ENERGY EFFICIENT VENTILATION STRATEGIES FOR SURGERY ROOMS

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EXECUTIVE SUMMARY

Surgery rooms are a space type with particularly stringent indoor environmental quality (IEQ) requirements, which translate into high energy use. Due to the unclear IEQ and infection control requirements for surgery rooms in Spain, these spaces are often designed and operated 24 hours per day and 7 days per week, to meet the most stringent recommendations (not only the requirements) in the available guidelines. While health and safety must remain top priority in hospitals, the high energy use of HVAC systems in surgery rooms makes these a clear energy efficiency target. The objective of this thesis is to identify and evaluate energy efficient ventilation strategies in surgery rooms that maintain acceptable indoor environmental quality and cleanliness while reducing the associated energy use.

A comprehensive and critical review of the indoor environmental quality and infection control requirements in surgery rooms identifies the key performance goals of the requirements in the available standards, and sets the boundaries for the definition of energy efficiency improvements in surgery room systems. The intrinsic performance motivations for the requirements for total supply airflow, outdoor airflow, temperature, and relative humidity are different, which brings the opportunity to improve energy performance by individually controlling the different setpoints. A general method to adjust system operation (outdoor airflow rate, total supply air, indoor air temperature, and indoor air relative humidity) to meet IEQ performance goals while reducing energy use is developed.

A calibrated computer-based energy model of a standard surgery room system is used to assess the potential benefits of control strategies. A careful control of a standard surgery room air handling unit can reduce primary energy use and associated CO_2 emissions and energy costs by up to 83% while meeting all the indoor environmental quality and infection control requirements in the standards. In view of the magnitude of the potential energy savings, control measures for surgery rooms should be strongly encouraged for their wide application. Further savings are possible by controlling supply airflow based on real time measurement of particle concentration. However, the potential benefits of this strategy are constrained by the current unavailability of particle count targets during surgery room operation as a function of surgery type. Real performance-based infection control will not be possible until real-time sensors are capable of counting and identifying microorganisms.

A calibrated energy model is also used to assess the potential energy use and thermal comfort benefits of controls in old and non-standard systems. Results show that customized control strategies can also be successfully implemented as a retrofit solution.

The large volumes of outdoor air supply in surgery rooms make these particularly suitable for energy recovery systems. An evaluation of the thermal energy use required for ventilation air conditioning across Catalonia is provided. This is meant as a tool to assess the potential benefits of different types of heat recovery units. Ventilation air conditioning energy use is dominated by heating thermal energy over cooling thermal energy even in the warmest regions in Catalonia.

Energy efficiency in surgery rooms could be largely improved with control and heat recovery strategies that fall within the limits of the current indoor environmental quality standards. Future research should study appropriate technologies to monitor surgery room occupancy for air handling unit control purposes, and work towards defining infection control performance targets and monitoring tools.

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LIST OF ACRONYMS

AHU – Air Handling Unit

ASHRAE – American Society of Heating, Refrigerating, and Air Conditioning Engineers

AIA – American Institute of Architects

CAV – Constant Air Volume

DOAS – Dedicated Outdoor Air System

EIA – Energy Information Administration

HEPA – High Efficiency Particulate Air

HML – Hospital de Mollet

HVAC – Heating, Ventilation, and Air Conditioning

HVN – Hospital Virgen de las Nieves (Granada)

IAQ – Indoor Air Quality

IEQ – Indoor Environmental Quality

LMA - Local Mean Age

NREL - National Renewable Energy Laboratory

PMV – Predicted Mean Vote

PPD – Predicted Percentage of Dissatisfied

RITE - Reglamento de Instalaciones Térmicas de los Edificios

RBT – Reglamento de Baja Tensión

VAV – Variable Air Volume

MATHEMATICAL SYMBOLS

$C_{I,min}$ - Minimum total supply airflow rate

C_I^* - Reference airflow rate

ε_{si} - Maximum allowed relative concentration of germs in the protection zone

h - Enthalpy

p – Total pressure

p_w – Pressure of water vapor

p_{ws} – Saturation pressure of water vapor

RH- Relative humidity

t – Temperature

μ_s - Germ concentration level

v – Specific volume

W – Humidity ratio

1 INTRODUCTION

1.1 HVAC ENERGY USE IN HOSPITALS

Hospitals are among the largest energy users in the building sector. According to the EIA (Energy Information Administration 2008), healthcare buildings are the second largest energy users per unit floor area of all building types. The US Department of Energy (cited in (ASHRAE 2003)) states that the average acute care, full-service hospital is documented to have an average consumption of about 1040 kWh/m^2-yr. The average specific final energy use for tertiary and residential buildings in the Mediterranean area is 275 and 150 kWh/m^2-yr, respectively (Ortiz et al. 2012). The large energy use of hospitals is due to their unique processes and their continuous operation 24 hours a day, 365 days a year. HVAC is usually the largest energy use in hospitals accounting for roughly 30-50% of the total final energy (although this largely varies depending on the type of hospital and its location) (Barrachina 2012; Fundación de la Energía de la Comunidad de Madrid 2010; Bonnema et al. 2010; ASHRAE 2003), including ventilation fan energy, outdoor air cooling and dehumidification, outdoor air heating and humidification, as well as thermal mixing and reheating required to maintain space comfort. This is mainly due to their particularly stringent Indoor Environmental Quality (IEQ) requirements, which translate into large outdoor airflow rates and narrow control windows for indoor air temperature and relative humidity. Although energy use in hospitals is among the largest in absolute terms, it often receives relatively little attention from hospital managers, as energy costs typically range 1-2% of the annual total budget (Barrachina 2012; Fundación de la Energía de la Comunidad de Madrid 2010).

Figure 1 shows the final energy use breakdown for a large hospital in climate zone 1A according to (Bonnema et al. 2010). These values result from calibrated simulations performed by the U.S. National Renewable Energy Laboratory (NREL). The same reference provides equivalent values for other climate zones. The HVAC Design Manual for Hospitals and Clinics (ASHRAE 2003) also provides energy use breakdowns for “typical” hospitals in different climate zones, although using different categories (more HVAC focused). It must be noted that (apparently) both references use hospital models without internal laundry and kitchen services, which would increase the share of non-HVAC energy uses in the pie-chart.

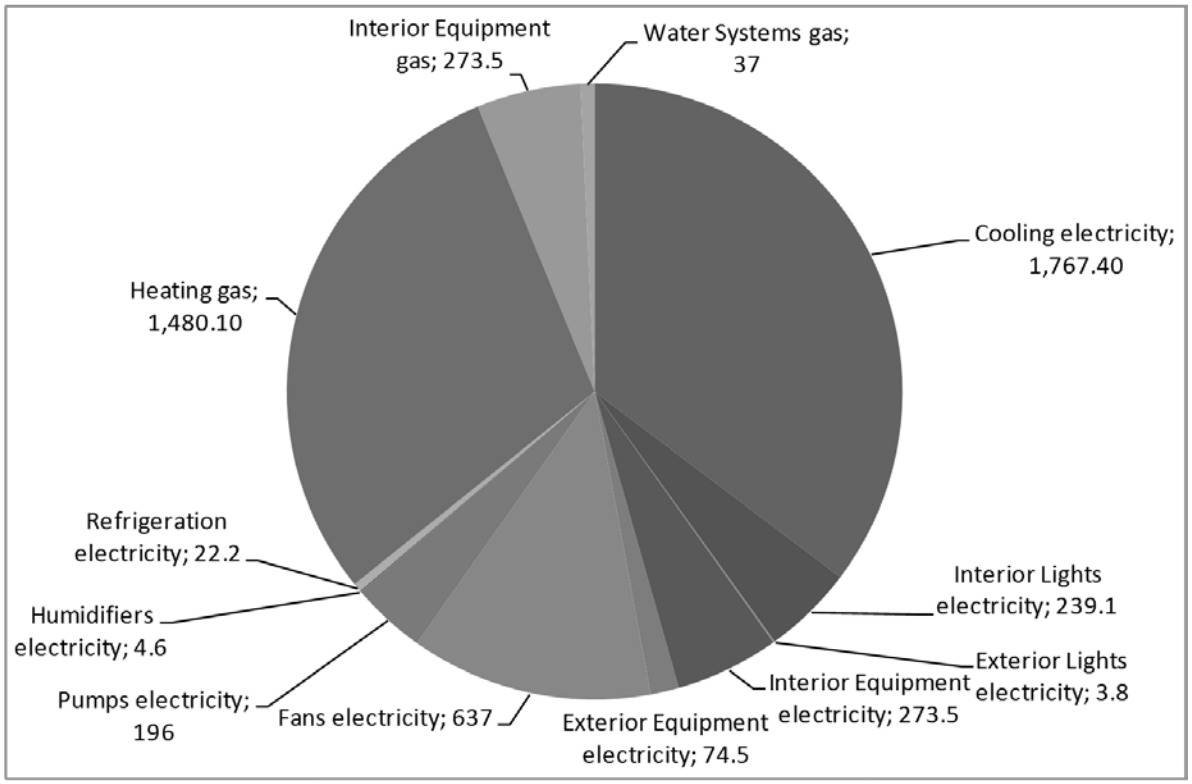

Figure 1 Final Energy Use breakdown for a large hospital in climate zone 1A (Bonnema et al. 2010). Values in MJ/m^2-yr

"HVAC systems that can deliver clean air quietly and at the correct volume, temperature, humidity, and pressure to support infection control and help keep patients comfortable" (ASHRAE et al. 2012). While health and safety must remain top priority in hospitals, the high energy use (and derived energy cost) of HVAC systems in hospitals makes these systems a clear target for energy efficiency strategies.

In non-health care facilities, energy efficient HVAC control strategies at system level (i.e., space conditioning, air handling and distribution) are often seen as a "low hanging fruit" because they can be "easily" implemented in already existing buildings and systems, and do not require major hardware changes and investments. However, most of the energy efficiency recommendations for hospitals focus on plant components (i.e., hot and cold water production), and fail to address air handling based opportunities (Fundación de la Energía de la Comunidad de Madrid 2010; EPTA Ltd 2007) to avoid dealing with potential tradeoffs between energy use and indoor environmental quality. Low-investment, widely applicable, cost effective solutions to reduce energy use in public buildings are particularly interesting. It makes sense, therefore, to seek energy efficient ventilation strategies for hospitals.

As a measure towards meeting Europe's self-imposed energy and climate targets (European Commission 2014), the European Commission passed a very ambitious directive on energy efficiency in the built environment (European Comission 2010). According to the directive on building energy efficiency, from 2020 on new buildings in the European Union must meet the "Nearly-net zero energy" performance standard (as defined by the corresponding member state). Hospitals are very high energy users, and not likely to meet a net-zero energy target. Nevertheless, efficiency measures should consistently be applied in hospitals too. Energy savings in the 194 hospitals and 700 surgery rooms in Catalonia (Generalitat de Catalunya - Departament de Salut 2011) could be seize a substantial contribution to meeting the region's overall climate target.

Beyond the direct benefits of cutting energy use and derived costs, energy efficiency projects in hospitals and healthcare buildings are particularly important in terms of dissemination and public awareness. "Healthcare facilities play an influential role in promoting public wellness by educating their staff on the importance and techniques of sustainability, which they take home and spread to their communities at large. Some healthcare institutions have leveraged sustainability efforts to provide even greater value to their communities" (ASHRAE et al. 2012). In view of the strategic role of hospitals in terms of both energy use and access to public, the European Commission has recently funded two projects that specifically address energy efficiency in hospitals. Hospilot (Hospilot Project 2014) developed a software tool to assess the potential benefits of basic energy efficiency measures in a hospital setting. The measures addressed in Hospilot focus on lighting and HVAC efficiency, which could be largely applied in different hospital areas. On the other hand, Green@Hospital (Green@Hospital) aims to better control and integrate key the energy systems in hospitals. Green@Hospitals performs in-depth analysis of hospital systems that offer the largest potential for energy savings through control, and that can be easily replicated in hospitals elsewhere. Other EU-funded hospital related projects include Streamer (Streamer 2014), which focuses on mixed-use healthcare districts, and Reshospitals (Res-Hospitals 2014), which explored options to introduced renewable energy systems in hospitals.

Surgery rooms is the space type within hospitals with the most stringent and demanding conditions of supply airflow, overpressure and indoor environmental quality (ASHRAE 2003). These requirements translate to very large energy use intensities. This thesis addresses strategies to reduce energy use in surgery rooms without compromising the fundamental indoor environmental quality requirements.

1.2 INDOOR AIR QUALITY AND OUTDOOR AIR REQUIREMENTS

Indoor Air Quality is defined by ASHRAE et al. (ASHRAE et al. 2009) as "[…] air in occupied spaces in which there are no known or expected contaminants at concentrations likely to be harmful and no conditions that are likely to be associated with occupant health or comfort complaints and air with which virtually no occupants express dissatisfaction. It includes consideration of both indoor air pollution levels ant thermal environmental parameters". Similarly broad definitions of Indoor Air Quality are found in the mandatory Spanish building codes for residential and non-residential buildings (Ministerio de Vivienda 2006; Ministerio de Industria Turismo y Comercio 2007) as well as in standard ASHRAE 62.1 (ASHRAE 2010). Standard EN 15251 (European Committee for Standardization (CEN) 2007) addresses design conditions for indoor air quality, but does not include a straightforward definition of the term "indoor air quality".

The ambiguity in the definitions of "indoor air quality" in the standards is the result of the weak scientific evidence of the relationship between indoor air characteristics (such as concentration of contaminants) and health. The ASHRAE et al. Indoor Air Quality guide acknowledges that "[…] the limits of existing knowledge regarding the health and comfort impacts of specific contaminants and contaminant mixtures in nonindustrial environments, coupled with the variations inhuman susceptibility, make it impossible to develop a single IAQ metric that can provide a summary measure of IAQ in buildings" (ASHRAE et al. 2009). The Lawrence Berkeley National Laboratory is currently working on a project to develop a health-based ventilation standard for the residential sector (Logue et al. 2011; Sherman et al. 2011b; Sherman et al. 2011a; Sherman et al. 2012), but has yet to explore non-residential.

Since the standards fail to agree on a performance-based method for specifying the level of indoor air quality in a building (Olesen 2004), they address indoor air quality by requiring minimum levels of ventilation (outdoor air) rates for different types of space, occupation, and floor area. The prescriptive outdoor air requirements in the standards are based on human perception of indoor air quality.

"The quality of the indoor environment may be expressed as the extent to which human requirements are met. Requirements vary, however, for different individuals. […] To cope with these individual differences the environmental quality can be expressed by the percentage of persons who find an environmental parameter unacceptable (=%dissatisfied). […] Prediction of the percentage of dissatisfied is used to establish requirements for the thermal environment and for ventilation. A predicted value may not be equal to the actual percentage of dissatisfied in practice, where other factors such as stress can have an influence." (European Committee for Standardization (CEN) 1998)

To conclude, indoor air quality standards do not provide a parametric definition of “Indoor Air Quality” and, therefore, cannot set quantitative performance-based indoor air quality thresholds. Instead, they provide prescriptive compliance paths that are usually based on outdoor airflow rates that should “guarantee” a given percentage of occupant satisfaction, which has no scientifically demonstrated relation to human health.

1.3 VENTILATION AND IAQ REQUIREMENTS IN SURGERY ROOMS

Surgery rooms are complex environments that require ventilation for comfort and to control hazardous emissions. Indoor air quality is particularly critical in surgery rooms due to a variety of microbial and chemical agents present and the increased susceptibility of patients (El Gharbi et al. 2012).

As thoroughly addressed in the literature review chapter, the current mandatory ventilation and indoor air quality requirements for surgery room in Spain are often unclear. However, the basic parameters and the motivation for their requirement can be conceptually summarized as follows (see Section 2 for details and references):

- Outdoor airflow rate requirement: meant to reduce occupant exposure (mainly health care professionals) to anesthetic gasses and disinfectants.

- Total airflow rate requirement: along with filtering requirements in the air handling units, it is meant as an indirect means to reduce infection risk for the patient by reduce germ concentration. Germs are only present in air if carried by particles. The purpose of the total airflow requirement is to reduce germ concentration by enhancing air filtering frequency, thus reducing particle and germ concentrations

- Overpressure requirement: Surgery rooms are required to maintain a higher pressure than the adjacent spaces to avoid particle infiltration and remain clean.

- Temperature and relative humidity requirements: Comfort requirements in surgery rooms are particularly unclear. They are meant to provide thermal comfort to occupants, but can be modified if required by the type of operation under development.

The limited knowledge regarding health impacts of specific contaminants acknowledged in the previous section also applies to surgery rooms. Most requirements in the standards can only be met through prescriptive paths (e.g., minimum airflow requirements) rather than performance paths (e.g., maximum concentrations allowed). Furthermore, the standards seldom scientifically justify their prescriptive compliance thresholds.

1.4 ENERGY EFFICIENCY OPPORTUNITIES IN SURGERY ROOM VENTILATION SYSTEMS

The different standards, while unclear, allow for some degree of flexibility in the design and operation of surgery rooms that could be used to improve their energy efficiency. Namely, the standards allow (under certain conditions, and using prescriptive compliance paths) to adjust airflows, temperature and relative humidity when surgery rooms are not operational. Furthermore, they provide minimum heat recovery requirements, but leave room for improvement.

However, probably as a result of confusion (due to the unclear requirements in the standards) and risk aversion (surgery rooms are particularly critical spaces), engineering companies and facility managers often design and operate surgery rooms to meet the most stringent recommendations (not only the requirements) in the available standards and guides. Experience shows that the allowances in the standards are seldom used in reality (CatSalut and Corporació Sanitària de Barcelona 2012).

Additionally, current commercial development of real time particle concentration measuring devices may allow performance-based methods to comply with the standards infection control intent (CLIMET Instruments Company 2014). This would imply an alternative to the currently mandatory prescriptive total airflow requirements in the standards.

1.5 OBJECTIVES

The global objective of this thesis is to identify and evaluate energy efficient ventilation strategies in surgery rooms that maintain acceptable indoor air quality and cleanliness (as defined in the available literature and according to the performance requirements in the available standards) while reducing the associated energy use.

The associated specific objectives of this thesis are:

- To perform a comprehensive and critical review of the indoor environmental quality and infection control requirements in surgery rooms
- To identify novel energy efficient ventilation strategies for surgery rooms
- To define an assessment method to consistently assess control strategies in surgery room ventilation control through computer-based energy models
- To evaluate the ventilation strategies in terms of indoor environmental quality and energy use.

Surgery rooms are chosen for this study because they are the spaces with the most stringent IAQ requirements in hospitals (and derived high energy use), and they often have a dedicated system that can be operated independently.

This thesis uses the surgery rooms in the “Hospital de Mollet” (Mollet, Spain) and the “Hospital Virgen de las Nieves” (Granada, Spain) as case studies to assess efficiency measures. Hospital de Mollet is a recently built hospital that is already equipped with control capabilities that allows for advanced control strategies. On the other hand, the system in Hospital Virgen de las Nieves is much older (the air handling unit is dated from late 1970’s) and, while still allows for control, offers less flexibility (also, its airflow and thermal power capacities are more limited, which leaves less room for management). While the sample in this analysis is too small to draw robust conclusions on the potential energy savings of HVAC control strategies in any conceivable surgery room in Catalonia, the case studies provide examples of surgery rooms that are at opposite ends of the “controllability spectrum”. Furthermore, the air handling unit studied in Hospital de Mollet features the standard system configuration implemented in modern surgery rooms in Spain. Therefore, findings from Hospital de Mollet can be easily adapted to describe new or recently built surgery rooms.

1.6 WORK PLAN

The work plan and intermediate objectives that lead to the final objectives are:

- To quantitatively define “indoor air quality in surgery rooms” by critically reviewing indoor environmental quality requirements in the current standards for surgery rooms
- To review the most commonly implemented ventilation strategies in surgery rooms
- To identify potential improvements that meet the afore-defined “indoor air quality” criteria while offering energy saving opportunities. Energy saving strategies focus on control and heat recovery implementation
- To adapt the strategies to the available case studies
- To develop dynamic simulation models of the ventilation strategies in the case studies
- To use monitoring data to verify hypotheses made and calibrate the models
- To use both simulation and monitoring results to evaluate the performance of the novel ventilation strategies in the case studies.

It is critical for this thesis to guarantee that the energy efficiency strategies do not compromise surgery room performance in terms of cleanness, indoor environmental quality, and infection control during operation. Performance based requirements are sought in the available standards to define the minimum performance boundary that the strategies must meet. Chapter 2 “Literature Review” elaborates on the (sometimes unclear and controversial) requirements for the above parameters in the Spanish and international standards.

1.7 CONTRIBUTION OF THIS THESIS

This thesis builds on the existing knowledge in the areas of HVAC control, surgery room design and operation requirements, and thermal energy systems performance analysis. The main contributions of this thesis are:

- A comprehensive and critical review of the indoor environmental quality and infection control requirements in surgery rooms. The review identifies the key performance goals of the requirements in the available standards, and sets the boundaries for the definition of energy efficiency improvements in surgery room systems. No such comprehensive review is currently available in the literature.

- A general method to adjust system operation (outdoor airflow rate, total supply air, indoor air temperature, and indoor air relative humidity) to meet IEQ performance goals while reducing energy use. Based on the requirements identified in the literature review, this method provides a systematic framework to define setpoints of all the control parameters. No such method is available in the current standards and literature.

- Calibrated energy models of two surgery room systems. Previous computer-based models of surgery rooms used computational fluid dynamics (CFD) to assess spatial distribution of air properties within a surgery room. However, energy models for surgery room systems were not found in the literature. The models in this thesis couple room dynamics with an air handling unit model.

- Identification and assessment of control strategies for two surgery room settings (Hospital de Mollet and Hospital Virgen de las Nieves). Due to the standard nature of the system in Hospital de Mollet, the recommendations of this case study can be generalized to other modern surgery rooms in locations with similar climate characteristics.

- The assessment of a ventilation control strategy based on real time measurement of particle concentration in the surgery room. The particle concentration-based airflow control is implemented in a surgery room in Hospital de Mollet. Using monitored values of

particle concentration and supply airflow the calibrated energy model assesses annual energy performance of the control strategy. No previous experiences of particle concentration-based airflow control are reported in the literature.

- The assessment of the thermal energy use for ventilation air conditioning in the two case study locations as well as all the regions in Catalonia. Thermal energy use is broken down into heat/cold and sensible/latent components. While the analysis method is not new, this thesis provides valuable climate information, which was not available to the general public, digested for an easy application for heat recovery design purposes.

1.8 THESIS CONTEXT AND OUTPUTS

This thesis is largely developed as part of IREC's contribution to the Green@Hospital project (http://www.greenhospital-project.eu/). The case study hospitals, Hospital de Mollet and Hospital Virgen de las Nieves, are members of the project consortium and provided all the relevant information for the development of the models. The control strategy based on fuzzy logic described in Section 4.2.2.2 was developed by researchers at the Technical University of Crete, and coupled with the TRNSYS energy model. Except for this contribution by TUC, all the research methods and results presented in this thesis are the work of the signing author.

The contents of this thesis have been published in the following outputs:

Journal articles:

- Cubi, Eduard, Jaume Salom, and Nuria Garrido (2014). "Energy Efficient Ventilation Control Strategies for Surgery Rooms". HVAC&R Research. (Accepted)
- Cubi, Eduard, Jaume Salom, and Nuria Garrido (2014). "Indoor Environmental Quality and Infection Control in surgery rooms: Code requirements vs. Performance motivation. A critical review". HVAC&R Research. 20, 643-654. DOI: 10.1080/10789669.2014.929423

Conference papers:

- Cubi, Eduard, Sotiris Papantoniou, Davide Nardi Cesarini, Jesus Arbol, Jose Maria Fernandez, Jaume Salom (2014). "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, Canada).

