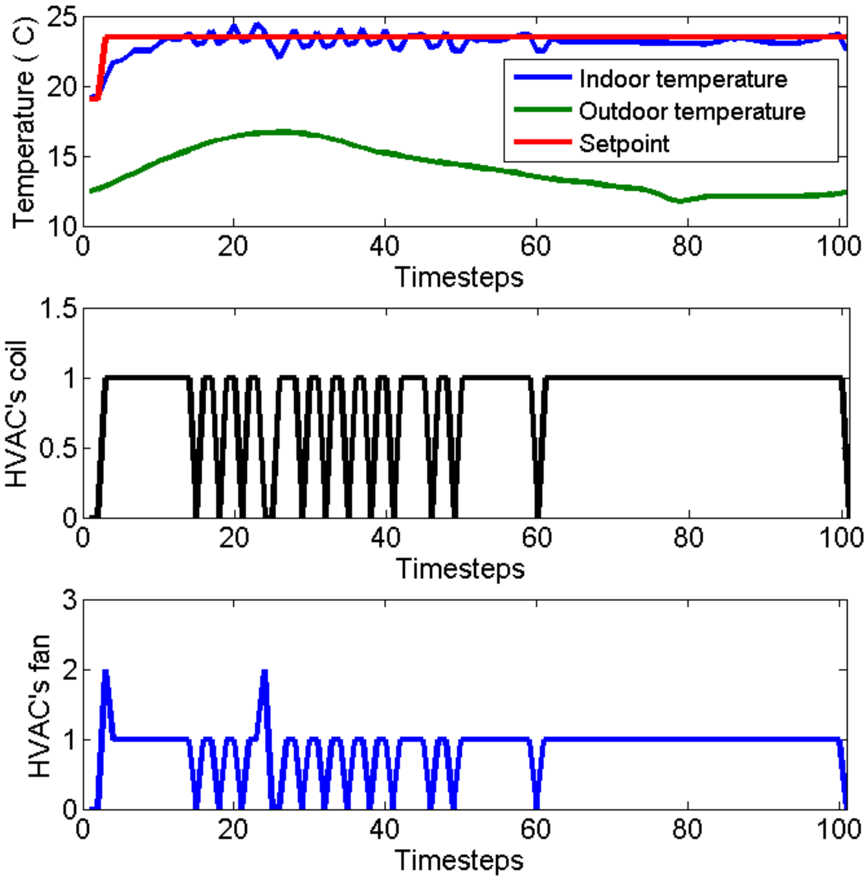


Figure 3- 19: Fine tuning of the control algorithm for Air handling units with fan coil and fan speed control

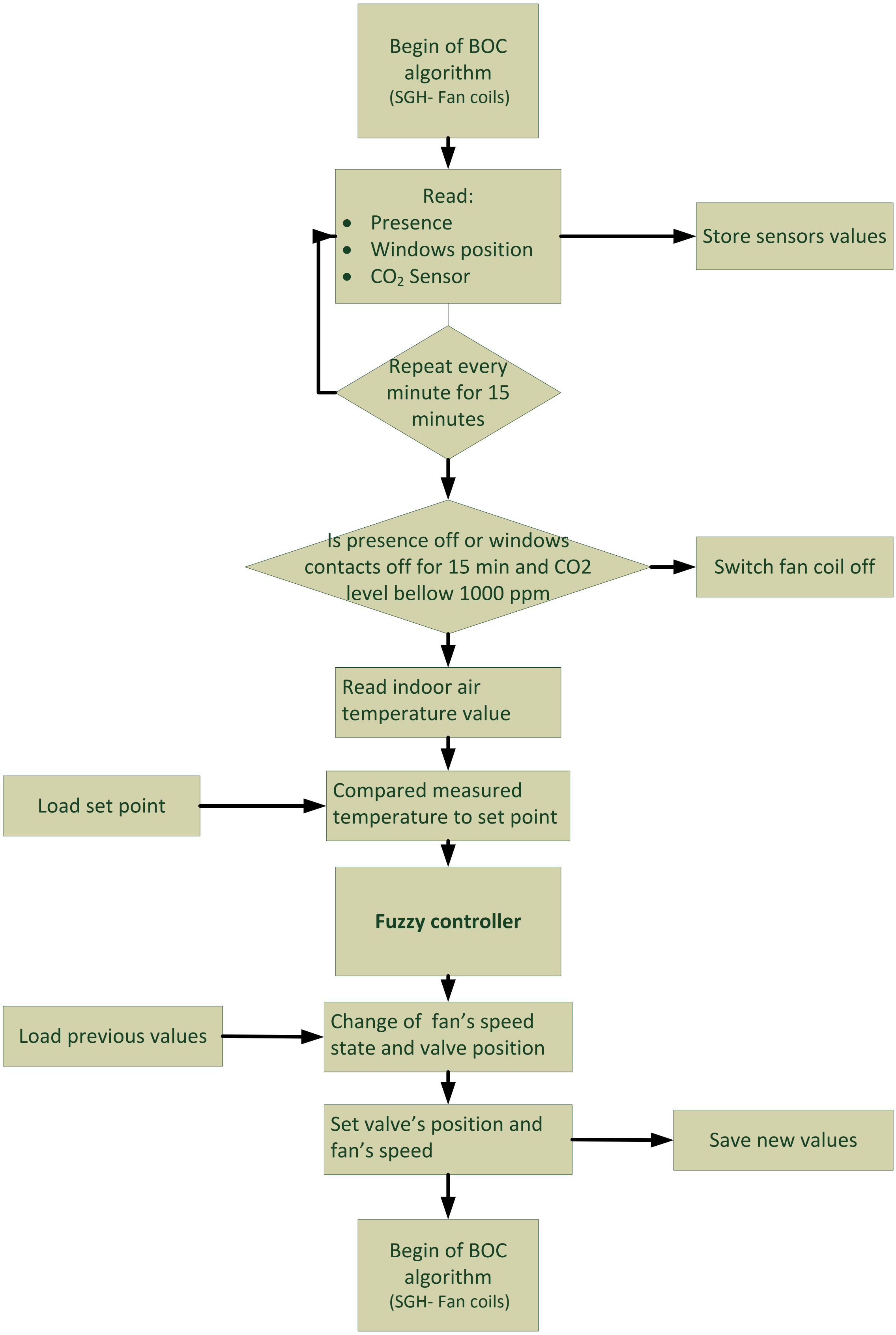


Figure 3- 20: Flowchart of the control algorithm for the Air handling unit, Chania Hospital, Chania

Comparing the operation of the air handling unit in the paediatric department using the developed controller (Figure 3- 22) and the operation of the air handling unit based on users operation (Figure 3- 21), it can be seen that indoor air temperature is maintained and energy demand is reduced.

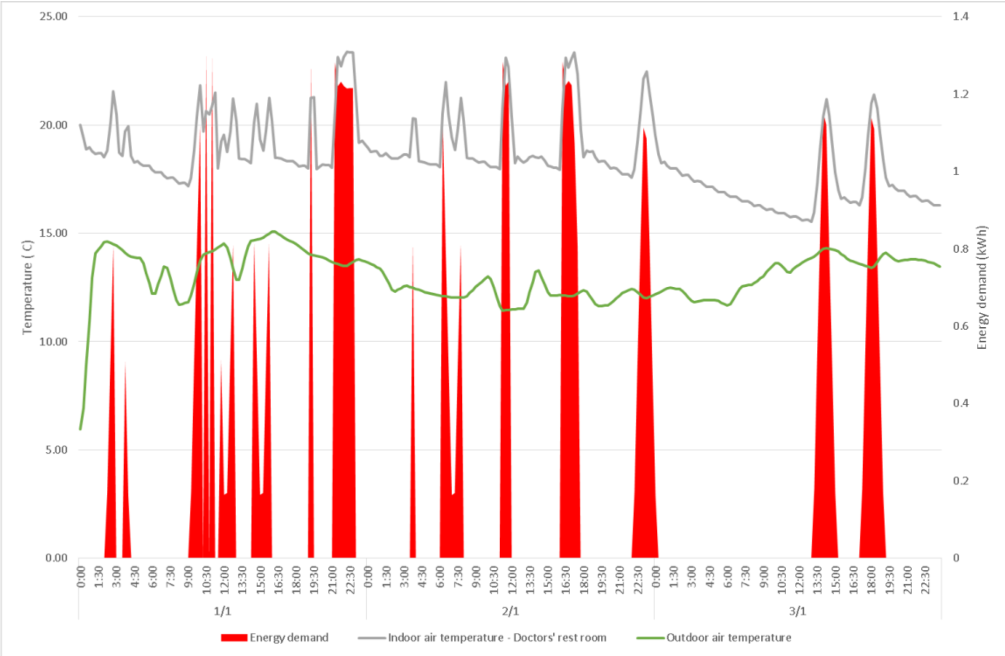


Figure 3- 21: Indoor air temperature and heating energy demand for doctor's office operating based on users' commands

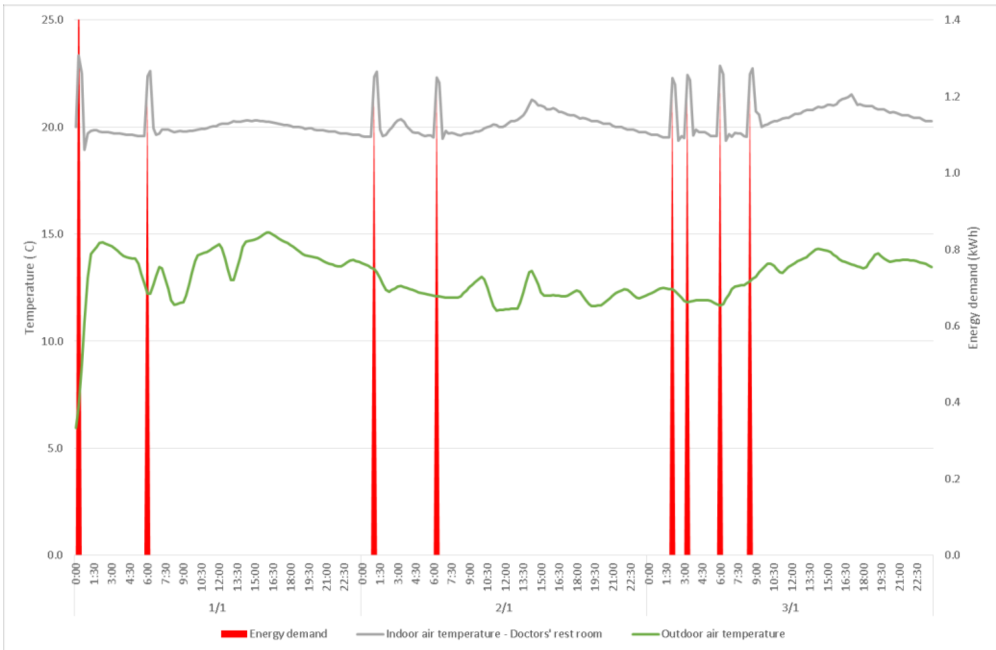


Figure 3- 22: Indoor air temperature and heating energy demand for doctor's office operating based on the commands of the fuzzy controller

The annual energy efficiency potential of the control algorithms (*Table 3- 7*) is estimated by comparing the energy consumption based on the users wishes and the energy consumption based on the commands sent by the developed control algorithms.

Table 3- 7: Primary energy and energy efficiency potential of the AHUs in Chania Hospital, Chania

	Heating (kWh)	**Cooling (kWh)**	**Total (kWh)**
Current condition	4494.05	961.46	5455.5
Matlab BOC	1428.1	2073.28	3501.4
% Energy efficiency	68.22 %	-115.6 %	36 %

--Chapter 4 ---

DEVELOPMENT OF IDENTIFICATION ALGORITHMS

4 Development of identification algorithms

4.1 Introduction

The aim of the present chapter is to describe the development of identification algorithms which will be used to estimate in advance the indoor conditions of the selected solution sets. This corresponds to Phase 2 of the research methodology depicted in Figure 1- 2.

While the on-line control systems can react only to the actual building conditions a model-based predictive control can move forward in time to predict the buildings reaction to alternative control schemes. Therefore different control scenarios can be evaluated based on suitable objective functions and create a control state space that corresponds to a buildings performance space.

Although the developed thermal models developed in Chapter 2 can be used, identification algorithms are selected which estimate the indoor conditions of the rooms without analysing the physic laws which imply. Identification algorithms are selected over the thermal models because:

1. The execution time is less compared to the thermal models
2. Identification algorithms adjust their parameters to their latest acquired measurements compared to the thermal models which may require to be re-verified.
3. Identification algorithms can be integrated to an existing BEMS as it is a combination of linear and non-linear equations.

A model can be either a “black box” or a “physical” model. In the “black box” or non-physical model approaches, self-learning algorithms, reinforced learning (Dalamagkidis and Kolokotsa, 2007) or neural networks (Kolokotsa et al., 2003) are some of the methodologies found in the literature. The benefits of the mentioned approaches are low computational time and the fact that they do not require any specific building modelling expertise, while their limitations are that on the one hand neural networks require reliable training data that may not be available and on the other hand self-learning algorithms cannot move beyond the limits of their experience. When physical models are utilized, the expert has the opportunity to understand the cause-and-effect relationship between the various building components, the control strategies and the climatic conditions. The physical models approach can use stochastic mathematical models (Loveday et al, 1992) or simulation-assisted predictive control (Clarke et al, 2004). Some physical models though require high computational skills and effort. For this reason integration of whole-building thermal models with (cognitive-based) control is quite interesting and with significant potential – see (Spindler et al, 2009a and Spindler et al 2009b) for some efforts.

Adaptive control has been developed for decades, and now it has become a rigorous and mature discipline which mainly focuses on dealing with uncertainties in control systems. Since adaptive control usually involves adaptive estimation algorithms, it can deal with relatively large uncertainties and gain flexibility to fit the unknown system, therefore playing a role of "learning" in some sense (Ma et al, 2009).

The adaptive control systems in solar buildings are used to modify the controller dynamically during its operation, i.e. adjusting the controller to building users preferences, modifying the control actions so as to fit to specific operational usually predefined performance

As an example of the above, a bilinear model-based predictive control is proposed by (Kolokotsa et al., 2009a), so as to achieve optimum indoor environmental conditions while minimizing energy costs by the prioritization of natural ventilation for cooling, shading regulation for optimum daylight utilization and window operation for a building energy management system. Bilinear models are developed for the thermal comfort, visual comfort and indoor air quality where the indoor temperature, relative humidity, indoor carbon dioxide concentration and indoor illuminance behaviour are modelled. The least squares estimation is performed separately for each actuator that influences the corresponding environmental parameter by putting the BEMS in continuous operation mode for at least 48 hours.

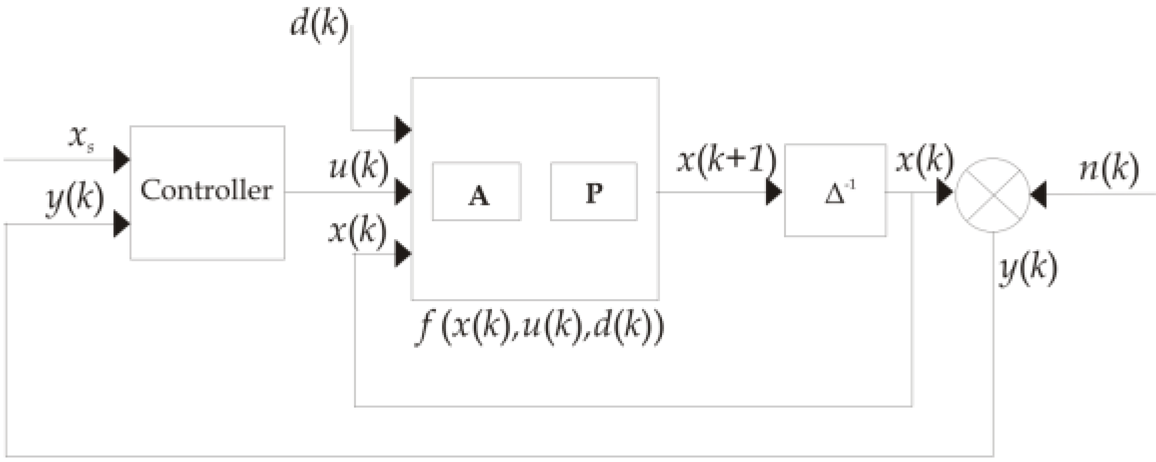


Figure 4- 1: Model based predictive control for indoor comfort and energy efficiency regulation (Kolokotsa et al, 2009)

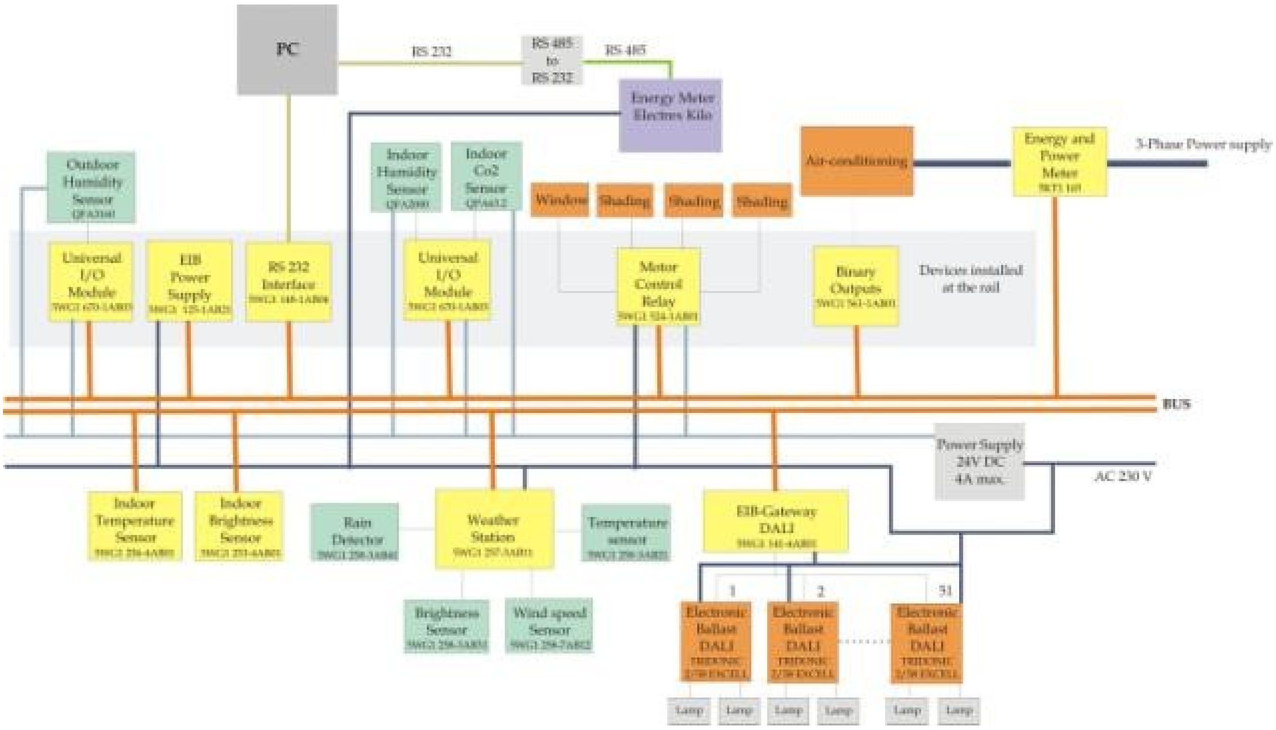


Figure 4- 2: The bilinear model based predictive control BEMS architecture (Kolokotsa et al, 2009)

4.1.1.1 Development of neural networks

Thermal models are developed to predict the indoor conditions of buildings based on the external conditions and the operation of the HVAC systems. The developed thermal models require significant computational power and execution time. The optimization algorithms presented in Chapter 5 require continuous and multiple simulations of the models, selecting different configurations of the systems. Thus, the computational time would be significantly high. On the other hand, other techniques such as neural networks which are part of the identification algorithms run very fast (less than a second to execute) and require very small computational power.

Neural networks are used due to their adaptive nature to collected measurements. Artificial Neural Networks (ANN) is an attempt to approach the operation of the human brain. The topology of the ANN is based on the architecture of biological neural networks found in the human brain. In a single neuron (Figure 4- 3), the input data is multiplied by the weight factors and they are summed up. The sum of the values is used as an input of the transfer function which can be either “linear transfer”, “sigmoid” or “threshold”.

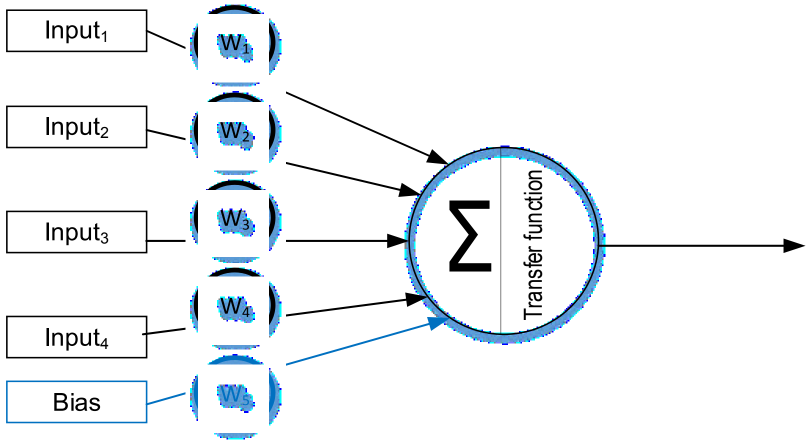


Figure 4- 3: Architecture of single neuron

A combination of neurons creates a network and the neurons are organized in layers. A neural network consists of 3 types of layers, an input layer where the data is inserted to the neural network, the hidden layer which contains numerous neurons according to the programmer and the output layer, where all the neurons output from the last hidden layer are connected to the exit of the neural network.

Figure 4- 4 shows the structure of a typical feedforward ANN; discern the inputs, the input layer, the hidden layer, the output layer and the outputs. Each neuron has many inputs but only one output which in turn can provide input for other neurons. The connections between neurons differ in their importance through a weight factor. The processing of each neuron is determined by the transfer function that defines each output in relation to the inputs and rates of the weight. To be used, a NN first must be trained. Learning consists in determining the appropriate weight factors and biases of the NN to perform the desired calculations, which is performed using algorithms known as learning rules-algorithms. The role of weight coefficients can be interpreted as a store of knowledge which is provided through collected measurements. In this way the NN learn from their environment, the physical model that provides the data.

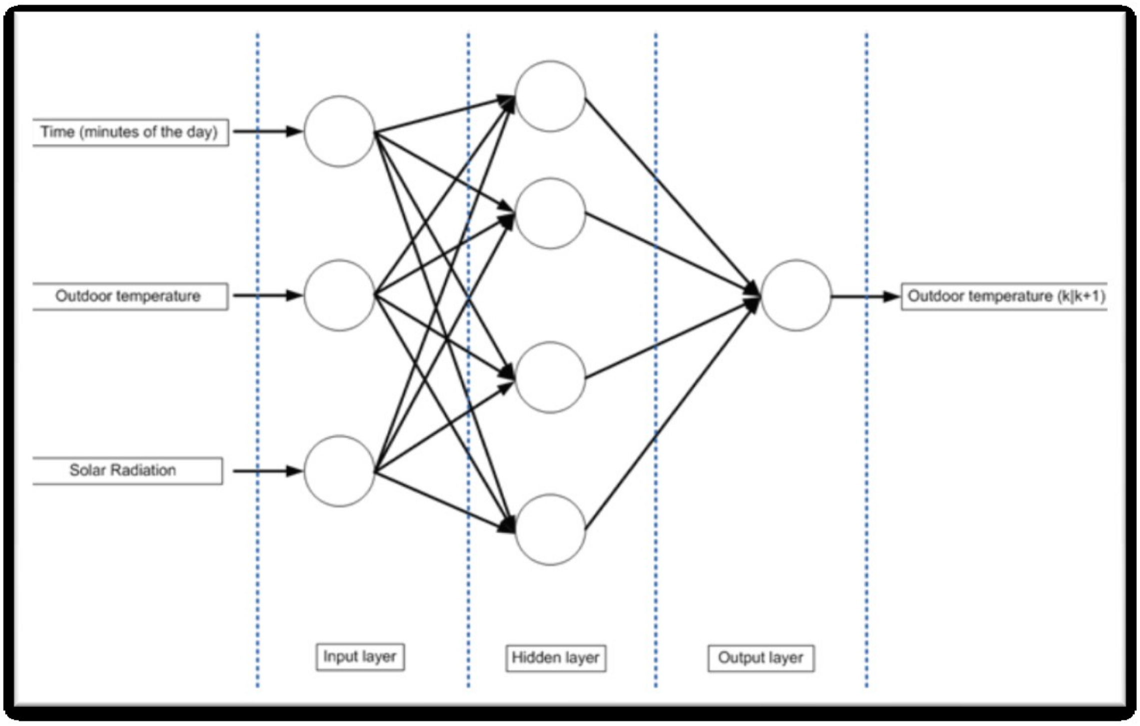


Figure 4- 4: Architecture of a feedforward Neural Network

4.2 Development of neural networks for outdoor air temperature prediction

Outdoor air temperature prediction is necessary for the selected pilot hospitals since outdoor temperature expresses the main parameter of the environment which interacts with the pilot's hospitals building fabric.

Moreover, outdoor air temperature is used as an input parameter for the systems that are modelled in the pilot hospitals. Although outdoor temperature prediction from meteorological sites can be used, it should be noticed that the predictions of temperature apply to whole cities and usually varies from local measurements.

4.2.1 Properties of neural networks

A methodology has been developed for the prediction of outdoor air temperature using Artificial Neural Networks (ANN) for the cities of **Ancona (Italy) and Chania (Greece).**(Papantoniou and Kolokotsa, 2014) Historical data is obtained and used for training, validation and testing of the networks. The predictive horizon for outdoor temperature is selected to be: 4 to 24 hours. Specifically, for each city the following data is used by the networks:

- Time (minutes of day)
- Outdoor temperature
- Solar Radiation
- Wind Speed
- Relative Humidity

The required inputs for the city of Ancona were delivered in Excel form from AEA - Loccioni, while the data for the city of Chania was delivered in text form Atmospheric Aerosols Laboratory database located in the Technical university of Crete Campus (Simeonidis, 2012). All the data was transformed into Excel files which could be read by Matlab[1]. All the necessary inputs were imported in Matlab. For each city the pre-mentioned data is obtained for a specific period. The period and the reference of the data is mentioned in Table 4- 1.

Table 4- 1: Period and origin of weather data

City (Country)	Period of data	Origin
Ancona (Italy)	2011	AEA - Loccioni
Chania (Greece)	2006	Technical University of Crete

After the first pre-process phase, the data is saved in different files depending on the city and the predictive horizon of the network. Specifically since the ANN requires input and output parameters in order to train properly, an *output* variable is created containing the outdoor temperature values of the next time-step. For example, for a 4 hour prediction the 1st data of the output variable is the 9th data of the outdoor temperature variable.

[1] For this research tool Matlab v. 8.3.0.532 (R2014a) is used.