Technology transfer articles:

- Cubi, Eduard, Josep Piquer, Marius Gamissans, Christoph Peters (2012). “Estudio de las perdidas energeticas asociadas a climatizacion del aire de renovacion”. El Instalador. 499, 18-26.

The above articles are included as Annexes to this thesis.

1.9 THESIS OUTLINE

Chapter 2 provides a critical literature review of the indoor air quality and infection control requirements for surgery rooms in the available standards. Based on the performance motivation in the requirements, Chapter 2 identifies control strategies to improve energy performance of surgery room systems. Chapter 3 introduces the general method used to evaluate the control strategies drafted in Chapter 2. Chapter 4 applies the control strategies identified in Chapter 2 to two case studies. Section 4.1 assesses control strategies that can be implemented in a standard surgery room air handling unit, using a surgery room in Hospital de Mollet as the case study. The results of Section 4.1 can inform on the potential performance of newly implemented systems in Catalonia. Section 4.2 focuses on the analysis of control strategies that can be implemented in a non-standard multizone air handling unit at Hospital Virgen de las Nieves (Granada). The case studies in Chapter 4 focus on control strategies and do not assess potential energy performance improvements with heat recovery. Chapter 5 assesses the thermal energy use associated to ventilation air conditioning in the locations of the two case studies (Mollet and Granada), and applies the method to all the regions in Catalonia. The results of Chapter 5 are meant as a tool to assess the potential benefits of different types of heat recovery systems in different locations. Chapter 6 wraps up the thesis providing overall conclusions and an outlook for future research. The publications derived from this thesis are included in the Annexes. The simulation models of the two case studies are provided in the digital copy of this thesis.

2 LITERATURE REVIEW

The objectives of this critical review are: 1) to clearly identify the mandatory IEQ requirements for surgery rooms in Spain, 2) to check whether these are consistent with their intrinsic motivation (performance goal) and international standards, 3) to draft a method to adjust system operation to meet IEQ performance goals while reducing energy use and 4) to identify code-compliant opportunities for improving energy performance of surgery rooms in Spain. While the mandatory IEQ requirements reviewed in this thesis focus on the Spanish context, the discussion on the associated performance goals is valid for surgery rooms located in any other country. Note that this thesis focuses only on IEQ requirements and does not review system and plant energy efficiency requirements in the standards and guidelines, which vary depending on climate. Sections 2.1 to 2.6 address indoor environmental quality and infection control requirements in surgery rooms.

2.1 IAQ REQUIREMENTS IN SURGERY ROOMS

There are several national and international standards that provide indoor air quality requirements and recommendations for buildings, hospitals, and even reach the level of surgery rooms. Both ISO and CEN have technical committees currently working on cleanroom technology standards (European Committee for Standardization (CEN) 2013; International Organization for Standardization 2013) (both committees are working on the development of the series of Standard ISO 14644 (European Committee for Standardization (CEN) 1999) that will be addressed below). While the wide spectrum of standards may help understand how IAQ in surgery rooms is approached worldwide, only the standards that are linked to a Royal Decree (RD) are mandatory in Spain. The “Reglamento de instalaciones térmicas de los edificios” (Ministerio de Industria Turismo y Comercio 2007) (building thermal installations code), hereafter referred to as “RITE”, was approved by Royal Decree 1027/2007 in July 2007. RITE is the only standard for non-residential building systems that is linked to a Royal Decree, and therefore, it establishes the regulatory framework for HVAC systems in hospitals and surgery rooms. RITE includes some explicit requirements, but also cites other standards as means to compliance for some specific sections and applications.

This section reviews the individual HVAC controlled parameters that affect IEQ in surgery rooms. The performance goal (i.e., the motivation for establishing requirements) is presented first[1] to set

[1] The main motivation for the total supply airflow requirement is rather complex, and can be found in section “HVAC and infection control”

the basis for discussion, followed by the quantitative requirements in the applicable Spanish standards. RITE (Ministerio de Industria Turismo y Comercio 2007) is used as the starting point because it sets the regulatory framework for HVAC systems in hospitals and surgery rooms in Spain. Finally, requirements and recommendations in standards and guidelines from different countries (EU and US) are reviewed and compared against the Spanish case. Table 1 summarizes the reference values in the reviewed international standards (Ministerio de Industria Turismo y Comercio 2007; AENOR 2005; ASHRAE 2008, 2003; American institute of Architects (AIA) 2001; Deutsches Institut fur Normung (DIN) 2008; Department of Health - Estates and Facilities Division 2007; Working Party on Infection Prevention (WIP- The Netherlands) 2005; Servizi Sociali Sanità ed Assistenza 1997; Regioni ed alle Province autonome di Trento e Bolzano 2000; (CTI) 2010; Instituto Superiore per la Prevenzione e la Sicurezza del Lavoro (ISPESL) 2009; Technical Chamber of Greece 2010; Ministry of Health - Greece 2010)

Table 1 Comparison of IEQ requirements and recommendations in the reviewed standards. Reference values (please see the individual standards for further details)

	Temperature	Relative Humidity	Outdoor airflow	Total airflow	Overpressure
RITE (SP, mandatory code)	No quantitative requirement	No stated quantitative requirement	Refers to UNE 100713	Unclear. No reference to any other standard	No stated quantitative requirement and no reference to any other standard
UNE 100713:2005 (SP)	22-26ºC (Recommendation, operation)	45-55% (Recommendation, operation)	1200m^3/h (roughly 10ACH)	2400m^3/h (roughly 20ACH) for Type B. 3600m^3/h (roughly 30ACH) for Type A. Lower values may be allowed with experimentally proven laminar flow systems	Overpressure (no stated quantitative requirement)
ASHRAE 170 (US)	20-24ºC (Requirement, design)	30-60% (Requirement, design)	4ACH (Classes B, C), 3ACH (Class A)	20ACH (Classes B, C), 15ACH (Class A)	2.5Pa
ASHRAE Applications Handbook (US)	16.7-26.7ºC (Recommendation, design)	45-55% (Recommendation, design)	5ACH for recirculating air systems, 15ACH for all outdoor air systems. (Recommendation)	25ACH for recirculating air systems (Recommendation)	Overpressure (no stated quantitative requirement)
ASHRAE HVAC Design Manual (US)	20-24ºC (Recommendation, design)	30-60% (Recommendation, design)	5ACH	25ACH (Recommendation)	10-15% of air volume
AIA guidelines [2] (US)	20-23ºC (Recommendation design)	30-60% (Recommendation, design)	3ACH	15ACH	2.5Pa
DIN 1946-4 2008 (DE)	19-26ºC	35-60%	1200m^3/h, roughly 10ACH in a conventional OR, or 7.6ACH in a 45m^2 OR (minimum according to DIN 1946)	8800m^3/h ([3]). This is roughly 75ACH in a conventional OR, or 56ACH in a 45m^2 OR (minimum according to DIN 1946)	Overpressure (no stated quantitative requirement)

[2] Operating cystoscopic rooms

[3] Driven by laminar flow requirements: downflow velocity (>0.23m/s) x diffuser area (3.2mx3.2m).

HTM 03-01 2007 (UK)	19-23ºC	35-60%	25ACH	11900m³/h ([4]). This is roughly 100ACH in a conventional OR, or 61ACH in a 55m² OR (minimum according to HTM 03-01)	25Pa
WIP (NL)	18-22ºC	50-65%	2000m³/h (roughly 17ACH). Can be reduced to 1200m³/h (10ACH) if exhaust provisions are made	9000m³/h (roughly 76ACH), driven by laminar flow requirements (diffuser size and air velocity)	5-10Pa
DPR 14/01/1997 DCR 616-3149/2000 (IT)	20-24ºC	40-60%	15ACH	15ACH	10-15Pa
CTI 2010 (IT)	20-24ºC	40-60%	15ACH	15ACH	5Pa
ISPESL 2009 (IT)	20-24ºC	40-60%	15ACH	15ACH	5Pa
20701-1/2010 (GR)	Winter: 18ºC, Summer: 20ºC	Winter: 35%, Summer: 55%	80m³/h_person (roughly 4.7ACH) or 0.25m³/h_m² (roughly 0.8ACH)	No stated requirement	No stated requirement
49727/26-04-2010 (GR)	21-24ºC	50-60%	17ACH (85% of the total)	20ACH	No stated requirement

2.1.1 THERMAL COMFORT

Temperature and relative humidity control in health care facilities is not only required for thermal comfort, but also because patients are more likely to be physically challenged by an environment that may be tolerable to healthy occupants. Patients with cardiovascular diseases suffer in high space temperature and humidity (Burch and Pasquale 1962) (cited in (Hermans 2000)), and patients with thyrotoxicosis tolerate hot, humid conditions very poorly because their metabolism is high and therefore their heat production is excessive (Hermans 2000). In turn, humidity affects

[4] Driven by laminar flow requirements: downflow velocity (>0.38m/s) x diffuser area (2.8mx2.8m).

infection control, as it is often linked to the growth of a bacteria, viruses, and fungi (Sterling et al. 1985) (cited in (Hermans 2000)).

Indices to evaluate general thermal comfort in buildings found in literature are typically based on the Fanger model (Fanger 1970), which introduced “Predicted Mean Vote” (PMV) and “Predicted Percentage of Dissatisfied” (PPD) as comfort indices. These indices are also used in standards EN ISO 7730:2005 (European Committee for Standardization (CEN) 2005) and EN 15251:2007 (European Committee for Standardization (CEN) 2007). Carlucci and Pagliano (Carlucci and Pagliano 2012) provided a detailed review of thermal comfort indices for general use spaces. However, due to their unique characteristics, “Fanger-based” indices are not used in standards and guidebooks for surgery room design and operation.

The mandatory thermal comfort requirement in RITE reads: “indoor design operative temperature and relative humidity shall be set based on occupant activity level, clothing, and predicted percentage of dissatisfied (PPD)”. However, RITE does not include acceptable ranges of PPD as a function of space use, nor the “thermal comfort category” that would be required in the different space use types.

RITE cites standard EN ISO 7730:2005 – “Ergonomics of the thermal environment. Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria” (European Committee for Standardization (CEN) 2005) as the valid procedure to calculate acceptable temperature ranges as a function of desired PPD and clothing level. Appendix A in EN ISO 7730:2005 standard defines “thermal comfort categories”, as shown in Table 2. Furthermore, the standard includes (in informative appendixes) examples of design criteria (temperature and relative humidity acceptable ranges) for a variety of space use types and thermal comfort categories. However, these examples do not include surgery rooms or any other space in hospitals and, most importantly, the standard does not provide recommended categories by space use type (e.g., does not assign surgery rooms to any of the thermal comfort categories).

Table 2 Thermal comfort categories definition in EN ISO 7730:2005. Reproduced from (European Committee for Standardization (CEN) 2005)

	Global parameters			Local discomfort parameters		
Category	PPD (%)	PMV	DR (%)	Vertical temp differential (ºC)	PD due to hot/cold floor	Radiant asymmetry
A	<6	-0.2<PMV<+0.2	<10	<3	<10	<5
B	<10	-0.5<PMV<+0.5	<20	<5	<10	<5
C	<15	-0.7<PMV<+0.7	<30	<10	<15	<10

In lieu of a classification of surgery rooms in RITE and EN ISO 7730:2005, Standard EN 15251:2007 – "Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics" (European Committee for Standardization (CEN) 2007) provides recommended categories by space use, and assign hospitals to "Category 1" (which is the equivalent of "Category A" in EN ISO 7730:2005). However it must be noted that the standard acknowledges that "this standard suggests how the thermal categories may be used, but does not impose any requirements. This is competence of national regulations or the specifics of individual projects". Also, EN 15251:2007 does not provide temperature and relative humidity design recommendations for hospitals, as this depends on all the parameters that are necessary in the PPD calculation (activity level, clothing, etc…), which are not included in the standard.

Table 3 Thermal comfort categories application in EN 15251:2007. Reproduced from (European Committee for Standardization (CEN) 2007)

Category	Explanation
I	High expectations, recommended for spaces with weak and sensible occupants, handicapped, sick, babies and the elder
II	Normal expectations, should be used for new and refurbished buildings
III	Acceptable expectations, to be used for existing buildings
IV	Outside criteria in the above categories. This category should only be accepted for limited parts of the year

All in all, RITE does not provide a quantitative definition of "acceptable thermal conditions" in terms of temperature and relative humidity, nor it does in terms of PPD or "thermal category". Furthermore, RITE cites Standard EN ISO 7730:2005 for the PPD calculation method, but fails to cite Standard EN 15251:2007 or any other standard that assign a "Thermal Category" to surgery rooms (EN 15251:2007 assigns "Thermal Category 1" to hospital spaces). Therefore, it appears that there are no quantitative mandatory thermal comfort requirements in the non-residential build environment in Spain (including hospitals and surgery rooms).

The Spanish Standard "UNE 100713:2005 - Instalaciones de acondicionamiento de aire en hospitals" (AENOR 2005) is not cited in the thermal comfort section of RITE (and, therefore, their recommendations and requirements on thermal performance are not mandatory), however, it is often used as the "de facto" standard in the health care sector (Rosell Farrás and Muñoz Martinez 2010; Barrachina 2012; Ministerio de Sanidad y Política Social 2009). UNE 100713:2005 lists its requirements in a clear and easy to use table, partly reproduced in Table 4 (see columns 5,6,7).

Table 4 Thermal comfort requirements in UNE 100713:2005. Reproduced from (AENOR 2005)

Space type	Class	Minimum OA flow (m3/h-m2)	Min temperature (ºC)	Max temperature (ºC)	Relative humidity (%)	Max sound pressure (dB)
Surgery rooms type A and B	I	See 6.6	22	26	45-55	40
Corridors, storage rooms, clean material	I	15	22	26	45-55	40
Waiting room	I	15	22	26	45-55	35
Other	I	15	22	26	45-55	40

According to UNE 100713:2005, thermal comfort requirements for surgery rooms are:

- Acceptable temperature range: 22-26ºC
- Acceptable relative humidity range: 45-55%

Note, however, that the standard explicitly states that “hygienists may set different values according to their preferences and operation type”. UNE 100713:2005 fails to provide a justification (or a citation/reference to a scientific report) for the stated limits in temperature and relative humidity.

To conclude, the comfort parameters in UNE 100713:2005 are widely used in the Spanish health care sector, probably because it is the only Spanish standard that specifically addresses hospital spaces (Ministerio de Sanidad y Política Social 2009), and because it sets clear windows of acceptable temperature and relative humidity. However, these values should not be considered mandatory requirements, since 1) UNE 100713:2005 itself accepts variations according to the hygienists’ will, and 2) RITE does not refer to UNE 100713:2005 in its thermal comfort section and, therefore, does not make it mandatory.

For comparison, ASHRAE Standard 170 (ASHRAE 2008) requires design temperature and relative humidity ranges to be 20-24ºC and a 30-60% respectively. The same values are recommended in the HVAC Design Manual for Hospitals and Clinics (ASHRAE 2003), while and the Applications Handbook (ASHRAE 2011) recommends a narrower range for relative humidity (45-55%) and a wider range for temperature (16.7-26º.7C) design. It must be stressed that these are system design ranges: the systems must be capable of maintaining the rooms at any point within the range during normal operation. However, this does not imply that their setpoints either during operation or when not in use must fall within these ranges.

2.1.2 SUPPLY AIRFLOW CONDITIONS

The only "quantitative" insights to the general indoor air quality requirement in RITE (Ministerio de Industria Turismo y Comercio 2007) are found in its technical instruction "1.1 – Wellbeing and hygiene requirements" (IT 1.1). Since it is the only applicable technical instruction on the subject, it can be assumed to be the only compliance path for the mandatory general IAQ requirement.

Within IT1.1, "IT 1.1.4.2 – Indoor air quality requirements" establishes several indoor air quality categories, and allocates hospital spaces to "IDA 1" (the highest category). RITE provides several methods for meeting the IDA targets, although it also sets extensive constraints depending on the space use type. In any case, IDA requirements translate into outdoor air supply requirements.

The most relevant statement in RITE regarding supply air requirements in surgery rooms is that made in IT 1.1.4.2.3 – Minimum outdoor airflow: "The values in UNE 100713 are valid for hospitals and health care buildings" (Ministerio de Industria Turismo y Comercio 2007). This statement virtually makes UNE 100713 mandatory for outdoor airflow requirements in hospital spaces. Note, however, that RITE cites UNE 100713 only within the outdoor air requirements section. UNE 100713:2005 (AENOR 2005) provides requirements on several parameters other than outdoor airflow (e.g., total supply airflow), however, based on a strict application of RITE, these do not appear to be mandatory.

2.1.2.1 Outdoor air requirements

As mentioned above, UNE 100713:2005 is referred to in RITE as the standard that provides the valid values of outdoor air requirements in hospitals (i.e., the mandatory requirements). Table 5 in UNE 100713:2005 (partly reproduced in Table 4 above) provides the minimum outdoor airflow requirements per unit floor area for spaces other than surgery rooms (e.g., patient rooms are required $10 m^3/h\text{-}m^2$).

Surgery rooms are addressed in section 6.6.3 of the standard, which requires a minimum outdoor airflow rate of $1200 m^3/h$ to maintain concentration of anesthetic gases and disinfectants below 0.4ppm. It is a prescriptive requirement and does not allow performance compliance path (i.e., based on real time measurements of anesthetic gases concentration). Note also that this requirement does not take into account surgery room size (volume) or the specific use intensity of anesthetic gases in a given operation, therefore, the $1200 m^3/h$ requirement does not suffice to guaranteeing that the gas concentration stays below the 0.4ppm threshold.

Anesthetic gases used to be flammable and, combined with an oxygen-rich environment, often caused fires and explosions in surgery rooms. However, flammable anesthetic gases are no longer available in most of the countries (MacDonald 1994), and thus not a fire concern anymore.

Several studies associated (with different degrees of confidence) exposure of health care professionals to anesthetic gases with health problems such as reproductive toxicity (Gardner 1989; Ahlborg and Hemminki 1995; Guirguis et al. 1990) and heart diseases (Hüneke et al. 2001). A more recent study concludes that "the scientific evidence for hazards is weak. Nonetheless, it is good practice to limit levels of exposure" (Burm 2003). Concerns for the health care professionals that are often exposed to anesthetic gases explain a possible motivation for the mandatory outdoor air requirement in UNE 100713:2005. However, the standard fails to provide the rationale for the requirement, as well as a scientific justification for the 0.4ppm threshold.

Although it is not referenced in RITE, the mandatory Spanish code for Low Voltage Electric Systems (Ministerio de Ciencia y Tecnologia 2002) includes a provision on ventilation requirements in surgery rooms in its technical instruction ICT-BT-38. This requirement is also motivated by the high flammability of anesthetic gases used in the past (the code was updated in 2002, but some of its technical instructions remain outdated). The prescriptive path for compliance requires 15 air changes per hour. However, designers are allowed to reduce this ventilation rate if they can technically justify that their solution is as safe as the prescriptive path. Since highly flammable anesthetic gases are no longer used in surgery rooms, the 15ach requirement can be easily skipped within the code limits. The minimum ventilation requirements in the code for Low Voltage Electric Systems could be deleted in future code updates.

For comparison, ASHRAE recommends a minimum of 5 Air Changes per Hour (ACH) of outdoor air in both the HVAC Design Manual for Hospitals and Clinics and the Applications Handbook, while requires only 4ACH of outdoor air in Standard 170. The AIA Guidelines for design and construction of hospital and health care facilities (American institute of Architects (AIA) 2001), cited in (ASHRAE 2003) recommends 3ACH in operating cytoscopic rooms. It should be noted that the ASHRAE publications use "air changes per hour" (ACH) as the unit for their recommendations and requirements, which takes into account the volume of the surgery rooms, and is consistent with the implicit motivation of outdoor air supply (i.e., to dilute concentration of anesthetic gases and other contaminants). For a $37m^2$, $118m^3$ "typical" surgery room in a Spanish hospital (Hospital de Mollet), the $1200m^3/h$ requirement in UNE 100713:2005 translate into roughly 10ACH, which doubles the recommendations in the ASHRAE HVAC Design Manual for Hospitals and Clinics (which in turn, are 25% higher than the ASHRAE requirements in Standard 170). It should also be noted that the ASHRAE outdoor airflow values for surgery rooms are roughly the same as these required in RITE for general hospital spaces. At the other end of the spectrum, EU standards range from 10ACH (Deutsches Institut fur Normung (DIN) 2008) up to 25ACH (Department of Health - Estates and Facilities Division 2007), with typical values in Italy, Greece and the Netherlands around 15-17ACH. Considering that the purpose of outdoor air

supply is to dilute anesthetic gases and other indoor-generated pollutants (which is independent on HVAC system characteristics), there is no clear reason for the much larger outdoor air requirements in EU (and particularly in the UK) compared to the American Standards.

Table 5 compares outdoor air requirements and recommendations in various standards and manuals. Values in "bold" show the actual requirement/recommendation, while the others are calculated based on the characteristics of a typical surgery room in Hospital de Mollet (Barrachina 2012). The table illustrates that the Spanish outdoor airflow requirements in UNE 100713 roughly double the recommendations in the ASHRAE HVAC Design Manual for Hospitals and Clinics (which in turn, are 25% higher than the ASHRAE requirements in Standard 170 (ASHRAE 2008)). It should also be noted that the ASHRAE outdoor airflow values for surgery rooms are roughly the same as these required in RITE for general hospital spaces.

Table 5 Outdoor airflow requirements and recommendations in different standards (for a 37m^2 , 118m^3 surgery room with 7 occupants)

	RITE (Ministerio de Industria Turismo y Comercio 2007)	UNE 100713 (AENOR 2005)	RBT (Ministerio de Ciencia y Tecnologia 2002)	ASHRAE (ASHRAE 2003)
Airflow per occupant (l/s)	**20**	48	70	23
Total supply airflow (m^3/h)	504	1200	1776	592
Total supply airflow (ach)	4.3	**10.1**	**15**	**5**

The ASHRAE HVAC Design Manual for Hospitals and Clinics (ASHRAE 2003) provides a more comprehensive justification for the outdoor air requirements. This reference states that the actual requirement is "exhaust of contaminants", while outdoor air supply required as a consequence to match the air balance. Exhaust systems provide for removal of contaminants, moisture, flammable particles, aerosols, and odors. "Surgery rooms are often equipped with special exhaust connections or trunk ducts […] to remove waste anesthesia gases or the aerosolized particles in laser plumes" (ASHRAE 2003). According to this reference, there are several (and apparently independent) parameters to control through exhaust air, and not only anesthetic gas concentrations. Therefore, outdoor air requirements in surgery rooms fall in a similar ambiguity as the other purpose spaces.

2.1.2.2 Total supply airflow

There are no total supply airflow requirements in RITE, but only outdoor air supply requirements (Ministerio de Industria Turismo y Comercio 2007). UNE 100713:2005 includes total airflow requirements for surgery rooms, although it is unclear as to whether these are mandatory since RITE cites UNE 100713:2005 only for outdoor air requirements.

The basic requirement in UNE 100713:2005 is that total supply airflow should be enough so that the average concentration of indoor generated germs in the protection zone (surgery zone and instrumentation tables) is lower than that provided by a mixing air system that supplied 2400m^3/h, the so called “reference airflow rate” (based on experience) (AENOR 2005). This requirement translates into the following equation:

$$C_{I,min} = C_I^* \frac{\mu_s}{\varepsilon_{si}} = 2400 \frac{\mu_s}{\varepsilon_{si}}$$

Equation 1

Where:

$C_{I,min}$: Minimum total supply airflow rate (in m^3/h)

C_I^*: Reference airflow rate (2400m^3/h)

μ_s: Concentration level – calculated as the ratio of average concentration of germs in the protection zone (operations zone and auxiliary table) over the average concentration of germs in the surgery room. It is an index that describes the ventilation effectiveness of the system, and often varies with supply airflow.

- For mixing systems the UNE 100713:2005 standard assumes μ_s = 1
- For laminar flow systems μ_s may be lower than 1. However, since μ_s depends on a variety of system characteristics including supply airflow itself, it must be experimentally demonstrated.

ε_{si}: Maximum allowed relative concentration of germs in the protection zone. It depends on the hygienic requirements of the operations to be performed in the surgery room.

- For surgery rooms type A: ε_{si} = 2/3
- For surgery rooms type B: ε_{si} = 1

In terms of system type, UNE 100713:2005 recommends (yet does not require)

- For surgery rooms type A – Use laminar flow systems
- For surgery rooms type B – Use either laminar or mixing systems

It must be noted, however, that when laminar flow systems (or any system other than mixing) are used, the corresponding μ_s must be demonstrated experimentally. The easiest compliance path

is therefore to use mixing systems (no need for experimental verification), for which the supply airflow requirements become:

- Type A surgery rooms:

$$C_{I,min} = 2400\frac{\mu_s}{\varepsilon_{si}} = 2400\frac{1}{(^2/_3)} = 3600\, m^3/h$$

Equation 2

- Type B surgery rooms:

$$C_{I,min} = 2400\frac{\mu_s}{\varepsilon_{si}} = 2400\frac{1}{(1)} = 2400\, m^3/h$$

Equation 3

UNE 100713:2005 provides some examples of surgery types that "belong" to Type A surgery rooms, but does not specify whether these are requirements or recommendations. Furthermore, other than total supply airflow rate, the standard does not provide a classification method for surgery rooms nor cites another standard to be used for surgery room classification. Section 2.2 provides further details on surgery room classification issues in the standards.

The standard allows (and mandates) a performance based compliance path to the μ_s requirement. However, there is neither an explanation nor a reference to another standard that addresses μ_s testing procedure. Standard "UNE 171340:2011 – Validation and evaluation of controlled environment rooms in hospitals" (AENOR 2012), which includes most of the verification procedures for Standard UNE 100713:2005 requirements, does not include any mention to μ_s. With no reference as to the test and verification procedure, there is no way to formally demonstrate concentration levels μ_s provided by systems other than mixing. This virtually bans the use of a high efficacy ventilation system to reduce total airflow compared to a mixing system.

UNE 100713:2005 does not cite the source of the reference airflow (2400m^3/h), although it is probably Standard DIN 1946/4 (Deutsches Institut fur Normung (DIN) 1999) (cited in (Memarzadeh and Manning 2002)), and does not include acceptable ranges of germ concentration in the protection zone (which is the stated motivation of the total supply airflow requirement). Furthermore, μ_s is the ratio of average concentration of germs in the protection zone over the average concentration of germs in the surgery room, but does not information on germ concentration in the protection zone in absolute terms. Therefore, compliance with the requirement in Equation 1 does not directly guarantee any degree of germ concentration control

in the protection zone (the requirement could be met if germ concentration was high in both protection zone and average surgery room).

Finally, the standard states that “determining germ concentration requirements in surgery rooms (as a function of operation type, duration, daily schedule of the surgery room, number of occupants and patient conditions) is responsibility of hygienists” (AENOR 2005). While this provision in UNE 100713:2005 seems to provide an opportunity to adjust supply airflow based on germ concentration, in reality it is unlikely that hygienists take the risk and effort of setting germ concentration requirements and verification methods, particularly because the standard does provide any reference value of absolute concentrations.

All in all, total supply airflow requirements in UNE 100713:2005 seem to be unclear to the healthcare sector. Regardless of airstream type (mixed or laminar) or surgery room type (A or B), professional practice (Pi 2008; Cruceta 2010) as well as publications by the National Institute of Safety and Hygiene (Rosell Farrás and Muñoz Martinez 2010) recommend 2400m^3/h as the total supply airflow requirement, which, as shown in the equations above (and also in accordance with (CatSalut and Corporació Sanitària de Barcelona 2012)), is not applicable in all cases. E.g. a type A surgery room equipped with mixing air system would require a total airflow rate of 3600m^3/h rather than 2400m^3/h (see Table 9).

It is worth noting the different motivations for outdoor vs. total supply airflow requirements within UNE 100713:2005. The outdoor air requirement is driven by the necessity to dilute anesthetic gases and disinfectants, while the total supply air is driven by germ concentration control in the protection zone. The difference in the requirements is likely due to the fact that germs can be removed from recirculation air in the AHU filtering stages, while this is not the case with anesthetic gases. As explained in Section 2.2, “particle concentration” will be used as a proxy for “germ concentration” for surgery room classification purposes.

ASHRAE recommends a minimum of 25ACH in both the HVAC Design Manual for Hospitals and Clinics and the Applications Handbook (partly to accommodate the high cooling loads in modern surgery rooms), while only requires 20ACH in Standard 170. The 2400m^3/h and 3600m^3/h requirements in UNE 100713:2005 translate into roughly 20ACH and 30ACH, respectively, in a typical surgery room setting (37m^2, 118m^3). These values, as well as those in the Italian and Greek standards, are comparable to the recommendations in the ASHRAE references. Total airflow requirements for ultra-clean environments in the Germany, the Netherlands, and the UK are 3- to 4-fold these in the US and elsewhere in EU. These large total airflow requirements are not directly related to infection control, but rather a consequence of the required supply air

velocities and diffuser areas in laminar flow systems. It must be noted, therefore, that laminar flow systems can come with a heavy energy penalty, particularly if not combined with air recirculation.

2.1.2.3 Air recirculation

Air recirculation is generally accepted in RITE (Ministerio de Industria Turismo y Comercio 2007), although it does not make any special note for hospitals or surgery rooms. RITE does not cite UNE 100713:2005 in terms of recirculation requirements/allowances in hospitals, therefore, requirements on this topic in UNE 100713:2005 are not mandatory.

Nevertheless, it is worth noting that UNE 100713:2005 (AENOR 2005) allows recirculation of air if 1) it is from the same space to which will be supplied and 2) it goes through the same filtering stages as the fresh outdoor air. While recirculation is allowed, section 6.6.3 in UNE 100713:2005 recommends (yet does not mandate) 100% outdoor air systems. Rosell et al., (Rosell Farrás and Muñoz Martinez 2010) acknowledge that “while criteria in the different standards are not consistent, there is no requirement of 100% outdoor air in surgery room ventilation systems”.

Air recirculation in surgery rooms is allowed (under certain conditions) in both the mandatory standard (RITE) and the “de facto” standard used for HVAC design and operation in the health care sector (UNE 100713:2005). However, air recirculation is used only in about 14% of the surgery rooms in Catalonia (CatSalut and Corporació Sanitària de Barcelona 2012), and is even more seldom used in air handling units for surgery rooms in Spain (Abad Baig 2013; Barrachina 2012) partly due to the recommendation in UNE 100713:2005.

Similarly, the ASHRAE publications (ASHRAE 2011, 2003, 2008) also allow air recirculation in surgery rooms, provided that this is done through air handling units equipped with the required HEPA (high efficiency particulate air) filtering stages for infection control.

2.1.3 OVERPRESSURE

There are no explicit overpressure requirements in RITE. UNE 100713:2005 does not provide quantitative overpressure requirements either, however it requires air circulation among hospital spaces to follow the “high germ control requirements to low germ control requirements” direction (which in practice translates into pressure differences among spaces). Allowed air circulation directions are detailed in Table 2 of UNE 100713:2005. Air from surgery rooms can flow towards adjacent rooms and the outdoors. However, no air infiltrations are allowed in aseptic surgery rooms.

Some sources recommend pressure differentials in the 5-15Pa range (Pi 2008; Ministerio de Sanidad y Política Social 2009) and up to 20-25Pa (Rosell Farrás and Muñoz Martinez 2010)

depending on the cleanliness requirements of both the surgery room and the adjacent room. ASHRAE Standard 170 (ASHRAE 2008) requires only a 2.5Pa positive pressure with respect to all adjacent spaces, while the HVAC design manual for hospitals (ASHRAE 2003) recommends that “positive pressure should be between 10% and 15% of air volume”. UNE 171340:2011 (AENOR 2012) uses 6Pa as the pressure differential validation threshold. Although this standard is not explicitly mandatory, the Catalan health agency refers to UNE 171340 for a quantitative reference of overpressure requirements (CatSalut and Corporació Sanitària de Barcelona 2012).

It must be noted that “overpressure” is not a system design parameter that can be directly adjusted, but rather a consequence of space air tightness and the ratio between outdoor and exhaust airflows (recirculation air equally affect supply and return, therefore, does not contribute to overpressure). Air tightness depends on the quantity, size and quality of fittings in the space enclosure (doors, windows, duct dampers), and therefore, cannot be adjusted during operation (although should be maximized in design). Therefore, the required overpressure in a surgery room must be provided by adjusting outdoor and exhaust airflows in the HVAC system. These adjustments must, in turn, be compatible with the operation requirements explained in Section 2.1.2.1.

Furthermore, the HVAC system must be capable of quickly adjusting the outdoor vs. exhaust airflow ratio to guarantee surgery room overpressure in case a door opens.

2.1.4 CONTROL

Control requirements in RITE fall under the “Energy Efficiency” section (Ministerio de Industria Turismo y Comercio 2007). The prescriptive compliance path sets a series of control categories. Surgery rooms in hospitals would fall under “IDA-C1” category, which implies continuous operation. However, the whole energy efficiency section in RITE allows for a performance based compliance path, which requires proving that the designed alternative system would perform better than one designed according to the requirements in the prescriptive path in terms of efficiency (primary energy and CO_2 emissions). In airflow control the performance based path can lead to controversial situations in which efficient controls would we allowed on the account of their energy performance, even if they achieve the energy benefits in lieu of indoor air quality. Therefore, even RITE itself is unclear.

Similarly to other sections above, UNE 100713:2005 is not cited in the “controls” section of RITE, however, it is used as the “de facto” standard for systems in hospitals. Section 6.7 in UNE 100713:2005 defines conditions of system operation when not in use mode. The basic requirements are:

- Air circulation among spaces should remain according to their use type (which implies maintaining appropriate pressure differentials among spaces, see Section 2.1.3)
- Minimum air velocity in the supply duct = 2 m/s (only if the 3rd filtering stage is not located in the terminal unit)

The standard does not require temperature or relative humidity conditions, and does not require outdoor air supply.

In terms of energy efficient control strategies, UNE 100713:2005 provides more flexibility than the prescriptive method in RITE. Meeting the requirements of UNE 100713:2005 could probably be used as a safe way to deal with the "energy efficiency vs. IAQ" tradeoff in the performance based compliance path of RITE.

The Catalan health agency (CatSalut and Corporació Sanitària de Barcelona 2012) acknowledges the control allowance in UNE 100713:2005, and encourages hospitals to take advantage of it to reduce energy use when surgery rooms are unoccupied. The document recommends hospitals to strongly reduce exhaust airflows so that the aforementioned over-pressure requirements in UNE 100713:2005 can be met with the least outdoor airflow. In terms of temperature and relative humidity, the Catalan health agency recommends widening system deadbands to avoid space conditioning with the only (recommended) constraint that the system is capable of bringing the surgery room back to design conditions within 30 minutes.

Although UNE 100713:2005 allows system setpoints reset when surgery rooms are unoccupied, only about 39% of the surgery rooms in Catalonia use this provision (CatSalut and Corporació Sanitària de Barcelona 2012). In other words, roughly 60% of surgery room HVAC systems operate at design conditions of airflows, temperature, and relative humidity, 24 hours a day and 7 days a week, regardless of their occupancy.

ASHRAE acknowledges that "number of air changes can be reduced when the room is unoccupied if pressure relationship is maintained and the number of air changes indicated is reestablished any time the space is being utilizes" (ASHRAE 2003). Furthermore, the temperature and relative humidity ranges in its manuals and standards (ASHRAE 2011, 2003, 2008) are meant for system design purposes, and do not impose any operational constraint.

ASHRAE recommends VAV systems (which imply airflow control) in spaces where there are significant unoccupied hours (ASHRAE 2003). Most surgery rooms fall into the previous condition. According to data derived from multiple field surveys cited in (ASHRAE 2003), operating rooms are occupied about 65 hours a week (i.e., less than 40% of the time).

All in all, the different standards appear to agree in the requirement of maintaining the overpressure requirement at all times, but leave some degree of freedom to control the other parameters depending on the operation mode.

2.1.5 HEAT RECOVERY

Similarly to control, provisions and requirements for heat recovery in RITE fall under the "energy efficiency" section. The basic requirements in the prescriptive compliance path are:

- Air-based systems with capacities larger than 70kW must be equipped with freecooling controls
- Ventilation systems with airflows larger than 500l/s must be equipped with heat recovery units (sensible heat recovery, with minimum efficiencies described in Table 2.4.5.1 in RITE, as a function of operation hours and airflow rate) with evaporative cooling in the exhaust air side.

Table 6 Heat recovery unit minimum sensible efficiencies in RITE. Reproduced from (Ministerio de Industria Turismo y Comercio 2007)

Annual operation hours	Outdoor air flow (m^3/s)									
	>0.5…1.5		>1.5…3.0		>3.0…6.0		>6.0…12		>12	
	%	Pa	%	Pa	%	Pa	%	Pa	%	Pa
<2000	40	100	44	120	47	140	55	160	60	180
<2000… 4000	44	140	47	160	52	180	58	200	64	220
<4000… 6000	47	160	50	180	55	200	64	220	70	240
>6000	50	180	55	200	60	220	70	240	75	260

RITE also allows for a performance based compliance path, although in this case there is no room for controversy as heat recovery does not tradeoff with IAQ.

UNE 100713 is not cited in the heat recovery section of RITE, and therefore, not strictly mandatory. According to UNE 100713 heat recovery is allowed, provided that "the particle transmission index from exhaust air to inlet air is lower than 1/1000. Verification of particle transmission index shall be performed by using an appropriate gas (such as NO)"(AENOR 2005). UNE 100713 does not provide further details on the verification process, nor cites a standard that includes a proper description of the verification protocol. UNE 171340:2011 (AENOR 2012) does not include a verification protocol for heat recovery unit particle transmission index.

ASHRAE Standard 170 (ASHRAE 2008) focuses only on ventilation requirements, and does include any provisions regarding heat recovery units. However, the ASHRAE Manual strongly recommends using air-to-air heat recovery strategies in surgery rooms (and hospitals in general), as "the significant amount of outside air required to meet code requirements in health care facilities [make] air-to-air heat recovery strategies a very cost-effective means of reducing energy consumption" (ASHRAE 2003)

2.2 CLASSIFICATION OF SURGERY ROOMS

The different standards use different classification methods for surgery rooms. This section summarizes the classification motivation in the relevant standards, aiming to identify equivalences. Standards usually assign requirements and applications to spaces based on their classification, therefore it is important to find equivalences among classification criteria to come up with a complete list of requirements per space type.

2.2.1 FILTERING CRITERION - UNE 100713:2005

UNE 100713:2005 (AENOR 2005) classifies spaces based on germ concentration control requirements in the supply air and the environment. According to this standard, surgery rooms (both types A and B) are classified "Class 1 – very high requirements", while other hospital areas such as patient rooms are classified "Class 2 – usual requirements".

The difference in class translates into filtering requirements:

- AHUs serving Class 1 spaces are required 3 filtering stages
- AHUs serving Class 2 spaces are required 2 filtering stages

The standard provides further details on the filtering requirements. However, it does not provide a definition or classification criterion for surgery rooms (type A vs. type B), and does not refer to any other standard. Therefore, the only clear conclusion in terms of surgery room classification in UNE 100713:2005 is that all surgery rooms are classified "Class 1", and therefore required 3 filtering stages (for germ concentration control purposes).

2.2.2 PARTICLE CONCENTRATION CRITERION - EN ISO 14644-1:1999

EN ISO 14644:1999 is cited neither in RITE nor in UNE 100713:2005, however, it is the only standard available that provides a clear classification method that can be applied to surgery rooms, as acknowledged in (Pi 2008; Rosell Farrás and Muñoz Martinez 2010). It is also cited in

Standard “UNE 171340:2011 - Validation and evaluation of controlled environment rooms in hospitals” as the reference document for cleanroom classification tests (AENOR 2012).

EN ISO 14644:1999 “assigns ISO classification levels to be used for the specification of air cleanliness in cleanrooms and associated controlled environments exclusively in terms of concentration of airborne particles” (European Committee for Standardization (CEN) 1999). It must be noted that EN ISO 14644:1999 applies not only to surgery rooms but also to cleanrooms for other applications (e.g., aerospace, microelectronics, pharmaceutical). The standard thoroughly describes the classification method, but does not include “ISO Class” requirements for the specific applications, as this belongs to application-oriented standards and codes.

The classification criteria in EN ISO 14644:1999 is based on the application of the following equation:

$$C_n = 10^N \times \left(\frac{0.1}{D}\right)^{2.08}$$

Equation 4

Where:

C_n is the maximum permitted concentration (in particles per cubic metre of air) of airborne particles that are equal to or larger than the considered particle size.

N is the ISO classification number

D is the considered particle size, in micrometres

Table 7 below reproduces Table 1 in Standard EN ISO 14644:1999, which presents selected airborne particulate cleanliness classes and the corresponding particle concentrations for particles equal to and larger than the considered sizes shown in the column headers.

Table 7 Selected airborne particulate cleanliness classes for cleanrooms and clean zones. Reproduced from (European Committee for Standardization (CEN) 1999)

ISO classification number (*N*)	Maximum concentration limits (particles/m³ of air) for particles equal to and larger than the considered sizes shown below (concentration limits are calculated in accordance with equation (1) in 3.2)					
	0,1 µm	0,2 µm	0,3 µm	0,5 µm	1 µm	5 µm
ISO Class 1	10	2				
ISO Class 2	100	24	10	4		
ISO Class 3	1 000	237	102	35	8	
ISO Class 4	10 000	2 370	1 020	352	83	
ISO Class 5	100 000	23 700	10 200	3 520	832	29
ISO Class 6	1 000 000	237 000	102 000	35 200	8 320	293
ISO Class 7				352 000	83 200	2 930
ISO Class 8				3 520 000	832 000	29 300
ISO Class 9				35 200 000	8 320 000	293 000
NOTE Uncertainties related to the measurement process require that concentration data with no more than three significant figures be used in determining the classification level						

According to the standard, the designation of airborne particulate cleanliness for cleanrooms and clean zones must include:

- the classification number, expressed as “ISO Class N ”
- the “occupancy state” to which the classification applies
- the considered particle size(s), and the related concentration(s), as determined by the classification equation where each considered threshold particle size is in the range from 0,1 µm through 5 µm.

Occupancy states in the standard are defined as follows:

- “As-built” – condition where the installation is complete with all services connected and functioning but with no production equipment, materials, or personnel present.
- “At-rest” – condition where the installation is complete with equipment installed and operating in a manner agreed upon by the customer and supplier, but with no personnel present.
- “Operational” – condition where the installation is functioning in the specified manner, with the specified number of personnel present and working in the manner agreed upon.

The example designation included in the standard is: ISO Class 4; operational state; considered sizes: 0,2 μm (2 370 particles/m^3), 1 μm (83 particles/m^3)

EN ISO 14644:1999 provides a clear classification method for cleanrooms (which can be applied to surgery rooms) and a detailed explanation on the testing procedure and data analysis method. However, the standard does not include application-driven parameters such as:

- The “ISO class” required for different operation types
- A standard set of conditions (occupancy state and considered particle sizes) to be used in surgery room classification

The “application-oriented” standard UNE 171340:2011 – “Validation and evaluation of controlled environment rooms in hospitals”(AENOR 2012) requires the annual validation of particulate classification in surgery rooms to be performed “at rest”. This requirement is also included the guide published by the Catalan health agency (CatSalut and Corporació Sanitària de Barcelona 2012).

Finally, it should be noted that ISO classification according to the sole application of this standard does not imply any explicit requirement other than cleanliness in terms of airborne particles. EN ISO 14644:1999-1 does not explicitly include operation requirements for the HVAC system (e.g., supply airflow).

2.2.3 CLASSIFICATIONS EQUIVALENCES

A publication by the National Institute of Safety and Hygiene (Ministerio de Sanidad y Política Social 2009) classifies surgery rooms in types A, B, and C depending on their HVAC system. Type A surgery rooms are the best equipped, while type C are the worst. The document provides some general system layout “requirements” for type A and type B, but does not include the classification criteria, or a comprehensive list of requirements, or surgery types that can be performed in each of the classes. This publication does not cite any standards for reference.

A similar publication by the Catalan health agency (CatSalut and Corporació Sanitària de Barcelona 2012) also uses the A, B, C classification nomenclature, but provides further details on the surgery room type, and even the equivalences with the ISO classification system in EN ISO 14644:1999. Table 8 summarizes surgery room type description, application, and ISO equivalents.

Table 8 Basic surgery room classification and recommended ISO Class equivalents in (CatSalut and Corporació Sanitària de Barcelona 2012)

Class	Description and Application	EN ISO 14644 equivalent
A	High technology surgery rooms	ISO Class 5
	- Heart, lung, and liver transplants	ISO Class 6
	- Cardiac and aorta surgery	
	- Orthopedic surgery	
B	Conventional surgery rooms in hospital urgency areas	ISO Class 7
	- Other surgery interventions	
C	Minor surgery in outpatients clinics and delivery rooms	ISO Class 8
	- Minor interventions and deliveries	
	- Endoscopy	

Rosell et al., (Rosell Farrás and Muñoz Martinez 2010) suggest the same classification equivalences between “A, B, C” types and ISO Classes, although it leaves the list of applications for type A surgery rooms open.

It must be noted that the above equivalences were found in documents by national and regional agencies rather than in standards. Furthermore, only the document by the Catalan health agency (CatSalut and Corporació Sanitària de Barcelona 2012) specifies the “occupancy state” in which classification should be done (“at rest”, as also indicated in UNE 171340:2011 (AENOR 2012)).

The Catalan health agency notes that “Bacteria, viruses, and fungi (infection sources) can only propagate through air when there are solid or liquid particles that these can attach to. Therefore, the lower the particle concentration in air, the lower the risk of micro biotic contamination is. However, a statistical correlation between particle concentration and surgical infections is yet to be found” (CatSalut and Corporació Sanitària de Barcelona 2012). This statement is consistent with the driving force of total supply airflow requirements (i.e., germ concentration control in the protection zone), therefore, the same reference recommends total supply airflow depending on the surgery room ISO Class (Table 9). Note that while the basic germ concentration control requirement would intuitively apply when the surgery room is operational, its ISO classification corresponds to “at rest” mode.