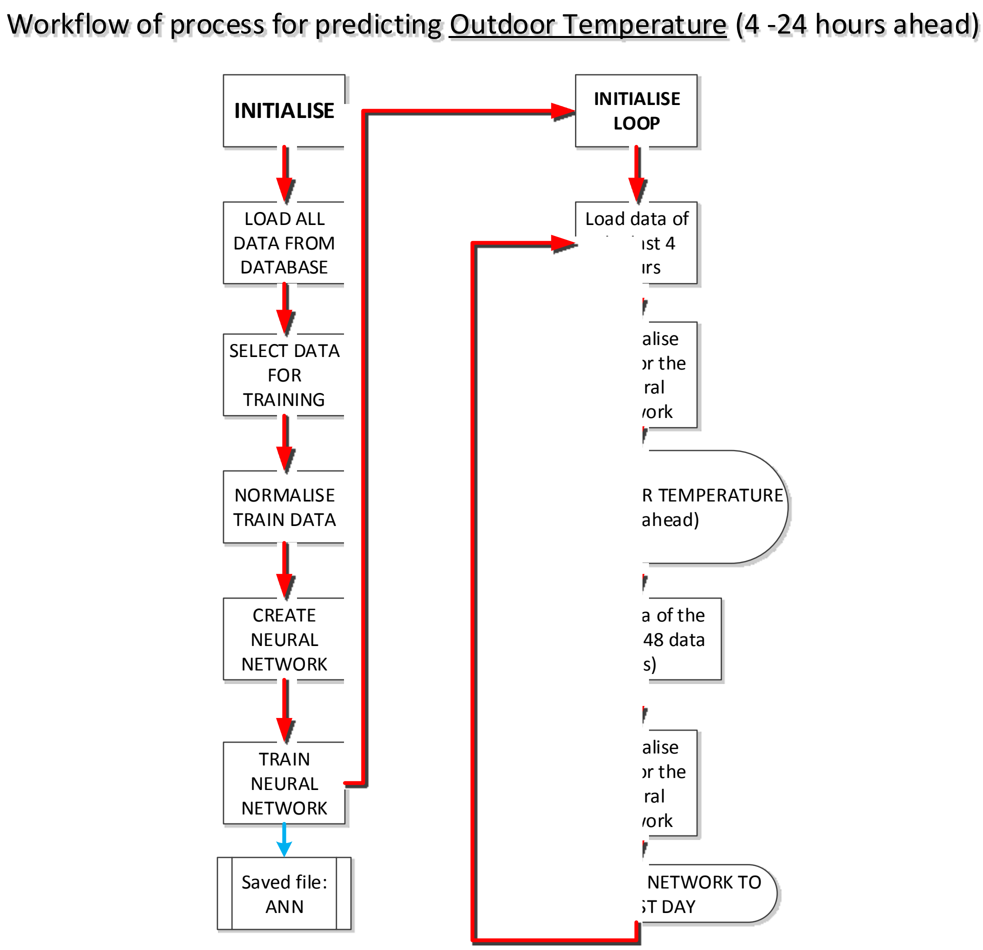


Figure 4- 5: Methodology for training and using the neural network for outdoor air temperature prediction

The selected properties of the neural networks (Table 4- 2) define its training process.

Table 4- 2: Parameters of the developed neural networks for outdoor air temperature prediction

Parameter name	Value	Description
Epochs	3000	Maximum number of epochs to train
Goal	0	Performance goal
Lr	0.01	Learning rate
lr_inc	1.05	Ratio to increase learning rate
lr_dec	0.7	Ratio to decrease learning rate
max_fail	40	Maximum validation failures
max_perf_inc	1.04	Maximum performance increase
Mc	0.9	Momentum constant
min_grad	1^{-10}	Minimum performance gradient

The transfer function used for the neurons is the "tan-sigmoid" transfer function with the following equation

$$a = \frac{2}{1 + e^{-2 \cdot x}} - 1$$

4.2.2 Evaluation of identification algorithms with actual measurements

The evaluation of the identification algorithms is performed with a data set which is not used in the training process nor the validation phase. This data is fed to the neural network and the prediction of outdoor air temperature is calculated for different predictive horizons. The properties of the neural networks are tabulated in Table 4- 3.

Table 4- 3: Properties of neural network used for outdoor air temperature prediction in the city of Chania and Ancona

Parameter	Description
Architecture of identification algorithm	Artificial Neural Network
Topology of identification algorithm	Elman/ Feed forward/ Cascade
Construction of the model	Black box
Number of inputs	3 - 5
Inputs	1. Outdoor air temperature T_in 2. Time (minutes of day) t 3. Solar radiation Rad 4. Relative humidity 5. Wind speed
Number of outputs	1
Output	Outdoor air temperature T_out (k+32|k)
Number of Hidden Layers	3
Size of Hidden layers	[3 5 3]
Performance function/ indicator	"Mean square error"
Size of initial train data set	1000
Number of epochs	3000
Number of maximum fails	3000
Predictive horizon	1 step (8 hours)

4.2.2.1 Outdoor air temperature prediction for the city of Chania

The aforementioned methodology is applied in the weather data of the city of Chania and the results are presented in this chapter.

The selection among different inputs and different neural network architectures for the city of Chania has been performed based on the comparison of the predicted values and the measured ones. Their difference should be minimized and thus the percentage of values with error less than 1 C has been calculated and plotted in Figure 4- 6. The plot indicates that the best performance is achieved by the Elman architecture with all the available inputs (Time of the day, temperature, radiation, wind and humidity).

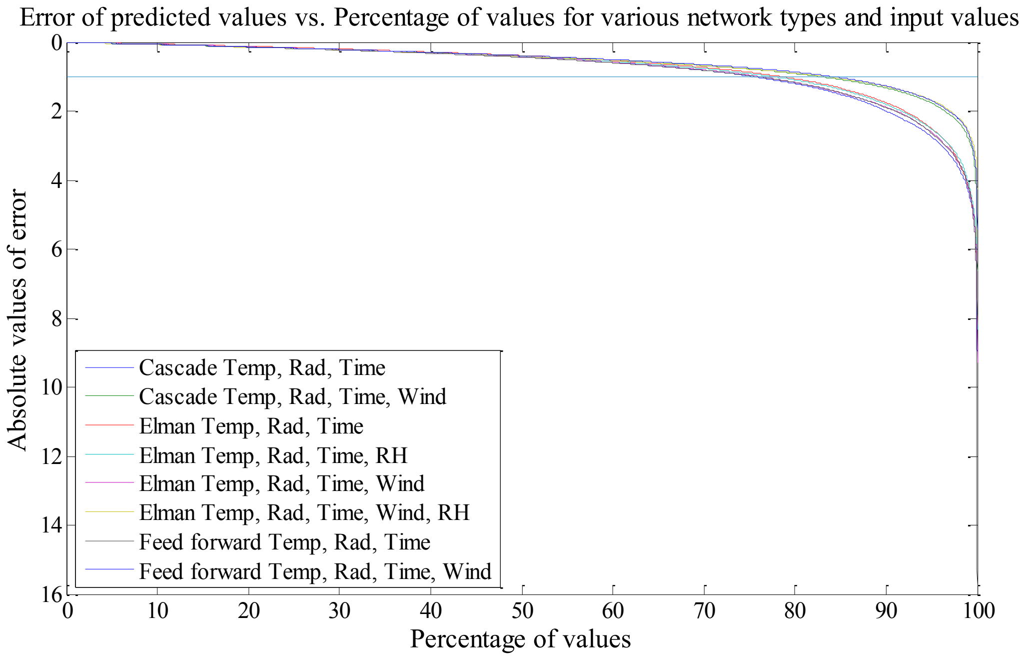


Figure 4- 6: Performance of different architecture and inputs in the prediction of outdoor air temperature for the city of Chania

The outdoor air temperature predicted under different predictive horizons using the aforementioned architecture and inputs and the measured values are plotted in Figure 4- 7.

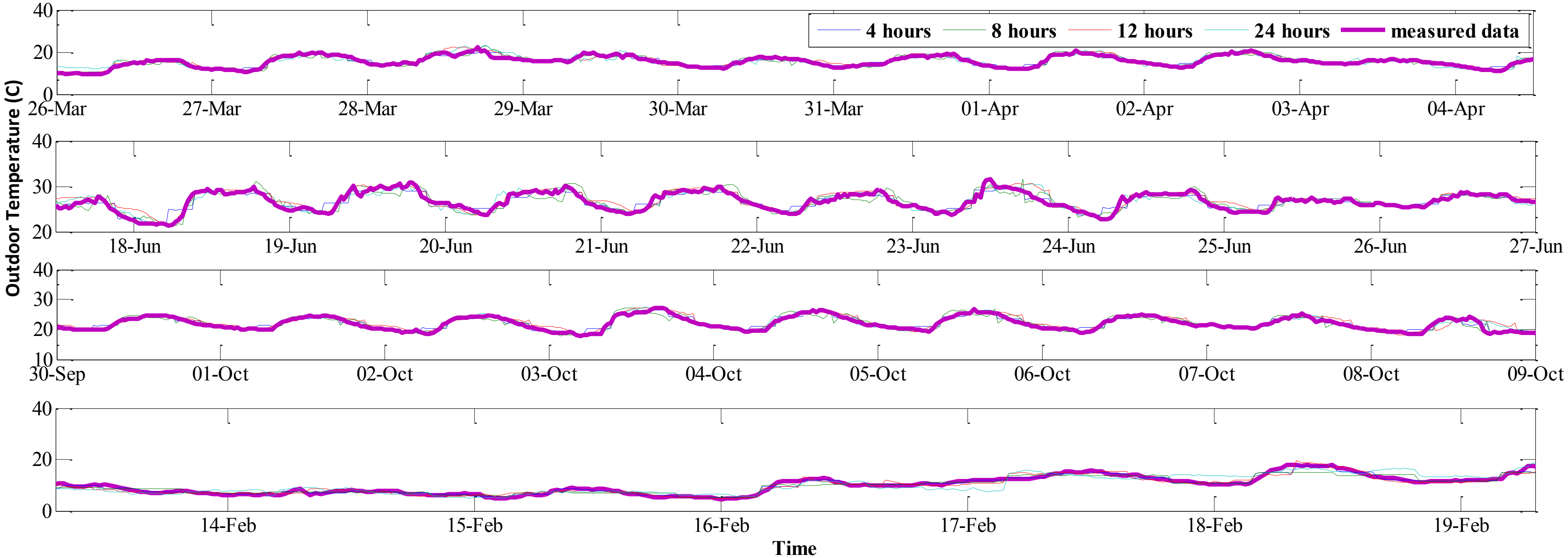


Figure 4- 7: Measured vs. predicted values for Chania (spring, summer, autumn)

As it can be seen in Figure 4- 7 all the predicted values follow the curve of the measured outdoor temperature for the 4 different seasons. Finally, on Figure 4- 8 the reader can see the comparison of predicted and measured values of outdoor temperature on an annual base for different predictive horizons.

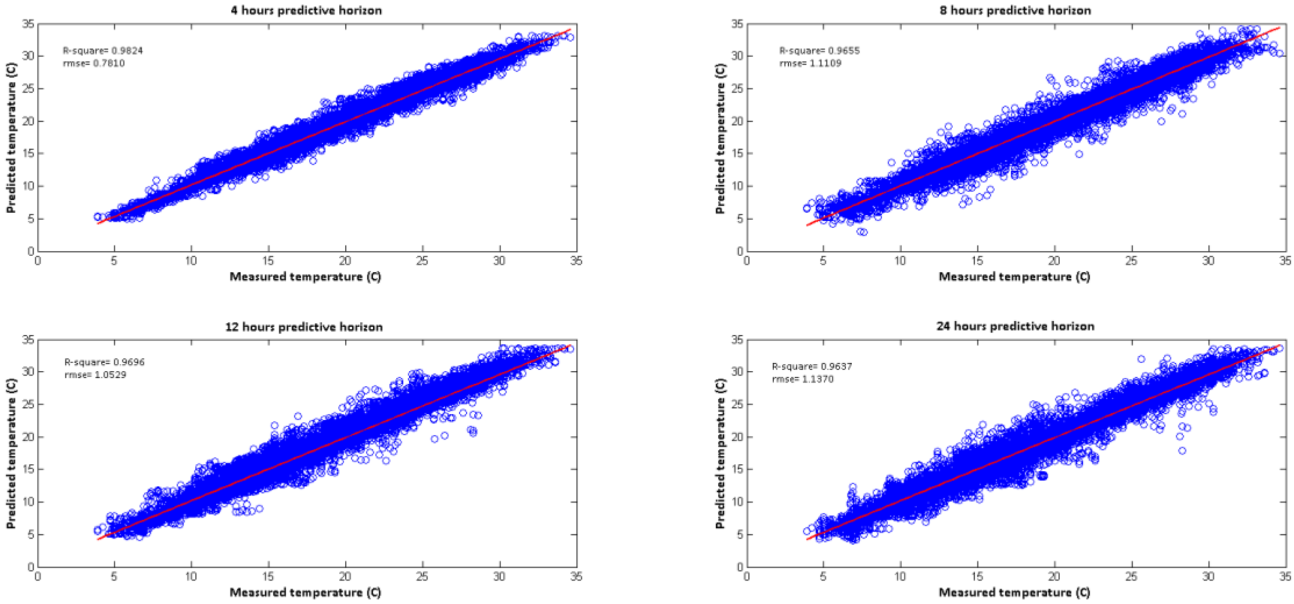


Figure 4- 8: Comparison of measured and predicted values of outdoor temperature for Chania

The regression plot (Figure 4- 8) shows that the neural network accurately predicts outdoor air temperature throughout the year. Analysing the statistical parameters of the overall performance of the neural network the R^2 values is above 0.95 for all the predictive horizon indicating an accurate prediction on an annual level (Table 4- 4). The RMSE is below 1 °C for 4 hours prediction and is around 1 °C for the other predictive horizons which indicate a very accurate prediction of outdoor air temperature.

Table 4- 4. Statistical analysis of annual performance of neural network for Chania - Greece

	Predictive horizon			
	4 hours	8 hours	12 hours	24 hours
R^2	0.98	0.97	0.97	0.96
RMSE	0.78	1.11	1.05	1.14

The results indicate that outdoor air temperature is predicted accurately using the neural network and it will be used as an input for predictive algorithms which require outdoor air temperature.

4.2.2.2 Outdoor air temperature prediction for the city of Ancona

The methodology is also applied for the prediction of outdoor air temperature in the city of Ancona. The comparison of the performance for different architectures and inputs is illustrated in Figure 4- 9.

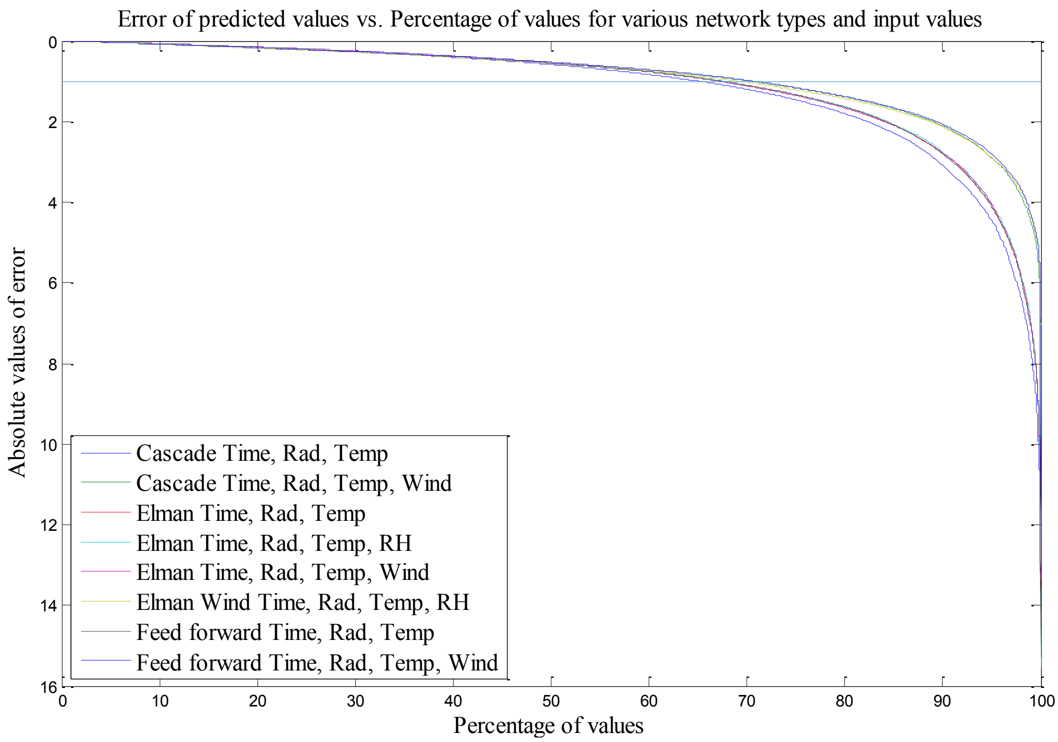


Figure 4- 9: Performance of different architecture and inputs in the prediction of outdoor air temperature for the city of Ancona

The comparison of measured and predicted temperature is illustrated in Figure 4- 10.

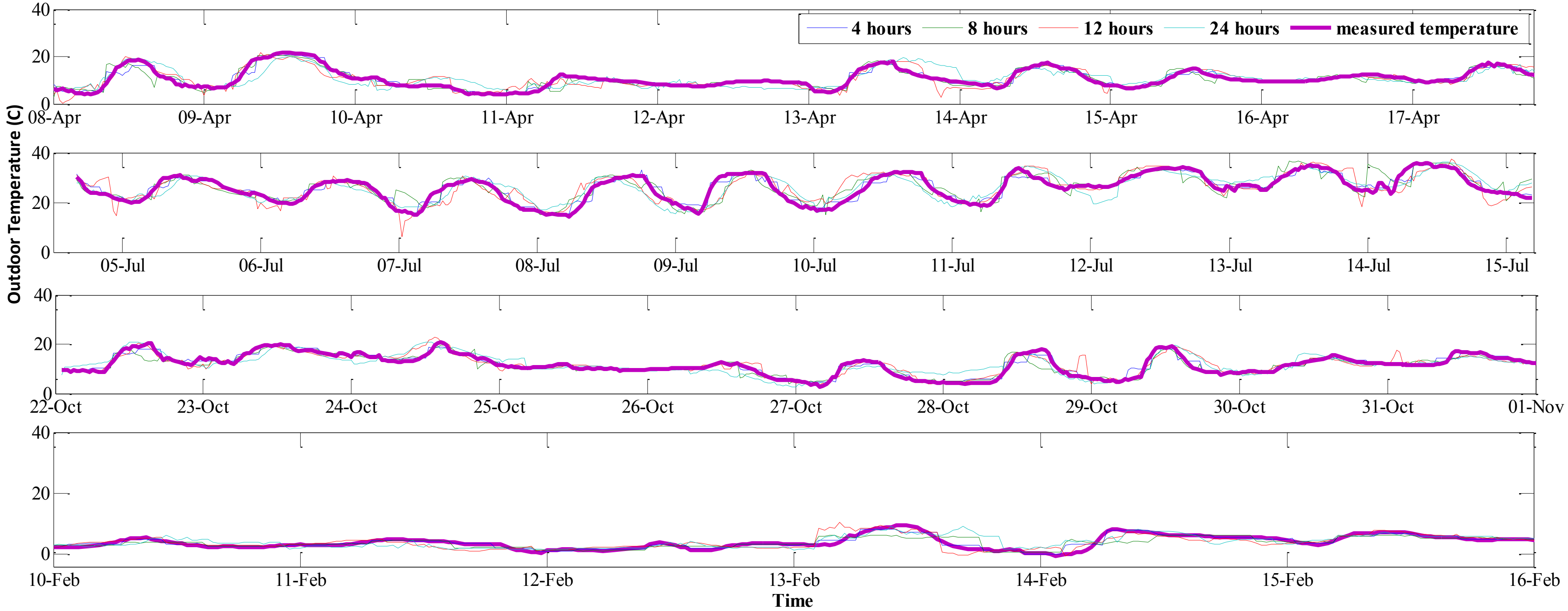


Figure 4- 10: Measured vs. predicted values for Ancona (spring, summer, autumn)

In Figure 4- 10 it can be seen that the results, for the different predictive horizon, the predicted temperature follow the curve of the measured one. Moreover, on Figure 4- 11 the reader can see the comparison (regression plot) of predicted and measured values of outdoor temperature on an annual base for different predictive horizons.

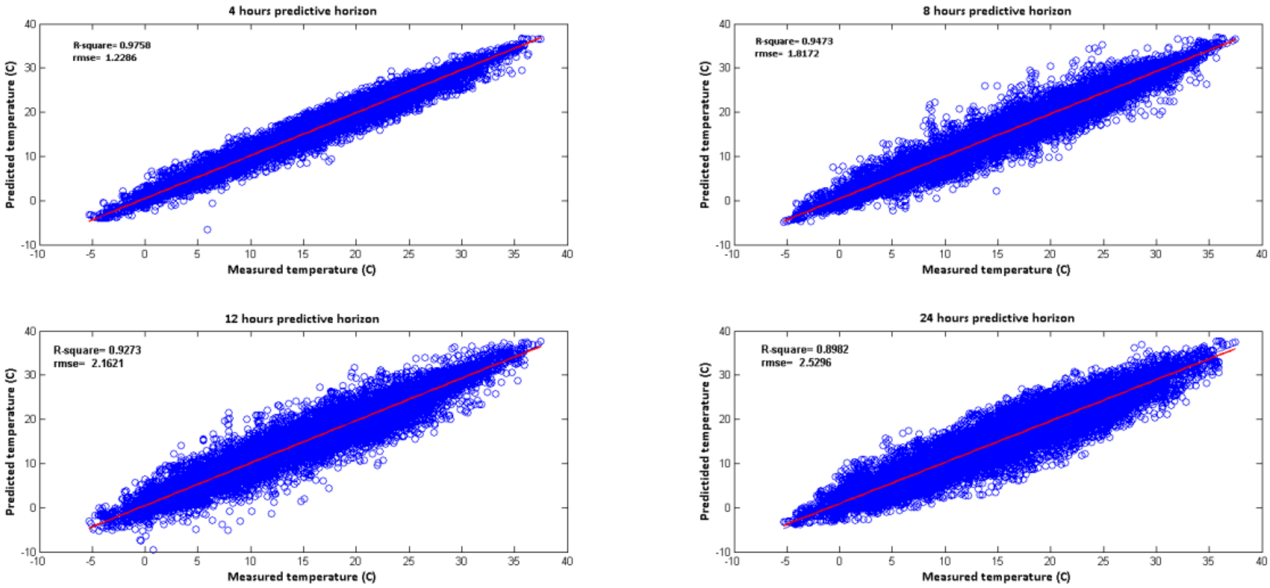


Figure 4- 11: Comparison of measured and predicted values of outdoor temperature for Ancona

The regression plot (Figure 4- 11) for the prediction horizon within 8 hours shows that the neural network accurately predicts the temperature including minimum and maximum values. The statistical analysis verifies the performance of the neural network. In Table 4- 5, the R^2 value is above 0.9 for all the predictive horizons which indicates that the predicted values fit the measured ones. The RMSE increases with the increase of the predictive horizon, but running the neural network repeatedly (every 4 or 8 hour) the error is not very significant.

Table 4- 5. Statistical analysis of annual performance of neural network for Ancona - Italy

	Predictive horizon			
	4 hours	**8 hours**	**12 hours**	**24 hours**
R^2	0.98	0.95	0.93	0.92
RMSE	1.23	1.82	2.16	2.13

The analysis of the results indicate that the neural networks accurately predicts outdoor air temperature for the 2 selected cities where the pilot hospitals are located.

4.3 Development of identification algorithms for indoor air temperature

The operation of the selected rooms in the paediatric department of the hospital of Chania is monitored using the equipment mentioned in Chapter 2. Monitored data is collected and stored locally. The data collected per room is illustrated in Figure 4- 12. A similar monitoring approach is followed for each room. The collected data will be used for development of the neural networks which will predict indoor air temperature. Part of the collected values are related to parameters that can be controlled based on the installed infrastructure. These parameters are tabulated in Table 4- 6.

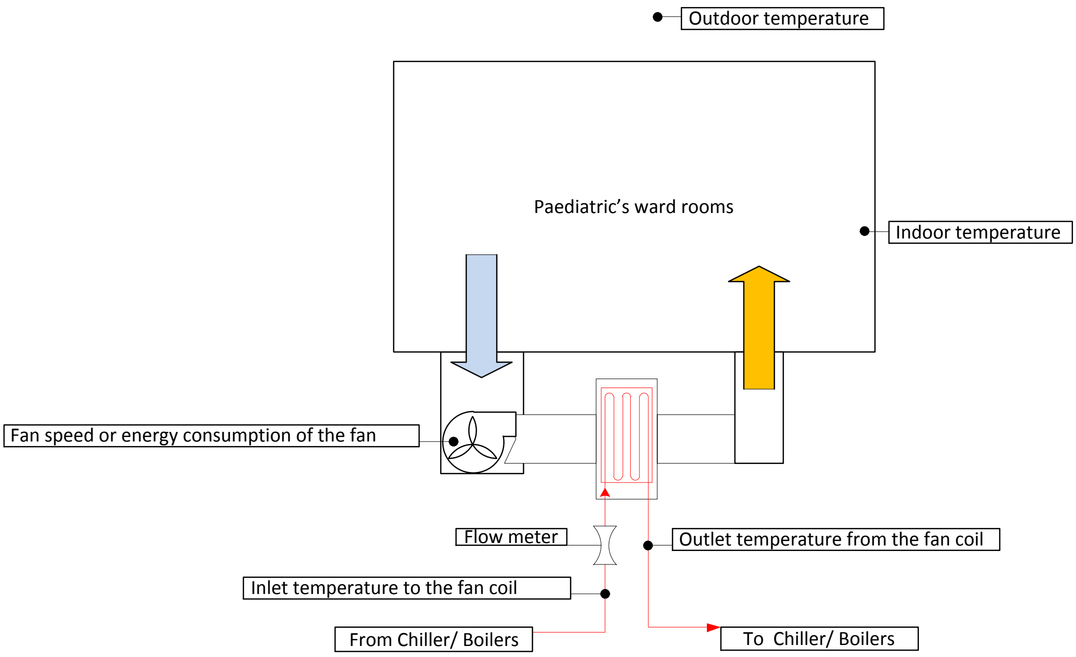


Figure 4- 12: Schematic description of the selected solution set of Chania Hospital

Table 4- 6: Controlled and uncontrolled parameters of the selected solution set (AHU – Chania Hospital)

Parameters	Values	Controlled/ Uncontrolled
Outdoor temperature	(°C)	Uncontrolled
Indoor temperature	(°C)	Controlled
Presence indication	(digital)	Uncontrolled
Windows contacts	(digital)	Uncontrolle

Parameters	Values	Controlled/ Uncontrolled
		d
Flow of coolant in AHU	(cu fit/min)	Controlled
Temperature of coolant entering the AHU	(°C)	Uncontrolle d
Temperature of coolant leaving the AHU	(°C)	Uncontrolle d
Energy consumption of fan of the AHU	(kWh)	Controlled

This data is used as input for a neural network which predicts indoor air temperature for the next time step (15 min) based on the current conditions ($T_{in(k+1|k)}$). Then the output of the algorithm is used as an input for the next time-step prediction (Figure 4- 13).

1.1.1 Properties of neural networks

The algorithm predicts 8 hours ahead which equals to 32 time-steps ahead. The parameters which are used for the development of the identification algorithms are selected based at first, on the operation of the system and second, their effect on the output variable which for the specific system is the indoor air temperature. The architecture of the specific identification algorithm can be seen in Table 4- 7.

Table 4- 7: Architecture of the predictive algorithm of Chania Hospital-AHU

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 T_in Time (minutes of day) t Energy transferred through open windows Windows*(T_in – T_out) Fan coil operation Coolant's flow*(Coolant temperature inlet – Coolant's temperature outlet) Fan coil's fan consumption
Number of outputs	1
Output	Indoor temperature T_in (k+1|k)
Number of Hidden Layers	3
Size of Hidden layers	[3 5 3]
Performance function/ indicator	"Mean square error"
Size of initial train data set	1000

Parameter	Description
Number of epochs	3000
Number of maximum fails	3000
Predictive horizon	1 step (15 min)

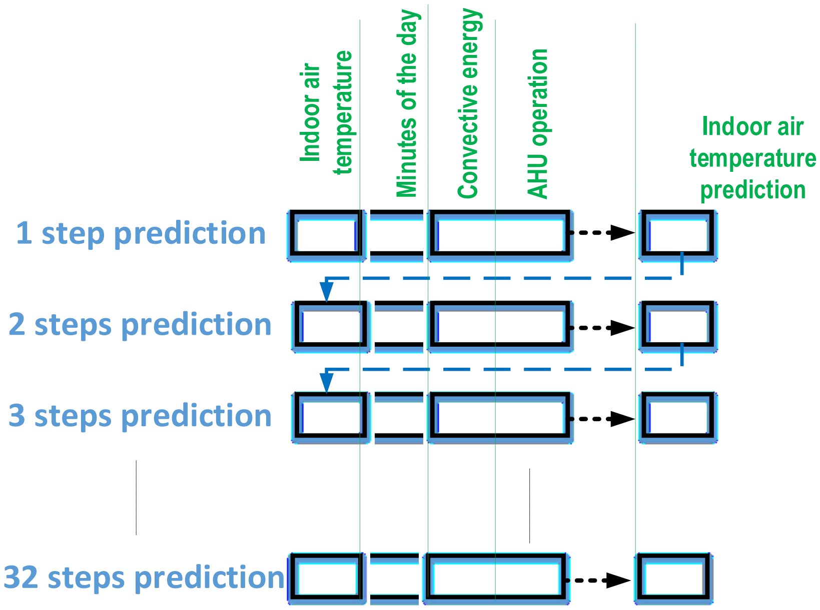


Figure 4- 13: Execution of the neural network with resupply of the predicted value as input

1.1.2 Evaluation of identification algorithm with measurements

The identification algorithms are trained with actual measurements collected from Chania Hospital. The first collection period started on the 17th of May 2013 and the reported algorithms were tested initially until 3rd of July 2013. During the training process, the data are separated into 3 categories:

1. Train
2. Validation
3. Test

The separation is performed by Matlab automatically using 70 % for training, 25 % for validation and 5 % for testing. Figure 4- 14, illustrates the training development of the neural network, which improves its performance continuously, until epoch 300, without performing overtraining of the neural network with the training set.

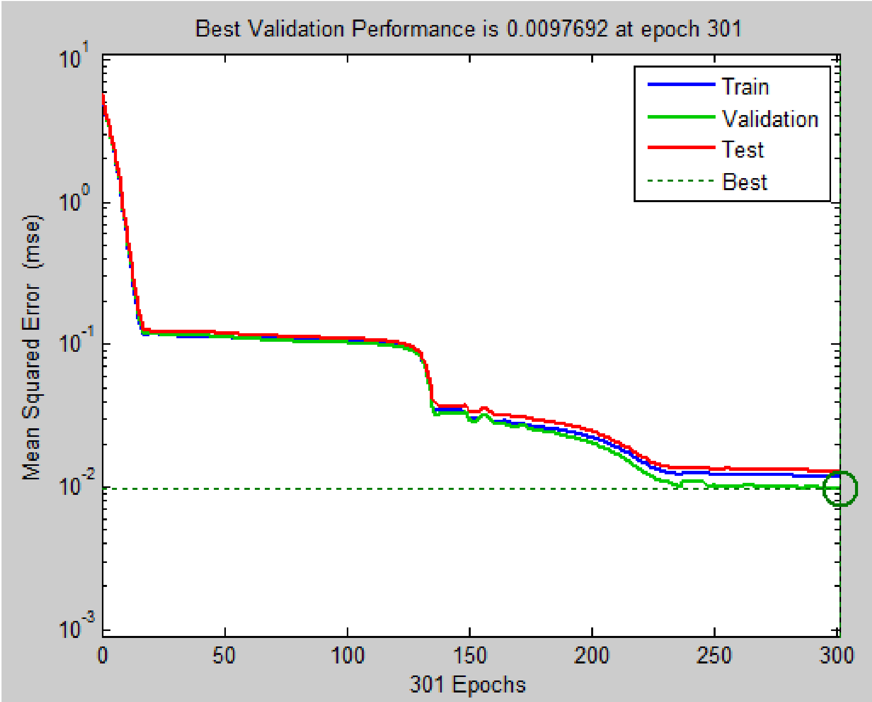


Figure 4- 14: Training process of the neural networks for the prediction of indoor air temperature

After the training of the model, it started to predict accurately indoor air temperature for the data presented to it. The output of the comparison is illustrated in Figure 4- 15, Figure 4- 16 and Figure 4- 17 for Doctors' room, Patients' room and Doctors' rest room respectively. The selected days represent typical days of summer period, for July until September of 2013.

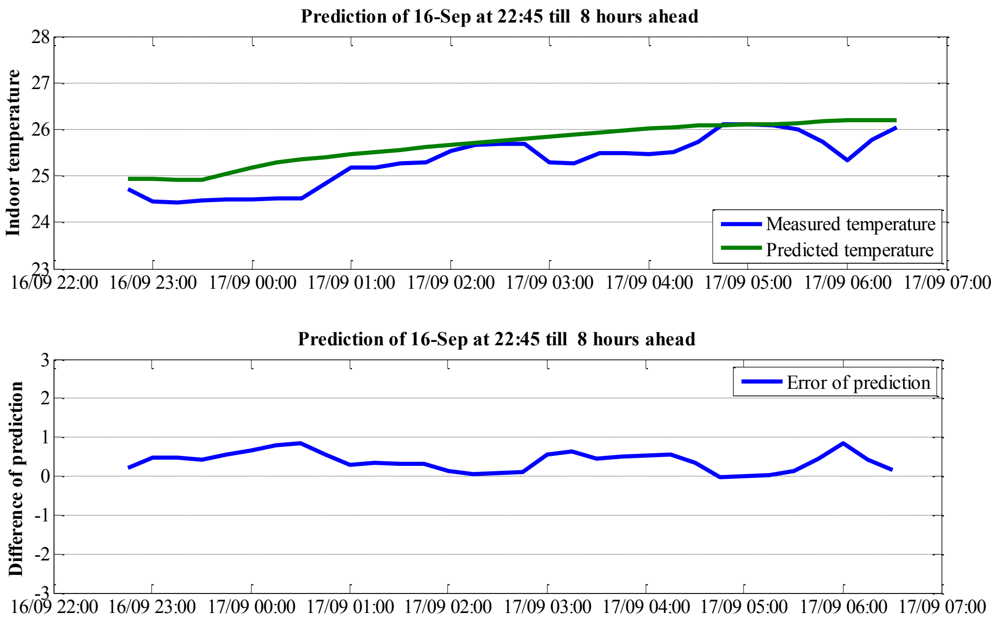


Figure 4- 15: Comparison of measured and predicted temperature for a predictive horizon of 8 hours (Patients' room)

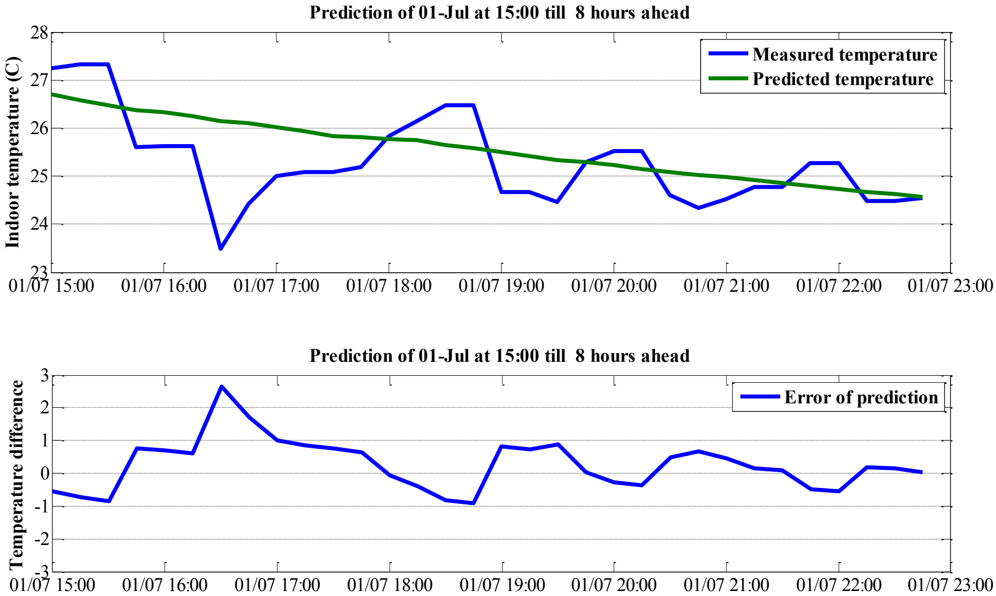


Figure 4- 16: Comparison of measured and predicted temperature for a predictive horizon of 8 hours (Doctors' room)

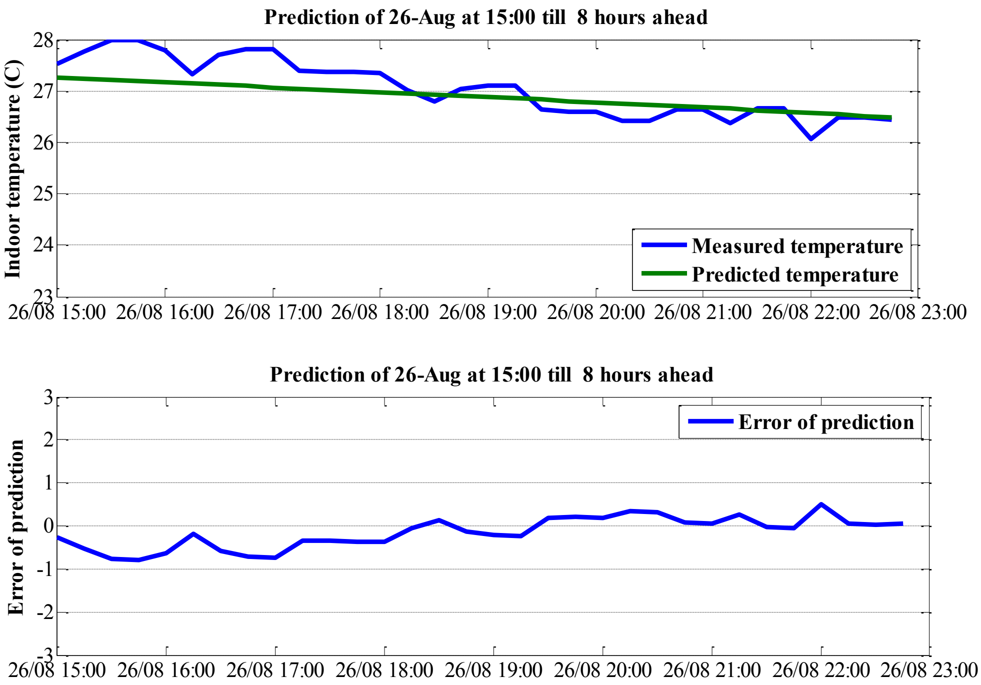


Figure 4- 17: Comparison of measured and predicted temperature for a predictive horizon of 8 hours (Doctors' rest room)

The aforementioned Figures illustrate the accurate prediction of indoor air temperature, considering current conditions, external conditions and the future usage of the AHU. The error of the prediction is less than ± 1°C, while the error of the temperature sensor according to the datasheet is ± 0.5 °C. The prediction of indoor air temperature will be used for the evaluation of possible operation conditions of the Air handling unit using the Genetic algorithms.

The neural networks for indoor air temperature prediction are evaluated and re-trained continuously. The retraining process is performed using the latest collected data from the selected rooms. During the training process the algorithm adapts its weights and biases to latest available measurements and predicts more accurately the latest conditions of the system. The comparison for the 3 selected rooms of paediatric department is presented in Figure 4- 18, Figure 4- 19 and Figure 4- 20 for Doctors' room, Doctors' rest room and Patients' room respectively.

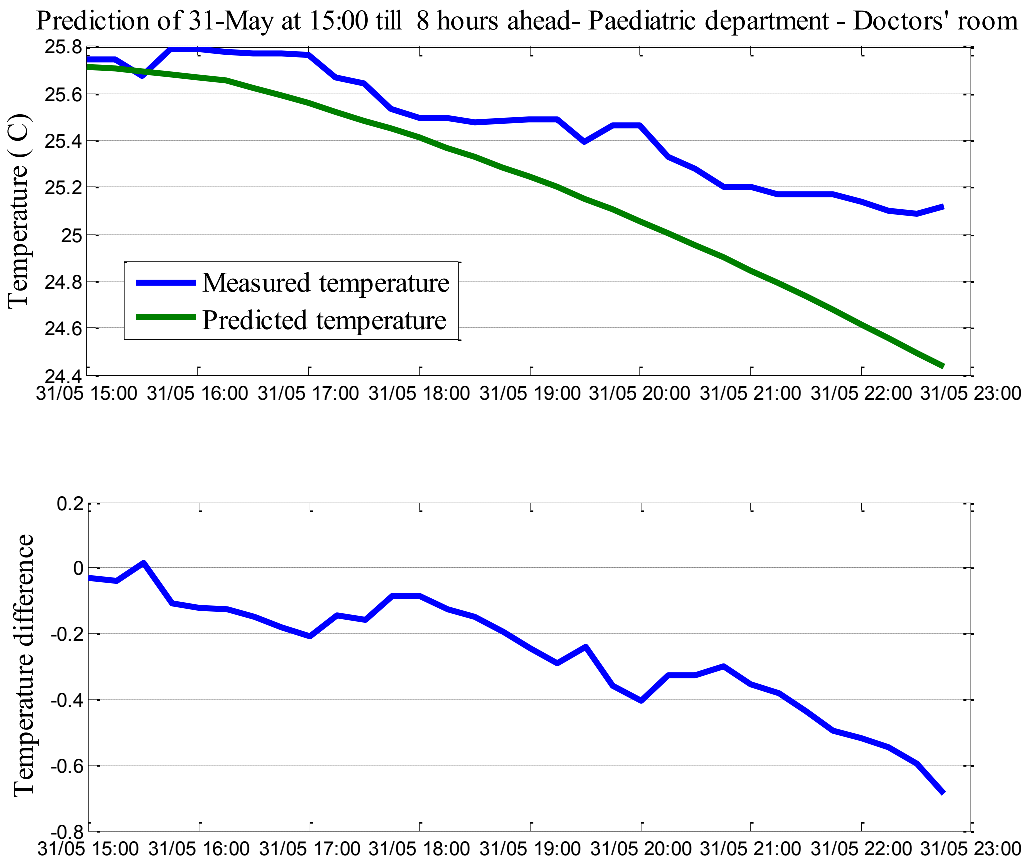


Figure 4- 18: Doctors' room 8 hour ahead prediction

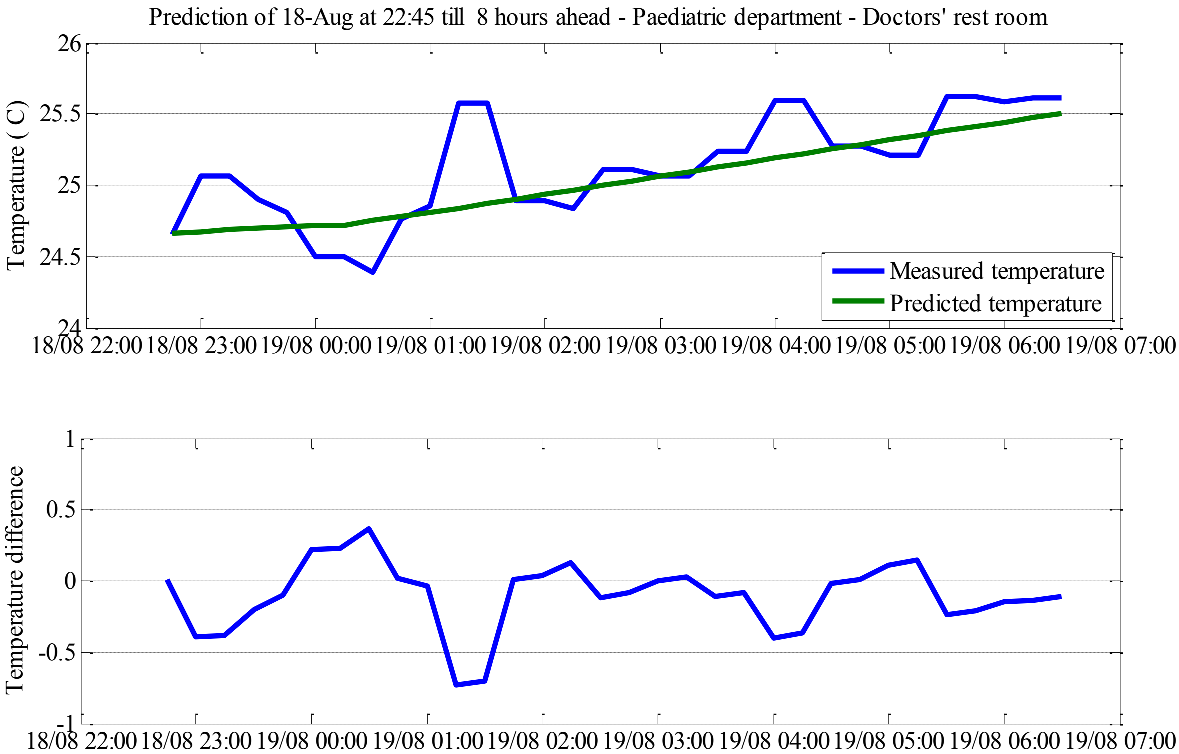


Figure 4- 19: Doctors' rest room 8 hour ahead prediction

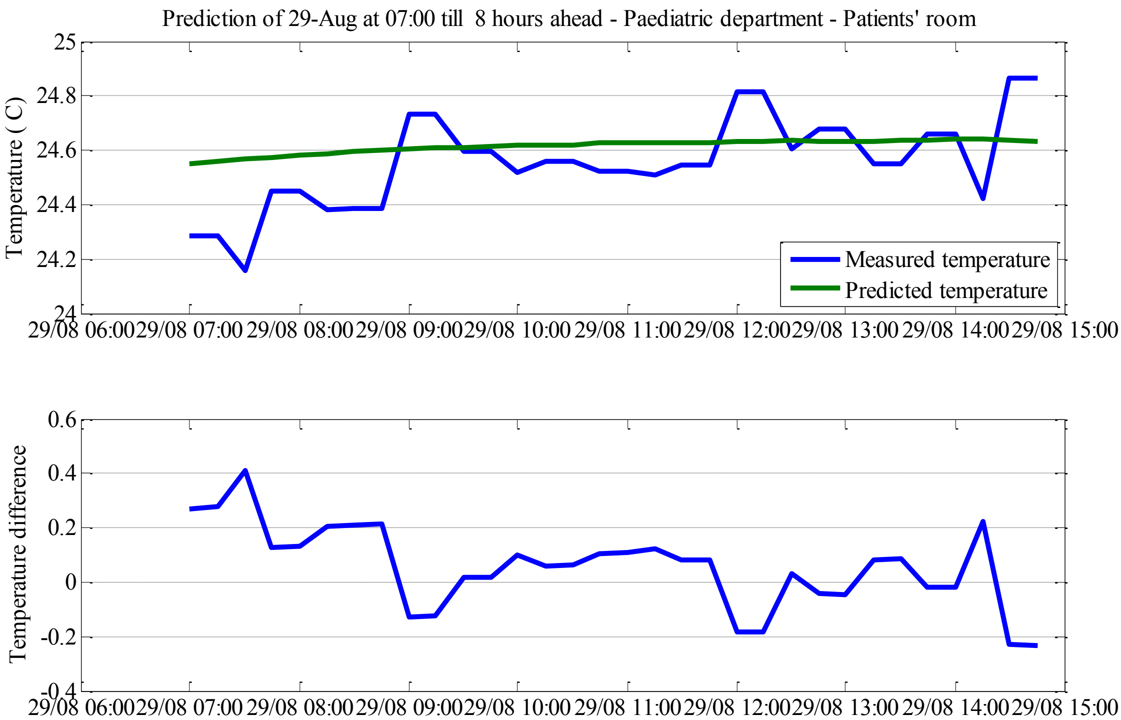


Figure 4- 20: Patients' room 8 hour ahead prediction

The illustration of predicted and measured data indicates that the re-trained neural networks predict indoor air temperature accurately. The error remains below ± 1 °C.

4.4 Development of control algorithm for data centers' cooling system using the prediction of outdoor air temperature

The data centre control system of Ancona Hospital allows the use of free-cooling when outdoor air temperature is reduced bellow a specific value. During free-cooling the chiller is switched off, and supply water temperature to the indoor units is cooled using the cooling capacity of outdoor air temperature.

However, in order to assure the proper operation of the in-row units the supply water temperature must be below 17°C. The developed BOC algorithm allows free cooling to start when supply water temperature is below 17°C. Supply water temperature is affected directly by the operation of the chiller. During the summer period, when the chiller operates, supply water temperature is maintained below 17°C and based on the controller presented free cooling starts. When outdoor air temperature is above 10°C, supply water cannot be cooled using free cooling and the chillers start again. This cycle of continuously starting and stopping the chiller causes problems that increase the maintenance cost of the cooling system.

The prediction of outdoor air temperature (Chapter 1.1.2) is used as a critical parameter of the BOC algorithm. Using the neural network developed for the prediction of outdoor air temperature the performance of the data centre's free cooling operation can be optimized. Outdoor air temperature is predicted for 8 hours ahead and if outdoor air temperature is below 10°C for more than 1 hour, free cooling is activated, otherwise cooling is provided from the chillers.

Its strategy can be seen in Figure 4- 21.

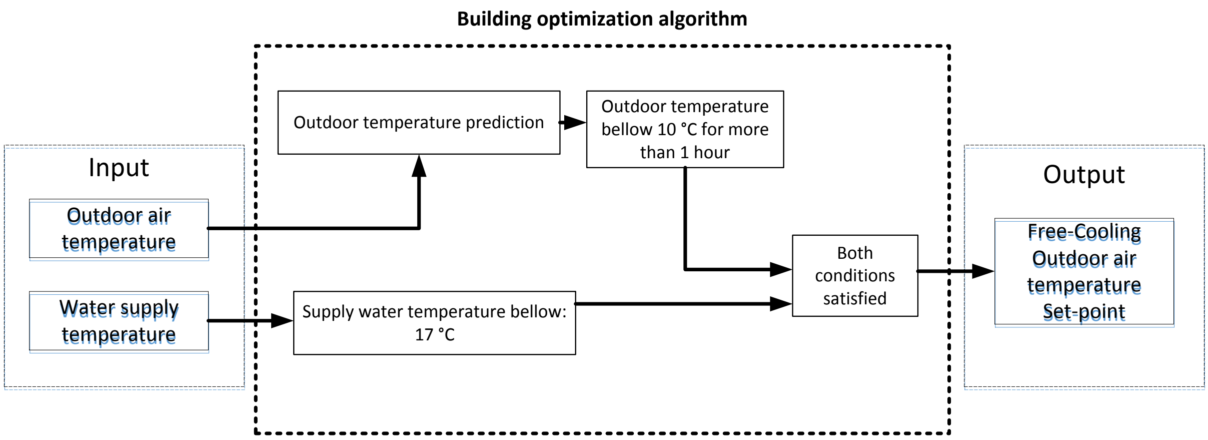


Figure 4- 21: Structure of the BOC algorithm for the chillers of Ancona Hospital Data centre

The BOC algorithm activates free cooling in periods when outdoor temperature allows free cooling to work for more than one step. Based on the analysis of simulation results, when outdoor temperature is below 10 °C free cooling can start without stopping at the next time-step due to supply water temperature limitation.

The implementation of the BOC algorithm is evaluated on the TRNSYS model concerning Ancona Hospital data centre. The BOC algorithm does not affect the operation of the system during the summer period because outdoor air temperature is always above 10 °C. The BOC algorithm prevents free cooling from starting. The operation of the chiller during the summer period a priori and a posteriori the implementation of the BOC algorithm is presented in Figure 4- 22 and Figure 4- 23. Both figures illustrate that the energy consumption and the PUE value are identical before and after the implementation of the BOC algorithm.

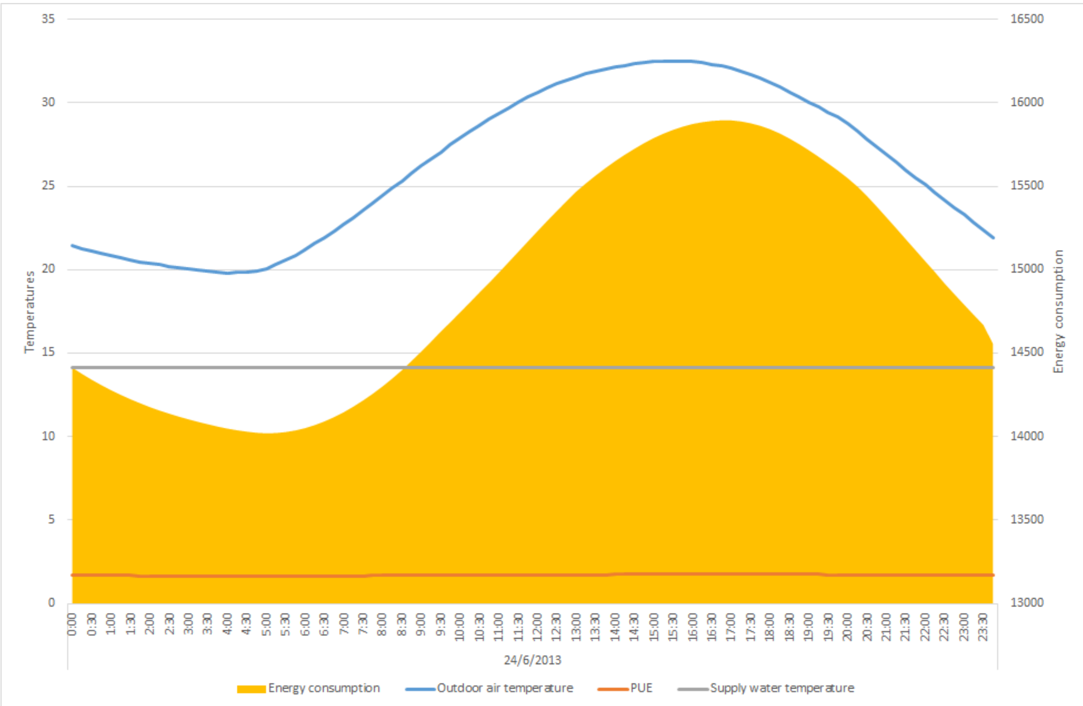


Figure 4- 22: Operation of the data centre's chiller during summer (current operation)

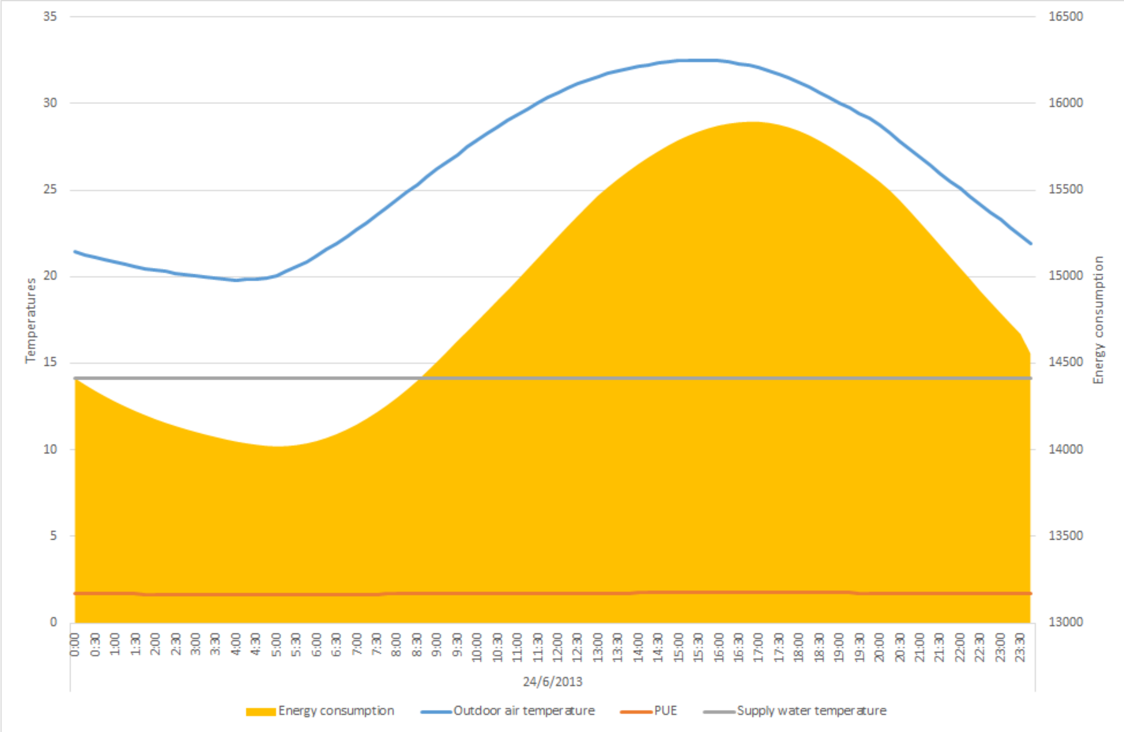


Figure 4- 23: Operation of the data centre's chiller during summer implementing the BOC algorithm

During the winter period, when outdoor air temperature decreases below 10 °C for some hours, BOC algorithm activates the operation of free-cooling. Figure 4- 24 illustrates the current performance of the data centre chiller for the 2nd of January. PUE factor is constantly 1.6, and supply water temperature is estimated at 14°C, although outdoor temperature drops below 10°C for many hours during the day.