Table 9 Outdoor air and total supply air recommendations by the Catalan health agency. Reproduced from (CatSalut and Corporació Sanitària de Barcelona 2012)

Surgery room class UNE 100713	Class ISO 14644	Flow type	Minimum OA flow (m^3/h)	Contamination level μ_s	Max relative concentration ε_{si}	Minimum total supply airflow (m^3/h)	Minimum air recirculations per hour
Class A	5	Laminar	1200	1	2/3	3600	20
Class A	6	Turbulent	1200	1	2/3	3600	20
Class B	7	Turbulent	1200	1	1	2400	20
Class C	8	Turbulent	1200	1	-	2400	20

2.3 SURGERY ROOM VALIDATION PROTOCOLS

UNE 171340:1999 (AENOR 2012) is not cited in RITE or UNE 100713:2005, however, it is the only standard available on "validation and evaluation of controlled environment rooms in hospitals". Hence, even if not explicitly mandatory, it is the reference standard for surgery room validation. Table 10 summarizes the validation requirements in UNE 171340:2011.

Table 10 Validation parameters according to UNE 171340:2011. Reproduced from (AENOR 2012)

Clean rooms	Validation at commissioning stage	Validation post maintenance	Annual validation "at rest"
Validation institution	External	Either external or internal	External
Environmental parameters	Temp and RH Microbiology Particles classification Noise level	Temp and RH Microbiology Particles classification Noise level	Temp and RH Microbiology Particles classification Noise level
System parameters	Pressure differential Filter location Airflows Air direction Airflow type analysis Room recovery	Pressure differential Surgery room classification Depending on refurbishment scope	Pressure differential Filter location Airflows Air direction Room recovery

The standard requires an annual validation test to be performed in occupancy state "at rest" (i.e., system running without occupation). This test includes verification of HVAC performance parameters such as temperature, relative humidity, pressure differentials or airflow rates, but it also includes the particle concentration test to validate the ISO classification of the surgery room. The benchmarks for temperature, relative humidity, outdoor airflow, and total supply airflow validation are the requirements in UNE 100713:2005.

It must be noted that UNE 171340:2011 is a validation standard, thus, meant to verify that systems perform according to their design intent. It makes conceptual sense to perform the verification test of system performance parameters (e.g., supply airflow) with the systems running at design conditions (which would correspond to “operational” state) but avoiding occupation so not to interfere with the hospital activity. However, a particle concentration test in “at rest” mode provides very limited (if any) information about the effectiveness of the system at removing indoor generated particles and delivering a low particle concentration in the protection area under “operational” conditions.

The “at rest” mode requirement in this standard does not preclude setpoint adjustments when the system is not in use (i.e., does not mean that the systems must always work under “at rest” conditions). System operation setpoints (including airflows, temperature, pressure, and relative humidity) when not under test are beyond the scope of this standard.

2.4 INFECTION CONTROL IN SURGERY ROOMS

An infection is defined as a “pathologic condition of tissue characterized by signs of inflammation with or without general bodily reaction (e.g., fever)” (ASHRAE 2003). Surgical infection is initiated by contamination, which in turn is defined as “the seeding of microorganisms” either in an open wound or into the respiratory system. Sources of contamination and infection in a surgery room include the patient itself and exogenous sources such as airborne particles. According to Laufman ((Laufman 1994), cited in (ASHRAE 2003)), airborne infectious contamination comes from two primary sources: 1) aerosolized microorganisms generated within the operating room and 2) aerosolized microorganism introduced by ventilation or infiltration. “Bioparticles are microscopic particles that carry microorganisms (bacteria, viruses, fungi, etc.). Airborne bacteria or viruses may be carried on bioparticles – such as dust particles, lint particles, shed skin scales (scurf) – or in moisture globules or may be airborne as actual bacteria or spores, singly or in clusters” (ASHRAE 2003).

“Certain types of particles are more likely to infect the human respiratory tract. The resistive force of air governs the movement of small particles suspended in the air. Particles that fall into a certain range of aerodynamic diameter from 0.2 microns to 2.0 microns also have an excellent chance of being inhaled deeply into the lungs, bypassing all of the upper respiratory tract defenses” (Morrow 1980), cited in (Hermans 2000). Troublesome organisms that fall into this size range include staphylococcus, legionella, influenza and M. tuberculosis.

Size is arguably the most important physical characteristic to use for airborne microbe classification, since it has a salient impact on filtration requirements and efficiency. Figure 2

compares relative sizes of airborne respiratory pathogens. It must be noted that the size range in airborne microorganisms spans almost four orders of magnitude. While there is some size overlap, spores, bacteria, and viruses can be well differentiated based on size alone (Kowalski and Bahnfleth 1998).

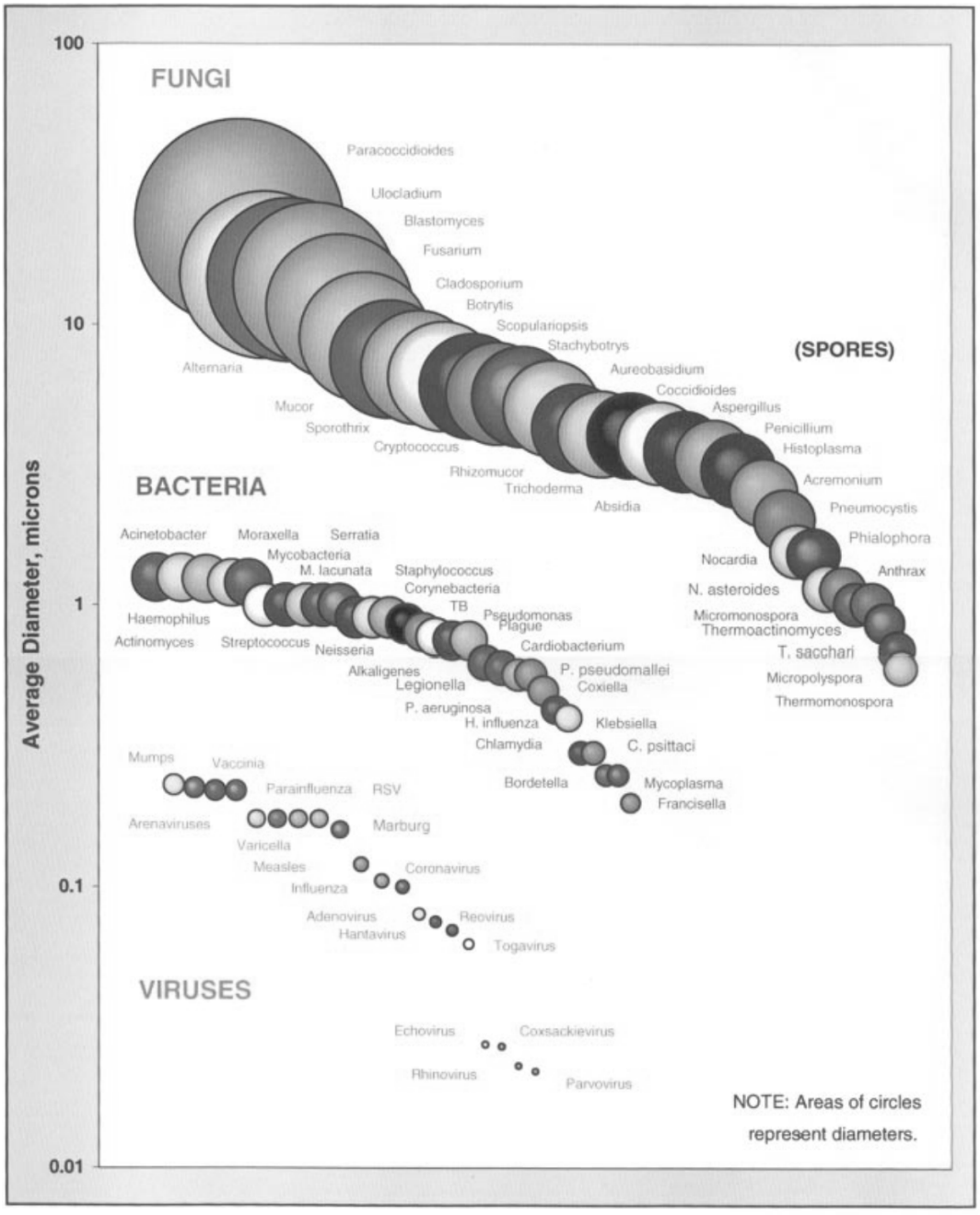

Figure 2 Relative size of airborne respiratory pathogens. Reproduced from (Kowalski and Bahnfleth 1998)

As stated above, airborne microorganisms in a surgery room may come from a variety of sources. Kowalski and Bahnfleth provide insight on the typical sources of the different airborne pathogens

in an air handling unit (Figure 3). “Contagious viruses and bacteria come almost exclusively from humans, and they will appear only in the return air. Spores and environmental bacteria may enter from the outdoors, but once growth (amplification) occurs indoors, they may appear in the return air at higher levels than in the outdoor air. Environmental bacteria are rarely pathogenic for healthy people, but they may provide a nutrient source for pathogenic fungi”.

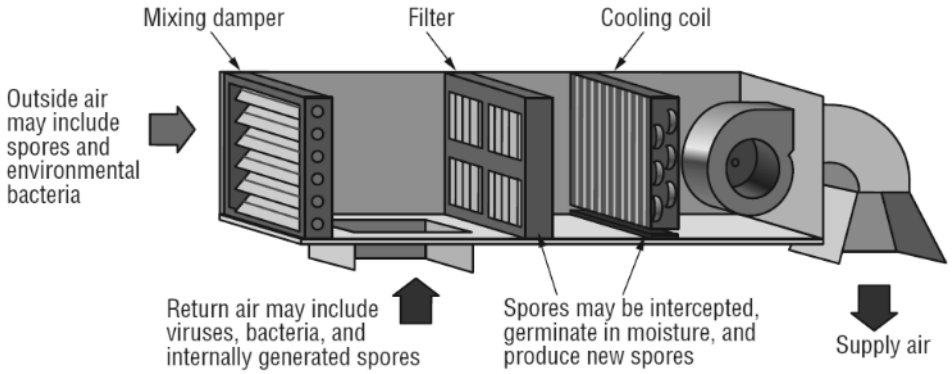

Figure 3 Sources and pathways of microbial contamination in a typical air handling unit. Reproduced from (Kowalski and Bahnfleth 1998)

Strict hygiene procedures and proper design sharply reduce the chances of microbial growth in air handling units and within surgery rooms (amplification) (Kowalski and Bahnfleth 1998; ASHRAE 2003). Outside air cleanliness (concentration of spores and environmental bacteria) strongly depends on location (hospital site), while return air microbe concentration strongly depends on the type of surgery under development.

2.4.1 HVAC AND INFECTION CONTROL

Presence of particles or even presence of infectious particles does not necessary lead to infection. The process of infection is conceptually described by the “biological force of infection relationship” ((Heirholzer Jr 1993), cited in (ASHRAE 2003; Hermans 2000)):

$$Infection \cong \frac{Dose \times Site \times Virulence \times Time}{Level\ of\ Host\ Defense}$$

Equation 5

Dose is the quantity (concentration) of infectious particles, site refers to the specific location where infection starts, virulence represents how aggressive the microorganisms are, time is the time of exposure of the patient to the infectious particles, level of host defense refers to the health condition of the patient.

According to this relationship “airborne infectious particles must be present in a concentration equal to or greater than the infectious dose for a long enough time in a susceptible host for a colonization to occur to the point where an infection begins” (ASHRAE 2003).

The basic role of HVAC systems in infection control is to reduce the concentration of airborne infectious particles in the protection zone by supplying filtered air. “Ventilation can affect the infectious dose by control of the airborne infectious particle concentration and the time of exposure by lowering the mean age of air in a space. By concentrating on the control of contaminant concentration and time of exposure, real engineering can be accomplished with measurable results” (Hermans 2000; ASHRAE 2003). Level of host defense and location where microorganisms build up are beyond the control of any HVAC system. Kowalski and Bahnfleth (Kowalski and Bahnfleth 1998) also note that “the dose received from an airborne concentration of microbes could be considered a factor under engineering control since it depends on the local air change rate and degree of mixing as well as the generation rate”, yet, they warn that “dose” is only one of the several factors (see Equation 5) that drive success in infection transmission (i.e., there may be infection transmission in low dose, if the other factors are favorable).

In 2000 Hermans claimed that “unfortunately, ventilation control systems do not measure the concentration of infectious particles in a space. A ventilation system cannot, therefore, increase airflow rates, vary the air cleanliness, or improve air distribution in response to a burst of airborne infectious particles. Until a real-time and cost-effective monitor for infectious particles (or a valid surrogate) is created, ventilation systems will be designed for fixed conditions of source generation of contaminants. Ventilation system design will be controlled by the traditional parameters of temperature, humidity, flow rate, and pressure. These are the tools the designer has available to address infection and comfort control” (ASHRAE 2003; Hermans 2000).

The above statement was valid at the time of publication of the work by Hermans (2000) and also the ASHRAE HVAC Design Manual for Hospitals and Clinics (2003). However, real-time particle concentration sensors are commercially available in 2013 (CLIMET Instruments Company 2014), and they would be easily cost-effective if could be used to reduce unnecessary airflow in surgery room ventilation. If “particle concentration” was considered a valid surrogate of “infectious particles”, the “real-time and cost-effective monitor for infectious particles” would be a reality. This could open the door to real-time control of HVAC operation based on the actual infection control performance requirements in the surgery room. Given some constant filter characteristics (filtering efficiency at different particle sizes), air cleanliness would be controlled by adjusting total supply air in the operation room (i.e., the rate at which air is filtered).

However, the type of particles and corresponding acceptable concentrations to use for ventilation control remains unclear in the literature. Hermans (Hermans 2000) acknowledges that "the choice of which particles to use for a ventilation design (or for a ventilation standard) depends entirely upon the expected clinical use of the space. Airborne candidates for control in most common patient-occupied spaces are M. tuberculosis, measles virus, Varicella zoster, and some fungal spores". This list provides a starting point for defining general particle control strategies, but does not provide acceptable particle dose ranges (concentration and exposure time) that could be directly used for ventilation control. The microorganisms included in the list vary in average size from 0.12-0.16 microns (measles virus and Varicella zoster) to 0.86 microns (M. tuberculosis), and up to 1-10 microns depending on the spore type (Kowalski and Bahnfleth 1998). This would translate into a relatively wide range of particle size control (if "concentration of particles of a given particle size" was to be the control variable), but consistent with the particle sizes used for ISO classification of cleanrooms (European Committee for Standardization (CEN) 1999).

According to Kowalski and Bahnfleth, "few infectious doses have been established, but for purposes of making rough or conservative estimations, as few as 1-10 TB bacilli can be infectious for humans, while a total of 200 Rhinovirus virions may be required to cause a cold" (Ryan 1994; Kowalski and Bahnfleth 1998). Franz et al. (Franz et al. 1997) summarized infective doses for 10 classic biological warfare agents. Kowalski and Bahnfleth acknowledge that computations of infectious airborne doses remain very uncertain. It must be noted that "average" infective doses may be conservative for patients under anesthesia (who are intubated and ventilated) and medical staff (who usually wear masks).

2.4.2 HVAC TECHNOLOGIES FOR INFECTION CONTROL

The basic available engineering alternatives for infection control in surgery rooms are:

- Outside air
- Filtration
- Ultraviolet germicidal irradiation (UVGI)

These three technologies have advantages and limitations, and are often combined to complement each other (Kowalski and Bahnfleth 1998).

The lower concentration of microorganisms in outside air compared to return air translates into an opportunity to use 100% outside air systems as a means of infection control. This opportunity is limited by the fact that outside air often includes spores and environmental bacteria and, therefore, it cannot meet cleanliness requirements if not combined with another technology such

as filtration. Note, however, that spores (the most potentially infectious microorganisms carried in outside air) are large enough in size to be effectively filtered with medium efficiency filters, and therefore, in some cases there is no need for HEPA filtration.

Using HEPA filtration is the most effective means of controlling airborne particle concentration, resulting in the highest microorganism removal rates. Furthermore, HEPA filtration is equally effective in all microorganism sizes (spores, bacteria, and viruses). “The use of HEPA recirculation carries a lower total energy penalty in hot or cold climates” than outdoor air systems (Kowalski and Bahnfleth 1998) because recirculation air is already conditioned. HEPA filtration can be easily combined with outdoor air supply in air-side freecooling systems for energy optimization purposes. “Combining outdoor air with HEPA filtration results in performance that is essentially additive” (Kowalski and Bahnfleth 1998).

Ultraviolet germicidal irradiation (UVGI) lamps can “kill a significant percentage of the viable particles floating in the air of a room” provided that air is well mixed (ASHRAE 2003). Airborne microorganisms are destroyed by exposure to direct UVGI in the wavelength range of 200-270 nanometers. Air-handling unit and duct-mounted and packaged UV-fan recirculation units are available that help eliminate viable microortanisms from the air supply or prevent their growth on irradiated equipment. UVGI is not as effective as HEPA filtration in microorganism removal (it is particularly ineffective with spores). “A single pass through a UVGI system may have a limited effect, but recirculation […] will result in multiple exposures or chronic dosing” (Kowalski and Bahnfleth 1998). UVGI can be an efficient method to use for microbial growth control in AHU components such as cooling coils.

2.4.3 AIRFLOW DYNAMICS IN A SURGERY ROOM. LAMINAR FLOW

Hermans provides a clear description of the intrinsic motivation for laminar flow systems in surgery rooms: “the cleanest air available [in the surgery room] is that which is leaving the diffusers. This air begins to become contaminated as it travels around the room. An ideal ventilation system is one that provides air directly from the diffuser to the patient without picking up contaminants” (Hermans 2000). A CFD-based study by Memarzadeh and Manning (Memarzadeh and Manning 2002) compared ventilation performance of conventional, laminar, nonaspirating, and displacement diffuser types. They found that ventilation systems that provide laminar flow conditions are the best at controlling risk of contaminant deposition on an operating room surgical site.

In an ideal laminar flow system air from the diffusers should reach the protection zone fast enough to avoid contamination, however air velocity in the room should remain low enough to avoid mixing

(i.e., to maintain the laminar flow). Furthermore, velocity at the surgical site should be low enough to allow the wound's thermal plume to carry away any airborne particles released into the sterile field (ASHRAE 2003). The trade-off in air velocity requirements drives most of the design criteria for laminar flow systems.

One measure of a system's ability to provide clean air to the protection zone is local mean age of air. The local mean age (LMA) of air is defined as the average time needed for the supply air to reach the location of interest. The volumetric flow rate, the temperature difference between the supply air and the room, and the velocity distributions in the space all affect LMA. […] Lowering the LMA in a room increases protection of the patient. LMA is lowered as air volume flow rates increase. Diffusers that are nonaspirating with enough velocity to reach the patient in both cooling and heating conditions decrease the LMA. (Hermans 2000)

A means to provide large flow rates at relatively low discharge velocities is using large diffuser areas. The ASHRAE HVAC Design Manual for Hospitals and Clinics recommends to "provide ceiling diffusers of low-velocity and high-volume output. Design for lower velocity and lower volumetric flow rate while maintaining stable direction and low-turbulent (low mixinig) characteristics; this results in less possibility of contamination impinging upon the surgical wound and lower operating cost. Provide low sidewall returns. Provide Group E outlets only, located in the ceiling and of non-aspirating type" (ASHRAE 2003). In terms of quantitative values for air velocities, the ASHRAE manual cites the conclusions of the study by Memarzadeh and Manning, according to which diffuser face air velocities should be no higher than 0.15-0.18m/s (Memarzadeh and Manning 2002). It must be noted, however, that this study is solely focused on 10-micron particles, which is a rather large particle size compared to most bacteria and viruses (see Figure 2)[5]. These conclusions may not be applicable to particles of other sizes.

2.5 TOWARDS A PERFORMANCE BASED SURGERY ROOM IEQ AND LOW-ENERGY OPERATION STANDARD

The prescriptive minimum requirements of outdoor and total supply airflow in the reviewed standards are meant to achieve certain performance goals in terms of dilution of anesthetic gases and other pollutants, overpressure, infection control, and indoor environmental control (temperature and relative humidity). The method summarized in Figure 4 proposes to dynamically adjust outdoor and total supply airflow based on the actual performance requirements. Except for OA2 (overpressure), conditions are dynamic and depend on operation type and room status (in

[5] Memarzadeh and Manning selected 10 microns as the study size based on the hypothesis that squames, or skin scales or particles, are the primary source of bacteria that cause infection.

use / not in use). Following this method, both outdoor air (OA) and total supply air (SA) would change to meet the most demanding condition at a given time.

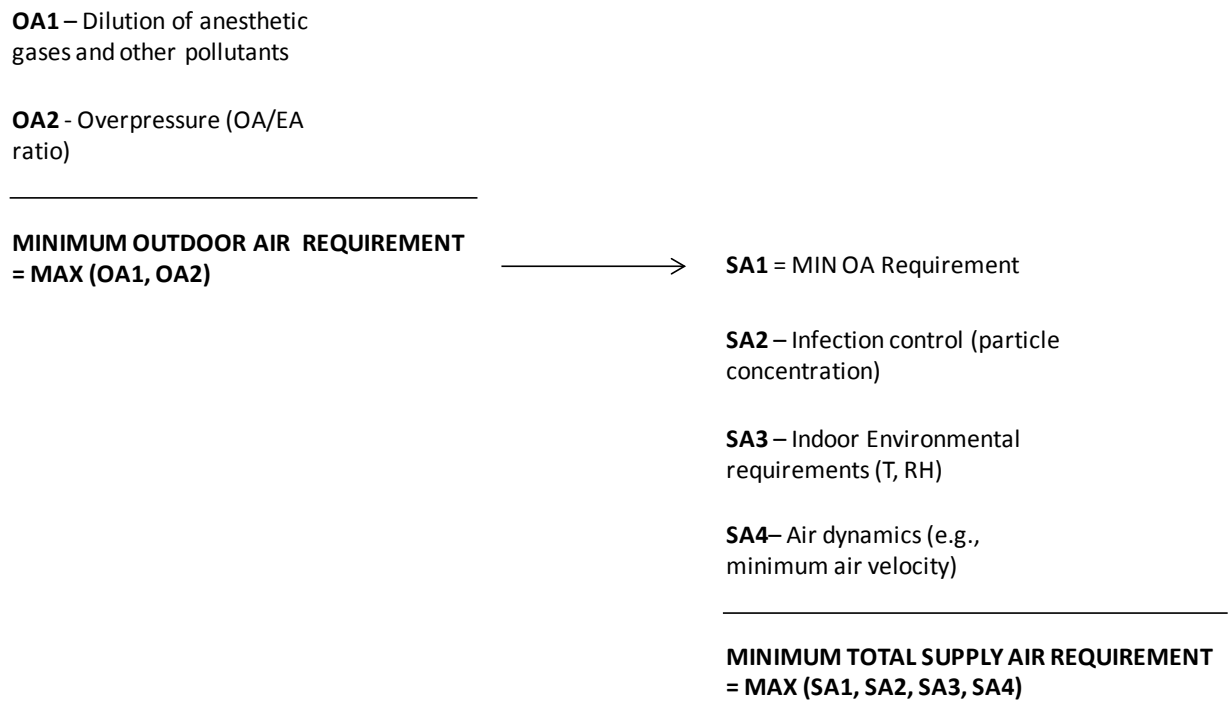

Figure 4- Proposed method to define outdoor and total supply airflows based on performance conditions

Condition OA1- Dilution of anesthetic gases and other pollutants. Under operation, outdoor airflow supply could ideally be controlled based on real time measurements of concentration of anesthetic gases and/or other pollutants. This is difficult to implement in reality because there is more than one pollutant to control and the maximum concentrations allowed are largely undefined in the standards and available literature. While further research is required to define acceptable pollutant concentration thresholds, the lowest OA rates in the reviewed standards could be used, since this condition affects all surgery rooms regardless of the system type. Namely 3ACH (American institute of Architects (AIA) 2001) or 4 ACH (ASHRAE 2008) should be enough to meet this condition. When the room is not in use (and is already clean), there is no generation of pollutants and no need for air to dilute them.