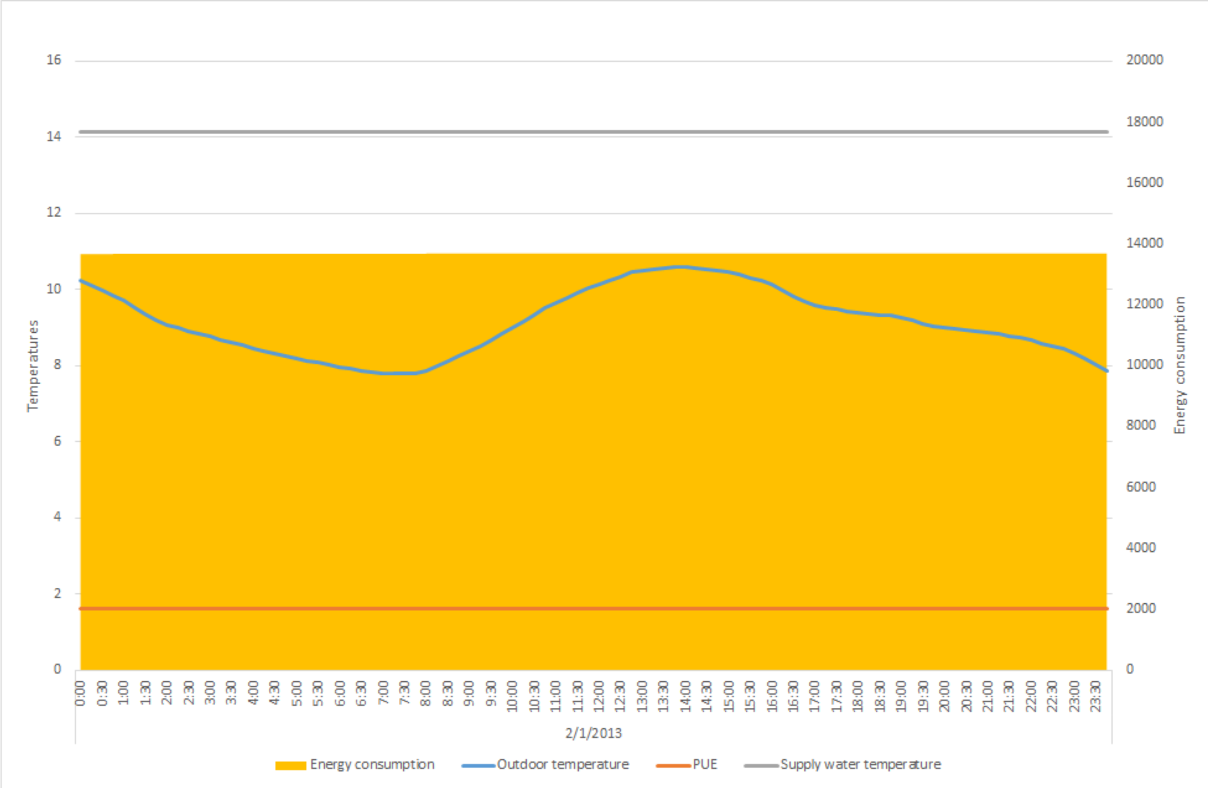


Figure 4- 24: Operation of the data centre's chiller during winter (current operation)

On the other hand, the BOC algorithm predicts outdoor temperature and if it decreases below 10 °C for more than 1 hour it allows free cooling to operate. In order to preserve the proper operation of the data centre, supply water temperature is measured and if the value exceeds 17 °C free cooling stops and chillers start again.

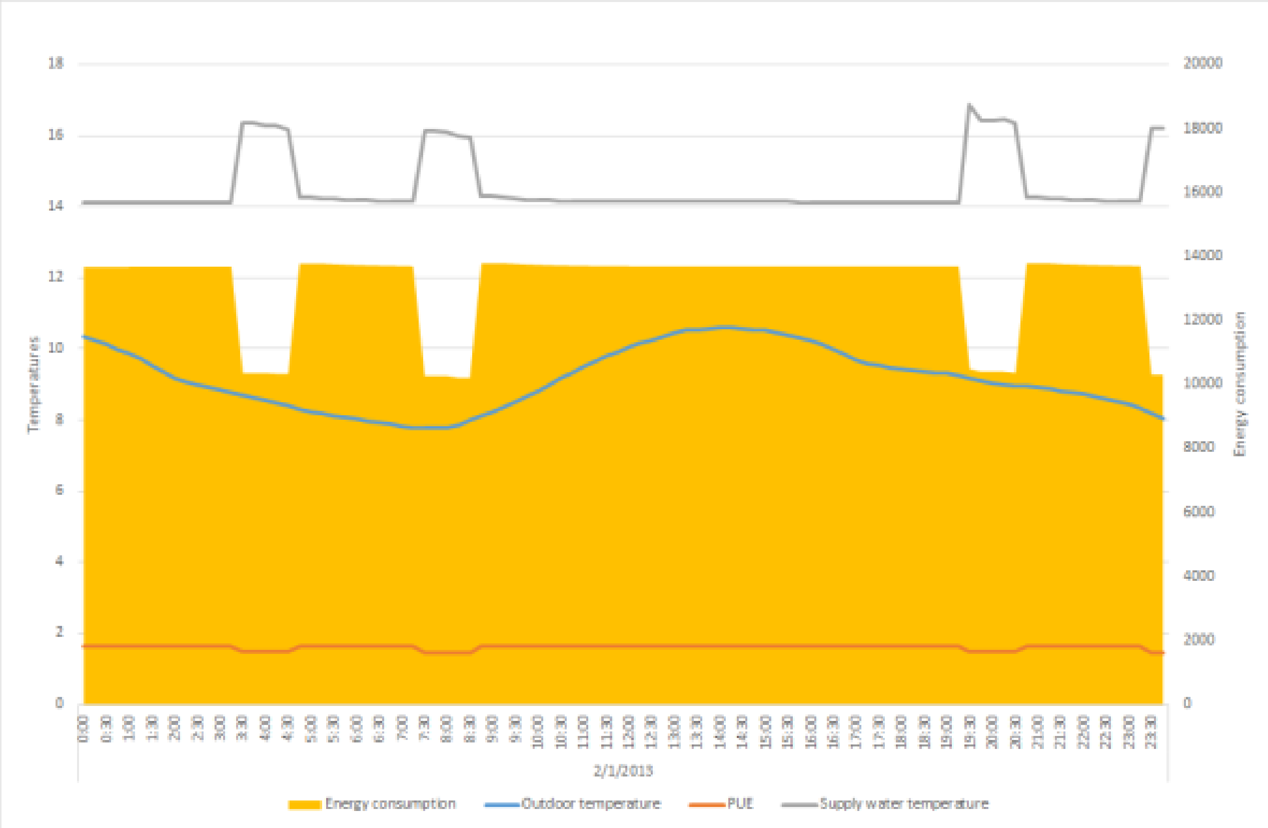


Figure 4- 25: Operation of the data centre's chiller during winter (BOC algorithm)

In order to obtain results for potential energy efficiency, the TRNSYS model coupled with the BOC algorithm runs for a year period and the results are presented in Table 1.

Table 1: Annual energy consumption and energy efficiency potential applying the BOC algorithm

Current annual consumption (MWh)	135.4
BOC algorithm consumption (MWh)	130.2
Energy efficiency potential (%)	3.8 %

Technical problems from the hospital of Ancona did now allow the integration of the developed BOC algorithms in the hospital facilities.

--------------------------------------<u>Chapter 5</u> ---

DEVELOPMENT OF OPTIMIZATION ALGORITHMS

5 Development of optimization algorithms

Buildings store thermal energy in their construction by increasing the temperature of the inner layers of the buildings' constructions. The stored energy is transferred to the air when the heating/ cooling system is switched off. Thus, part of the provided energy is stored in the construction when the Air Handling Units start (pre-heat period), and the building remains partly conditioned for a small period, depending on the construction, when the air handling units are switched off (Figure 5- 1).

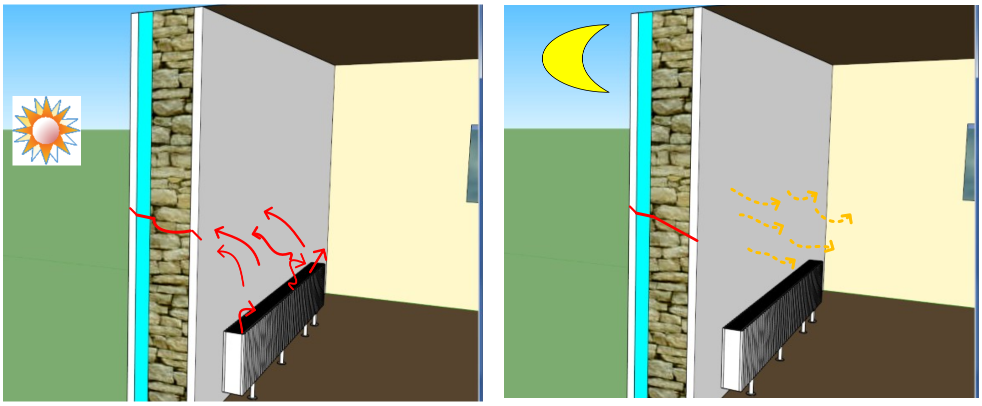


Figure 5- 1: Illustration of thermal storage in the building's fabric construction

Controlling the energy transferred from the construction to indoor air, the demand for heating and cooling can be reduced. The reduction of heating and cooling demand can be used to shrink the cost for operating the Air Handling Units during hours with potential higher cost of energy power (Provata et al., 2015).

An optimization algorithm selects the finest combination values for the operation of an Air Handling Unit which will reduce the energy consumption and the maximum power demand of the building, while maintaining indoor air temperature at the desired levels. The evaluation of the optimization algorithms potential output is performed using algorithms which can evaluate the effect of the selections and estimate the effect for indoor comfort and energy consumption. The output of the optimization algorithms is the selection of parameters which will minimize the overall cost of an objective function and the operation of the system under optimization.

The optimization algorithms are developed in the Matlab[2] environment following the work performed for the development of control and identification algorithms. The

[2] For this research tool Matlab v. 8.3.0.532 (R2014a) is used.

advantages of the latest versions of Matlab software is the parallel execution of the genetic code in multi-core computers and the utilization of the GPU for better performance. This corresponds to Phase 2 of the research methodology depicted in Figure 1- 2.

5.1 Development of optimization techniques for the Air handling units of based on genetic algorithms

The control algorithms developed in Chapter 3 for the air handling unit of the paediatric department of Chania Hospital, compare on-line the measured indoor conditions with a static set-point and adjust the operation of the Air handing units. Thus, the conditions of the selected rooms are maintained as desired. The optimization algorithms will change the static set-point with a dynamic one, which will be estimated from the optimization algorithm.

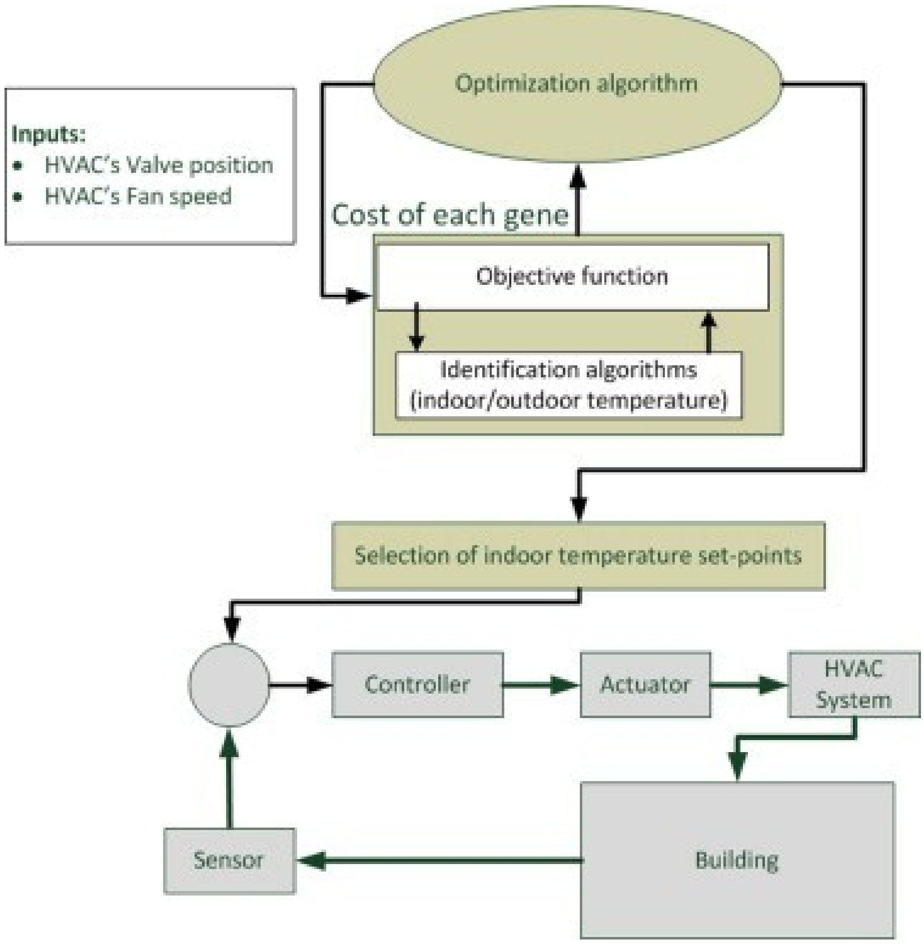


Figure 5- 2: Illustration of the operation of the optimization algorithm

The optimization algorithm runs every 3 hours to calculate the indoor air temperature set-points of the next 8 hours. The increased computational time required for the evaluation of the optimization algorithms mandates their execution off-line in order to avoid potential delays in the implementation of the control algorithms (Chapter 3) which run continuously.

5.1.1 Development of a user defined cost function

The prediction of indoor and outdoor air temperature using the neural networks developed in Chapter 4 will be used to assess the selection of the Air Handling Unit operation level.

The inputs of the identification algorithm are:

1. Outdoor air temperature
2. Indoor air temperature
3. Energy transferred from the windows
4. Operation of the AHU
5. Fan speed

The output is the prediction of indoor air temperature in the next time step (15 min ahead).

The developed identification algorithm is the core of the objective function which is illustrated in Figure 5- 3.

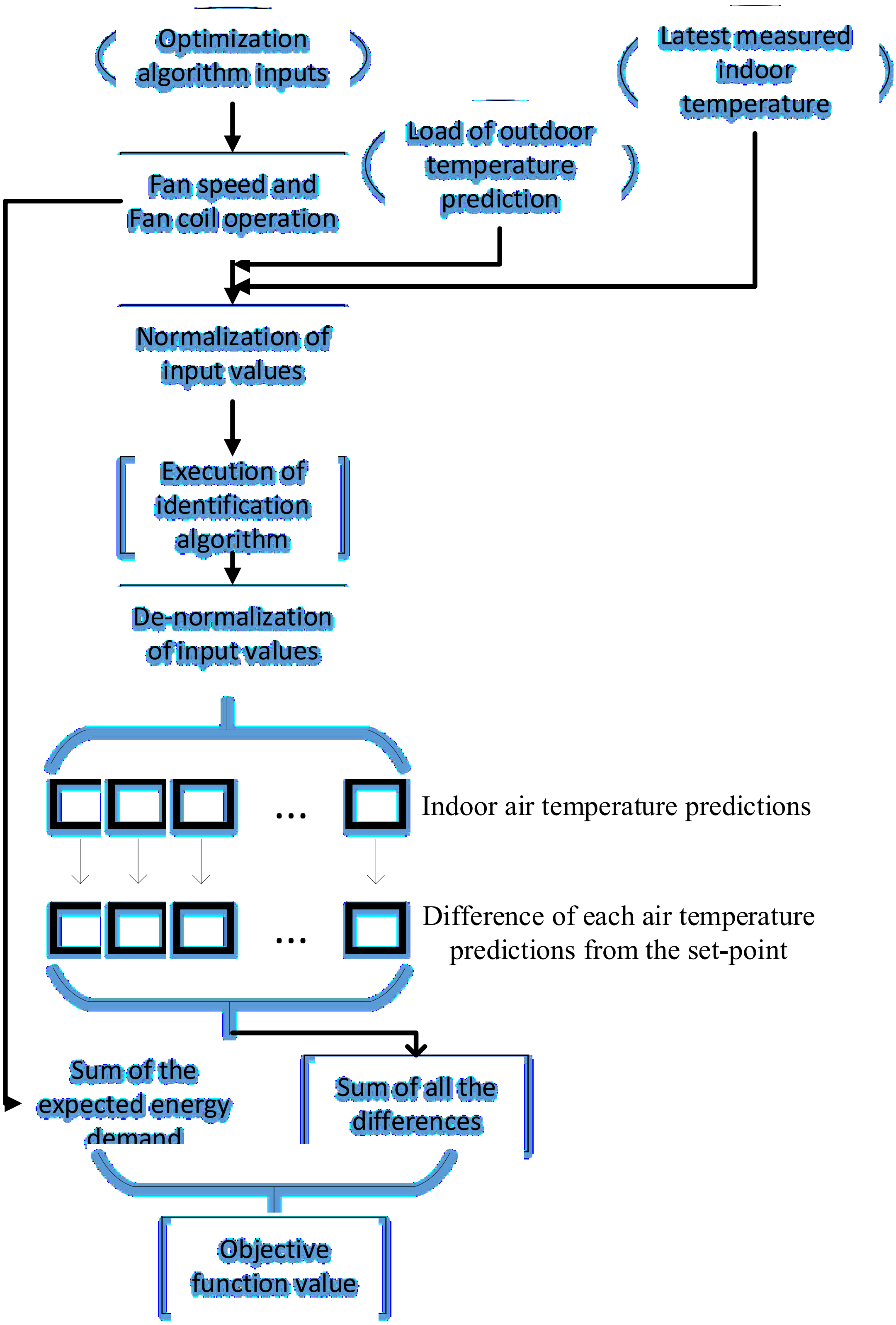


Figure 5- 3: Illustration of cost function operation

The optimization algorithm is trying to minimize the user defined cost function based on pre-defined constrains. For the specific solution sets the optimization algorithm will minimize the operation of the fan coil and the fan speed keeping indoor air temperature within the required values for a predictive horizon of 8 hours. The cost function inserted in the optimization algorithm is the following:

$$min\left(\sum_{1}^{32} Cost\ of\ operating\ the\ fan\ coil + Error\ of\ temperature\right)$$

So that:

- when AHU operates, windows must be closed

The optimization process uses 64 variables, 32 of which are used for the operation of the AHU and the rest are used for the selection of the fan speed.

5.1.2 Properties of genetic algorithms

The developed genetic algorithm optimises the performance of the Air Handling Units located in the paediatric department of Chania Hospital. The properties of the optimization algorithm are tabulated in Table 5- 1.

Table 5- 1: Parameters of the optimization algorithm

Parameter	Value
Mutation function	Mutationadaptfeasible
Display	Final
Use parallel	Always
Population size	100
Generations	300
Tolerance of function	10^{-20}

The properties of the genetic algorithm are selected focusing on the fast execution of the code and the convergence to the most suitable solution.

5.1.3 Evaluation of optimization techniques using the validated thermal models

The optimization algorithm output is the set-point of indoor air temperature for the next 8 hours. The optimization algorithm reads outdoor air temperature prediction, as well as current indoor air temperature. The execution of the optimization algorithm and the depreciation of the cost function is illustrated in Figure 5- 4.

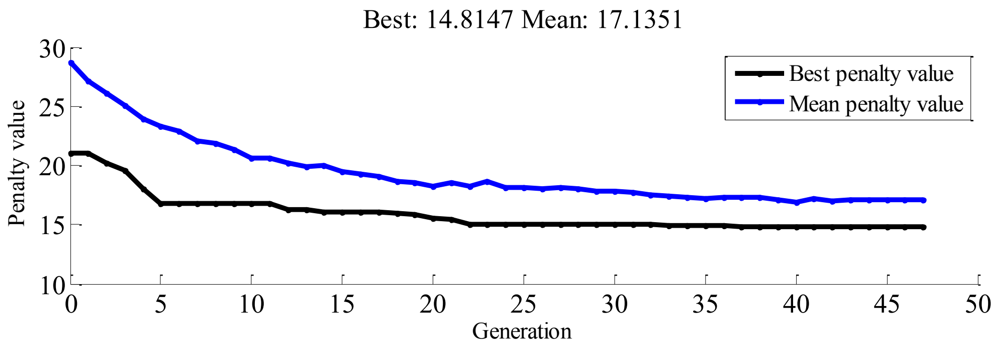


Figure 5- 4: Depreciation of cost function output value during the optimization phase

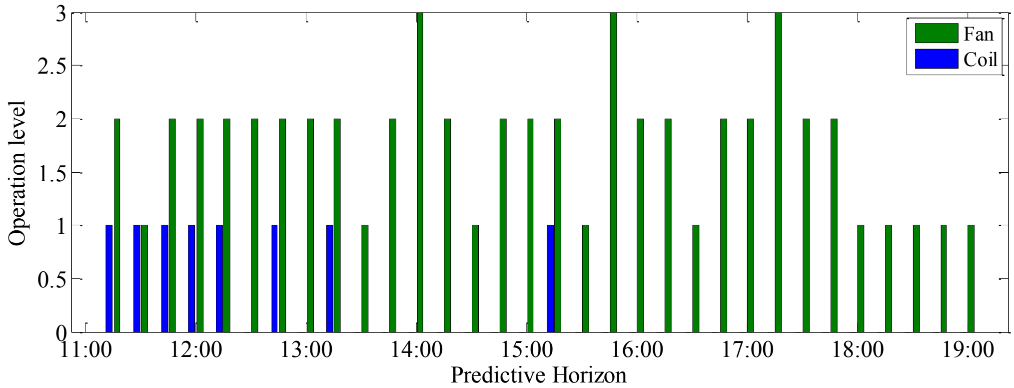


Figure 5- 5: Input which minimises the developed cost function

Figure 5- 5 illustrates the estimated vector which minimises the cost function. The vector consists of 64 variables. The first 32 represent the operation of the coil valve and the last 32 the speed level of the AHU.

The output of the optimization algorithm is plotted in Figure 5- 6. In Figure 5- 6, outdoor air temperature (optimization algorithm's input) is plotted. Furthermore, the change of indoor air temperature with the HVAC Off or ON is plotted to present the extreme conditions when the system is either in operation or not. Finally, Figure 5- 6 illustrates the optimal change of temperature as it is estimated by the optimization algorithm.

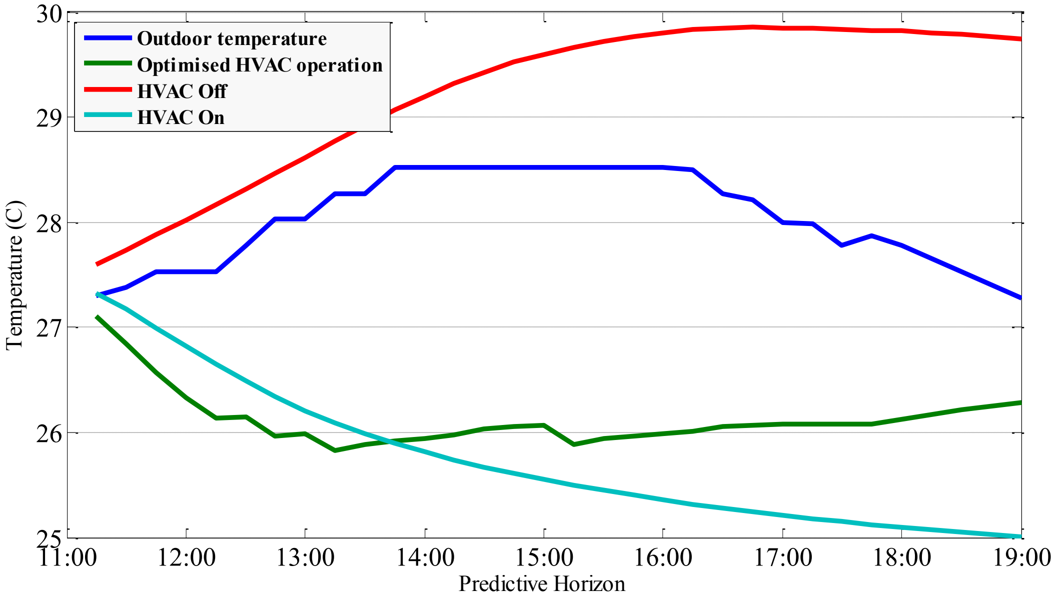


Figure 5- 6: Optimization algorithm output with 8 hour estimation of set-point

The performance of the genetic algorithm is evaluated during the winter period with the identification algorithm trained with measurements collected when the systems are producing heat. The evolution of the genetic algorithm results are presented in Figure 5- 7.

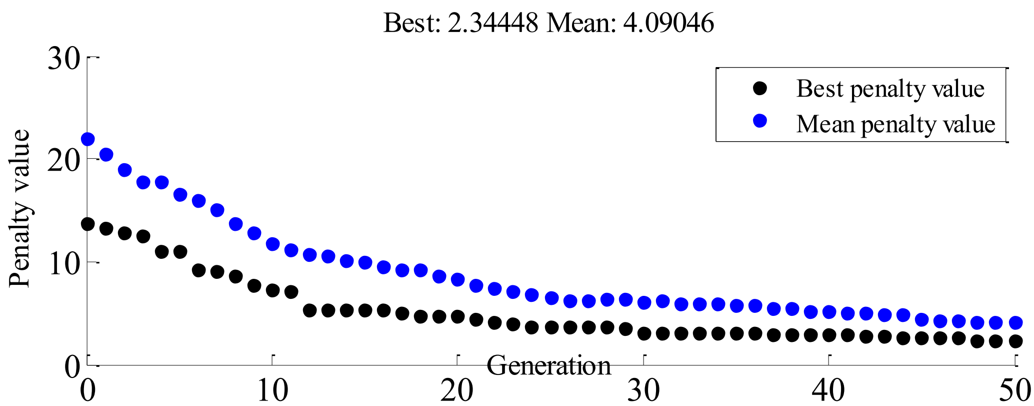


Figure 5- 7: Evolution of the genetic algorithms solution

The output of the genetic algorithm are the set-points of the next 8 hours and they are illustrated in Figure 5- 8.