Condition OA2 – Overpressure. Surgery rooms must remain with positive pressure at all times regardless of their operation mode. Therefore, this is a constant condition (although in practice doors would open more frequently under operation, and therefore there would likely be more need for OA supply).

Since conditions OA1 and OA2 are independent, the required minimum outdoor airflow supply corresponds to the highest of them (i.e., outdoor airflow rate should be the minimum that meets both conditions). By definition, total supply airflow must be, at least, as high as outdoor supply airflow. Therefore, the minimum outdoor airflow supply requirement corresponds to the first condition of total supply air – SA1.

Condition SA2 – Infection control. This condition largely varies depending on operation type. Different operation types generate particles of different sizes at different rates, and imply different levels of patient infection risk. Increasing total supply airflow reduces concentration of airborne infectious particles by supplying filtered air. Ideally, total supply air could be controlled based on real time measurement of particle concentration. This is currently hard to implement due to the lack of defined maximum concentration of particles (of different size ranges) as a function of surgery type. Infection control requirements during operation could be based on the ISO classes defined in Standard EN ISO 14644:1999 (e.g., “surgery type “A” must be performed under conditions ISO class “B”; operational state; considered sizes: “C” µm, “D” µm”). While the correspondence between operation types and ISO classes under “operational state” is not available, recommended equivalences in Table 8 could be used instead. It must be noted that ISO classes in Table 8 correspond to validation tests performed in “at rest” mode (thus, harder to achieve under “operational state”), however, some energy savings may still be possible when using a high technology surgery room (e.g., ISO Class 5) for a minor surgery type (e.g., ISO Class 8). Also, total supply airflow could be largely reduced when the room is not in use (and is already clean), since there is neither generation of particles nor risk of patient infection.

Condition SA3 – Indoor environmental requirements. Temperature and relative humidity requirements are largely dynamic, as they vary depending on operation type, season, and user preferences. Temperature and relative humidity setpoints should be defined either by the doctors themselves or by the system operator based on doctors’ feedback and comfort preferences. The system should adapt its settings to meet the setpoints. Similarly to conventional air-based space conditioning systems, total supply airflow could be easily controlled based on the usually available indirect readings of heating/cooling sensible/latent loads (room temperature and relative humidity). The standards reviewed in this article do not provide acceptable ranges of temperature and relative humidity when the surgery rooms are not under operation, which suggests that there are no constraints in widening the comfort window. However, a minimum control is recommended to avoid condensation in the room and in the air distribution system.

Condition SA4 – Air dynamics. Depending on the system type and configuration, there may be a minimum air velocity required to achieve a proper performance. When laminar flow systems are

applied, minimum supply air velocity is usually the driver for the total airflow requirements in the surgery room.

Since conditions SA1 to SA4 are independent, the required minimum total airflow supply corresponds to the highest of them (i.e., supply airflow rate should be the minimum that meets all the above conditions).

It must be noted that this method addresses only surgery room operation, and does not overlap with surgery room classification and validation protocols.

2.6 IEQ AND INFECTION CONTROL. CONCLUSIONS

The basic mandatory IEQ requirements (and their respective motivations) for surgery rooms in Spain, can be summarized as follows:

- Outdoor airflow rate requirement: meant to reduce occupant exposure to anesthetic gasses and other indoor generated pollutants. UNE 100713:2005 sets the mandatory minimum outdoor airflow rate requirement (1200m^3/h).

- Total airflow rate requirement: along with filtration requirements, it is meant as an indirect means to reduce infection risk for the patient. The purpose of the total airflow requirement is to reduce germ concentration by increasing air filtration rate, thus reducing particle and germ concentrations. UNE 100713:2005 sets minimum total airflow rate requirements depending on surgery room type (2400-3600m^3/h); however, it is unclear as to whether these requirements are mandatory.

- Overpressure requirement: Surgery rooms are required to maintain a higher pressure than the adjacent spaces to avoid particle infiltration. There are no mandatory pressure differential values in the Spanish code, although UNE 171340:2011 uses 6Pa as the validation threshold.

- Temperature and relative humidity requirements: meant to provide thermal comfort to occupants. Apparently, there are no quantitative mandatory thermal comfort requirements in surgery room operation, but rather design values.

The most salient regulatory ambiguities identified in this review are found in 1) the total supply air requirements (method to proof concentration levels μ_s for non-mixing systems), 2) the justification for the mandatory outdoor air requirement, 3) the allocation of applications (i.e., types of operations) in surgery room classes, and 4) the requirement to perform the surgery room particle test in “at-rest” mode. Regulatory bodies should be clearer in the code requirements, and make

them more consistent with their intrinsic performance motivation (e.g., by providing a performance based compliance path).

The requirements and recommendations in the standards and guidelines included in this review differ in their magnitude (particularly the airflow requirement), but are similar in their prescriptive nature. This review identifies the performance goals associated to the prescriptive requirements, and proposes a method to adjust system operation (outdoor airflow rate, total supply air, indoor air temperature, and indoor air relative humidity) to meet IEQ performance goals while reducing energy use. Easily applicable energy efficiency measures that follow this method and would comply with most of the reviewed standards (including the mandatory code in Spain) include:

- Temperature and relative humidity reset when the room is unoccupied: to widen temperature and relative humidity deadbands to minimize space conditioning when the surgery room is not in use.

- Use recirculated air in operational mode: provide the minimum outdoor air as required in the corresponding standard, and use recirculated air to meet the total airflow requirement. This measure is particularly suitable for laminar flow systems, as these carry an associated 3- to 4-fold total supply airflow requirement compared to conventional mixing systems.

- Outdoor and total supply airflow reset when the room is unoccupied: to reduce airflows when there are no sources of germs and contaminants in the room.

Thanks to recent developments in commercially available sensors, HVAC operation (total supply airflow) could be controlled based on real time measurements of particle concentration in the surgery room. This measure does not comply with the current prescriptive code requirements, but addresses the performance motivation in the codes (infection control). Prior to the application of this measure further work is required to quantitatively define “acceptable” particle dose ranges (concentration and exposure time) in the protection area during operation. Performance-based operation infection control requirements for the different surgery types could be based on the ISO classes in Standard EN ISO 14644:1999.

3 METHOD OVERVIEW

The control strategies for surgery room air handling units explored in this thesis are evaluated in terms of energy performance and/or thermal comfort, and compared with the reference case (baseline: the systems as currently set up and operated). The energy efficiency measures conceptually identified in Chapter 2 are tested in the Hospital de Mollet case. The control measures applied to Hospital Virgen de las Nieves are very case-specific and defined in the corresponding section. The control strategies tested in both cases meet the key performance indoor environmental quality and infection control requirements identified in Chapter 2.

Figure 5 illustrates the overall method. While the basic framework is the same in both case studies, the very different natures of the air handling unit types and data available in the two cases required tailor-made models and analysis processes.

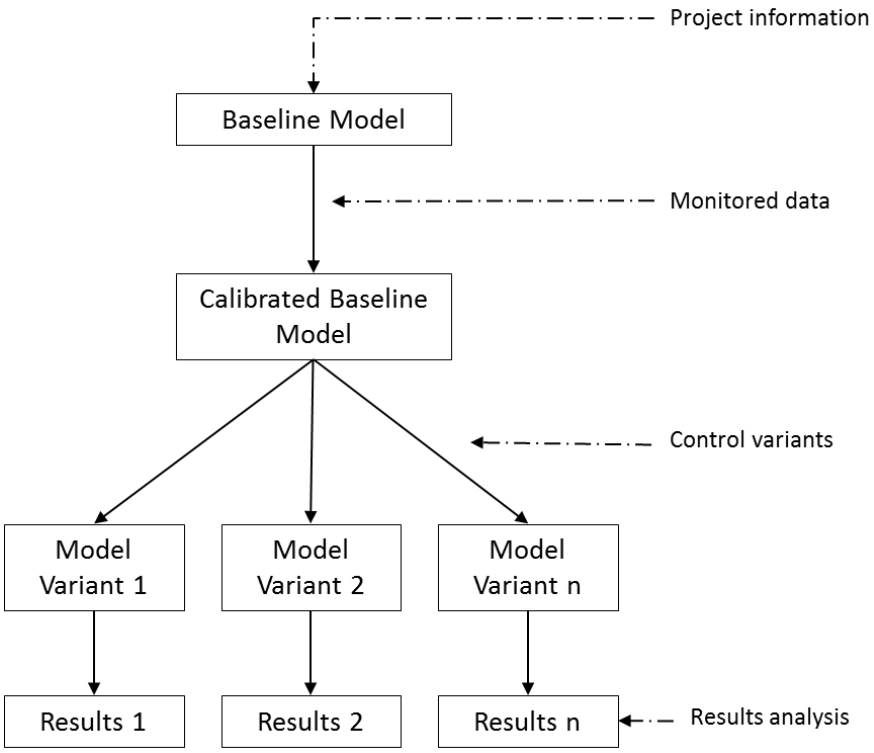

Figure 5 Method overview

A baseline model is developed based on initial project information such as surgery room geometry, envelope characteristics (thermal properties), air handling unit specifications (e.g., rated supply airflow rate) as well as operational information such as preliminary use schedules

and AHU control logic. Project information is retrieved from the technical personnel of Hospital de Mollet and Hospital Virgen de las Nieves.

The model is calibrated based on monitored data, which is generally available from the monitoring equipment installed for the Green@Hospital project. Monitoring equipment includes thermal energy and electricity meters. Thermal energy meters provide not only thermal power readings, but also fluid temperatures and flow rates. Some spot measurements are performed to verify non-metered variables (e.g., airflow rate in Hospital Virgen de las Nieves, real occupancy profile in Hospital de Mollet). Monitored values are used in the calibration process with two purposes:

1- As model inputs. Some monitored data is used as an accurate and reliable replacement for some modeling assumptions in the baseline model.

2- As a reference to check the model outputs against. Model results are compared to monitored data to verify the accuracy of the model. Model parameters are adjusted in order to improve the fit between model outputs and monitored data

The calibrated baseline model is used as the starting point in the definition of model variants to assess the performance of the new control strategies. Due to the major differences in air handling unit characteristics, energy efficient control strategies are specifically defined for each case study. Variants are obtained by modifying internal variables in the model according to the control logic under study. Generally, model variants cannot be calibrated with monitored data, as the strategy has not been implemented in reality and, therefore, monitored data is not available.

Model results are compared to assess the relative performance of the different variants. System performance is assessed in terms of energy use and indoor environmental quality. In the case of Hospital de Mollet, indoor environmental quality during operation is set as a boundary condition (i.e., all control variants provide the same performance), and therefore results are limited to energy use. Energy use is primarily assessed in terms of the specific energy uses in the air handling units:

- Thermal energy use in the heating and cooling coils and
- Electricity use in fans

Final energy use (natural gas for heating and electricity for cooling) is computed for the Hospital de Mollet case by applying average efficiency values of the heating and cooling plant. Primary energy use, energy cost, and CO_2 emissions are calculated based on the final energy results. Equivalent information on plant efficiency is not available for Hospital Virgen de las Nieves, which

precludes comparing alternatives in terms of final energy use, primary energy use, and CO_2 emissions.

Model details and control variants are thoroughly adapted to the two case studies, Hospital de Mollet and Hospital Virgen de las Nieves, and described in Sections 4.1 and 4.2, respectively. It must be noted that the "Baseline results" shown in Sections 4.1 and 4.2 correspond to the "Calibrated baseline model" step in Figure 5. Sections 4.1.2.4 and 4.2.2.3 describe the modeling and calibration process in the two case studies, respectively, and indicate which model inputs are based on assumptions and system characteristics (which correspond to the "Baseline model" step) and which are monitored values.

3.1 SELECTION OF COMPUTER-BASED MODELS FOR SURGERY ROOMS

Computer-based models of surgery rooms found in literature are strongly focused on airflow dynamics and particle concentration distribution for infection control purposes. The main objective of the models found in literature is to assess ventilation effectiveness (i.e., how well the system provides clean air in the protection zone) under different conditions of surgery room geometry and supply airflow. The work by Memarzadeh et al. (Memarzadeh and Manning 2002) is probably the most comprehensive and recognized, as it is reproduced in the HVAC Design Manual for Hospitals and Clinics (ASHRAE 2003) and used as the main reference for the air distribution recommendations. Further work by Memarzadeh (Memarzadeh and Jiang 2004) builds on the previous results and explores the influence of room shape on particle distribution within the surgery room. Additional surgery rooms models include these by Huzzain et al. (Huzzain and E.khalil 2005), Khalil et at. (Khalil 2008, 2011; Khalil 2012) and Pereira et al. (Pereira et al. 2011).

All the above models where 3D time-dependent Computational Fluid Dynamics (CFD) models, and were used to assess airflow characteristics and particle dynamics within the surgery room. Model inputs included the detailed room geometry (including location of obstacles, heat sources, and location of supply diffusers and return grills), some sort of subroutine to model contaminant generation, and the characteristics of the supply airflow (velocity, temperature, relative humidity). Model outputs are usually 3D distributions of air velocity, temperature, and particle concentration, which can in turn be used to calculate effectiveness indexes. Some of these models (such as this by Memarzadeh et al. (Memarzadeh and Manning 2002)) were successfully compared to monitored values. These models do not include the HVAC system itself, but only the characteristics of the supply and return air. These CFD models are meant to study short-term (few hours) dynamics of air distribution and particle concentration during processes such as operation, surgery room recovery after operation or stand-by. These models provide great detail

of useful information for air distribution design, however, they are not suitable for simulation of annual energy performance.

Unlike room air distribution models, the present literature review failed to identify any relevant papers on HVAC systems models for surgery rooms. Building energy simulation is a powerful tool to perform ex-ante assessments of energy performance of buildings and building systems. Building energy modeling is widely used to evaluate energy performance of commercial and residential buildings, and sometimes used for mandatory energy rating systems (Ministerio de Industria Turismo y Comercio 2010) or voluntary third-party environmental performance evaluation systems such as the USGBC LEED certificate (U.S. Green Building Council 2010). Building energy simulation increasing popularity among researchers and professional practitioners lead to the creation of the International Building Performance Simulation Association (IBPSA) (International Building Performance Simulation Association 2013), which aims to "provide a forum for researchers, developers and practitioners to review building model developments, facilitate evaluation, encourage the use of software programs, address standardization, accelerate integration and technology technology transfer". IBPSA organizes an annual international conference (e.g., "Building Simulation 2013" is held in Chambery) and holds its own journal (Journal of Building Performance Simulation).

The most widely used building simulation software packages include DOE2 interfaces (U.S. Department Of Energy 2013a), EnergyPlus (U.S. Department Of Energy 2013b), TRNSYS (University of Wisconsin et al. 2013), and ESP-r (Energy Systems Research Unit. University of Strathclyde et al. 2013). DOE2 was the pioneer building simulation system. Its interfaces (the most popular being e-QUEST) are still valid for LEED certification and energy certification (e.g., Calener GT, the Spanish official software for energy certification, is an interface of DOE-2), however, it is hard to model novel high energy performance systems in DOE2, and therefore, its use for modeling high performance buildings is becoming marginal. EnergyPlus is the next generation of building energy simulation tools supported by the U.S. government. It is currently among the most used simulation tools in the U.S. and worldwide (U.S. Department Of Energy 2013b), and it is capable of better handling advanced building features. EnergyPlus remains a "building-focused" modeling tool (i.e., the focus of the model is the building itself, and the systems are included in the model as a means to match the building's needs). Standalone models of systems are not possible in EnergyPlus. TRNSYS is "a transient systems simulation program with a modular structure. […] the user specifies the components that constitute the system and the manner in which they are connected. The TRNSYS library includes many of the components commonly found in thermal and electrical energy systems, as well as component routines to handle input of weather data or other time-dependent forcing functions and output of simulation

results. The modular nature of TRNSYS gives the program tremendous flexibility, and facilitates the addition to the program of mathematical models not included in the standard TRNSYS library. TRNSYS is well suited to detailed analyses of any system whose behavior is dependent on the passage of time.[…] Main applications include: solar systems (solar thermal and photovoltaic systems), low energy buildings and HVAC systems, renewable energy systems, cogeneration, fuel cells" (University of Wisconsin et al. 2013). Therefore, while TRNSYS allows simulation of buildings, it is also capable of defining tailor-made HVAC systems outside the building model. ESP-r "is an integrated energy modeling tool for the simulation of the thermal, visual and acoustic performance of buildings and the energy use and gaseous emissions associated with associated environmental control systems. In undertaking its assessments, the system is equipped to model heat, air, moisture and electrical power flows at user determined resolution" (Energy Systems Research Unit. University of Strathclyde et al. 2013). ESP-r is, therefore, a "building-focused" modeling tool.

The aforementioned building energy simulation software packages define spaces as a single (or very few) airnode, assuming homogeneous environmental conditions in the entire space (or the volume associated to the airnode). This simplification of reality precludes accurate evaluations of local environmental conditions (for which the CFD models are a more suitable tool), but allow annual simulations runs of both the spaces and the associated HVAC systems. Experience-based assumptions on ventilation effectiveness can be introduced in the TRNSYS models to account for the non-homogeneous conditions in the room and better couple the building and HVAC system models. Some building energy simulation tools include simplified models for non-homogeneous air distribution systems (e.g., EnergyPlus features a module for displacement ventilation and UFAD (Bauman et al. 2007)).

All in all, CFD models have been successfully used to accurately model air distribution within surgery rooms, but they are not suitable for annual simulations of energy use of the associated HVAC system. On the other hand, building energy simulation tools are commonly used to model energy performance of buildings and their associated systems, however, they are not capable of accurately account for non-homogeneous conditions in the spaces. Furthermore, no references to energy models of surgery rooms were found during this literature review. Since the objective of this thesis is to assess energy performance of ventilation systems for surgery rooms, energy simulation tools (rather than CFD) are used.

3.2 DYNAMIC SIMULATION MODELS OF SURGERY ROOM AIR HANDLING UNITS

Air Handling Units (AHUs) provide ventilation and space conditioning (heating, cooling, humidity control) to spaces. AHU system performance is evaluated based on how well the system provides the desired thermal conditions to the space, and on the amount of energy required to do so. Therefore, the models include both the AHU system and the space (room).

Among the simulation tools currently available such as EnergyPlus or ESP-r, TRNSYS is selected as the modeling tool because it is capable of coupling spaces (rooms/buildings) to detailed and tailor-made HVAC systems in a single model. Furthermore, TRNSYS is a dynamic simulation tool capable of handling systems that feature rapid dynamics, such as air handling units. The time steps used in both models (Hospital de Mollet and Hospital Virgen de las Nieves) is 6 minutes (0.1 hour). The TRNSYS sub-routines that model individual system components (which are called “types” in the TRNSYS environment) have been extensively validated (University of Wisconsin et al. 2013). An additional reason for choosing TRNSYS as the modeling tool is its capability to communicate with Matlab (MathWorks 2013) through type 155. This feature is used in the Hospital Virgen de las Nieves case, for which the system model is developed in TRNSYS and a fuzzy-based controller is developed in Matlab. Communication between TRNSYS and Matlab has been successfully used in previous studies (Dounis et al. 2011).

The models of the two AHUs are substantially different; however, they both follow the basic conceptual schema shown in Figure 6.

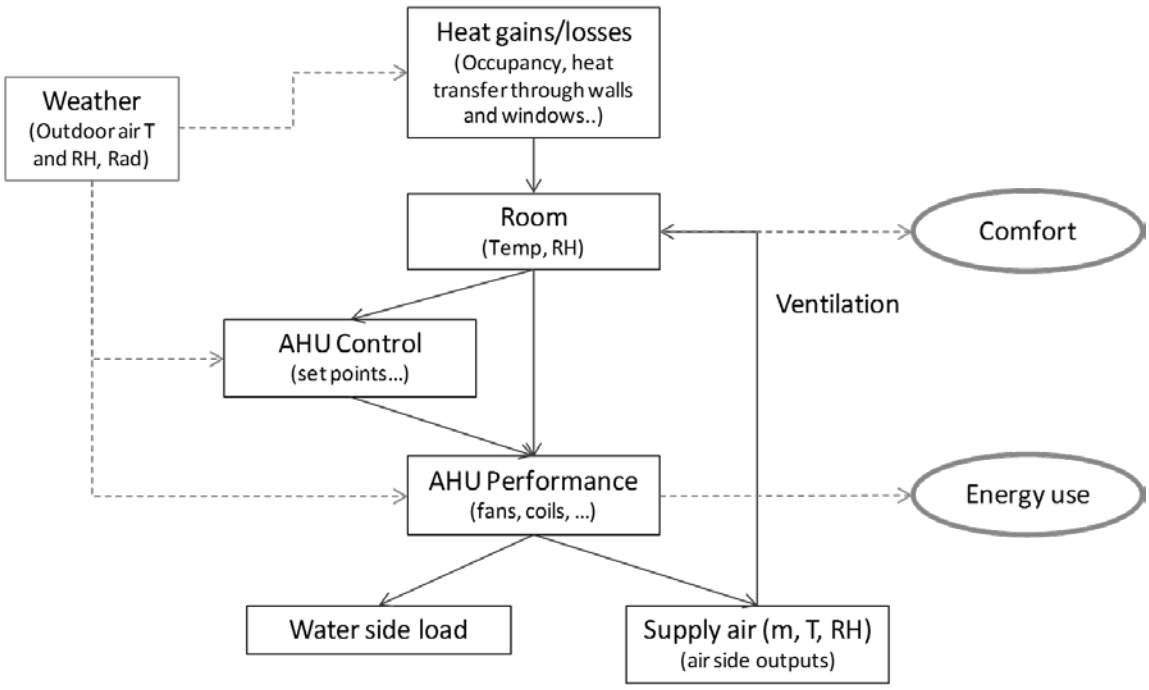

Figure 6 Conceptual schema – Air handling unit models

The spaces served by the air handling units are modeled according to their actual geometry, orientation, and wall and window properties. Heat gains/losses through the envelope are calculated based on the aforementioned building characteristics and the weather data (solar radiation, outdoor temperature and relative humidity), which is a model input (data file) based on synthetic data (METEOTEST 2014) (short-term monitored data is used for calibration). Furthermore, heat gains from occupants, lights and equipment (plug loads) are also included in the model. The total heat gains/losses in the space result in a variation of the air conditions' in the rooms (i.e., indoor air temperature rises when there is an overall heat gain in the space, and decreases when heat losses are larger than heat gains).

The "air handling unit control" uses the readings of room conditions (temperature and relative humidity) to adjust air handling unit set points.