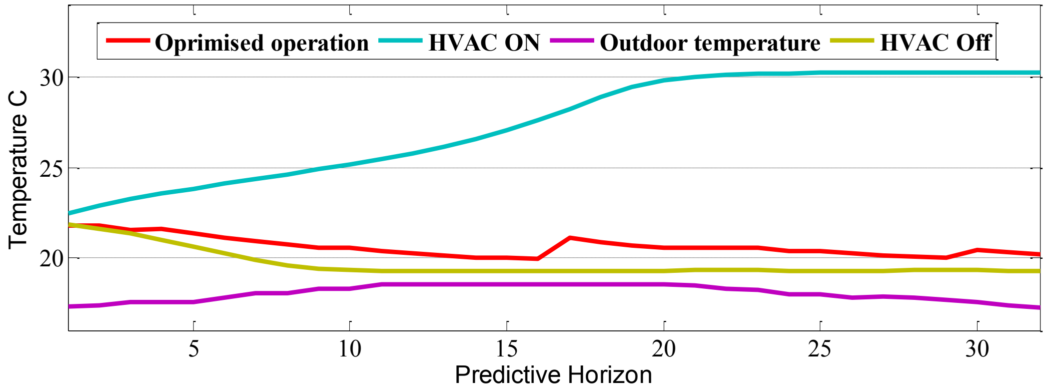


Figure 5- 8: Output of the optimization algorithm

Analysing Figure 5- 8, the dynamic set-point is maintained above the limit of 20 °C, which is a condition that minimises the value of the objective function. If the Air handling unit is off (both coil and fan) the temperature would fall below 20 °C and there is a penalty in the cost function. Similarly if the HVAC is switched on continuously indoor air temperature is high but the energy consumption increases the values of the objective function.

The values which minimise the objective function as they are selected from the genetic algorithm are presented in Figure 5- 9.

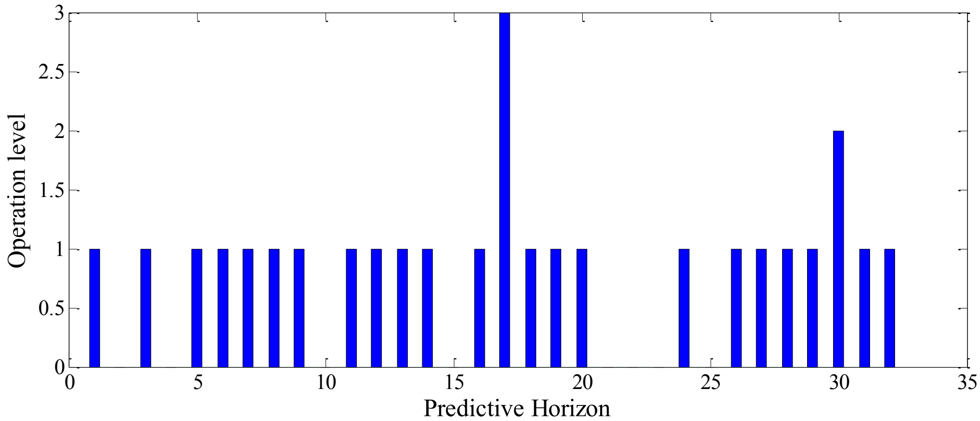


Figure 5- 9: Estimated values which minimise the objective's function value

-------------------------------------Chapter 6 --

EVALUATION OF A BUILDING INTEGRATED PHOTOVOLTAIC SYSTEM IN THE FABRIC OF PILOT HOSPITAL

6 Evaluation of a building integrated photovoltaic system in the fabric of the pilot hospital

Chania Hospital photovoltaic modules, can be integrated in the buildings' fabric to produce energy while replacing common fabric materials. Thus, the cost of photovoltaic module installation is reduced by abstracting the cost of the replaced materials. This corresponds to Phase 3 of the research methodology depicted in Figure 1- 2.

During the last century the transparent fraction of a building envelope has increased steadily. The larger the transparent fraction of the buildings envelope becomes the more important is the control of the solar energy flow to keep acceptable thermal and visual comfort levels in the rooms. In consequence, today's buildings are dominated by technical systems for heating, cooling, ventilation and artificial lighting – often resulting in high conventional energy consumption and poor daylight use. Photovoltaic modules can be integrated.

Photovoltaic modules can be integrated as shading devices which reduce the solar radiation entering the buildings.

J.J. Bloem et al (Bloem et al., 2005), presented an analysis based on simulation results using Esp-r software. In more detail a building is design and simulated for 3 European areas [Greece (Athens), Spain (Barcelona), Italy (Milan)]. According to the simulation analysis an office as presented by Bloem et al. (Bloem, 2008) has 99 photovoltaic modules mounted in a horizontal spandrel enclosure on the south façade. Natural ventilation was assumed in the module enclosure via grills in the upper and lower surfaces. Although photovoltaic modules cover part of the energy demand, their efficiency can be improved by changing seasonal inclination Bloem et al., (Bloem et al., 2005) Photovoltaic systems used as shading devices can reduce overheating in building which is currently covered by air-conditioning systems. Apart from overheating photovoltaic systems applied as shading devices can reduce glare effect.

Photovoltaic modules can be applied vertically, integrated in walls and combined with aluminium reflectors as it can be seen in Figure 6- 1 can increase their productivity, although their increase is not the expected one according to M. Brogren et al (Brogren et al., 2003).

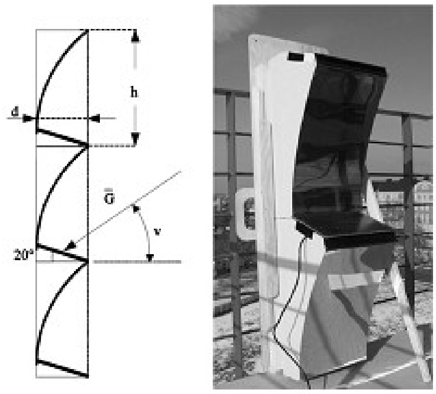


Figure 6- 1: Thin film photovoltaic modules combined with aluminium reflectors M. Brogren.

6.1 Simulation of the energy production of BIPV in the hospitals

For this simulation of photovoltaic modules has been accomplished using software Energy Plus. Specific parts of the shading systems have been used as photovoltaic surfaces**.** The shading devices which will be used for simulation and comparison have been published by Mandalaki et al. (Mandalaki et al., 2012) and can be seen in Figure 6- 2.

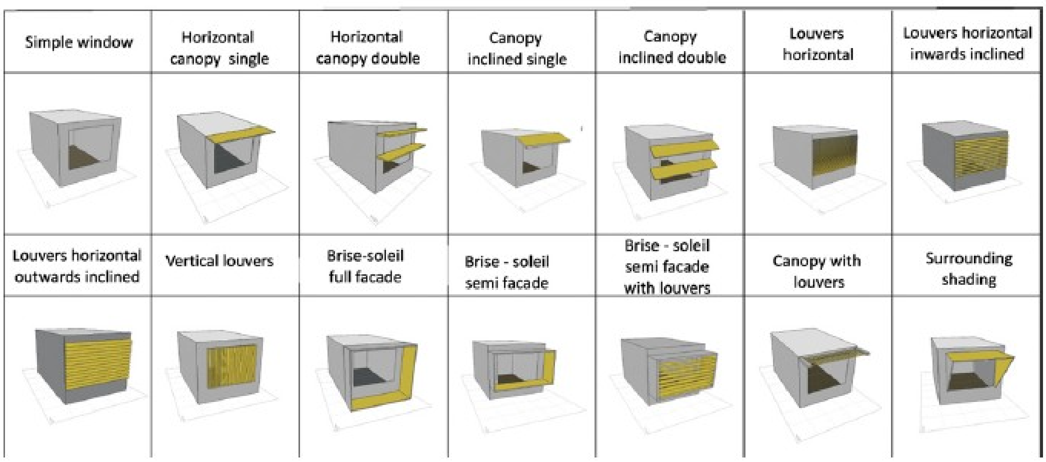


Figure 6- 2: Selected shading devices for simulation (Mandalaki et al., 2012)

The geometry of the typical offices with the shading devices has been provided in AutoCaD, dxf format and each one has been imported in Google Sketch Up in order to work with the OpenStudio Plug-in. From the available shading devices the “Brise-soleil semi façade” is used in Chania Hospital developed SketchUp model (Figure 6- 3). Since the building creates shades on the PV modules it has been redesigned using the open-studio plug-in (Figure 6- 4). The PV modules used as external shades in Chania Hospital model are illustrated in Figure 6- 5.

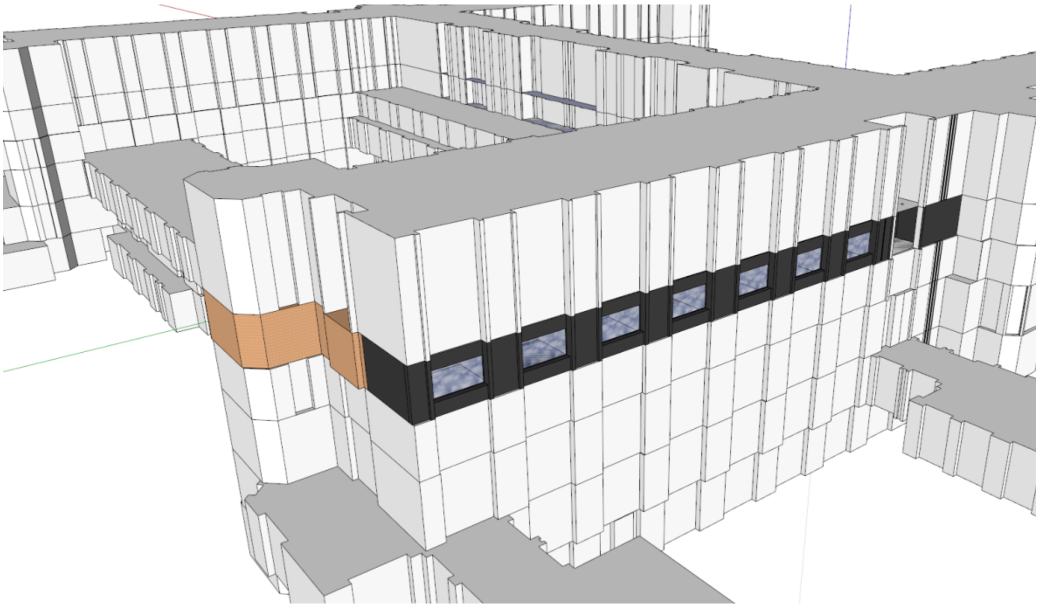


Figure 6- 3: Google Sketch Up model of Chania Hospital

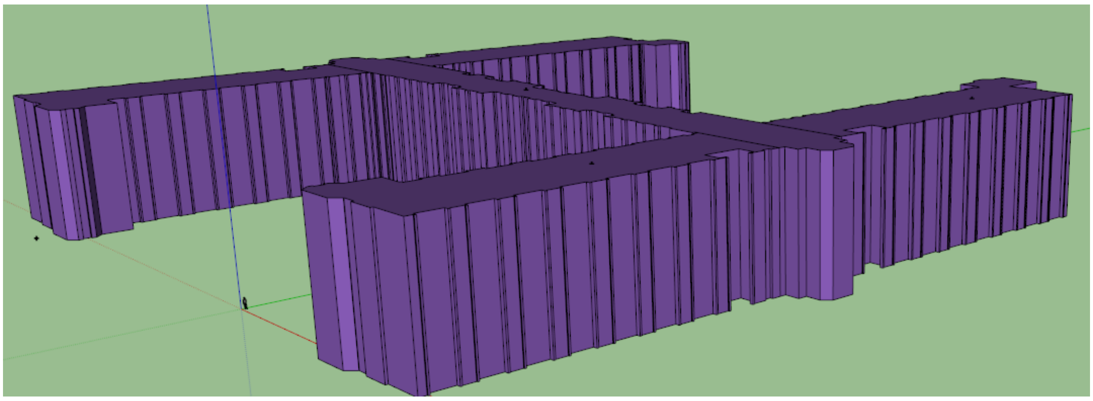


Figure 6- 4: Open studio: model of the hospital's construction as a shading device

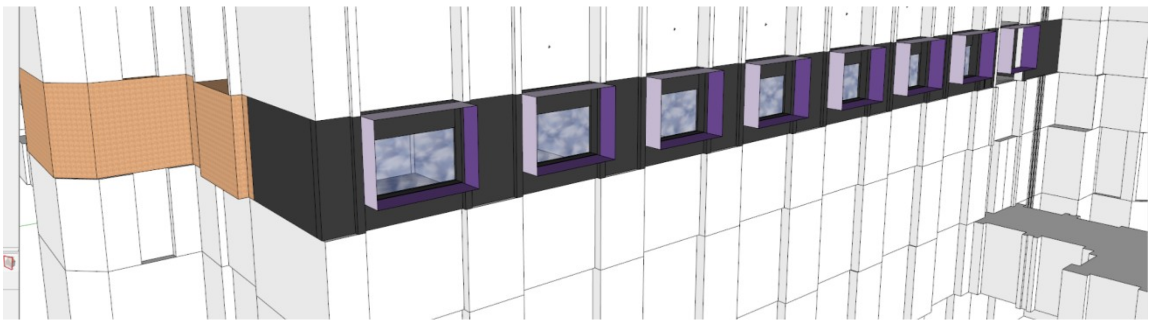


Figure 6- 5: The Sketch Up model including the shades which are used as photovoltaic modules

The simulation of the energy production of BIPV is performed using Energy Plus software which contains the sandia database for the modules. The Sandia method for the estimation of energy production of the photovoltaic modules has been used since

2004 when the methodology was published (King, Boyson, & Kratochvil, 2004). Although many more recent products can be found in the SAM (System Advisor Model) database, those selected can be fitted in the designed external shades. Moreover, the SAM database it-self is containing the methodology of the Sandia model (Blair, Mehos, Christensen, & Cameron, 2008; Cameron, Boyson, & Riley, 2008). The adjustment of the equations in order to be used by Energy-Plus or TRNSYS (Type 101) was done by Barker and Norton (2003). These equations used for the estimation of energy produced by each module are referred to the Engineering Reference of EnergyPlus software (2012): the model consists of a series of empirical relationships with coefficients that are derived from actual testing that are actually empirical coefficients (like empirical coefficient relating module temperature, empirical coefficients for polynomial function used to relate short-circuit current to the solar spectrum via air mass, empirical coefficients relating to 'Effective' solar irradiance and to Current at the maximum-power point (A), etc.). Once the coefficients for a particular module are available, it is straightforward matter to use the model equations for calculating the current–voltage curve. Additionally there are several climate and solar orientation inputs to the model including: incident solar beam, incident diffuse solar, incidence angle of beam solar, solar zenith Angle, outdoor dry bulb, wind speed, elevation, solar cells temperature.

The selected photovoltaic modules for integration are the model Astro APX-90 as presented by Mandalaki et al (Mandalaki et al., 2014). The properties of the photovoltaic module is tabulated in Table 6- 1.

Table 6- 1: Parameters of Astro APX-90 photovoltaic module

Parameters	**Value**
Power	90 W
Maximum power point tracking voltage	17,3 V
Maximum power point current	5,20 A
Open circuit voltage	21,9 V
Short-circuit current	5,80 A
Number of cells in the module	40
efficiency	8,35 %
module area	1,08 m^2

Running the simulation in Energy-Plus software the performance of the PV modules is estimated and for a typical summer day the energy production per 15 minutes is illustrated in Figure 6- 6. The monthly performance of the PV modules is illustrated in Figure 6- 7 and tabulated in Table 6- 2.

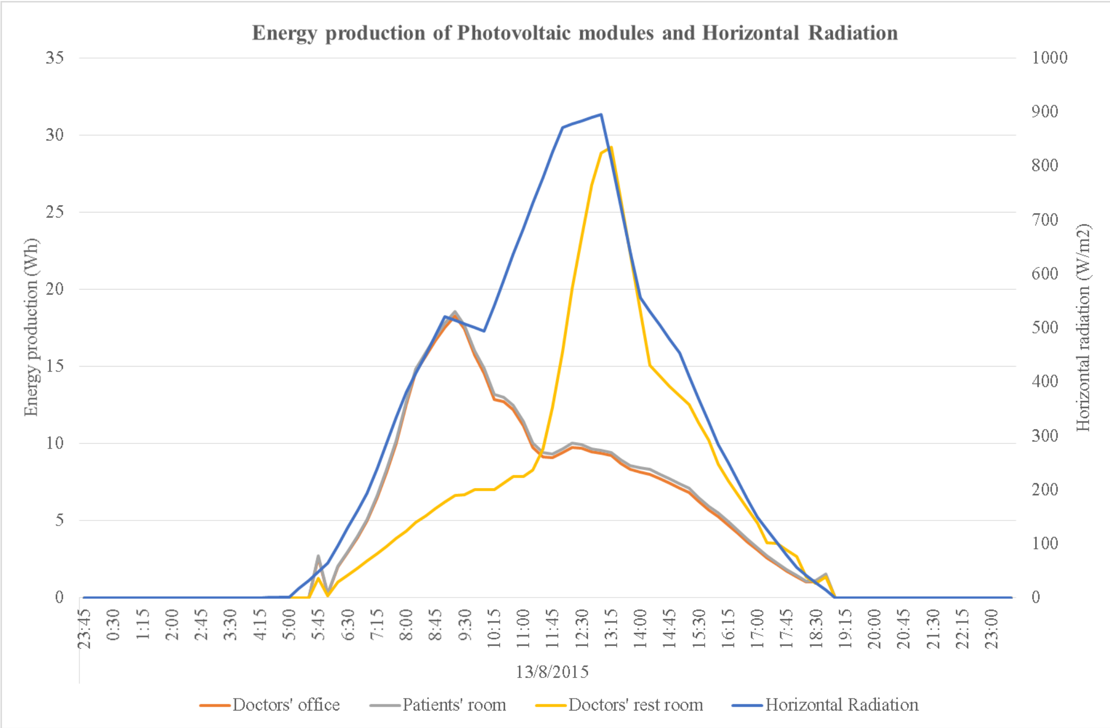


Figure 6- 6: Energy production of Photovoltaic modules during a summer day (13th August)

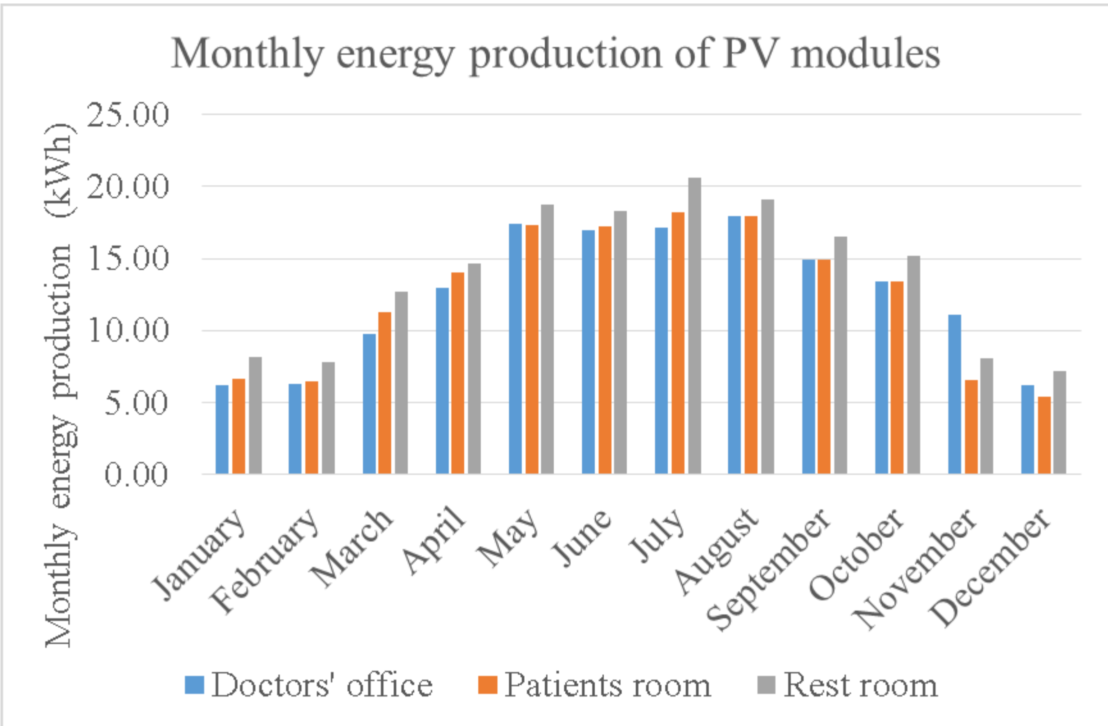


Figure 6- 7: Monthly energy production of PV modules

Table 6- 2: Monthly energy production (kWh) of PV modules installed as external shades

	Doctors' office	Patients room	Rest room
January	6.54	6.70	8.18
February	6.33	6.48	7.81
March	11.10	11.32	12.68
April	13.77	14.02	14.63
May	17.00	17.29	18.73
June	16.93	17.19	18.27
July	17.98	18.23	20.61
August	17.71	17.93	19.12
September	14.72	14.90	16.50
October	13.31	13.43	15.17
November	6.46	6.60	8.11
December	5.31	5.45	7.21
Total	147.16	149.54	167.02

6.2 Prediction of the energy production from the BIPV

The energy production of the photovoltaic system is mainly affected by:

- solar radiation
- Time of the day

Thus the prediction of the energy production should be based on these parameters. The architecture of the neural network is presented in Table 6- 3.

Table 6- 3: Architecture of neural network

Parameter	Description
Architecture of identification algorithm	Artificial Neural Network
Topology of identification algorithm	Feed forward neural network
Construction of the model	Black box
Number of inputs	2
Inputs	Solar radiation Rad (k|k) Time (minutes of day) t
Number of outputs	1
Output	Energy production Power (k|k)
Number of Hidden	3

Parameter	Description
Layers	
Size of Hidden layers	[2 2]
Performance function/ indicator	"Mean square error"
Size of initial train data set	15000
Number of epochs	1000
Number of maximum fails	6
Predictive horizon	1 step (15 min)

The predicted values of solar radiation are collected from on line weather stations which provide predictions of solar radiation based on the prediction of cloud coverage.

The data collected from the simulation of the photovoltaic modules is used for training and evaluating the performance of the neural network.

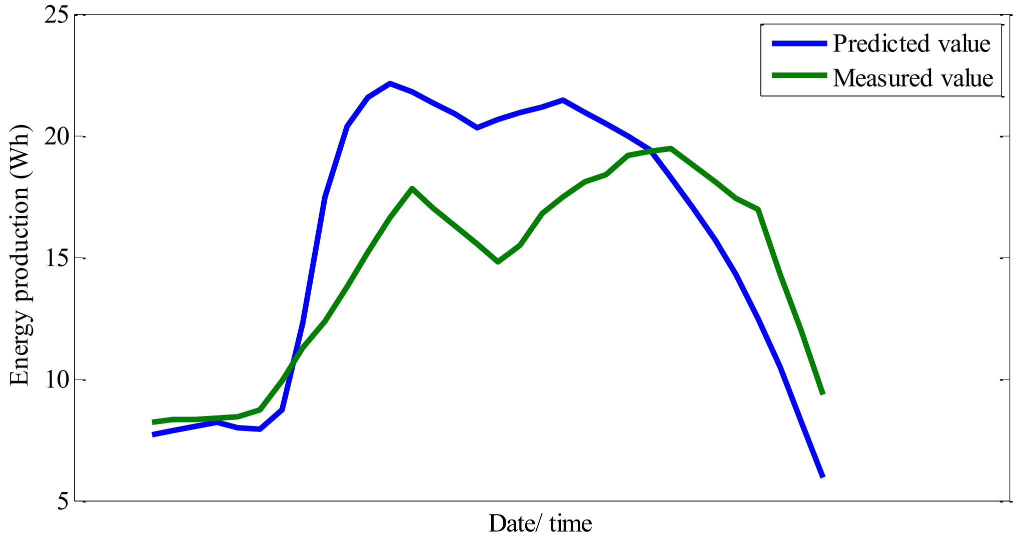


Figure 6- 8: Comparison of predicted and measured energy production of PV-modules in the doctors' office

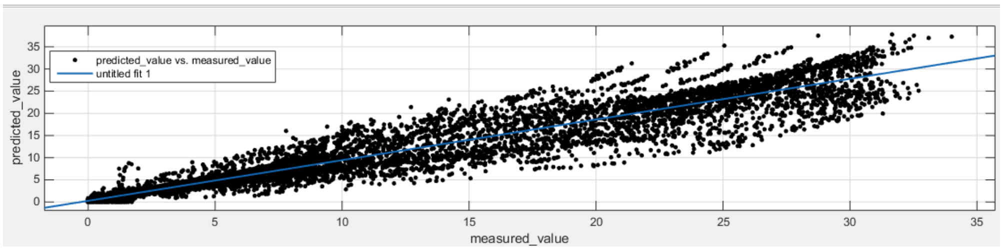


Figure 6- 9: Comparison of predicted and measured values of all predicting period

Comparison of the measured and estimated energy production from the PV is performed using the cftool of Matlab. The comparison between these 2 values provides as a result:

- R-square: 0.9554
- RMSE: 1.626

The comparison indicates that the NN accurately predicts the energy production of the PV panels.

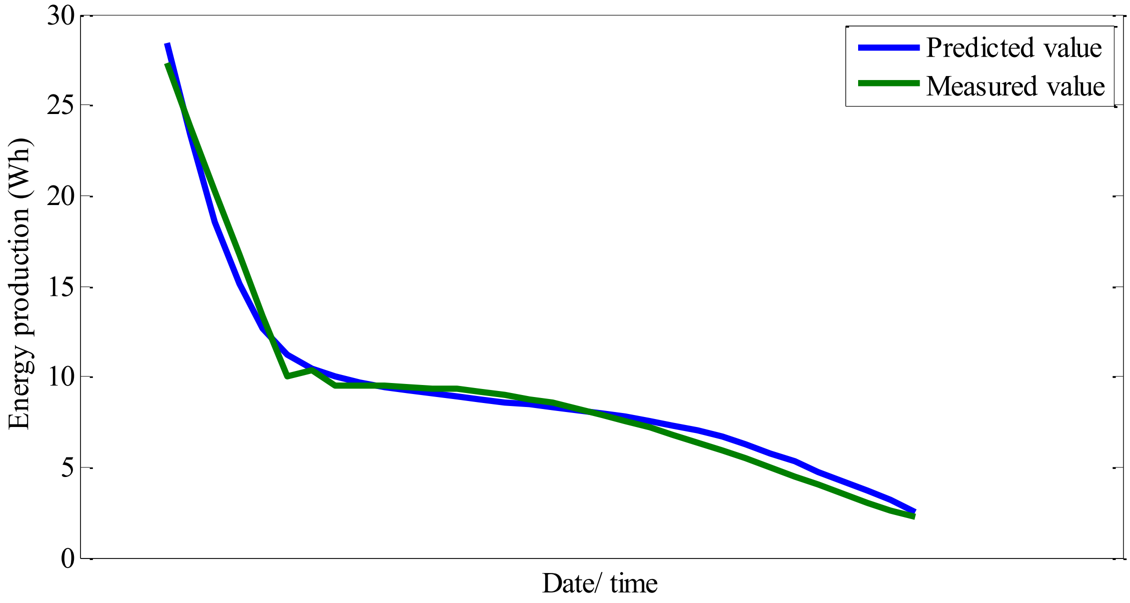


Figure 6- 10: Comparison of measured and predicted energy production for PV-modules in patients' room

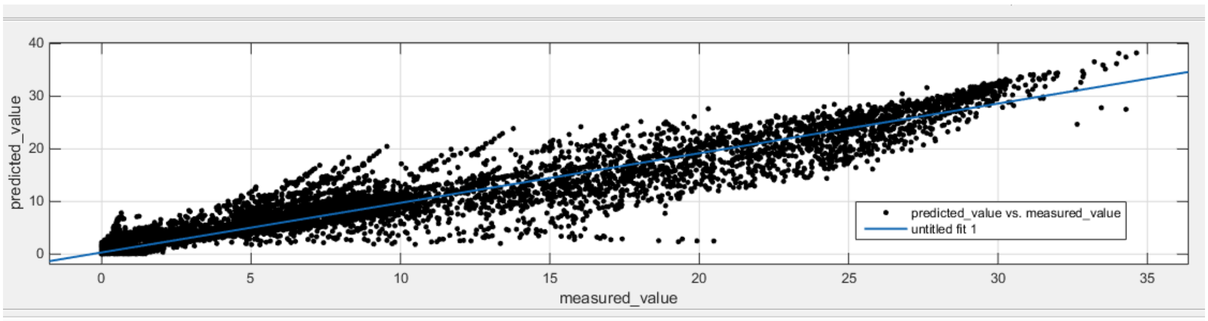


Figure 6- 11: Comparison of measured and predicted energy production for pv-modules in patients' room of all predicting period

Comparison of the measured and estimated energy production from the PV is performed using the cftool of Matlab. The comparison between these 2 values provides as a result:

- R-square: 0.9169
- RMSE: 2.237

The comparison indicates that the ANN accurately predicts the energy production of the PV panels.

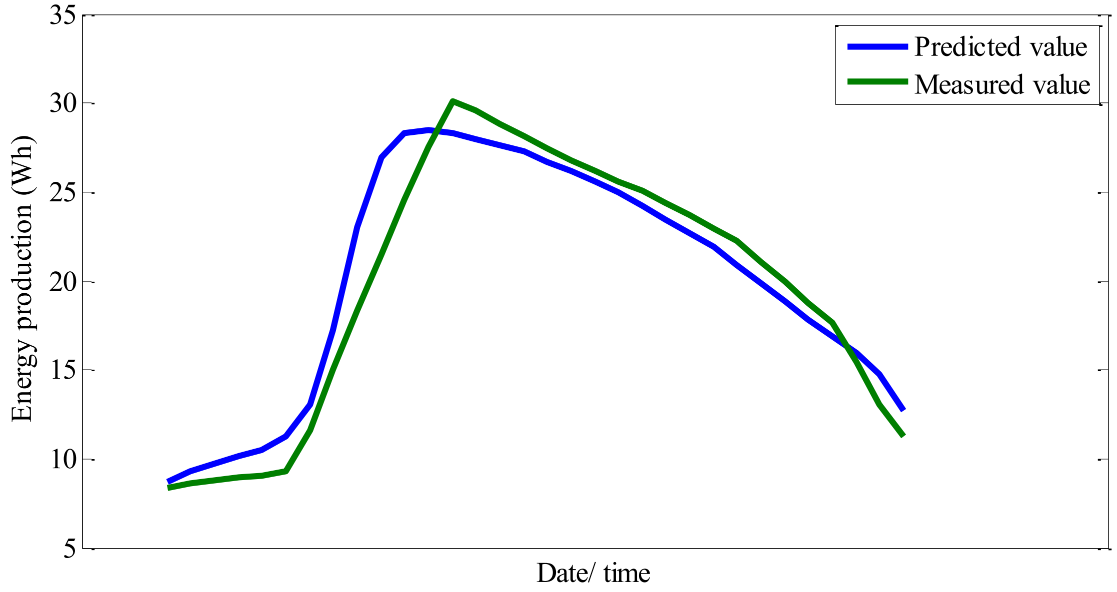


Figure 6- 12: Comparison of measured and predicted energy production for pv-modules in doctors' restroom

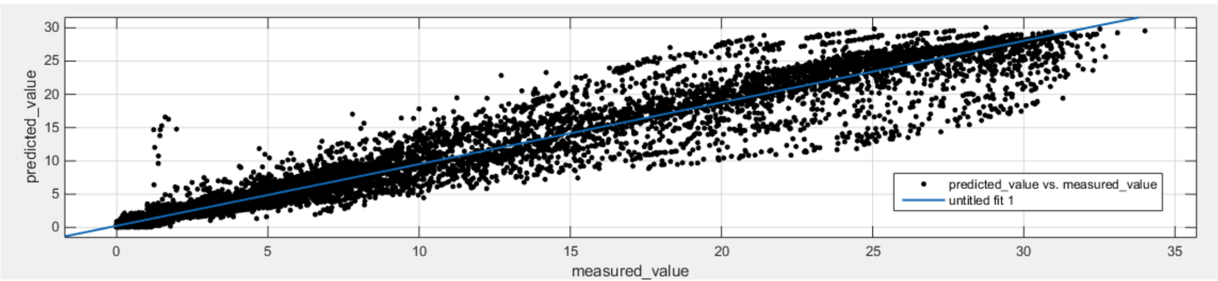


Figure 6- 13: Comparison of predicted and measured values of pv energy production for doctors' rest room of all predicting period

Comparison of the measured and estimated energy production from the PV is performed using the cftool of Matlab. The comparison between these 2 values provides as a result:

- R-square: 0.9476
- RMSE: 1.757

6.3 Potential update of the optimization algorithms with the usage of BIPV

The energy production from the photovoltaic modules can be included in the optimization process described in Chapter 5. The integration of RES can reduce the power demand from the grid and thus reduce the cost of electricity for the building owners. Electricity utility companies charge the electricity based on their maximum power demand combined with the energy consumed. RES, combined with optimization algorithms can reduce the overall cost of the building if the maximum required electricity loads are shifted when the RES provide electrical power.

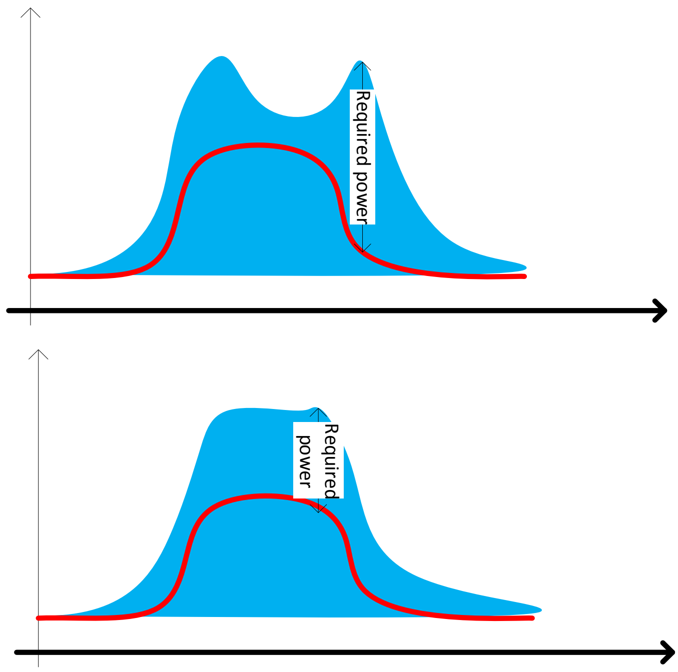


Figure 6- 14: Example of reducing maximum required power with shift load

The type of inputs of the optimization algorithm are not altered. The energy production from the PV is estimated before the execution of the control algorithm and it used as non-changing values in the objective function.

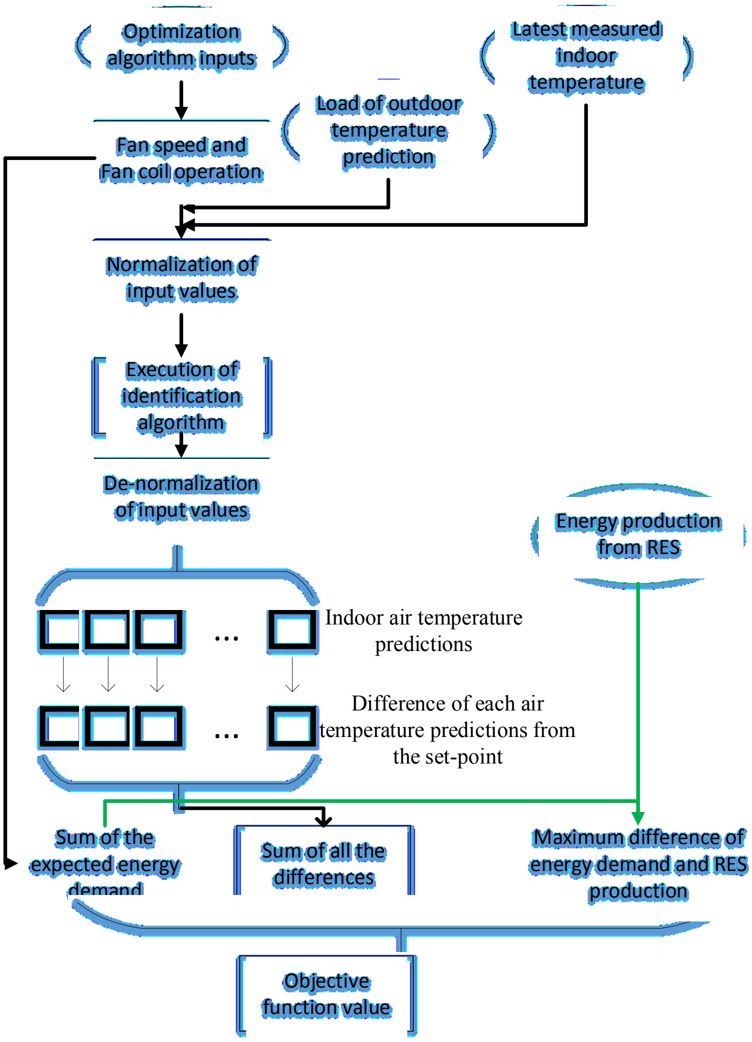


Figure 6- 15: Update of Objective function to include Energy production from RES

Load shifting can be achieved by applying a "penalty" in the maximum required power from the grid in the objective function of the optimization algorithm as described by Provata et al (Provata et al., 2015).

--Chapter 7 --

INTEGRATION

7 Integration of the proposed solution in hospital buildings

The control and optimization algorithms are developed in Matlab environment to be integrated in the hospitals' systems which do not have Matlab tool installed. The development process towards the integration of the BOC algorithms is illustrated in Figure 7- 1. This corresponds to Phase 4 of the research methodology depicted in Figure 1- 2.

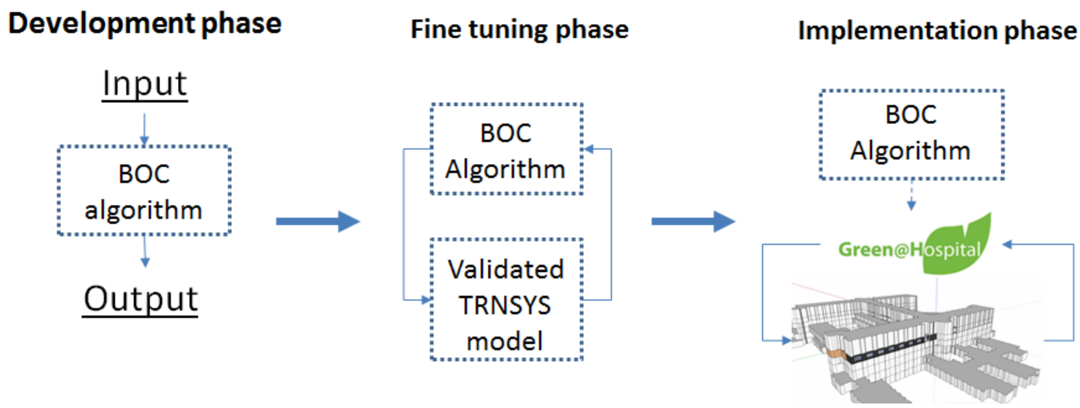


Figure 7- 1: From the development of BOC algorithms to their implementation

The development and the evaluation (Chapter 3) has already been performed. The implementation and the integration of the BOC algorithms requires firstly to read the data from the sensors located in the rooms as described in Chapter 2 and send commands to actuators. The installed equipment for the implementation of the BOC algorithms is described below.

7.1.1 Equipment installed in Chania Hospital

In Chania Hospital, equipment is installed to monitor and guarantee indoor conditions related to thermal and visual comfort. The monitor equipment is assembled from the following modules:

- in EE80 Series – HVAC Room Transmitter for CO_2, Relative Humidity and Temperature (Figure 7- 2)
- MDS – Ceiling multi-sensor 360° (Figure 7- 5)
- FX07 – Terminal Unit Field Controller (Figure 7- 2)
- Karmstrup 382 L - Energy meter (Figure 7- 3)

- Karmstrup Multical 602 - Calories meter for heating and cooling (Figure 7- 6)

Furthermore, some consumables are installed in a switch cabinet as illustrated Figure 7- 2.

Figure 7- 2: The installed controller in each room of the paediatric department

Figure 7- 3: Integration of power monitors in the main electrical board of the paediatric department

Figure 7- 4: The sensors for monitoring indoor air temperature, humidity, and [CO2]

Figure 7- 5: The illuminance and presence sensor

Figure 7- 6: Thermal meter installed for each air handling unit

The installation of the equipment in the rooms is also described by Papantoniou et al (Papantoniou et al., 2014a, 2013).

7.1.2 Equipment installed in the hospital of Ancona

In the hospital of Ancona the light fixtures have been refurbished by installing led lights (Figure 7- 7) which can be dimmed using the Dali System (Figure 7- 8). Apart from the update of the light fixtures, an MDS Ceiling multi-sensor has also been installed to read values of indoor illuminance and presence detection. All the collected readings are sent to the Automation server also located on the 2nd floor of the hospital.

Figure 7- 7: Update of light infrastructure using LED lights and presence detector

Figure 7- 8: Dali controlled system with lonworks communication protocol

The selected rooms for installation of the proposed control for artificial lights are presented in green colour in Figure 7- 9 and named as following:

The refurbished rooms of the hospital of Ancona are:

Oncology department:

- Visitors waiting room
- Archives
- Nurses office
- Patients waiting room
- Doctors office

Haematology department:

- Nurses office
- Warehouse
- Doctors office

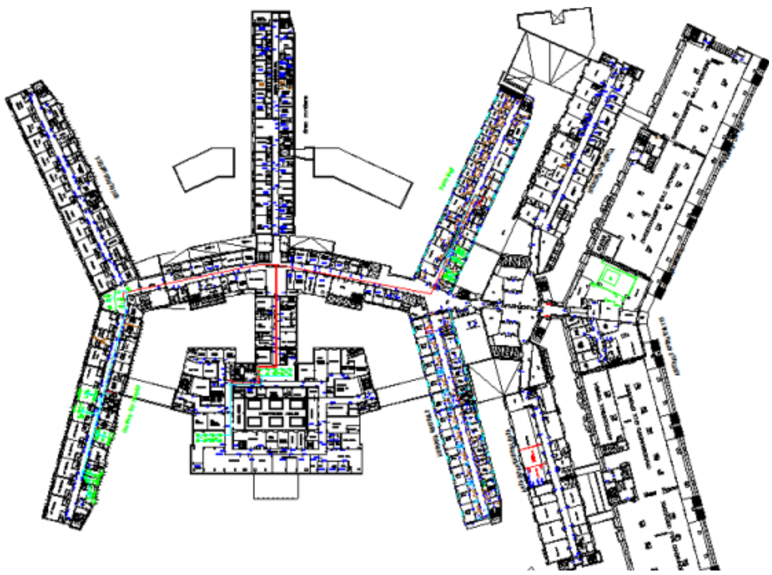


Figure 7- 9: Selected rooms for the implementation of the control algorithms

All the data accumulated from the sensors located in each hospital is transferred to the existing central BEMS as described in Chapter 7.1.

7.1 Analysis of data transfer to the control and optimization algorithms

The conditions and consumption of the rooms are measured using sensors and monitoring equipment. The collected data should be transferred to the BEMS for storage and fed to the control and optimization algorithms with the required inputs. Simultaneously, the output of the control algorithms should be sent back to the field controllers to select the operation of the actuators.

7.1.3 Data transfer in Chania Hospital

The measurements related to comfort accurately predicts from the rooms are transferred to the FX07 controller as analogue input signals of 0 – 10 V. The presence detection and the window contacts are sent to the controller in the form of digital input. The controller communicates with the existing BMS of the Hospital using Johnson's control closed protocols.

Furthermore data related to the energy consumption (electrical and thermal) of the artificial lights and the air handling units of each room are is measured using dedicated equipment for each room which communicates using LONworks protocol. An ilonserver publishes the data to a password protected the ftp server. The connection among the installed and existing modules is illustrated in Figure 7- 10.

- Installation of measuring equipment in the pilot hospitals

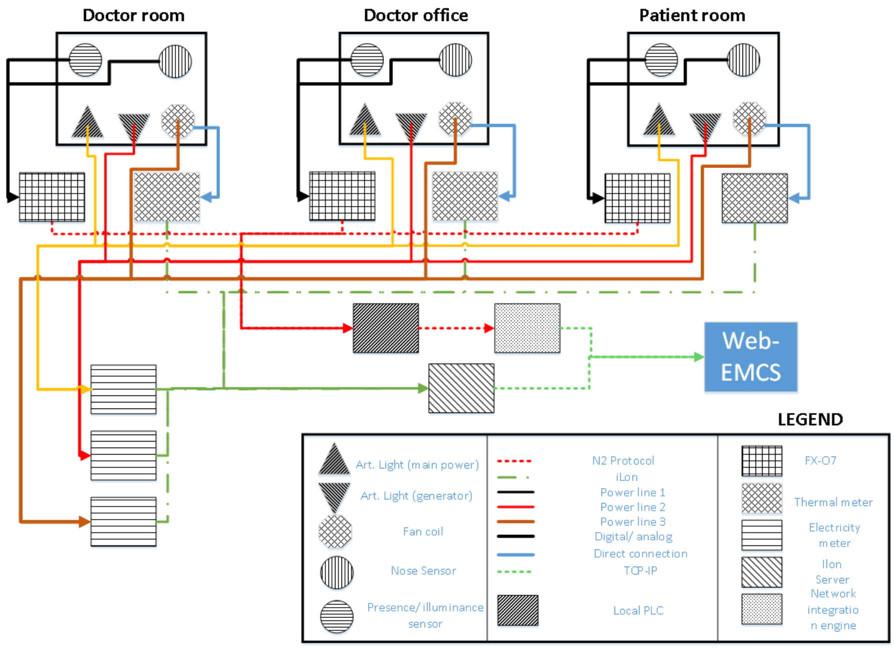


Figure 7- 10: Connection of installed and existing modules for data transfer

The data is transferred from the local controllers and the measurements are sent through the existing BEMS infrastructure to a local computer using TCP-IP technologies. Then a vpn-network is used to send the data to the Web-EMCS located away from the hospital and enables secured distant access to the system.

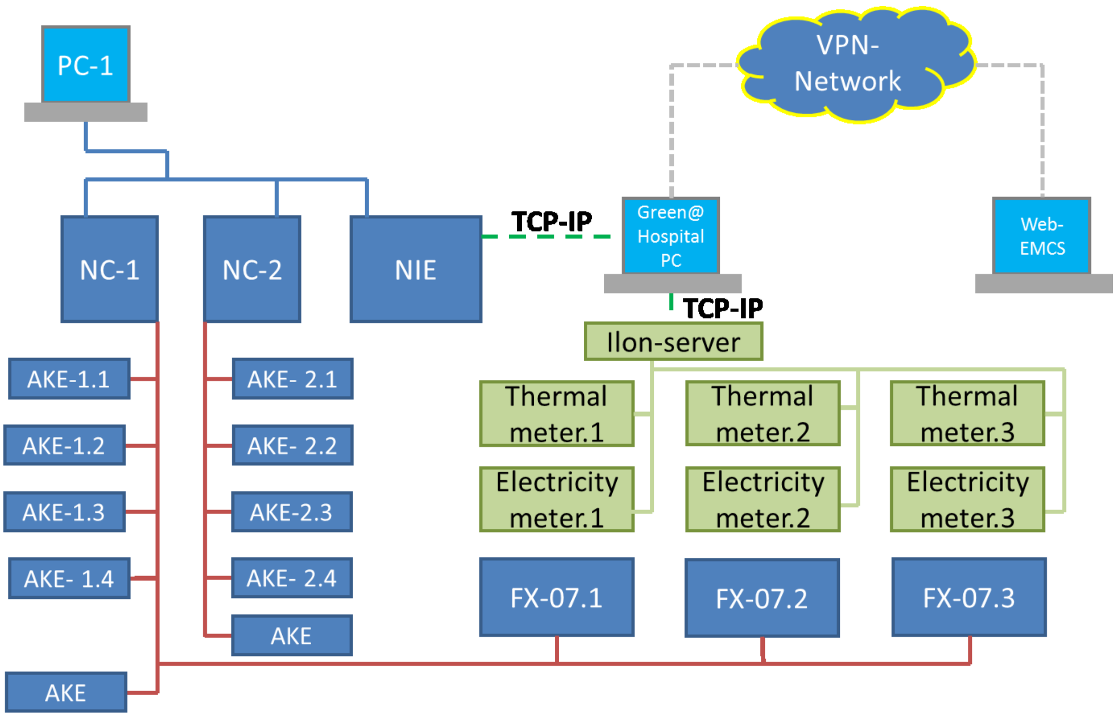


Figure 7- 11: Data transfer from local controllers to the main BMS framework

7.1.4 Data transfer at the hospital of Ancona

The developed controller runs on the dali infrastructure which is installed in each department. The controller uses the dali protocol to read data from the presence/illuminance sensors and send the proper commands to the lights in order for them to dim.

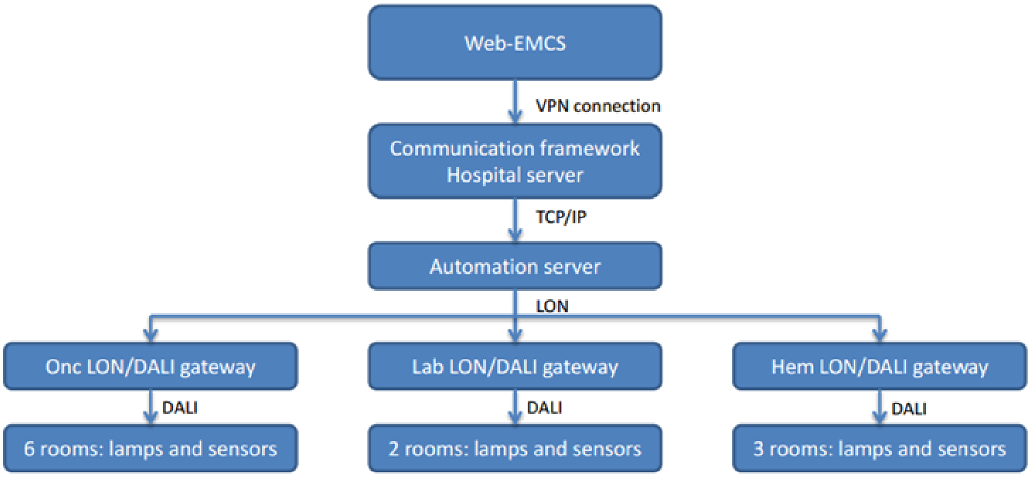


Figure 7- 12: Data transfer from local controllers to the main BMS framework

Each controller uses the LON protocol to transfer all the acquired data to the Automation server which uses TCP/IP protocol. A VPN connection sends the data to the database of project which hosts the web-site of the Web-EMCS.

7.2 Web-EMCS

The control and optimization algorithms run as part of an overall system which also includes the communication of the central computer with the hospitals' computers, the user interface and the required drivers for communicating with different systems. The Web-EMCS can be accessed from distant locations using a computer browser. It provides a Graphical User Interface (Figure 7- 13) which allows authorized users to monitor the conditions instantly and make the required changes if required.

Figure 7- 13: The Graphical User Interface of the Web-EMCS

Although the BOC (Building Optimisation and Control) system has the capacity to meet the restrictions and preferences imposed by the user, additional safety features are incorporated to avoid any possibility of circumvent conditions. The specially required conditions in the hospitals, combined with the requirement for constantly providing the comfort conditions has led to the development of a software based override system for all the aforementioned systems which allows authorised personnel handling a user friendly User Interface (Figure 7- 14) to switch the system back to manual in the unlikely event of a failed sensor or a communication problem between the control algorithm.

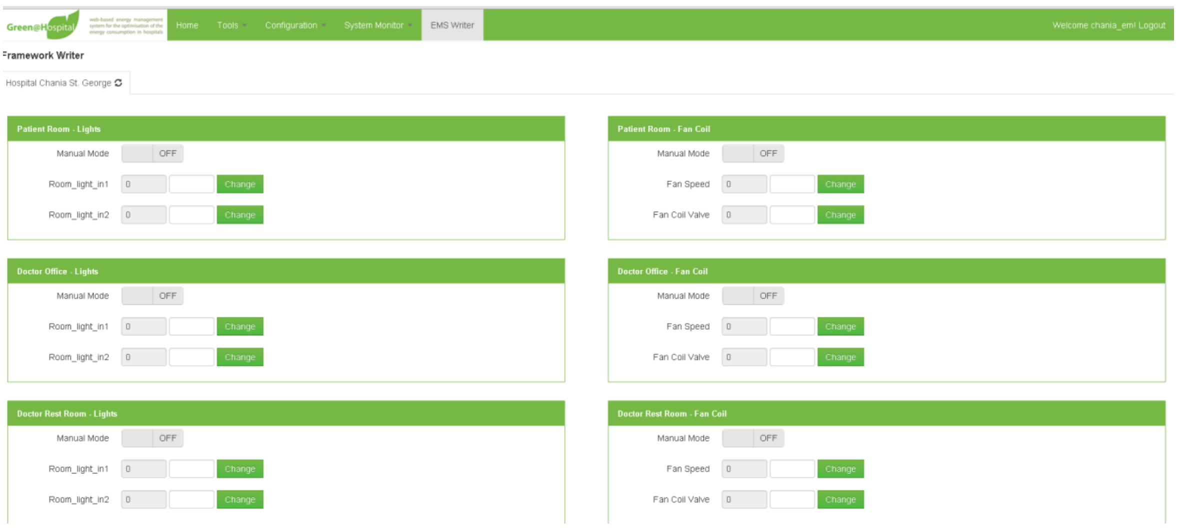


Figure 7- 14: The EMCS Writer for software override

The developed control algorithms read whether the system is overridden and in case override is activated it registers the input and without processing forward it sends them to the output (Figure 7- 15).

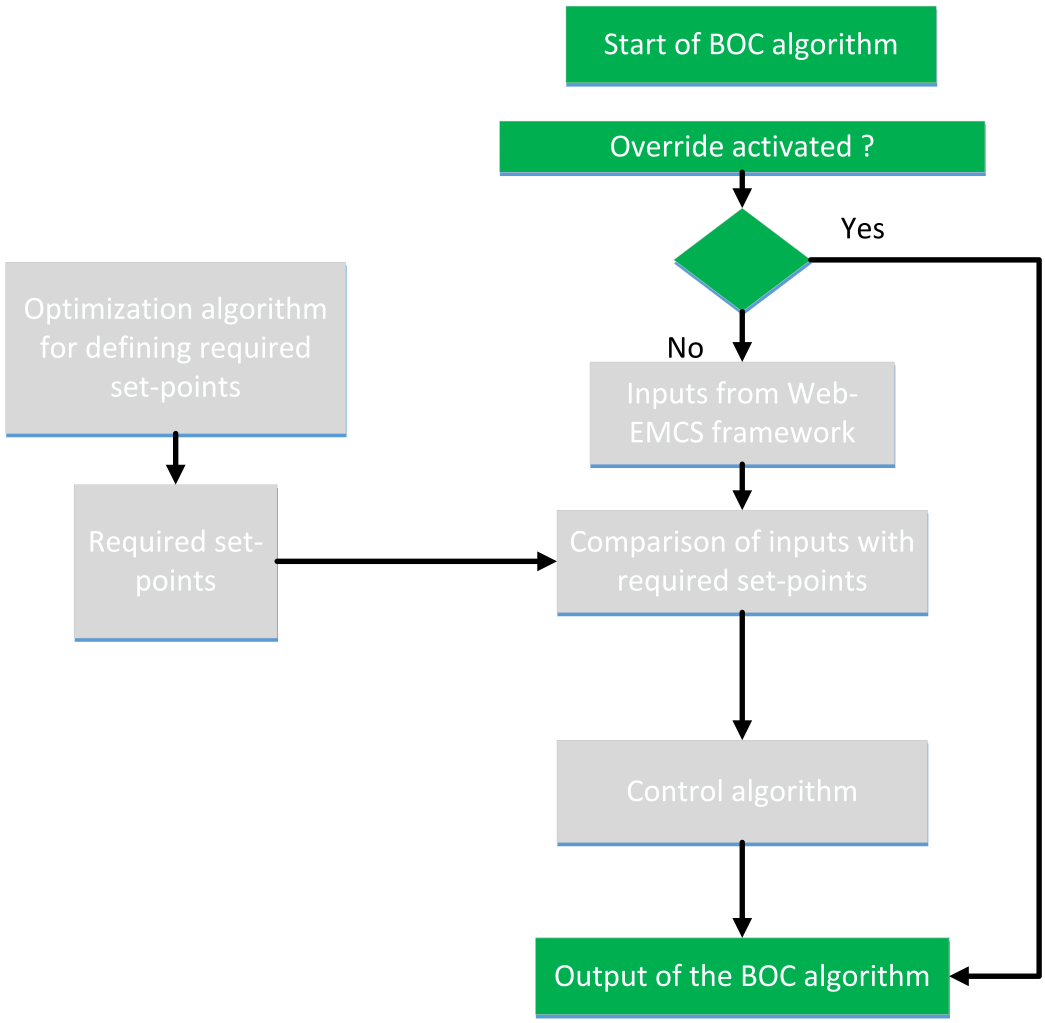


Figure 7- 15: Schematic of the override procedure for the BOC algorithms

7.3 Implementation of the smart algorithms in the Web-EMCS

The Web-EMCS is developed using Microsoft' tools for data acquisition (Microsoft SQL Server 2008 Enterprise) and the developed codes should be implemented in a format suitable for the web-EMCS to interact with. The codes are extracted from Matlab tool to ".net assembly" tool using Matlab's compiler: "deploytool". The deploytool selects the .net framework v 3.5 which belong to the same version as the web-EMCS. The codes are transformed into source code which can be accessed by the Web-EMCS interface as a plugin which is stored in a separate folder.