The air handling unit block includes all the equipment pieces that directly modify the conditions of the air to be supplied to the room: fans, heating/cooling coils, heat recovery units, air dampers. The air handling unit adjusts the settings of all its components according to the control inputs. The air handling unit in Hospital de Mollet has a standard layout and is be modeled with a dedicated air handling unit TRNSYS type 335 (TRANSSOLAR 2013). The non-standard unit in Hospital Virgen de las Nieves is modeled as a complex combination of components. The individual airstreams, dampers, valves and heating and cooling coils are modeled independently with more primary types and characterized based on monitored data. Detailed descriptions of the air handling units in the two case studies and their respective models can be found in Chapter 4.

The conditioned supply air is sent back to the space, and used as a ventilation input (i.e., a heat gain) in the calculation of room air conditions in the following time step.

Energy uses (fan power, heat transfer to/from cooling/heating coils) are obtained from the AHU model. AHU models do not include plant equipment (e.g., boilers and chillers) since they are usually supplied by chilled/hot water from a central plant. Thermal energy performance of AHUs is evaluated based on heat transfer in the heating and cooling coils and fan electricity use.

Comfort variables (temperature and humidity) are obtained from the room model.

4 APPLICATION

This chapter uses the assessment method described in Chapter 3 to test the control strategies in two case studies. Section 4.1 assesses control strategies that can be implemented in a standard surgery room air handling unit, using a surgery room in Hospital de Mollet as the case study. The control measures evaluated in Section 4.1 are based on the control strategies identified in Chapter 2. Section 4.2 assesses control strategies that can be implemented in a non-standard multizone air handling unit at Hospital Virgen de las Nieves (Granada). The control measures in the second case study are very specific to this system configuration, but remain consistent with the indoor environmental quality and infection control performance goals discussed in Chapter 2.

4.1 CONTROL STRATEGIES IN A STANDARD AIR HANDLING UNIT - HOSPITAL DE MOLLET

4.1.1 INTRODUCTION

The critical review of the currently available indoor environmental quality and infection control standards for surgery rooms in Chapter 2 identified the basic performance motivation behind the IEQ-related requirements:

- The minimum outdoor airflow rate requirement is meant to reduce occupant exposure to anesthetic gasses and indoor generated pollutants.
- The total airflow rate requirement is, in combination with filtration, meant to reduce the concentration of infectious airborne particles in the surgery room and, therefore, the risk of patient infection.
- The overpressure requirement is meant to prevent contamination from adjacent spaces.
- The temperature and relative humidity requirements address the comfort needs of physicians and patients (who are often weaker and more easily challenged by uncomfortable environments).

The different motivations for the requirements brings the opportunity to individually control HVAC setpoints for total supply airflow, outdoor airflow, temperature, and relative humidity. Control strategies to reduce surgery room energy use while meeting IEQ and infection control performance goals were identified in Chapter 2. However, these strategies were not quantitatively evaluated. The objective of Section 4.1 is to quantify the potential benefits of surgery room ventilation control strategies in a standard Air Handling Unit (AHU).

4.1.2 METHOD

This thesis uses monitored data of a surgery room in Hospital de Mollet (Barcelona, Spain) to calibrate a TRNSYS (University of Wisconsin et al. 2013) energy model. The calibrated baseline model of the surgery room (i.e., a model of the current configuration and control strategy) is modified to assess the performance of the alternative control strategies.

4.1.2.1 System description

The New Hospital de Mollet was built in 2010 and can be considered a pioneer public hospital in environmental responsibility and energy efficiency. As for the internal distribution, this has been designed in such a way as to avoid crossings between patients, visitors and health staff. It provides coverage to over 150,000 inhabitants of 10 municipalities. The hospital covers an area of 27,000m^2, it has 160 beds, 42 consulting rooms and 6 operating theatres and are a landmark in special fields such as kidney care, fibromyalgia and chronic fatigue.

The surgery room under study is 37m^2 in floor area and 118m^3 in volume (Figure 7). The AHU (Figure 8) is a dedicated unit that provides ventilation and space conditioning to the surgery room space through a laminar flow diffuser. The AHU is equipped with a 60% efficient sensible heat recovery unit to comply with the Spanish mandatory energy standard (Ministerio de Industria 2007). The AHU includes a heating coil, a cooling coil, and a reheating coil. The cooling and reheating coils can be used simultaneously to meet both the temperature and relative humidity requirements of the surgery room. The AHU also features a humidifier. The AHU includes a supply and a return fan. The supply airflow rate is higher than the return airflow rate to guarantee overpressure in the surgery room (which is a required condition for infection control purposes). High Efficiency Particulate Air (HEPA) filters are installed in the supply airflow stream for infection control purposes. This AHU is a 100% outdoor air system, and does not allow air recirculation. As discussed in 2.1.2.3, air recirculation in surgery rooms is allowed (and even encouraged) but seldom used in the Spanish surgery rooms. Although air recirculation cannot be implemented in the AHU in the Hospital of Mollet, this strategy is still assessed through modeling as a potential energy efficiency measure for AHUs that do have air recirculation capability.

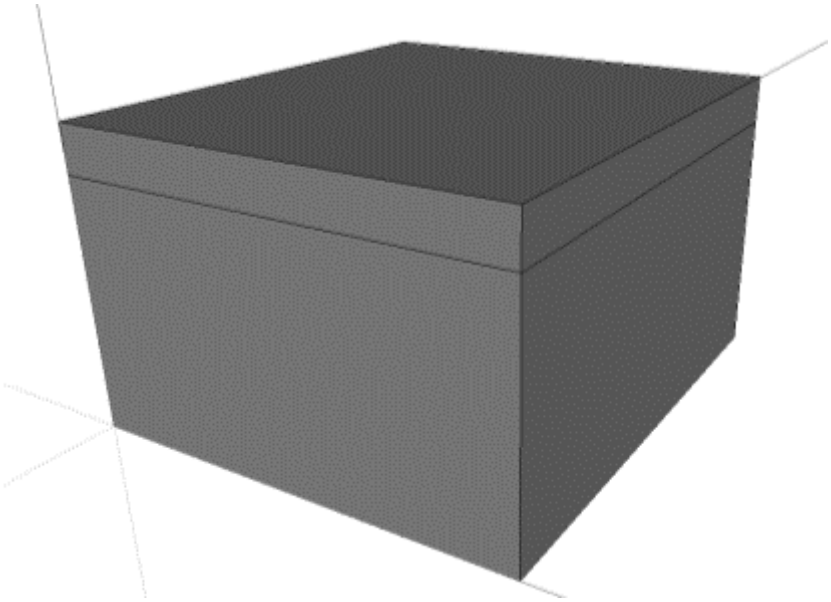

Figure 7- 3D Scketch of the surgery room in Hospital de Mollet

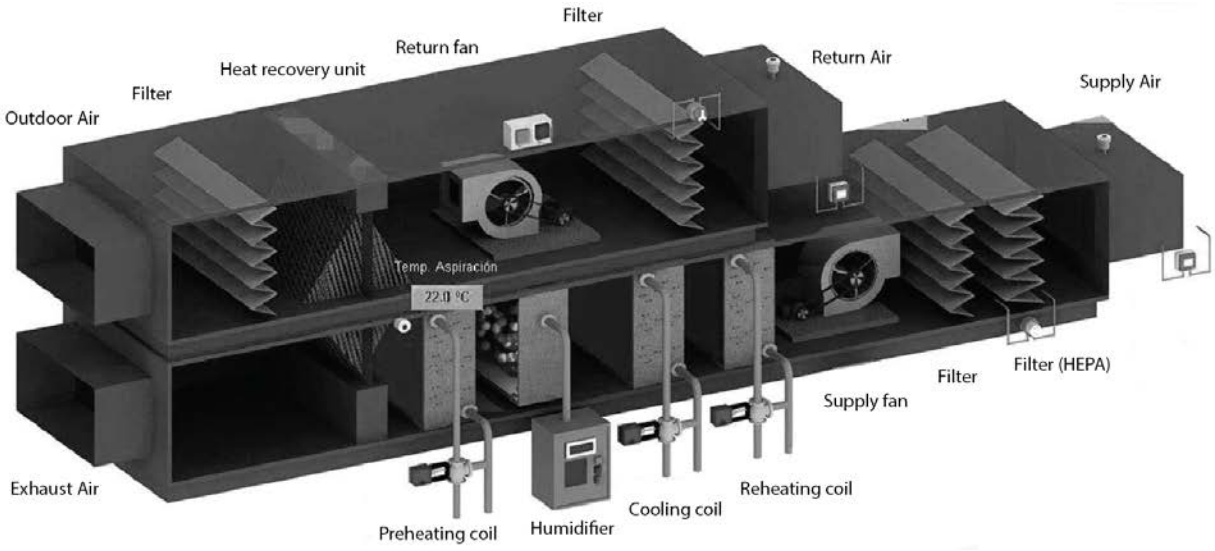

Figure 8- Schematic of the AHU in Hospital de Mollet

The standard operation setpoints in the surgery room are 3200 m3/h supply airflow rate and 50% ± 5% relative humidity. The return fan is controlled to maintain a 10 Pa overpressure in the surgery room, which in the studied surgery room corresponds to 2500 m3/h exhaust airflow rate when the doors are closed. The temperature setpoint can be manually adjusted by the user (physician) within the 18^0C-25^0C range (the default is 22^0C), however, the allowed temperature deadband is constant at ± 1^0C.

4.1.2.2 Energy efficient control strategies

The energy efficient control strategies assessed in this thesis are: 1) Temperature and relative humidity reset, 2) Air recirculation, 3) Airflow reset and 4) Airflow control based on real time measurement of particle concentration.

1) Temperature and relative humidity setpoints and deadbands can be reset to less stringent values when the surgery room is not in use. This strategy reduces the amount of heating and cooling energy used for space conditioning (temperature and relative humidity control). To assess temperature and relative humidity reset this thesis uses $20^0C \pm 5^0C$ and 50%±5% as the setpoints and deadbands for temperature and relative humidity when the surgery room is not in use.

2) Since the requirements for total supply airflow and outdoor airflow derive from different motivations (infection control and dilution of anesthetic gases and contaminants, respectively), a fraction of the return air can be recirculated. To assess air recirculation this thesis uses 1200m3/h as the outdoor airflow supply setpoint, which is the minimum outdoor airflow requirement in Spain (AENOR 2005; Ministerio de Industria Turismo y Comercio 2007). Air recirculation in surgery rooms is allowed under the Spanish standard (AENOR 2005) if the recirculated air comes from the same space to which will be supplied and flows through the same filtering stages as the outdoor air does. Similarly, ASHRAE (ASHRAE 2003, 2008) allows air recirculation in surgery rooms provided that HEPA filters are used.

3) The airflow reset strategy lowers both total supply and outdoor airflows when the surgery room is not in use. During non-use periods there is no generation of anesthetic gases or infectious particles in the room, however, the air handling unit must still maintain surgery room overpressure to avoid contamination from adjacent spaces (ASHRAE 2003; AENOR 2005). Since recirculated air does not contribute to room overpressure, the system is set to 100% outdoor air during non-use periods in the airflow reset strategy. Test results of the monitored surgery room in the Hospital of Mollet show that a $300m^3/h$ supply airflow are enough to maintain a 6Pa surgery room overpressure (threshold used for room validation in UNE 171340:2011 (AENOR 2012)). This thesis uses 500m3/h as the supply airflow rate to assess airflow reset when the surgery room is not in use.

4) The potential use of real-time measurement of concentration of infectious particles for ventilation control was first introduced by Hermans (Hermans 2000). Sensors of infectious particles are not commercially available, however there are sensors capable of reading real-time particle concentration (infectious or not) in a variety of particle size ranges that

could be used for ventilation control. Due to the lack of previous studies, performance targets (particle concentration during surgery room operation) in the current standards, and a clear regulatory framework for surgery room airflow control in Spain, the particle-based airflow control strategy tested in this thesis was defined in coordination with the infection control committee of the Hospital of Mollet and an external indoor environmental quality assurance consulting and certification body (Cruceta 2014). Based on the precautionary principle, the field test reported in this thesis targets a very high infection control performance during operation, and allows only a limited airflow reduction with low particle concentration readings. This thesis uses the threshold values for ISO Class 5 (European Committee for Standardization (CEN) 1999) as the target for airflow control during operation. It must be noted that ISO Class 5 is the highest standard for surgery room classification in (Rosell Farrás and Muñoz Martinez 2010; CatSalut and Corporació Sanitària de Barcelona 2012). Furthermore, surgery room classification under Standard UNE 171340:2011 (AENOR 2012) is performed in occupancy state “at rest” (i.e., system running without occupation) which, due to the absence of particle generation in the room, is a more favorable condition than “operational”. Total supply airflow rate is set to the maximum fan capacity (3200m3/h) when the 0.3µm particle concentration reading approaches 10,200ppm (ISO Class 5 limit). Total supply airflow setpoint proportionally decreases with particle concentration up to a lower limit of 1600m^3/h and 3500ppm. The minimum 1600m^3/h is maintained for particle concentration readings lower than 3500ppm. The 3,500ppm lower limit is arbitrary. Concentration of 0.5µm particles is also monitored in real time, however readings never approach the ISO Class 5 limit for this size (3,520ppm) and, therefore, this reading does not affect airflow control. Particle sizes 0.3µm and 0.5µm are considered the most likely to be infectious in general surgery interventions (Cruceta 2014). Larger particles are generated in traumatology interventions, but these are not likely to be infectious. The minimum total supply airflow (1600m^3/h) is 33% lower than the suggested 2400m^3/h in Standard UNE 100713:2005 (AENOR 2005), but still higher than the minimum mandatory 1200m^3/h outdoor airflow requirement in the same standard. The minimum supply airflow was not further reduced to guarantee the proper performance (supply air velocity) of the laminar flow diffuser.

Reset strategies 1) and 3) reduce the surgery room IEQ and infection control performance, respectively, when the room is not in use. A short surgery room recovery time (i.e., the time required by the system to bring the room back to the standard IEQ and infection control performance) is critical for the viability of these strategies in case of urgent (unscheduled) surgery interventions. The Spanish standard (AENOR 2012) provides guidelines to test infection control

recovery time, however, neither this standard nor the other relevant standards in Spain (AENOR 2005; European Committee for Standardization (CEN) 1999; Ministerio de Industria Turismo y Comercio 2007) provide acceptable ranges of recovery time for temperature, relative humidity, or infection control performance. Room recovery time tests at the Hospital of Mollet could not be performed. Assuming ideal air displacement, a complete air change in a surgery room like these in Hospital of Mollet (118 m^3 in volume) would require 2.2 minutes at full fan capacity (3200 m^3/h), or 3 minutes at the standard airflow rate (2400m^3/h). It must also be noted that during "not occupied" periods, strategy 1 maintains temperature within the 15-25ºC range and relative humidity within 35-65%, and strategy 3) maintains overpressure and a 500m^3/h supply of filtered air in a surgery room with no sources of contaminants. Experience in Hospital of Mollet as well as other hospitals in Spain (Barrachina 2012; Cubí 2014; Prat 2014) shows that in emergency interventions there is a minimum of 15-20 minute time-lag between operation notice and patient arrival to the surgery room. While the considerations above suggest that surgery room systems are likely capable of bringing the IEQ and infection control performance back to the standard conditions within the required response time, room recovery time tests should be performed before the practical application of reset strategies in emergency surgery rooms. It must be noted that the standard practice in small and medium size hospitals is to maintain only one of the surgery rooms prepared and equipped 24/7 for emergency operations, while the other surgery rooms are used for scheduled interventions. Large hospitals dedicate 10-20% of the surgery rooms to emergencies (Barrachina 2012; Cubí 2014; Prat 2014). Reset strategies could be applied to non-emergency surgery rooms at a lower risk.

The above energy efficient control strategies were assessed individually and in the combinations shown in Table 11. All the scenarios were evaluated using the same assumptions of surgery room occupancy profile, internal gains, and heat recovery properties. Except for the particle counter in the particle-based airflow control strategy (~3,000€), these control measures do not require any investment costs.

Table 11 Control strategies evaluated in this thesis. Temperature, relative humidity, total supply airflow, and outdoor airflow setpoints.

#	Description	Temperature and RH	Total Supply Airflow	Outdoor Airflow
0	Default values in Hospital of Mollet	Temperature = 22^{0}C ±1^{0}C Relative humidity = 50%±5% Continuous operation (24/7)	3,200m^3/h Continuous operation (24/7)	3,200m^3/h Continuous operation (24/7)
1	Baseline. Standard conditions in a Spanish hospital	Temperature = 22^{0}C ±1^{0}C Relative humidity = 50%±5% Continuous operation (24/7)	2,400m^3/h Continuous operation (24/7)	2,400m^3/h Continuous operation (24/7)
2	Temperature and relative humidity reset	Occupied setpoints: Temperature = 22^{0}C ±1^{0}C Relative humidity = 50%±5% Not occupied setpoints: Temperature = 20^{0}C ±5^{0}C Relative humidity = 50%±15%	2,400m^3/h Continuous operation (24/7)	2,400m^3/h Continuous operation (24/7)
3	Air recirculation	Temperature = 22^{0}C ±1^{0}C Relative humidity = 50%±5% Continuous operation (24/7)	2,400m^3/h Continuous operation (24/7)	1,200m^3/h Continuous operation (24/7)
4	Airflow reset	Temperature = 22^{0}C ±1^{0}C Relative humidity = 50%±5% Continuous operation (24/7)	Occupied: 2,400m^3/h Not occupied: 500 m^3/h	Occupied: 1,200m^3/h Not occupied: 500 m^3/h
5	Particle-based control, as tested in Hospital of Mollet	Temperature = 22^{0}C ±1^{0}C Relative humidity = 50%±5% Continuous operation (24/7)	3,200m^3/h when particle concentration (0.3µm) is ≥10,200ppm. 1,600 m^3/h when particle concentration (0.3µm) is ≤3500ppm. Proportional airflow control in between limits	3,200m^3/h when particle concentration (0.3µm) is ≥10,200ppm. 1,600 m^3/h when particle concentration (0.3µm) is ≤3500ppm. Proportional airflow control in between limits
6	Temperature and relative humidity reset + Air recirculation	Occupied setpoints: Temperature = 22^{0}C ±1^{0}C Relative humidity = 50%±5% Not occupied setpoints: Temperature = 20^{0}C ±5^{0}C Relative humidity = 50%±15%	2,400m^3/h Continuous operation (24/7)	1,200m^3/h Continuous operation (24/7)

#	Description	Temperature and RH	Total Supply Airflow	Outdoor Airflow
7	Temperature and relative humidity reset + Airflow reset + Recirculation	Occupied setpoints: Temperature = 22^{0}C ±1^{0}C Relative humidity = 50%±5% Not occupied setpoints: Temperature = 20^{0}C ±5^{0}C Relative humidity = 50%±15%	Occupied: 2,400m^3/h Not occupied: 500 m^3/h	Occupied: 1,200m^3/h Not occupied: 500 m^3/h
8	Particle-based control + airflow reset	Temperature = 22^{0}C ±1^{0}C Relative humidity = 50%±5% Continuous operation (24/7)	Occupied: 3,200m^3/h when particle concentration (0.3μm) is ≥10,200ppm. 1,600 m^3/h when particle concentration (0.3μm) is ≤3500ppm. Proportional airflow control in between limits Not occupied: 500m^3/h	Occupied: 3,200m^3/h when particle concentration (0.3μm) is ≥10,200ppm. 1,600 m^3/h when particle concentration (0.3μm) is ≤3500ppm. Proportional airflow control in between limits Not occupied: 500m^3/h
9	Particle-based control+ airflow reset + temperature and relative humidity reset	Occupied setpoints: Temperature = 22^{0}C ±1^{0}C Relative humidity = 50%±5% Not occupied setpoints: Temperature = 20^{0}C ±5^{0}C Relative humidity = 50%±15%	Occupied: 3,200m^3/h when particle concentration (0.3μm) is ≥10,200ppm. 1,600 m^3/h when particle concentration (0.3μm) is ≤3500ppm. Proportional airflow control in between limits Not occupied: 500m^3/h	Occupied: 3,200m^3/h when particle concentration (0.3μm) is ≥10,200ppm. 1,600 m^3/h when particle concentration (0.3μm) is ≤3500ppm. Proportional airflow control in between limits Not occupied: 500m^3/h
10	Particle-based control+ airflow reset + temperature and relative humidity reset + air recirculation	Occupied setpoints: Temperature = 22^{0}C ±1^{0}C Relative humidity = 50%±5% Not occupied setpoints: Temperature = 20^{0}C ±5^{0}C Relative humidity = 50%±15%	Occupied: 3,200m^3/h when particle concentration (0.3μm) is ≥10,200ppm. 1,600 m^3/h when particle concentration (0.3μm) is ≤3500ppm. Proportional airflow control in between limits Not occupied: 500m^3/h	Occupied: 1200m^3/h Not occupied: 500m^3/h

4.1.2.3 Particle concentration measurement. Experimental set up

An airborne particle counter was installed inside the surgery room, and connected to the existing AHU control system. The particle counter provides simultaneous readings of particle sizes 0.3μm and 0.5μm. The sensor (CLIMET Instruments Company 2014) is located above the operation table (where patients rest during operation), attached to the surgical light, to avoid interfering with

the surgery activities. Since the surgery room under study has a laminar flow air diffusion system, the infection control committee of the Hospital of Mollet and an external indoor environmental quality consulting body (Cruceta 2014) considered that this was the most representative location to measure septicity of air in contact with the patient. The particle counter runs continuously and is calibrated on a monthly basis.

4.1.2.4 Energy model and calibration

The energy model is developed in TRNSYS (University of Wisconsin et al. 2013), and includes both the space (surgery room) and the air handling unit (AHU). The total heat gains/losses in the surgery room model result in a variation of interior temperature and relative humidity. The AHU model compares these room conditions with the corresponding room setpoints and adjusts AHU operation accordingly. Constant space and system parameters (e.g., room geometry, AHU heat recovery efficiency) are embedded in the model. Variable model inputs (Table 12) are defined externally and linked to the model. Model outputs include room temperature and relative humidity as well as AHU performance variables such as thermal energy use in the heating/cooling coils and fan electricity use. The dynamic model does not include plant components (boilers and chillers), as the surgery room AHU uses thermal energy from generated in a central heating and cooling plant that serves the entire hospital. Seasonal boiler efficiency and chiller EER are 80% and 3.25, respectively (Catalonia Institute For Energy Research et al. 2012). Table 13 shows the conversion factors used for the environmental and cost analysis. Most of the modeling effort focuses on the AHU control, which had to be implemented outside the AHU type (335) (TRANSSOLAR 2013) due to its limitations. The AHU type requires desired supply air temperature and relative humidity as inputs, while the actual control is based on room (rather than supply air) conditions.

Table 12 Variable model inputs

Variable Input	Value / Source
Outdoor air temperature and relative humidity	Weather file for Mollet (METEOTEST 2014)
Surgery room occupancy profile	Use of the surgery room was monitored by Hospital of Mollet personnel during a week (May 5-11, 2014) (Figure 9). This weekly occupancy profile is replicated throughout one year of simulation
Internal heat gains during operation	Heat gains associated to 7 occupants (including the patient) and 2000W of equipment
Supply airflow based on particle concentration monitoring	The particle concentration based airflow control is implemented and monitored in a surgery room at the Hospital of Mollet. Monitored supply airflow values are used as an input for the energy model (when this strategy is assessed)

Table 13 Electricity and Natural Gas conversion factors (Instituto para la diversificacion y ahorro de la energia (IDAE) 2012)

	Electricity	Natural Gas
Primary energy factor ($kWh_{primary}/kWh_{final}$)	2.35	1.07
Carbon intensity (kg CO_2/kWh_{final})	0.34	0.19
Cost (€/kWh_{final})	0.10	0.04

Model results are compared to monitored values for period of a week (April 28-May 4, 2014) with the system running under particle-based airflow control (strategy #5 in Table 11). Hourly values of simulated and monitored cooling thermal energy correlate with a 0.84 r^2 factor, RMSE = 0.7kW (Figure 10). The difference between model results and monitored values of total (cumulative) cooling thermal energy use during the week is 10%. While a finer model calibration would likely be possible if sub-hourly monitored data were available, these results are considered acceptable for the purpose of this thesis (i.e., assess the relative benefits of different control strategies). Reliable monitored values of heating and fan energy use were not available for calibration.