The input and output variables of the control algorithms are connected with the values from the sensors and the actuators respectively, of the selected rooms in Chania Hospital and in the hospital of Ancona. Variable binding is performed by software based, separating the procedure per rooms and per solution set. Furthermore, for the air handling units of Chania Hospital the season is selected between winter and summer based on whether the system works on heating or on cooling respectively.

The input variables sent to the controller for the air handling unit in Chania Hospital are:

- Override indication
- Period (summer/ winter)
- Indoor air temperature
- Presence detection
- [CO_2]
- Windows state
- Air handling unit previous state
- Air handling unit new state (used in case of override)

Similarly, the values sent to the controller for the artificial lights in both hospitals are:

- Override indication
- Presence detection
- Illuminance level
- Input definition

For the evaluation of the performance of the control algorithms, the basic function also stores the collected values as well as the outputs of the control algorithms in Matlab format, variables stored locally in each computer of the pilot hospital. The stored data is used for evaluating the proper execution of the fuzzy controllers, for keeping a log when presence is detected and for storing the data for further analysis if required.

Specifically for Chania Hospital, the existing BEMS from Johnson Controls cannot obtain inputs from other programs externally. The update in the existing BEMS allows other software to read remotely the conditions from the installed sensors but no commands can be sent to the installed actuators. For this reason an internal subprogram of Johnson control named MetaSYS has been used to write the required values in the registry of the existing BEMS. However, MetaSYS requires excel macro commands to operate and write values. Thus, the developed Matlab based functions running in the .net framework also execute the required excel Macros. This solution demonstrates the versatility of the developed BOC algorithm to be implemented in several systems. The developed communication is illustrated in Figure 7- 16.

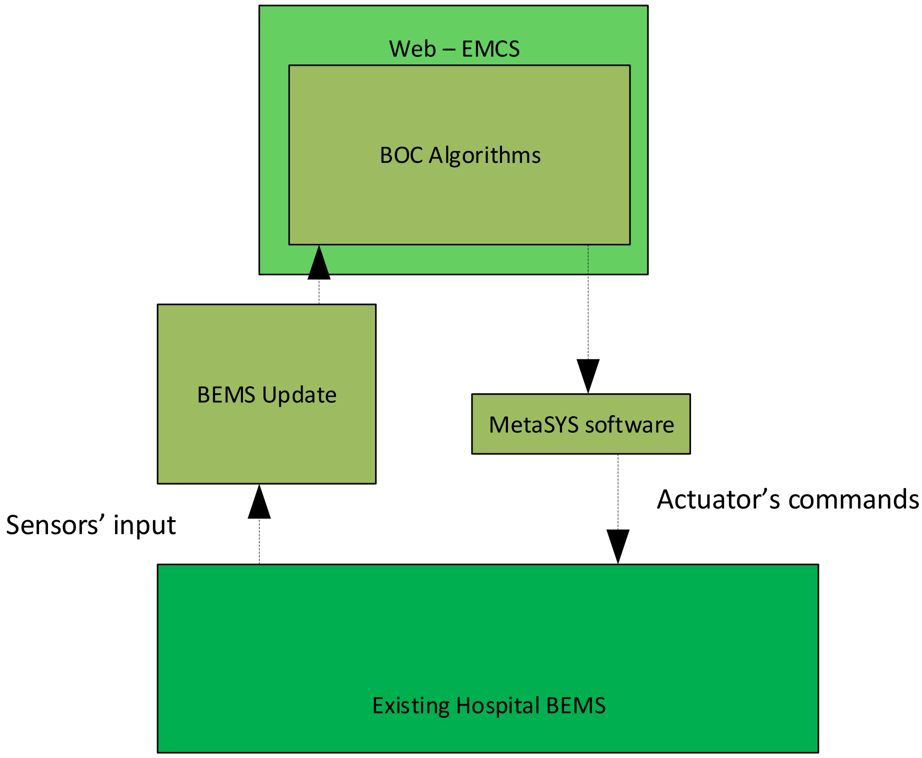


Figure 7- 16: Developed communication for Chania Hospital BEMS

Furthermore, Matlab access the ilon server illustrated in Figure 7- 3, using ftp functions and the stored data to automatically develop a figure for each selected room in Chania Hospital (Figure 7- 17) in order to identify the correct operation of the systems or a potential error. Moreover a csv file is attached to the same e-mail containing the latest collected variables.

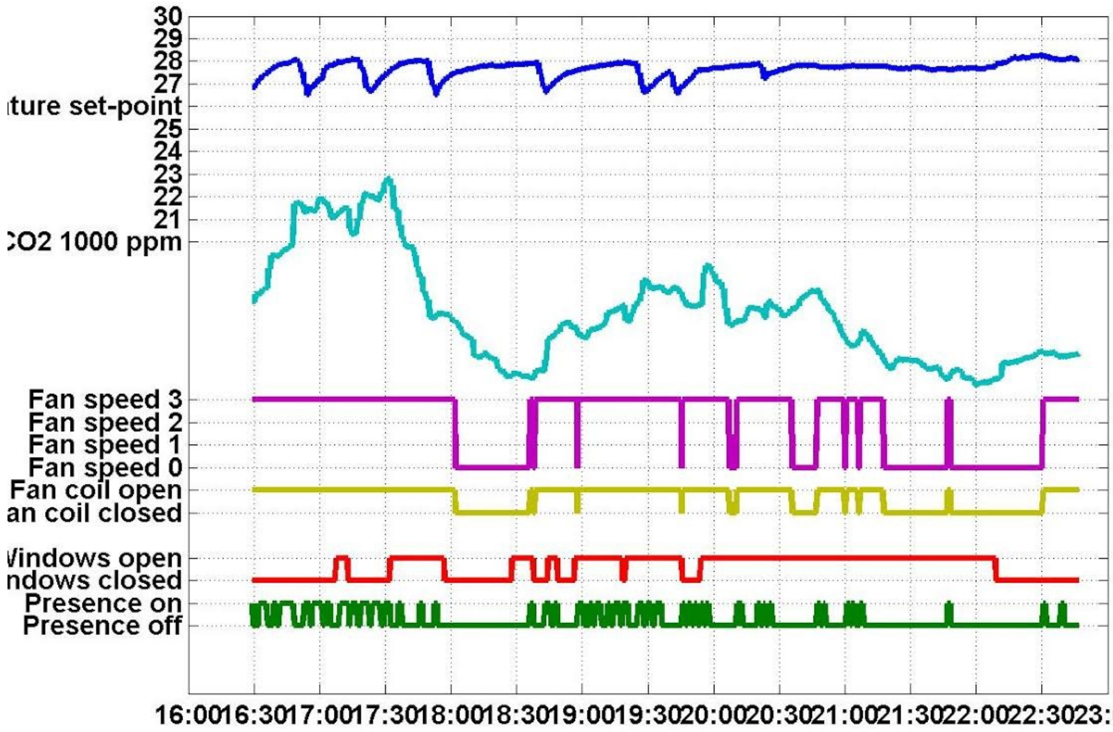


Figure 7- 17: Automated graph developed by Matlab and sent by e-mail to inform about the operation of the system

--------------------------------------Chapter 8 ---

RESULTS AND DISCUSSION

8 Results and discussion

In Chapter 8, the effect of the integration of the control and optimization algorithms is presented. This corresponds to Phase 5 of the research methodology depicted in Figure 1- 2. The algorithms need to guarantee the comfort level, while reduce the energy consumption. In this way the consumption of the HVAC + L systems is reduced towards zero energy buildings. Thus, for each integrated algorithm, the performance of the HVAC and the artificial lighting is presented with their energy efficiency analysis.

The integration of the developed control and optimization algorithms has been monitored for 1 year and the algorithms have been fine-tuned during this period to meet the personnel (doctors/ patients) criteria, while increasing the energy efficiency. All measured data is stored on a database for further analysis. The data is used to illustrate the proper performance of the developed algorithms and to estimate the annual energy efficiency. Furthermore, the effect of the development and integration of the control algorithms is analysed on the performance of European Standard: “EN 15232 -Energy performance of buildings - Impact of Building Automation, Controls and Building Management”.

8.1 Control algorithms for the artificial lights

Control algorithms for artificial lights are integrated in the field controllers of the Ancona hospital and the hospital of Chania. The control algorithms read data from the sensors and control the artificial lights. As aforementioned, the artificial lights in the hospital of Ancona can dim and they use led technology, while in the hospital of Chania the artificial lights can only switch on or off.

8.1.1 Artificial lights - Hospital of Ancona

The artificial lights of the Ancona Hospital have been charged for new ones using led technology which can dim the level of artificial lights comparing to the previous fluorescent technology which could only switch on/ off the artificial lights and consume more energy. The baseline energy consumption of the artificial lights is estimated considering the maximum power demand and their hours of operation. After the light fixture updates the developed control algorithms are integrated. The performance of the control algorithms in the field is presented and the annual energy performance is estimated.

8.1.1.1 Evaluation of the control algorithm performance

The control algorithms implemented in the field controllers monitor continuously presence and indoor illuminance and calculates the new dimming level which maintains indoor illuminance at the required set-point. The performance of the control algorithm is illustrated in Figure 8- 1.

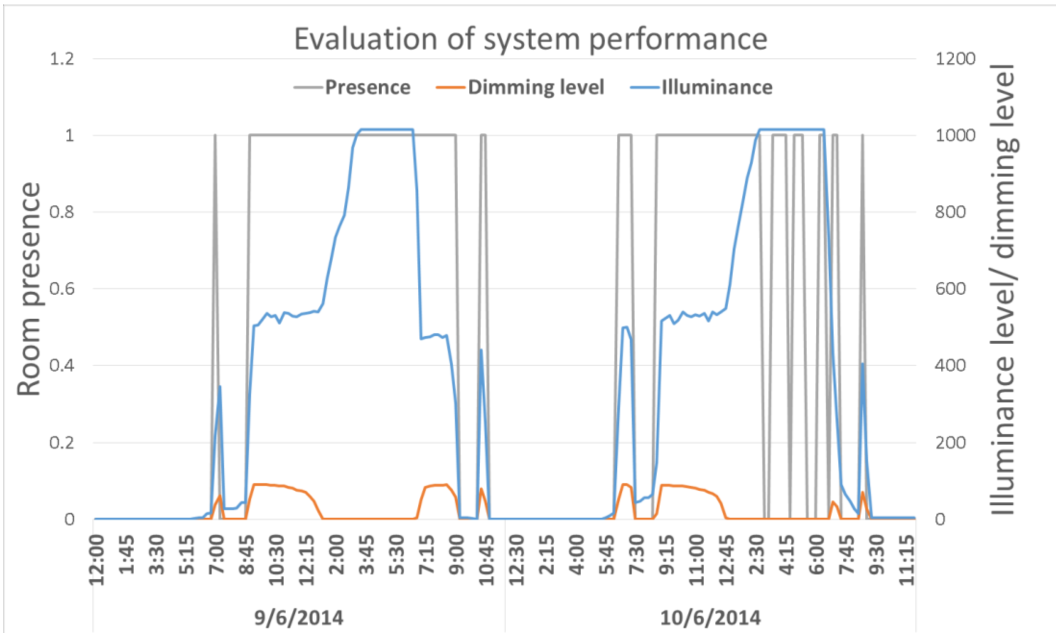


Figure 8- 1: Evaluation of the control algorithms for artificial lights with dimming

When the artificial lights dim bellow the maximum capacity, savings are achieved. Furthermore, the presence detector switches off the artificial lights if the room is un-occupied. When the dimming level is below 100% energy is saved comparing to the initial case when lights were working at their maximum power. In Figure 8- 1, it is illustrated that energy is saved during the biggest part of the day when outdoor daylight contributes to indoor illuminance level.

			Definition of classes							
			Residential				Non residential			
			D	C	B	A	D	C	B	A
5	LIGHTING CONTROL									
5.1	Occupancy control									
	0	Manual on/off switch					X			
	1	Manual on/off switch + additional sweeping extinction signal								
	2	Automatic detection								X
5.2	Daylight control									
	0	Manual					X			
	1	Automatic								X

Figure 8- 2: EN15232:2012 classes of Energy Efficiency for artificial lights Ancona Hospital

Figure 8- 2, illustrates the improvement in the energy efficient based on the EN15232:2012. The update of the BEMS and the installation of proper sensors and the BOC algorithms upgraded the class from D (Occupancy control: Manual on/off switch & Daylight control: Manual) to A (Occupancy control: Automatic detection & Daylight control: Automatic).

8.1.1.2 Savings of the control algorithms and the light fixture updates

Estimation of the annual savings is performed by comparing the baseline period, which is before the integration of the control algorithms and after the light fixture updates and the integration of the control algorithms. The baseline period is one week per room. Data collected during the baseline period for each room is reported in Table 8- 1.The weekly energy consumption is calculated by multiplying the power demand of the artificial lights by the time of operation.

Table 8- 1: Collected data for the baseline period, artificial lights, hospital of Ancona

		Weekly Energy consumption [kWh]	Weekly Occupancy [h]
Oncology	**Visitors waiting room corridor**	9.1	Always on
	Visitors waiting room middle	18.1	Always on
	Visitors waiting room window	9.1	Always on
	Archives PC	0.8	15.4
	Archives shelves	3.41	10.01
	Nurse office	9.8	46.77
	Patients waiting room	24.2	Always on
	Doctor office	1.9	12
Haematology	**Nurse office**	18.38	23.99
	Warehouse window	5.53	2.03
	Warehouse door	5.47	2.05
	Doctor office	15.61	23.18

During test period, energy consumption is measured indirectly from the average Dimmer percentage value which is multiplied by the installed power to obtain the average power consumed by each room.

A comparison between lighting installed power before and after the refurbishment is reported in Table 8- 2.

Table 8- 2: Comparison of baseline installed power and test installed power

		Baseline installed power [W]	Test installed power [W]
Oncology	**Visitors waiting room corridor**	54	35
	Visitors waiting room middle	108	70
	Visitors waiting room window	54	35
	Archives PC	72	70
	Archives shelves	72	70
	Nurse office	72	70
		72	70
	Patients waiting room	72	70
		72	70
	Day hospital room	0	70
	Doctor office	36	35
		36	35
Haematology	**Nurse office**	288	140
	Warehouse window	72	35
	Warehouse door	72	35
	Doctor office	288	140

With respect to "Always ON" areas, savings are calculated as the difference between baseline and test energy consumption while for the other areas savings are calculated as the difference between normalized baseline energy and test energy consumption.

It should be noted that all final energy values refer to electricity. Energy efficiency (kwh) are finally converted into primary energy, € and CO2 using the following conversion factors:

- 0.15 €/kWh
- 2.17 kwhpe/kwh
- 531 gCO2/kWh

Yearly savings in terms of percentage, electricity, primary energy and CO2 are presented in Table 8- 3.

Table 8- 3: Ancona Hospital Smart lighting system yearly results

		Saving				
	Room	**%**	**kWh**	**€**	**kWhpe**	**CO_2 [kg]**
ol	**Visitors waiting room**	80%	379	57	823	201

	corridor					
	Visitors waiting room middle	73%	688	103	1494	366
	Visitors waiting room window	82%	389	58	844	206
	Patients waiting room	76%	378	57	819	201
	Nurse office	56%	572	86	1242	304
	Doctor office	52%	59	9	127	31
	Archives shelves	94%	592	89	1284	314
	Archives PC	47%	56	8	122	30
Haematology	**Warehouse door**	63%	17	3	36	9
	Warehouse window	99%	622	93	1350	330
	Nurse office	82%	746	112	1620	396
	Doctor office	74%	3.3	0	7	2

Analysing the results, it can be noted that in all the retrofitted areas (except Archives PC) at least 50% energy efficiency are reached. Three areas are underperforming compared to the others: Oncology Nurse Office, Doctor Office and Archive PC area. It should be noted that a higher energy efficiency in term of percentage does not mean a lower PBT of the solution in the selected area. For example comparing Oncology Nurse Office and Oncology Patients waiting room (where the same peak power for lighting is installed) even if the first room presents higher savings in terms of %, the second room has higher savings in terms of energy and money. This is clearly due to the different light switch pattern of the two rooms.

The following figures (Figure 8- 3 - Figure 8- 5) show the evolution of the energy efficiency obtained in each area (areas are grouped by department) during the test period. Generally speaking different tendencies can be highlighted:

- Saving increase in the first month of the monitoring campaign due to algorithm optimization;
- A seasonal tendency can be highlighted: the higher availability of daylight during spring and summer increases the savings achieved thanks to dimming in rooms equipped with windows.

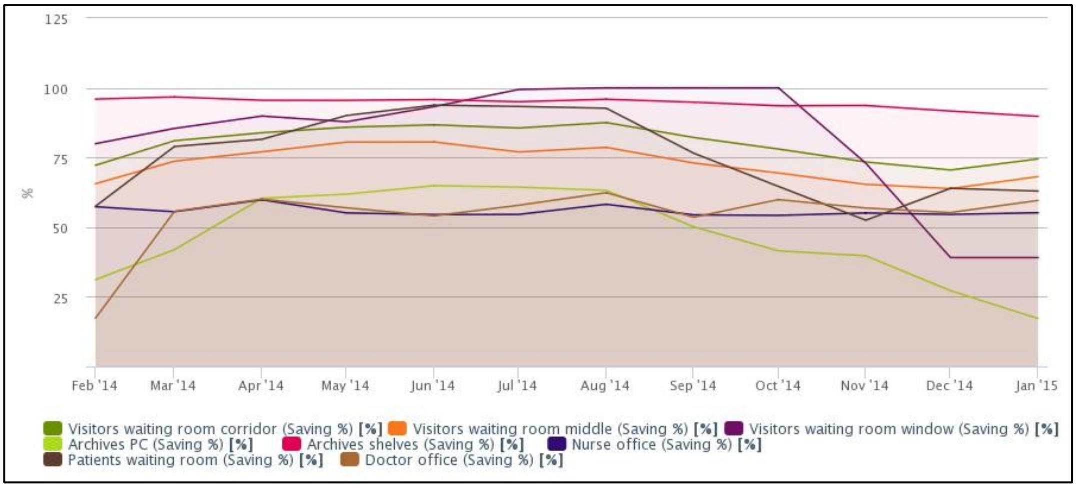


Figure 8- 3: Oncology department areas monthly savings

Figure 8- 4: Haematology department areas monthly savings

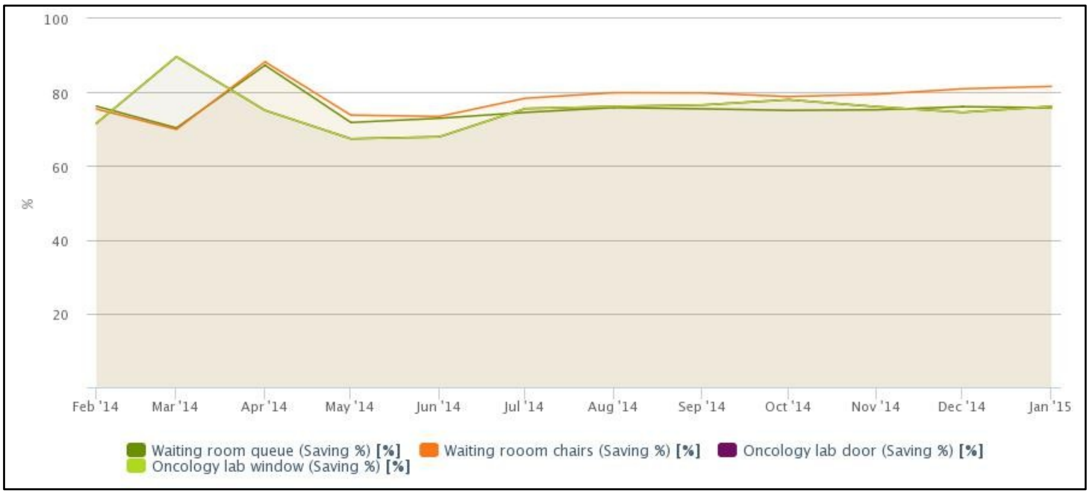


Figure 8- 5: Analysis lab department areas monthly savings

8.1.2 Artificial light – Hospital of Chania

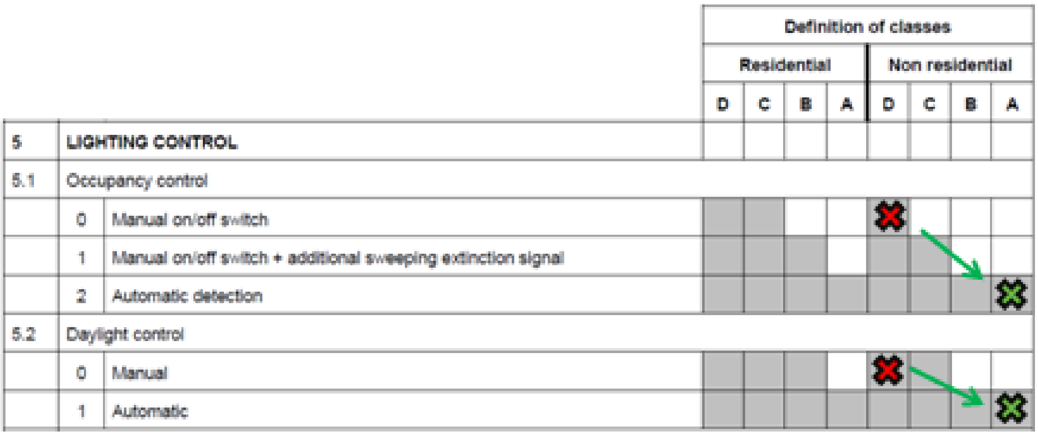


Figure 8- 6: EN15232:2012 classes of Energy Efficiency for artificial lights Chania Hospital

Figure 8- 6, illustrates the improvement in the energy efficient based on the EN15232:2012. The update of the BEMS and the installation of proper sensors and the BOC algorithms upgraded the class from D (Occupancy control: Manual on/off switch & Daylight control: Manual) to A (Occupancy control: Automatic detection & Daylight control: Automatic).

8.1.2.1 Annual savings of the control algorithms

Developed building optimization and control algorithms have been applied in the 3 selected rooms to preserve the illuminance level within limits set by the regulations and reduce the energy consumption from potential energy losses, such as operating the air handling units with the windows open or when no presence is detected.

8.1.2.2 Energy efficiency calculation methodology

The baseline period for artificial lights is 1st September 2014 – 30th September 2014. The selected variable for normalization is occupancy of the rooms as measured in each room. The calculations of energy efficiency are performed in a monthly base.

The normalization factors during the baseline month for the specific rooms are presented below:

Table 8- 4: Occupancy (h) during baseline period for artificial lights, Chania Hospital

Period	Doctor's room	Doctor's rest room	Patients' room
Baseline period occupancy (h)	133.5	585	93.5

The normalization values for the 3 rooms during the monitoring period are presented in the following table:

Table 8- 5: Normalizing factors (occupancy) for the 3 selected rooms

Month	Presence in doctor's room	Presence in doctor's rest room	Presence in patients' room
Feb-14	208.38	384.00	206.85
Mar-14	182.40	477.60	208.03
Apr-14	144.47	602.35	216.53
May-14	110.67	360.73	48.54
Jun-14	64.47	240.00	60.90
Jul-14	155.99	572.07	63.70
Aug-14	165.40	476.78	82.71
Sep-14	561.41	344.30	328.74
Oct-14	572.36	384.74	516.94
Nov-14	558.93	333.94	576.31
Dec-14	593.71	327.00	624.42
Jan-15	627.13	324.13	689.95

Using the normalization factors, baseline energy is calculated and the results are presented in the following table

Table 8- 6: Baseline and test energy for the artificial lights

	Total baseline monthly energy [kWh of electricity]	Measured energy consumption [kWh of electricity]
Feb-14	98.67	76.09
Mar-14	91.68	71.63
Apr-14	81.67	57.57
May-14	51.77	69.34
Jun-14	33.20	73.01
Jul-14	74.16	9.00
Aug-14	76.61	30.85
Sep-14	233.02	84.13
Oct-14	251.36	77.73
Nov-14	249.57	79.54
Dec-14	265.31	95.44
Jan-15	281.91	86.93

Energy efficiency (kWh) are converted to energy consumption and primary energy, € and CO2 using the following factors

- 0.07 €/kWh
- 2.9 kWh_{pe} /kwh for electricity
- 1062.5 gCO_2/kWh

The energy efficiency results during the last year are reported. The following table reports results in terms of saved electricity and thermal oil and percentage of savings

Table 8- 7: Solution set results in terms of final energy and percentage

	Final Energy Electricity saving [kWh]	Percentage [%]]
Feb-14	22.59	23%
Mar-14	20.05	22%
Apr-14	24.10	30%
May-14	-17.56	-34%
Jun-14	-39.81	-120%
Jul-14	65.16	88%
Aug-14	45.76	60%
Sep-14	148.89	64%
Oct-14	173.63	69%
Nov-14	170.03	68%
Dec-14	169.87	64%
Jan-15	194.97	69%
TOTAL	977.68	57%

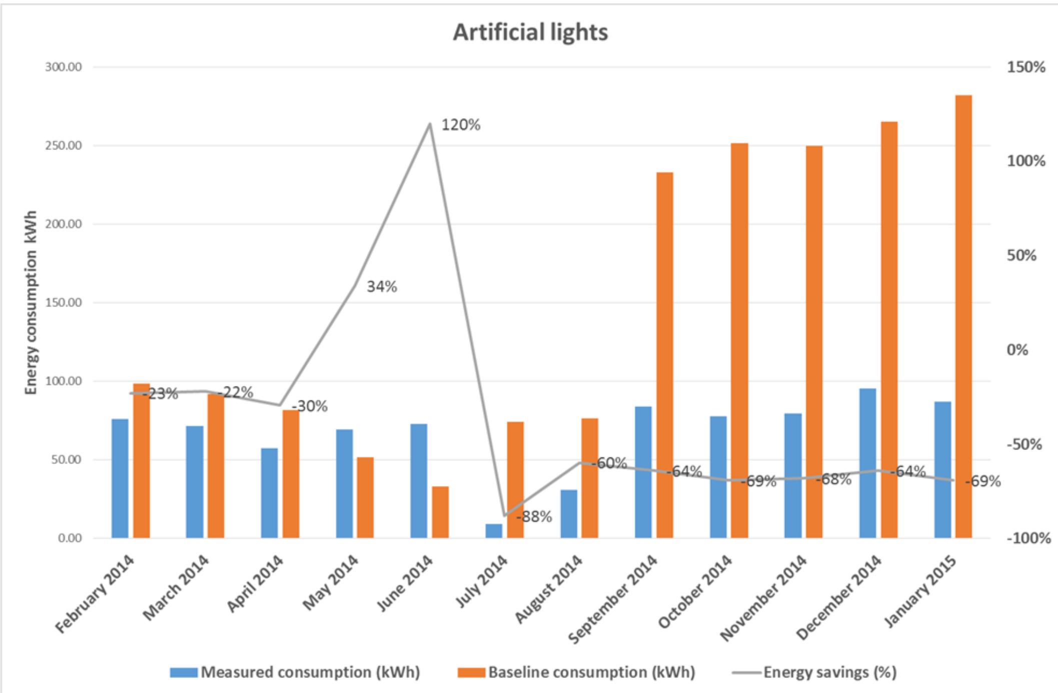


Figure 8- 7: Monthly Measured consumption a priori and a posteriori the integration of the BOC algorithm & savings (%) for the artificial lights

Figure 8- 7, illustrates the significant savings achieved using the BOC algorithms

Finally, energy results are converted into primary energy, CO2 emissions and Euros according to the conversion factors previously presented.