The calibrated energy model was modified in order to assess the control strategies summarized in Table 11. The model variants only differ in AHU control strategy, and maintain the same input assumptions.

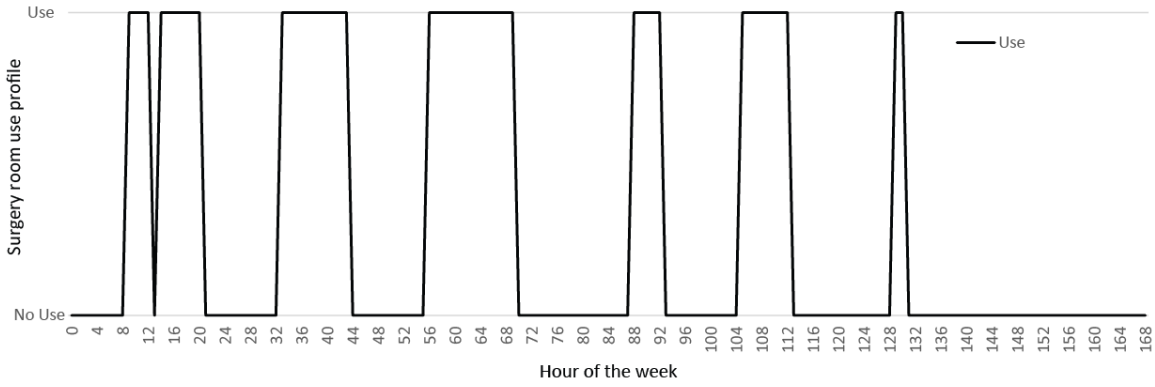

Figure 9- Surgery room occupancy profile (based on activity monitoring during the May 5-11, 2014 week)

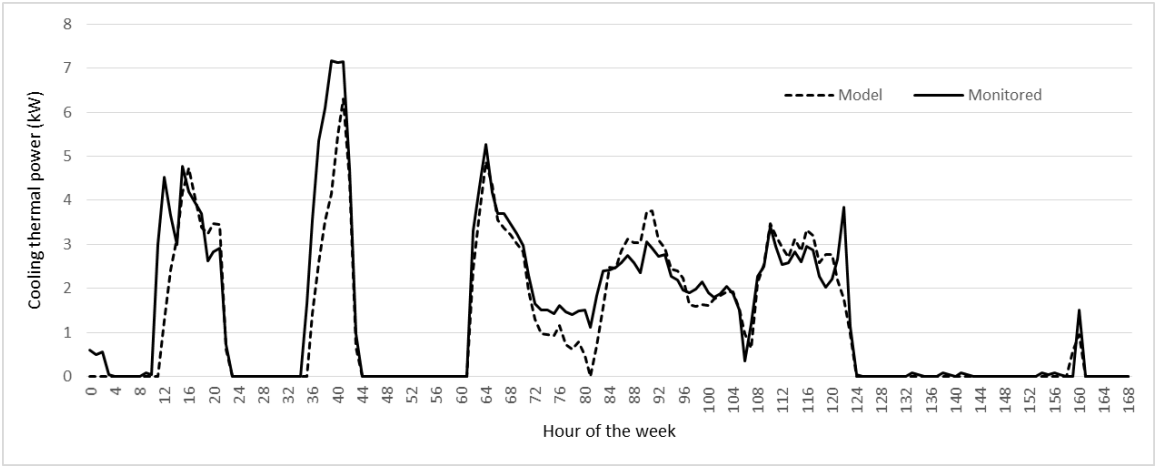

Figure 10- Cooling thermal power. Monitored values vs. model results (April 28-May 4, 2014)

4.1.2.5 Representativeness of the case study

Only one week of monitored surgery room occupancy is available for this study, and this occupancy profile (May 5-7, Figure 9) is replicated throughout the year in the energy model. However, the programs for the 6 surgery rooms in Hospital of Mollet for the whole month of May are available (6 rooms, 31 days). Occupancy profiles in surgery room programs are based on scheduled interventions and assumptions on intervention duration. The average monthly occupancy for the 6 surgery rooms according to the programs was 22% (i.e., on average, the surgery rooms were occupied 22% of the time). Monthly occupancy in the 6 surgery rooms ranged from 15% to 31%, with a 5% standard deviation. The monthly programs of the 6 surgery rooms showed scheduled interventions only during business hours, Monday to Friday. The occupancy during the study week was 26% according to the program and 30% according to monitoring. This result suggests that the programs provide a reasonably accurate approximation of the actual occupancy. According to data derived from multiple field surveys, ASHRAE (ASHRAE 2003) estimates that surgery rooms are occupied about 65 hours a week (39%). The occupancy rate used in this study is 9% lower than the estimated by ASHRAE, which may overestimate the benefits of the reset-based control strategies compared to an average American surgery room. No surveys of Catalan, Spanish or European surgery room occupancy were found.

4.1.2.6 Limitations

Evaluation of the particle concentration based control strategy is limited to the assessment of case #5 and its combination with other control strategies (cases #8, #9, #10). Variations of airflow reset as a function of particle concentration readings could not be tested. Further energy savings may be possible if infection control performance target (i.e., ISO Class) varied as a function of operation type or if total supply airflow was more aggressively reduced at low particle

concentration levels. Particle concentration acceptable ranges during operation are currently not defined in the available standards. It must be noted that the risk of infection depends on whether the particles are infectious or not, the type of microorganism (if they are infectious), and the dose (number of microorganisms). “As few as 1-10 TB bacilli can be infectious for humans, while a total of 200 Rhinovirus virions may be required to cause a cold” (Kowalski and Bahnfleth 1998). The particle concentration sensors currently available (such as the one used in this study) are not capable of distinguishing whether particles are infectious or not. Therefore, real performance-based infection control will not be possible until real-time sensors are capable of counting and identifying microorganisms.

This thesis assesses control strategies only. Further energy savings could be achieved by better adapting heat recovery properties as a function of climate. The results shown in this Chapter apply to the climate characteristics of Mollet.

4.1.3 RESULTS AND DISCUSSION

Results of total annual thermal and final energy use for the different control strategies are presented in Figure 11. The individual contributions of heating, cooling, and fan energy use are shown in separate columns because they differ in energy carrier. Figure 12 compares the control strategies in terms total primary energy use. As shown in Table 14, CO_2 emissions and energy cost results follow the same pattern as total primary energy use results.

Energy use associated with air conditioning (heating and cooling) is dominant over fan energy use. Heating is the largest final energy user, partly due to the relatively higher efficiency of the cooling equipment. The contribution of cooling and fan energy use relative to heating increases in terms of primary energy use and carbon emissions due to the relatively larger conversion factors of electricity compared to natural gas (Table 13). However, heating remains the largest contributor to the total.

Fan energy use (and derived carbon emissions and costs) decreases with strategies that reset total supply airflow based on either occupancy or particle concentration readings. The contribution of fan energy use to the overall results is marginal across all cases and performance metrics. However, strategies that reduce fan use also result in a lower energy use for heating and cooling, as the amount of air to be conditioned is reduced. Total primary energy use, CO_2 emissions and energy costs could be reduced by 35% if the default total supply airflow in the Hospital of Mollet was reset to the requirements in Standard UNE 100713 (AENOR 2005) (see cases #0 and #1).

Temperature and relative humidity reset when the surgery room is not occupied (case #2) shows the best environmental and economic performance among the individual strategies (cases #2 to

#5). This is largely due to the very narrow temperature and relatively humidity window allowed during operation combined with an extended unoccupied time. The surgery room tested in Hospital de Mollet was occupied only 30% of the time, allowing relaxation of the temperature and relative humidity requirements during the remaining 70%. Similar occupancy rates are reported in (ASHRAE 2003). Temperature and relative humidity reset alone result in 73% savings in primary energy use, CO_2 emissions and energy costs compared to the baseline (case #1).

Airflow reset (case #4) is the second best performing individual control strategy, saving 54% of the primary energy use, CO_2 emissions and energy costs compared to the baseline. Airflow reset also takes advantage of the extended unoccupied period of the surgery room. Air recirculation and particle concentration based airflow control result in 25% and 9% savings, respectively. The modest savings with the particle concentration based airflow control strategy are due to the "conservative" airflow reset with low particle concentration values. Total supply airflow with particle concentration based control range from 3200m^3/h to 1600m^3/h, while it is 2400m^3/h during occupied periods and 500m^3/h during non-occupied periods (70% of the time) with the airflow reset strategy. It is worth noting that air recirculation implemented on a continuous operation basis (case #3) requires hardware modifications in the AHU (a recirculation damper), but does not require any changes in the control settings.

Primary energy use, CO_2 emissions and energy costs can be further reduced if the control strategies are combined. Combinations of strategies that include temperature and relative humidity reset (cases #6, 7, 9, 10) result in savings ranging from 80% to 86% relative to the baseline (case #1). Savings are lower when temperature and relative humidity reset is not used (case #8). The best performing combination is case #10, which includes all the control strategies analyzed in this thesis. This combination uses strategies that reduce energy use when the surgery room is not used (temperature and relative humidity reset, airflow reset) and strategies that reduce energy use during operation (particle concentration based airflow control, air recirculation). It must be noted, however, that the incremental benefit of adding further control strategies tends to decrease.

Results show that the largest energy saving opportunities are associated with combinations of strategies that include temperature and relative humidity reset when the surgery room is not in operation. This thesis assumes an ideal use of the reset capability. However, experience in the Hospital of Mollet shows that physicians often forget to indicate a change in surgery room occupancy mode, making this strategy hard to implement in reality. Hospital of Mollet tried to implement temperature, relative humidity and airflow reset based on surgery room occupancy in the past. A manual switch was made available to physicians to indicate whether or not the surgery

room was in operation. Hospital of Mollet decided to go back to continuous operation because physicians failed to properly indicate the surgery room operational status. If real time particle concentration measurements could be used to automatically identify occupancy, the savings associated with temperature, relative humidity, and airflow reset could be partially attributed to particle concentration airflow control. Alternatively, surgery room occupancy could potentially be automatically assessed with other systems such as presence or motion sensors. Future research should investigate appropriate technologies to assess surgery room occupancy for AHU control purposes.

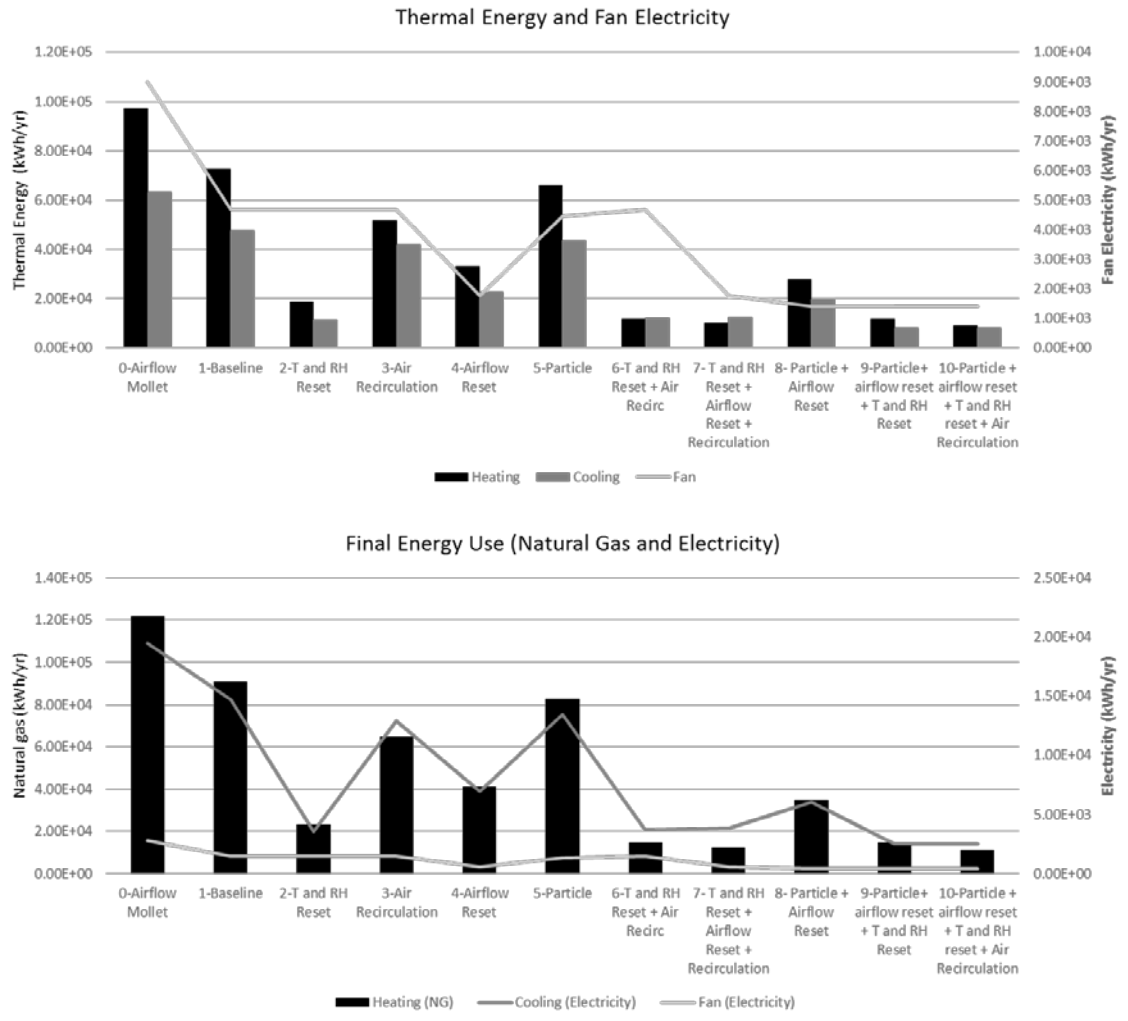

Figure 11- Thermal and final energy use

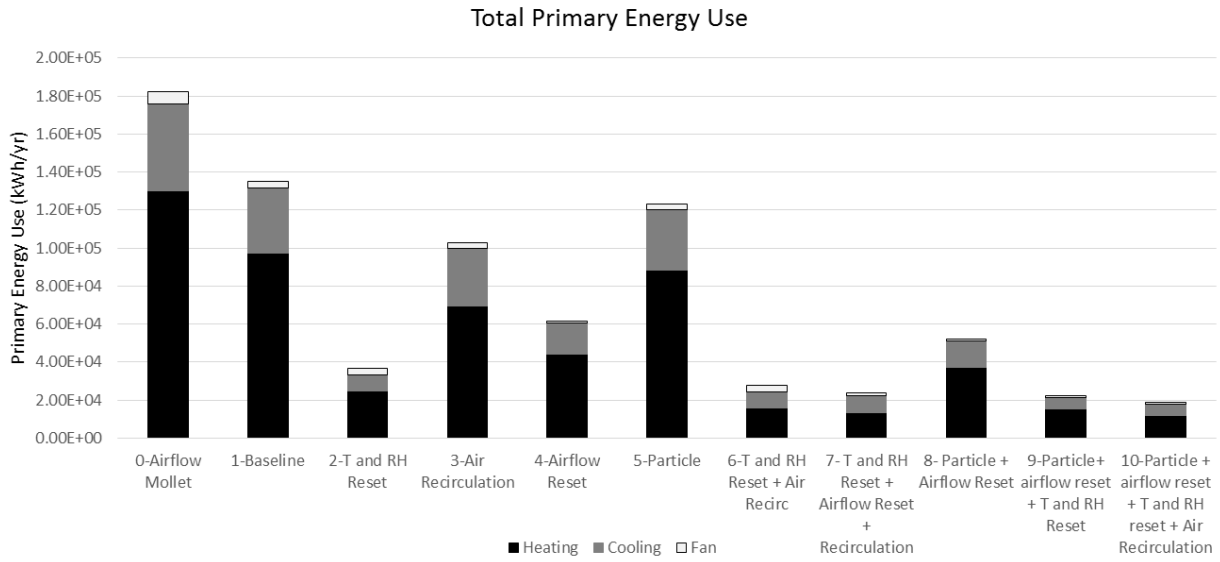

Figure 12- Primary energy use

Table 14 Primary energy use, CO_2 emissions, and Energy costs

	Primary Energy		CO_2 emissions		Energy Cost	
Case	**MWh/yr**	**Savings relative to baseline**	**kg/yr**	**Savings relative to baseline**	**k€/yr**	**Savings relative to baseline**
0- Airflow Mollet	182	-35%	31,200	-35%	7.09	-35%
1- Baseline	135	0%	23,100	0%	5.25	0%
2- T and RH Reset	37	73%	6,220	73%	1.43	73%
3- Air Recirculation	103	24%	17,400	25%	4.02	23%
4- Airflow Reset	62	54%	10,500	54%	2.40	54%
5- Particle control	123	9%	21,000	9%	4.78	9%
6- T and RH Reset + Rec	28	79%	4,610	80%	0.11	79%
7- T and RH Reset + Air Reset + Rec	24	83%	3,900	83%	0.93	82%
8- Particle + Air Reset	52	61%	8,920	61%	2.03	61%
9-Particle + Air Reset + T and RH Reset	22	83%	3,810	84%	0.87	83%
10-Particle + Air Reset + T and RH reset + Rec	19	86%	3,170	86%	0.74	86%

4.1.4 CONCLUSIONS

This chapter uses a calibrated energy model of a surgery room to assess the potential environmental and cost benefits of a variety of control strategies. Results show that control strategies could reduce primary energy use and associated CO_2 emissions and energy costs by up to 86% relative to the baseline case (standard continuous operation according to the requirements and recommendations in the Spanish standards). Should these measures be applied to the 6 surgery rooms available in Hospital of Mollet, their combined annual energy bill could drop from 42,000€/yr to 4,500€/yr. Except for the particle-based airflow control case, these control strategies could be implemented at no cost. Due to the very stringent space conditioning requirements during operation and the relatively low operation time of surgery rooms (30% in the studies room), temperature and relative humidity reset is the strategy that offers the largest environmental and cost benefits. Airflow reset is the second best performing strategy, followed by air recirculation and particle concentration based airflow control. Combining control strategies have the potential to further reduce energy use, although the marginal benefit of adding a strategy decreases as the system performance improves. It must be noted, however, that practical application of reset-based strategies is not straightforward, as it strongly depends on:

- An effective and reliable means to automatically assess surgery room occupancy for air handling unit control purposes
- A short surgery room recovery time (i.e., the time required by the system to bring the room back to the standard IEQ and infection control performance) in case of urgent (unscheduled) surgery interventions. While recovery time tests are not performed regularly, reset-based strategies should not be applied to emergency surgery rooms

Future research should investigate appropriate technologies to assess surgery room occupancy for AHU control purposes.

The benefits associated with particle concentration based airflow control (the most novel strategy included in this thesis) are modest compared to other control strategies. This is probably due to the relatively “conservative” infection control performance target and airflow setpoint with low particle concentration readings used in this thesis. The currently available standards classify surgery rooms based on particle concentration in “at rest” mode (system running without occupation), but do not provide acceptable particle concentration ranges during operation. Real performance-based infection control will not be possible until sensors are capable of assessing infectious agents. It must be noted that particle concentration based airflow control is the only control strategy that specifically addresses energy use reductions during operation.

4.2 CONTROL STRATEGIES IN A NON-STANDARD MULTIZONE AIR HANDLING UNIT - HOSPITAL VIRGEN DE LAS NIEVES

4.2.1 INTRODUCTION

Section 4.1 studied the potential benefits of control strategies in a modern surgery room facility equipped with a standardized air handling unit. This section complements the findings in Section 4.1 by exploring the potential thermal comfort and energy performance benefits of control strategies applied to a much older facility equipped with a highly non-standard system. While the system studied in Section 4.2 may not be representative of the stock of surgery room systems in Catalonia or Spain, it illustrates the potential application of controls as to retrofit in existing systems.

The University Hospital Virgen de las Nieves of Granada is one of the major hospitals of the public health system in southern Spain. It offers a wealth of health services, and the number of professionals working in is close to 5,000. This is a multi-centre Hospital with 11 buildings spread mainly into two main units separated geographically nearby, with the total area of approximately 133,000m². The main and oldest building dates from the 50′s and the rest is built in the mid-70′s.

Hospital Virgen de las Nieves (hereafter referred to as HVN) located in Granada (Spain) uses a multizone air handling unit (AHU) as the sole means to provide ventilation and space conditioning to 4 zones (2 of which include a surgery room). The system is not currently connected to the main building management system, and heavily relies on manual control. The system operators receive frequent comfort complains from the occupants. The system is to be connected to main building automation system, which will allow implementing control strategies to improve thermal comfort and energy use. HVN has the exact same system set up in 5 additional floors in which the control solutions developed here could be easily replicated.

The objective of this thesis is to define control strategies for the air handling unit to improve system performance in terms of thermal comfort and energy use. Control strategies are pre-evaluated using energy modeling tools (TRNSYS and Matlab).

4.2.2 METHOD

4.2.2.1 System description

The AHU in the surgery rooms of HVN is a multizone system that provides ventilation (fresh air) and space conditioning (either heating or cooling) to 4 zones (2 of which include surgery rooms). Figure 13 shows the SketchUp model of the spaces served by the AHU and the relevant shading elements.

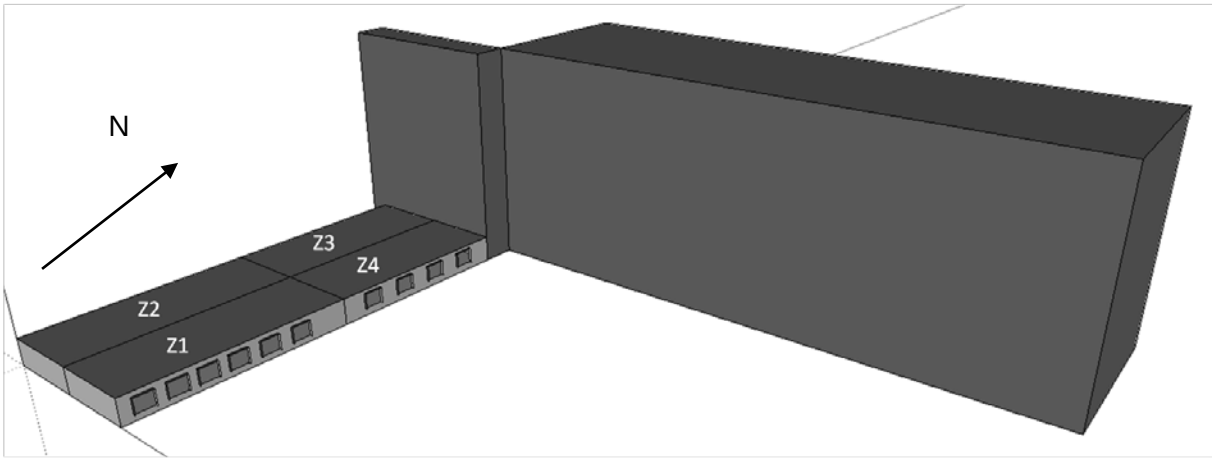

Figure 13 – SketchUp model - Zone layout

This AHU is a dedicated system (100% outdoor air) with no heat recovery. There is an independent supply duct for each of the 4 zones with an independent control damper for each of them. Figure 14 shows the AHU schematic.