Table 8- 8: Solution set results in terms of primary energy, CO2 and Euros

	Primary energy [kWh]	CO2 [kg]	Euro
Feb-14	65.50	22.34	1.58 €
Mar-14	58.14	19.83	1.40 €
Apr-14	69.89	23.83	1.69 €
May-14	-50.93	-17.37	-1.23 €
Jun-14	-115.44	-39.37	-2.79 €
Jul-14	188.97	64.44	4.56 €
Aug-14	132.71	45.26	3.20 €
Sep-14	431.78	147.25	10.42 €
Oct-14	503.52	171.72	12.15 €
Nov-14	493.08	168.16	11.90 €
Dec-14	492.64	168.01	11.89 €
Jan-15	565.42	192.83	13.65 €
TOTAL	2835.26	966.92	68.44 €

Furthermore the annual saving results are presented per type of room in order to point the significant role of the room's type.

Table 8- 9: Annual savings per room in paediatric department of Chania Hospital

Dept	Room	Saving [%]	Saving [kWh]	Saving [€]	Saving [kwhpe]	Saving CO2 [kg]
Paediatric	Doctors' rest room	26%	27.73	1.94	80.41	27.42
	Patients room	60%	123.55	8.65	358.29	794.97
	Doctors' office	51%	803.81	57.85	2331.06	122.19

The savings in the Doctors' room are much higher comparing to the other rooms. Savings achieved during the monitoring period with the implementation of the BOC algorithms are almost equal compared to the estimated result (57%).

8.2 Control and optimization algorithms for HVAC

8.2.1 HVAC – Hospital of Chania

The indoor and outdoor thermal conditions of the patients' and doctors' rooms in the paediatric department of Chania Hospital, are depicted in Figure 8- 8 and Figure 8- 9, 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 (Figure 8- 9), 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 Figure 8- 8 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.

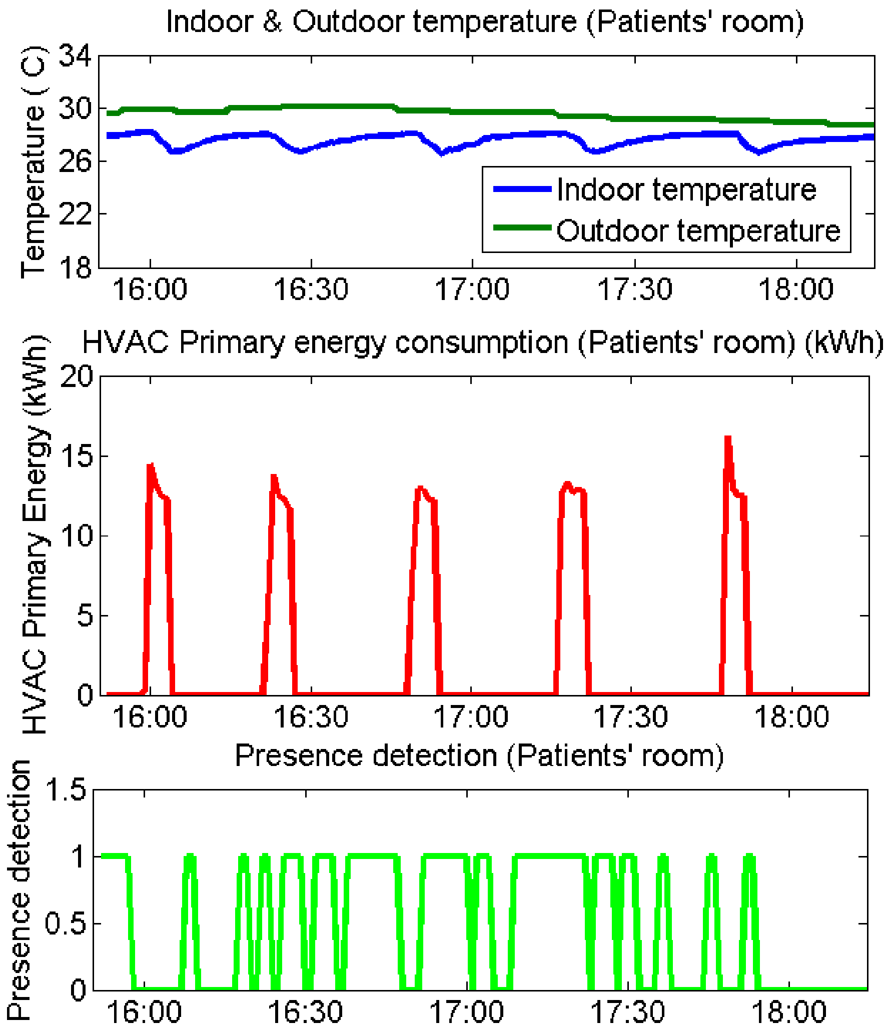


Figure 8- 8: Evaluation of the implementation of the control algorithm in Patients' room paediatric dept., Chania Hospital

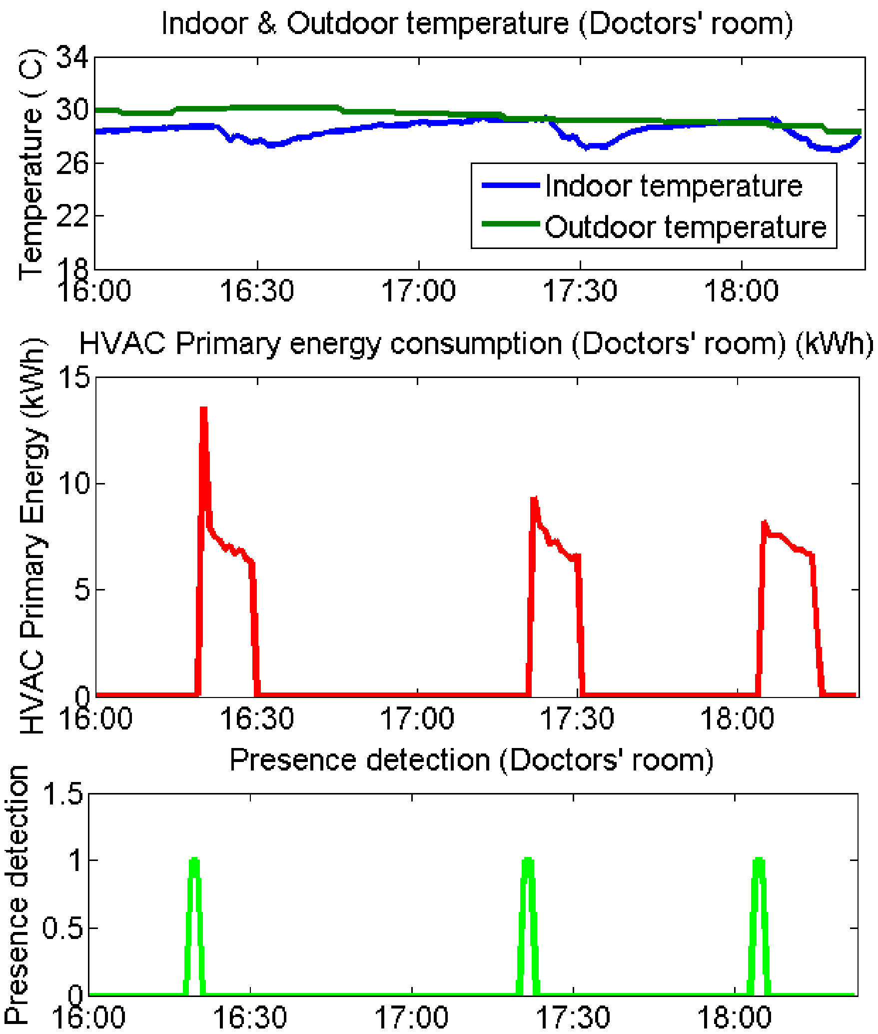


Figure 8- 9: Evaluation of the implementation of the control algorithm in Doctors' room paediatric dept., Chania Hospital

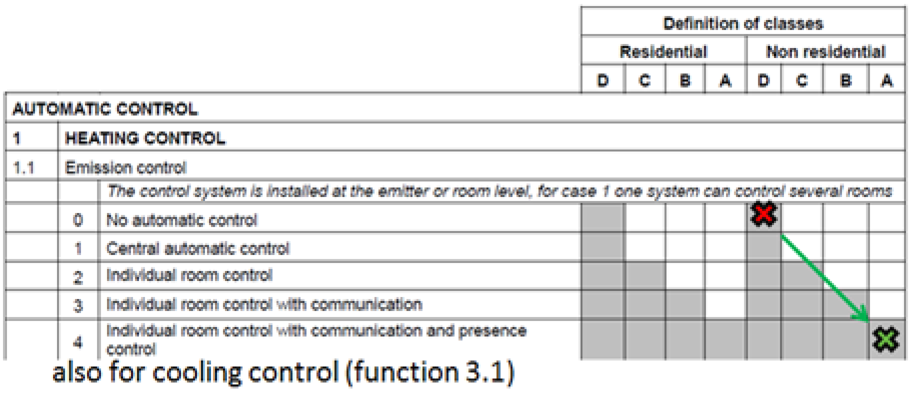


Figure 8- 10: EN15232:2012 classes of Energy Efficiency for air handling units Chania Hospital

As it can be in Figure 8- 10, the update of the BEMS and its communication with the integrated sensors and actuators has upgraded the class concerning the automatic control from D to A which increases significantly the energy efficiency potential according to EN15232:2012.

8.2.1.1 Annual savings of the control algorithms

In the 3 selected rooms of the paediatric department equipment is installed for the monitoring and control of the air handling units and the indoor comfort conditions of doctors and patients.

Developed building optimization and control algorithms have been applied in the 3 selected rooms to preserve the temperature within limits set by the regulations and reduce the energy consumption from potential energy losses, such as operating the air handling units with the windows open or when no presence is detected, or use indoor temperature set-points which significantly increase energy consumption.

8.2.1.2 Energy efficiency calculation methodology

The baseline period for heating is: 1st January 2014 – 31st January 2014. The period chosen for cooling baseline is 1st August 2013 – 31st August 2013 and for heating. The specific periods are chosen because:

- Selected rooms are fully monitored since May 2013.
- During these periods the Air handling units fully operate because the external conditions impose the operation of the systems.

The normalization factors during the baseline months for the specific rooms during heating period (November – April) and cooling period (May – October) are presented below:

Table 8- 10: Occupancy (h) during baseline period for air handling units, Chania Hospital

Period	**Presence in doctor's room**	**Presence in doctor's rest room**	**Presence in patients' room**
Heating period occupancy (h)	400	368	380
Cooling period occupancy (h)	136	540	250

The normalization values for the 3 rooms during the monitoring period are presented in the following table:

Table 8- 11: Normalizing factors for the 3 selected rooms

Month	Presence in doctor's room	Presence in doctor's rest room	Presence in patients' room
Feb-14	208.38	384.00	206.85
Mar-14	182.40	477.60	208.03
Apr-14	144.47	602.35	216.53
May-14	110.67	360.73	48.54
Jun-14	64.47	240.00	60.90
Jul-14	155.99	572.07	63.70
Aug-14	165.40	476.78	82.71
Sep-14	561.41	344.30	328.74
Oct-14	572.36	384.74	516.94
Nov-14	558.93	333.94	576.31
Dec-14	593.71	327.00	624.42
Jan-15	627.13	324.13	689.95

Using the normalization factors, baseline energy is calculated (for all the selected rooms) and the results are presented in the following table:

Table 8- 12: Baseline and test energy for air handling units

	Baseline monthly thermal energy [kWh for summer, litters for winter]	Test monthly thermal energy [kWh for summer, litters for winter]
Feb-14	147.20	141.20
Mar-14	149.87	176.28
Apr-14	152.95	73.58
May-14	767.50	91.54
Jun-14	509.04	590.00
Jul-14	1103.22	968.46
Aug-14	1134.31	1493.08
Sep-14	3351.76	911.54
Oct-14	3702.94	77.69
Nov-14	307.42	52.08
Dec-14	324.25	183.12
Jan-15	342.93	213.50

Energy efficiency (kWh) are converted to energy consumption and primary energy, € and CO2 using the following factors

- 0.07 €/kWh
- 1 €/litre
- 2.9 kwhpe/kwh for electricity
    - kwhpe/litre of oil

- 1062.5 gCO_2/kWh
- 263.6 $gCO_2/$ kWh of oil

The energy efficiency results during the last year are reported. Table 8- 13 reports results in terms of saved electricity and thermal oil and percentage of savings.

Table 8- 13: Solution set results in terms of final energy and percentage

	Energy Electricity [kWh]	Oil consumption (litres)	Percentage [%]]
Feb-14	0	6.00	4%
Mar-14	0	-26.40	-18%
Apr-14	0	79.37	52%
May-14	675.96	0	88%
Jun-14	-80.96	0	-16%
Jul-14	134.76	0	12%
Aug-14	-358.76	0	-32%
Sep-14	2440.22	0	73%
Oct-14	3625.24	0	98%
Nov-14	0	255.34	83%
Dec-14	0	141.14	44%
Jan-15	0	129.43	38%
TOTAL	6436.46	584.88	59%

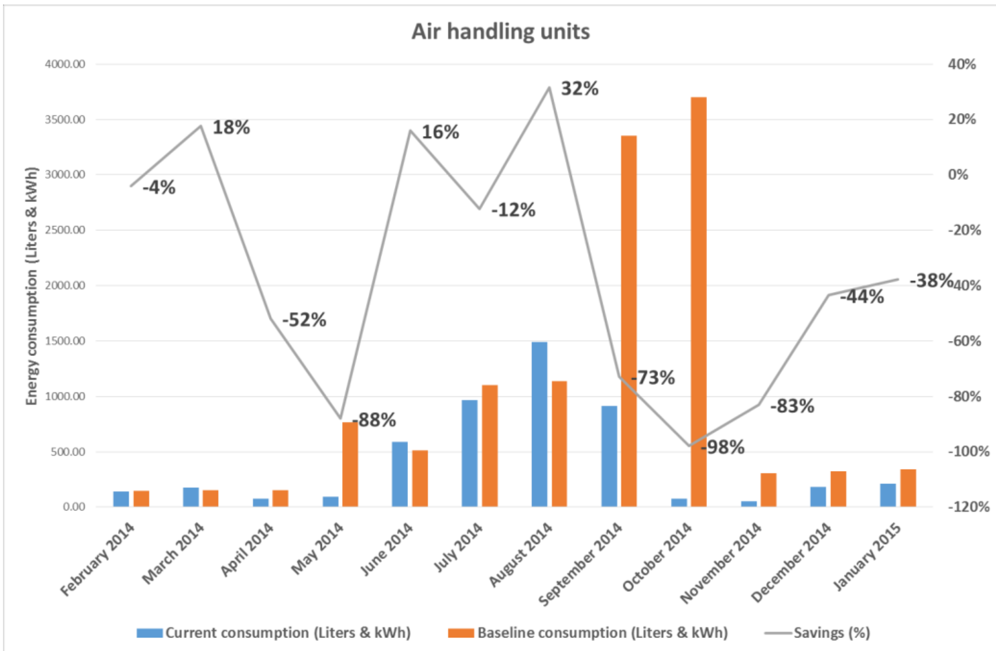


Figure 8- 11: Monthly Measured consumption a priori and a posteriori the integration of the BOC algorithm & savings (%) for the air handling units

Figure 8- 11, illustrates the monthly savings achieved due to the operation of the BOC algorithm for the air handling units.

Final energy results are converted into primary energy, CO2 emissions and Euros according to the conversion factors previously presented.

Table 8- 14: Solution set results in terms of primary energy, CO2 and Euros

	Primary energy [kWh]	**CO2 [kg]**	**Euro €**
Feb-14	78.54	18.85	6.00 €
Mar-14	-345.61	-82.95	-26.40 €
Apr-14	1039.00	249.36	79.37 €
May-14	1960.28	668.52	47.32 €
Jun-14	-234.78	-80.07	-5.67 €
Jul-14	390.81	133.28	9.43 €
Aug-14	-1040.42	-354.82	-25.11 €
Sep-14	7076.63	2413.38	170.82 €
Oct-14	10513.21	3534.94	253.77 €
Nov-14	3342.37	802.17	255.34 €
Dec-14	1847.52	443.40	141.14 €
Jan-15	1694.21	406.61	129.43 €
TOTAL	26321.76	8152.68	1035.43 €

Furthermore the annual saving results are presented per type of room in order to point the significant role of the room's type.

Table 8- 15: Annual savings comparing baseline and monitoring period

Dept.	**Room**	**Saving [%]**	**Saving [kWh]**	**Saving [€]**	**Saving [kwhpe]**	**Saving CO2 [kg]**
Paediatric	Doctors' rest room	14%		130.43	1567.48	348.34
	Patients room	46%		156.68	3746.66	1120.65
	Doctors' office	69%		748.32	20929.48	6664.94

The savings in the Doctors' room are much higher compared to the other rooms. Thus, in a potential generalization of the solution set the Doctors' offices should be selected first.

Savings achieved during the monitoring period with the implementation of the BOC algorithms are higher comparing to the estimated result (36%).

The solution sets, required the installation of new hardware and update of the BMS equipment.

The following investment costs are analysed:

- 1800 € implementation of control algorithm and hardware installation:
- 1561.56 € equipment cost

A PBT of 3.4 years is estimated.

8.3 Discussion of the achieved results

During the one year of the monitoring period for the control and optimization algorithms, data have been acquired for the performance of the different systems and the indoor conditions in the rooms of the 2 pilot hospitals. The acquired data illustrate the right operation of the BOC algorithms which contribute to the energy efficiency and the verification of the comfort level. The energy efficiency is calculated and the results are also tabulated in **Error! Reference source not found.**.

Table 8- 16: Overall results of achieved energy efficiency

Pilot hospital	**Solution set**	**Energy efficiency (%)**
Hospital of Ancona	Artificial lights	(52 % - 99 %)
Hospital of Chania	Artificial lights	(26 % - 60 %)
	Air handling unit	(14 %- 69 %)

These results demonstrate the significant contribution of the applied control and energy management techniques in the reduction of energy consumption and the overall target of zero energy buildings.

Furthermore, results from the integration demonstrate the effect of the control algorithms to guarantee the required comfort level in the selected rooms. The closed loop control algorithm adjusts continuously the operation of the Air handling units and the artificial lights as it is illustrated in the graphs of the acquired data from the pilot hospitals.

The acquired results demonstrate also the proper communication between the BOC algorithms and existing BEMS of the hospital of Chania and the new BEMS of the hospital of Ancona. This demonstrates the versatility of the developed BOC algorithms to be integrated in new or existing BEMS of different hospital buildings.

The achieved results concerning the energy saving are similar comparing to the energy saving performed in individual systems are described in the literature review. The energy saving of the artificial lights is higher from the initial controllers available in the market (Knight, 1998) and similar to the latest one as presented by (Frattari et al., 2009). Moreover, in systems with dimming installation the archived energy saving is higher demonstrating the energy saving potential of hospital buildings and the energy performance of the developed and implemented control algorithms.

Concerning the air handling units, the achieved results of energy saving are higher comparing to the research presented by (Rasouli et al., 2010) and (Huang et al., 2006).

Regarding the target of ZEB, the integrated control and management algorithms in the field controllers have achieved a significant reduction of energy consumption. The residual of the required energy in annual base can be covered with less RES which can reduce significantly the capital cost of the installation.

The overall integration of the solution sets has also been accepted by the medical community of the pilot hospitals which has adapted their energy behaviour during the monitor period towards a more energy friendly profile.

-------------------------------------Chapter 9 --

CONCLUSIONS AND FUTURE RESEARCH

9 Conclusions and further future research

The developed control and optimization algorithms are integrated in the field controllers of two pilot hospitals. As it is observed in the experimental results, energy efficiency are achieved, while the comfort level of the users is safeguarded. The main points of the presented work are:

- The architecture of the BOC algorithms, which are integrated in existing BEMS using the Web-EMCS. The aforementioned algorithms are developed in Matlab environment as a single function and they can be deployed in any of the available format, from standalone applications (exe) to Microsoft excel plug-ins. This architecture allows the replication of the integration into intelligent BEMS with different structure. Furthermore, the control algorithms can be integrated directly into field controllers (ex. MPM of Schneider Electric) as long as they are translated into the proper format (lua, C++ etc.). Moreover, the integration of the light controllers for example, demonstrates that the controllers' architecture can be integrated into different systems with small variations. At the hospital of Ancona, compared to the hospital of Chania, the artificial lights can be dimmed, but the structure of the control algorithm is almost identical in both hospitals. The BOC algorithms integrated in the Web-EMCS significantly reduce the energy consumption of the HVAC and the artificial lights, towards a zero energy building.
- The control algorithms safeguard the comfort level adjusting the operation of the HVAC and artificial lights based on the outdoor/indoor conditions. The integration of the control algorithms in the Web-EMCS has upgraded the performance of the HVAC system, which leads to energy efficiency and as a result less energy is required from the grid. The simulation and the monitoring results indicate the increased saving potential after the application of the control algorithms. The energy reduction is achieved by the temperature set-point regulation of and illuminance level according to the national regulations. Furthermore, the deactivation of the systems, in case that presence is not detected for a specific period, increases the energy efficiency. The reduction of the energy consumption contributes to the goal of a ZEB.

- The predictive algorithms based on neural networks estimate accurately the outdoor/ indoor conditions. The knowledge in advance of the energy requirements of the hospital facilities is evaluated using collected measured data. The personnel responsible for the energy consumption can review the daily requirements and propose methods for their reduction or negotiate different energy prices during the day. Furthermore the knowledge in advance of the energy requirements can be combined with energy storage systems, which can reduce the maximum power demand of the hospital. Thus the cost for power is reduced and the building can be considered as more environmental friendly.
- The optimization algorithms estimate the most suitable operation level of the HVAC during the next 8 hours. The prediction of energy requirements and indoor comfort conditions is exploited in a multi time-step optimization algorithm, which estimates the most suitable operation level of the HVAC in each room of the hospital. Thus, in a 8 hours horizon the operation of the HVAC systems is minimized, while comfort is maintained at suitable levels. In addition, the optimization algorithm is expandable. In the case of BIPV installation, the objective function is updated with the power provided from the RES. Combining the a priori knowledge of energy consumption and energy production, shift loading techniques are evaluated.
- The developed BOC algorithms are implemented in hospital facilities which require additional safety features. Although the BOC algorithms have the capacity to meet the restrictions and preferences imposed by the user, they incorporate software based override features in order to avoid any possibility of circumvent conditions (such as restrictions for minimum/maximum temperature or humidity). The BOC algorithms can be overridden by the authorised personnel of each hospital sending commands to the system manually. The nature of Web-EMCS allows remote connection to override features which increases the safety of the system. The activation of the safety features is expected only in case of potential sensor failure or during their maintenance. Thus the BOC algorithms is not allowed to be fed with fault data.

- <u>Passive energy efficiency techniques reduce the energy consumption of the hospital buildings.</u> The simulation results from the TRNSYS dynamic model indicate that significant energy efficiency can be performed by applying passive energy efficiency techniques. These savings combined with the integration of the BOC algorithms can transform a building to ZEB class.

Summarizing all the above points, the innovative parts of the present thesis are:

- ✓ The design and evaluation of fuzzy based control algorithms for controlling Air Handling Units and artificial light systems of healthcare facilities, including the safety features.
- ✓ The development and validation of predictive algorithms for indoor and outdoor conditions based on neural networks using measured data from healthcare facilities.
- ✓ Optimization algorithms, are synthesized to use the values of the predictive algorithms and calculate the optimized performance of the HVAC systems.
- ✓ Integration of BOC algorithms in existing BEMS through a Web-EMCS to improve their performance and the whole hospital energy efficiency towards a zero energy hospital state.

Finally, further future research effort should be put in:

- ➢ Implementation of demand response techniques in the BOC algorithms.
- ➢ Update of Control algorithm for artificial lights using external blinds and glare input.
- ➢ Update of HVAC control algorithm to control the fan speed of the ventilation system using an inverter for the mechanical ventilation.
- ➢ Research on implementing storage and generation systems to reduce the dependence of the hospitals from the main power grid.

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2. S. Papantoniou, Denia Kolokotsa, Kostas Kalaitzakis, Davide Nardi Cesarini, Eduard Cubi and Cristina Cristalli **Adaptive lighting controllers using smart sensors,** International Journal of Sustainable Energy, 2014
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4. Sotiris Papantoniou, Denia Kolokotsa, Kostas Kalaitzakis **Building optimization and control algorithms implemented in existing BEMS using a web based energy management and control system**, Energy and Buildings, In press
5. S. Papantoniou, D. Kolokotsa: "**Prediction of outdoor air temperature using Neural Networks; application in 4 European cities**", Energy and Building, under review

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1. Eleni Pyloudi, Sotiris Papantoniou, Dionysia Kolokotsa **Retrofitting an office building towards a net zero energy building,** Advances in Building Energy Research, 2014
2. Elena Provata, Denia Kolokotsa, Sotiris Papantoniou **Development of optimization algorithms for the Leaf Community microgrid,** Renewable Energy, 2015
3. Dionysia Kolokotsa, Christina Diakaki, Sotiris Papantoniou, Andreas Vlissidis: "**Numerical and experimental analysis of cool roofs application on a laboratory building in Iraklion, Crete, Greece**" Energy and Buildings, 2012, 55, pp. 85-93
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(Directly related to the PhD thesis field)

1. P. Foutrakis, S. Papantoniou, K. Kalaitzakis, D. Kolokotsa: "**Development of a smart sensor for controlling artificial lights and venetian blinds**", 34th AIVC Conference: "Energy conversation technologies for mitigation and adaptation in the built environment: The role of ventilation strategies and smart materials", pp. 1300 – 1309
2. S. Papantoniou, D. Kolokotsa, K. Kalaitzakis, D Nardi Cesarini, E. Cubi, C. Cristalli: "**A development of a lighting controller using smart sensors**" , 34th AIVC Conference: "Energy conversation technologies for mitigation and adaptation in the built environment: The role of ventilation strategies and smart materials", pp. 995 – 1003
3. S. Papantoniou, D. Kolokotsa, and A. Pouliezos, "**Neuro-fuzzy model based predictive algorithm for environmental management of buildings**." 3rd International Conference on Industrial and Hazardous Waste Management, Chania, pp. 1–8, 2012.

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1. Eduard Cubi, Sotiris Papantoniou, Davide Nardi Cesarini, Jesus Arbol, Jose Maria Fernandez, Jaume Salom **Potential benefits in terms of thermal comfort and energy use of adding a control loop to an existing multizone Air Handling Unit in a hospital setting** eSim 2014. Ottawa, May 7-9 2014
2. V. Tsilini, S. Papantoniou, D. Kolokotsa, E. Maria: "**Urban Gardens: As a solution to energy poverty and urban heat island**", 34th AIVC Conference: "Energy conversation technologies for mitigation and adaptation in the built environment: The role of ventilation strategies and smart materials", pp. 653 – 661
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