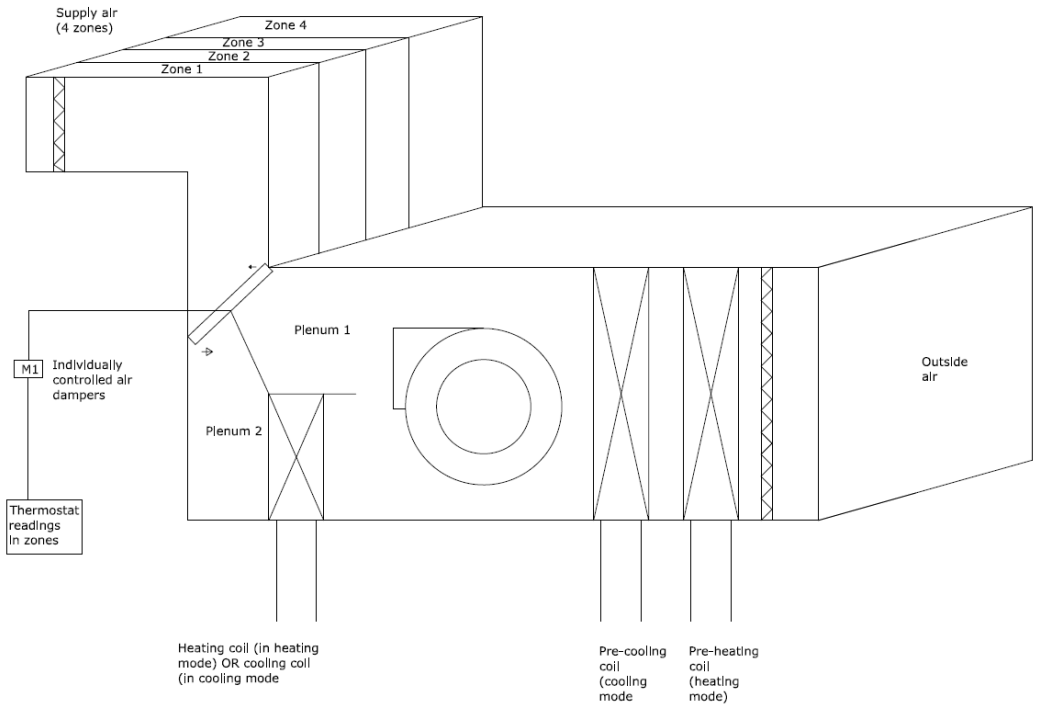

Figure 14 – Schematic of the multizone AHU in Hospital Virgen de las Nieves

The amount of supply air to the 4 zones is constant (constant volume system); the dampers change the ratio of air that comes from the 2 available plenums (at different temperatures): it could be 100% from one of the two sides, or a mix of the two. Air in Plenum 1 runs only through one pair of pre-conditioning coils ("1 stage conditioning", there are 2 coils heating/cooling in series, but only one active at a time), while air in Plenum 2 runs through an additional conditioning

coil ("2-stage conditioning", 1 coil that is either heating or cooling depending on the season). This AHU is connected to a 2 pipe system - therefore, all the water in the coils is either heating or cooling.

The control system is currently not integrated in the central building management system.

- Room temperature set-points are manual control inputs by the occupants (through thermostats).
- Room temperature set-point drives the individual dampers position (through an internal control).
- Valve positions of the 3 coils (the 2 stages of conditioning) are manually operated. There is no automatic control over coil water flow rates, and therefore, no control over air temperature in the 2 plenums.

The air handling unit has no humidity control capabilities (neither humidification nor dehumidification) and the spaces have no humidity sensors. Therefore, none of the models considered humidity control (although outdoor air relative humidity was accounted for in the heating and cooling coils energy exchange).

The HVAC Design Manual for Hospitals and Clinics (ASHRAE 2003) recommends variable air volume (VAV) systems in spaces where there are significant unoccupied hours (such as surgery rooms). While a VAV would likely enhance energy efficiency in this case study, HVN is postponing measures that imply hardware purchase and installation.

4.2.2.2 Control strategies

The first improvement to the AHU control is to add control loops in the conditioning coil flow rates so that air temperature in the two plenums remained “constant”. It must be noted that this is a 2-pipe system, and therefore, control capabilities of the AHU are limited: supply air temperature cannot be higher than outdoor air temperature in cooling mode, and cannot be lower in heating mode. This strategy is referred to as “Control strategy 1 – Constant Plenum Temperatures”.

The second control strategy uses a fuzzy logic controller to define the ideal supply air temperature setpoints for the 4 rooms. The input to the controller is the difference between the current temperature in each room separately from the defined set-point. Thus, the controller is trying to minimize the error between these two values. The controller dynamically adjusts the temperature setpoints in the two plenums. The values of these set-points depends on the minimum and maximum values of the new supply air set-points. For heating mode the pre-heating chamber

receives as set-point temperature the minimum value of the supply air temperature and the re-heating chamber receives the maximum value. Thus, the rooms which require these temperature can be pleased while the other 2 rooms can be pleased adjusting the dampers internally. Similarly for cooling mode, the pre-cooling chamber receives the maximum value of new supply air set-points while the re-cooling chamber receives the minimum value. This strategy is referred to as "Control strategy 2 – Dynamic Plenum Temperature Setpoints".

Table 15 summarizes the settings in the baseline case and the control strategies evaluated in this thesis.

Table 15 – Baseline and control strategies evaluated in this thesis

Case	First plenum control	Second plenum control	Zone air dampers control
Baseline	No control	No control	Proportional control
Strategy 1	Constant outlet air temperature setpoints for heating and cooling modes (parametric analysis)	Constant outlet air temperature setpoints for heating and cooling modes (parametric analysis)	Proportional control
Strategy 2	Heating mode: minimum supply air temperature Cooling mode: maximum supply air temperature	Heating mode: maximum supply air temperature Cooling mode: minimum supply air temperature	Fuzzy logic-based controller

4.2.2.3 Energy model and calibration

Both the building and the system are modeled in TRNSYS version 17 (University of Wisconsin et al. 2013). Version 17 features a new building model that contains 3D geometric surface information that is used for the detailed radiation calculations. The building model included only a single floor (which corresponds to the service space of the air handling unit), and assumes no heat transfer to/from the adjacent stories (which is considered a reasonable simplification, as the adjacent stories have the same space use and lay-out). Heating and cooling coils are modeled with TESS types 670 (heating) and 508 (cooling), which calculate outlet temperatures of air and water based on their respective inlet temperatures, flow rates, and a user defined by-pass factor (which is adjusted based on monitored data, as explained below). Zone geometry and envelope characteristics are modeled based on the documentation provided by Hospital Virgen de las Nieves. The weather file for Granada is obtained from the Meteonorm Database (METEOTEST 2014).

Internal gains in the selected areas are calculated based on approximate values of occupancy density, lighting, and equipment use provided by Hospital Virgen de las Nieves personnel. Zones 1 and 2 have the same floor area (158m^2) and space type distribution; therefore, they also have

the same (assumed) internal gains. The same is true for Zones 3 and 4 (floor area = 136m^2). Note, however, that total gains in the 4 zones are different due to the differences in orientation and exterior wall and window area. Table 16 summarizes the assumed internal gains in the zones. Table 17 summarizes zone characteristics.

Table 16 – Occupancy and internal gains in the zones

Time interval	Gains	Zones 1 and 2	Zones 3 and 4
Morning (8:00-15:00)	Occupants (#)	9	4
	Radiant (W)	2741	1852
	Convective (W)	1133	744
	Latent (W)	855	380
Afternoon (15:00-22:00)	Occupants (#)	10	0
	Radiant (W)	2773	1369
	Convective (W)	1191	152
	Latent (W)	950	0
Night (22:00-8:00)	Occupants (#)	5	0
	Radiant (W)	2615	1369
	Convective (W)	899	152
	Latent (W)	475	0

As part of the work developed within the EC-funded Green@Hospital project (Green@Hospital), the AHU was recently equipped with monitoring equipment that allow for the adjustment of some of the system parameters in the model. An energy meter was installed in each of the heating and cooling coils of the AHU. According to the data sheet, thermal energy metering error is:

$$Error = \pm\left(0.15 + \frac{2}{\Delta\theta}\right)\%$$

Equation 6

Where $\Delta\theta$ is the difference between inlet and outlet water temperature in the coil.

Model validation is mostly done based on data corresponding to the period between October 4 and 7, 2013 (cooling season). Total supply airflow rate is adjusted based on the heat transfer balance in the first conditioning coil (a monitoring input). The adjusted total supply airflow was 7700kg/h. It must be noted that this value is similar to the initial assumption, which was based on the results of air velocity spot measurements carried out by HVN personnel (8200kg/h).

The adjusted total supply airflow is used as a model input for the precooling coil. Precooling coil bypass factor is adjusted until the model outlet temperatures of both air and water show close

results compared to the monitoring values. The resulting by-pass factor (i.e., fraction of air that does not interact with the conditioning coil) is 75%, which is very large yet consistent with a very old air handling unit.

The same method is used to adjust the model of the second conditioning coil (recooling coil, in cooling mode), although only periods in which the 4 air dampers were fully closed can be used (necessary condition to know the corresponding airflow rate). The by-pass factor is adjusted to 85%, which provides a good match for both air and water side outlet temperatures.

Distribution of total supply airflow into the 4 zones is based on the relative size of duct section at the outlet of the AHU, which carries the implicit assumption that the pressure drop in the 4 distribution ducts is roughly the same.

Table 17 – Zone characteristics

Parameter	Zone 1	Zone 2	Zone 3	Zone 4
Floor area (m^2)	158	158	136	136
Exterior wall (m^2)	71	0	0	45
Window area (m^2)	16	0	0	11
Fraction of supply airflow (%)	52	26	7	15

Waterflow values for the two stages of conditioning are obtained via monitoring. There was only 12 days' worth of reliable data. Waterflow through the conditioning coils is not constant due to hydraulic instabilities (this AHU does not have a dedicated water supply loop), however, variations are relatively small (see Table 18). Because of the lack of more representative information, the 12-day waterflow profiles are used as a constant modeling input throughout the year (i.e., the same data series are repeated over and over). This assumption imposes a strong limitation on model reliability, as in reality the system operators would occasionally adjust coil valves based on comfort complains. Nonetheless, it is decided to repeatedly use these waterflow profiles because there is not an alternative method to more accurately describe operator's manual adjustments. Furthermore, while the results derived from this hypothesis may not accurately represent reality, they are a good illustration of the performance limitations of the currently implemented control system.

Table 18 – Water flow through conditioning stages. Monitoring results

Parameter	1st Stage	2nd Stage
Minimum flow (kg/h)	5460	1396
Average flow (kg/h)	6997	1772
Maximum flow (kg/h)	8436	2073
Standard Deviation (kg/h)	444	130

The supply air temperature control (i.e., damper position) is implemented in the model according to the following logic:

- Room air temperatures (readings from the building module) and room temperature setpoints (assumed 23ºC both for summer and winter, based on the expertise of HVN personnel) are compared. The default supply air temperature setpoints are set as the room air temperature setpoints (occupant input). When there is a >1ºC difference between room temperature reading and the corresponding temperature setpoint, a proportional control modifies supply air temperature setpoint to a lower or higher value depending on the zone cooling/heating requirements. This results in a set of “ideal” supply air temperature set-points for the 4 zones.

- The ideal supply air set-points are modified to fall within the feasible limits of the 2 stages of conditioning (in heating mode min = PHC Temp, max = RHC temp, where PHC is air at “preheating coil” outlet and RHC is air at the “reheating coil” outlet, the two plenums).

- The modified supply air temperature set-points for the individual zones are used as inputs for the flow diverters and mixers, which correspond to the air dampers in the multizone AHU.

- Supply air outputs of the AHU model are inputs for the zones in the building model.

Energy performance evaluation is based on the thermal energy use in the conditioning stages (both in heating and cooling). This is thermal energy (heating and cooling) provided by the conditioning coils, and does not account for the efficiency of the central heating and cooling plant. Fan electricity use is not included in the analysis because it is a constant volume system (i.e., fan energy use remains constant regardless of the control strategy).

In terms of thermal comfort, the difference between room air temperature and room air temperature setpoint is used to evaluate the effectiveness of the control strategy in delivering the desired comfort. The difference between delivered and desired supply air temperatures is integrated over time, and presented in terms of “degree-hours”. Thermal comfort in general use spaces is often evaluated with indices based on the work by Fanger. However, degree-hours are chosen as the indicator because 1) the system is only capable of controlling (and only to some extend) one of the comfort parameters: temperature, 2) surgery rooms do not have standard conditions of interior setpoints, clothing level, or metabolic rate that are required for the assessment of PMV and PPD, and 3) the purpose of the thesis is to assess how well the system

can match the local temperature setpoints. Previous studies (Stephan et al. 2011) have used degree-hours to assess systems based on a single control parameter (temperature).

Control strategy 1 (constant plenum temperatures) is modeled by using ideally controlled heating and cooling coils. These provide the required heating/cooling for the outlet air to exactly match a given temperature setpoint, however, they are still limited by the 2-pipe constraint (i.e., cooling is only possible in cooling season, and heating is only possible in heating season). A parametric analysis is run to evaluate the performance of the system under a variety of plenum temperature setpoints.

In order to model Control Strategy 2 (dynamic plenum temperature setpoints) an advanced controller is developed in Matlab's environment (MathWorks 2013). The specific programming environment is selected because it contains several toolboxes for advanced control techniques development. In order to initiate an interface between Matlab & TRNSYS, type 155 is used. Using the specific type, data are exchanged between Matlab and TRNSYS, so that Matlab is called after the convergence of the TRNSYS model. This condition reflects the approach followed in real-time implementation when a sensor is reading a condition, and then the controller is sending a command to the systems. Each time-step, TRNSYS sends selected data to Matlab, which in return sends back control commands to TRNSYS. Inside Matlab's environment a smart controller for the surgery room air handling unit, based on fuzzy logic, is called.

Fuzzy logic architecture is selected because it contains, in the form of rules, the knowledge of the personnel which is currently adjusting the system manually. The input to the controller is the difference between the current temperature in each room separately from the defined set-point. Thus, the controller is trying to minimize the error between these two values. Due to the installation and operation of a PID controller for basic control the smart controller is designed to adjust the supply air set-point of the 4 air streams. The architecture and the characteristics of the developed fuzzy controller can be seen in Table 19. Figure 15 shows fuzzification and de-fuzzification membership functions.

Table 19 - Architecture and characteristics of the fuzzy controller

Type of fuzzy controller	'Mamdani'
N. of inputs	4: error between current and desired indoor temperature
N. of outputs	4: change of supply air set-point
Fuzzification membership functions	5
De-fuzzification membership functions	5

The fuzzification parameters are similar for all 4 rooms and they can be re-adjusted if it required in case one of the rooms has different performance. Similarly, the de-fuzzification parameters can be re-adjusted if required.

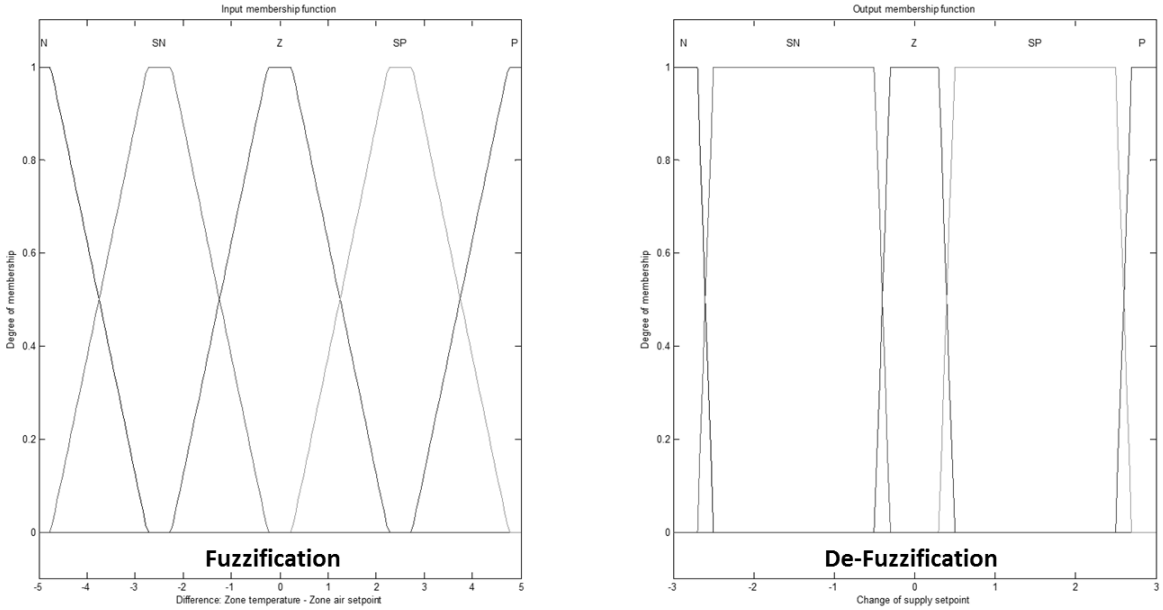

Figure 15 – Fuzzification and de-fuzzification. Input and output membership functions

Moreover the system can only provide heating or cooling based on the season of the year (2 pipe system). Thus, the controller has to be adjusted in order to operate for both heating and cooling season. In order to prevent an un-normal operation of the controller, the supply air temperature set-points has to be limited between some upper and lower boundaries. The boundaries for the set-points can be seen in Table 20.

Table 20: Boundaries of supply air temperature set-point

Seasons	Boundaries	Values
Cooling mode	Upper limit	25°C
	Lower limit	13°C
Heating mode	Upper limit	30°C
	Lower limit	13°C

In cooling mode supply air temperature should be above 13°C to avoid local discomfort (draft). Similarly, the minimum setpoint for heating cannot be below 13°C. The upper limits are selected based on the response of the system to the controller's commands. Each time-step the output of the controller (positive or negative) is added to the previous stored value and the new one is sent to the TRNSYS model. Thus, if the upper limit for cooling mode is higher than 25°C, it takes more

time-steps to find the required supply air temperature set point which balances indoor temperature close to the set point.

Finally, the controller adjusts the temperature set-point of the 2 chambers (pre-heating/cooling, re-heating/cooling) based on the maximum and minimum supply air temperature setpoints for the 4 rooms.

4.2.3 RESULTS AND DISCUSSION

4.2.3.1 Baseline Results

Figure 16 and Figure 17 show monthly profiles of heating and cooling thermal energy use, respectively. Both figures show the relative contributions of the 2 conditioning stages. Since this is a 2-pipe system, there is no simultaneous heating and cooling energy use. Based on the experience of Hospital Virgen de las Nieves personnel, the heating/cooling mode change dates were assumed to be June 1st and October 15th (hence, there is both heating and cooling energy use in October).

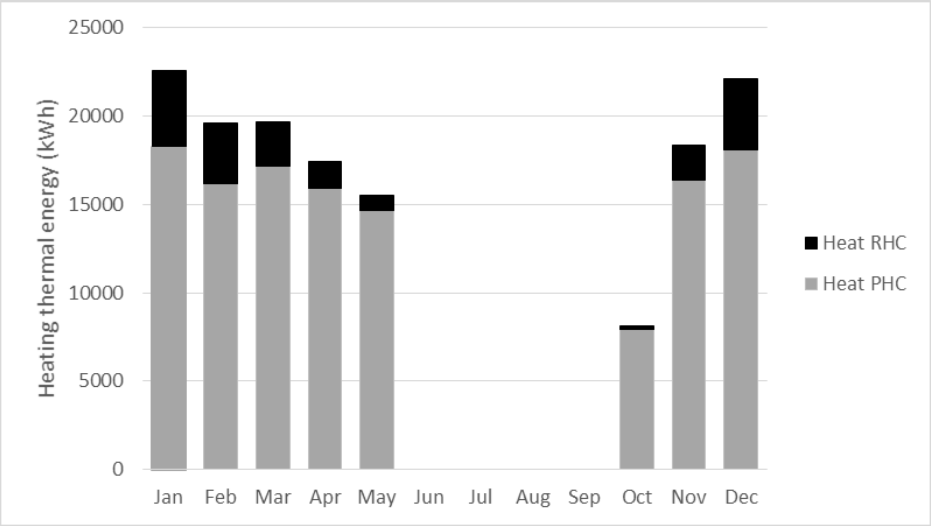

Figure 16 – Baseline results. Heating thermal energy use. PHC is energy use in the preheating coil (1st stage of conditioning), RHC is energy use in the reheating coil (2nd stage of conditioning)

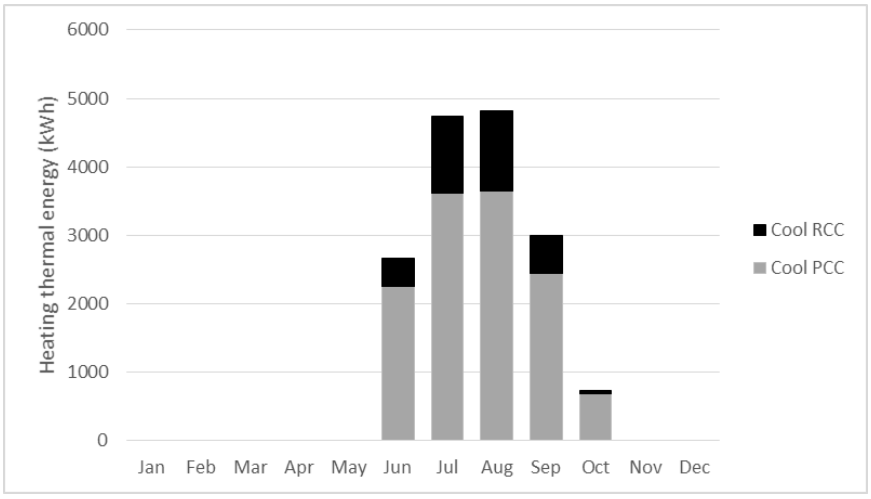

Figure 17 – Baseline results. Cooling thermal energy use. PCC is energy use in the precooling coil (1st stage of conditioning), RCC is energy use in the recooling coil (2nd stage of conditioning)

Although total heating and cooling thermal energy use follow the expected profile (larger heating energy use in the coldest months, larger cooling energy use in the hottest), heating energy use in the first stage of conditioning remains fairly constant throughout the heating season. The contribution of the first conditioning stage (both in heating and cooling) is largely dominant over the second stage of conditioning. Considering that the second stage of conditioning provides flexibility to adjust supply air temperatures according to the different requirements in the 4 zones, its very low energy contribution suggests that it is often by-passed due to a too hot (in heating mode) or too cold (in cooling mode) air temperature after the first stage of conditioning.

Figure 18 and Figure 19 show monthly profiles of degree-hours (cumulative deviation between air temperature and room temperature setpoint) in heating and cooling season, respectively. Both figures show the degree-hours break-down by zone. Table 21 summarizes the numerical values.

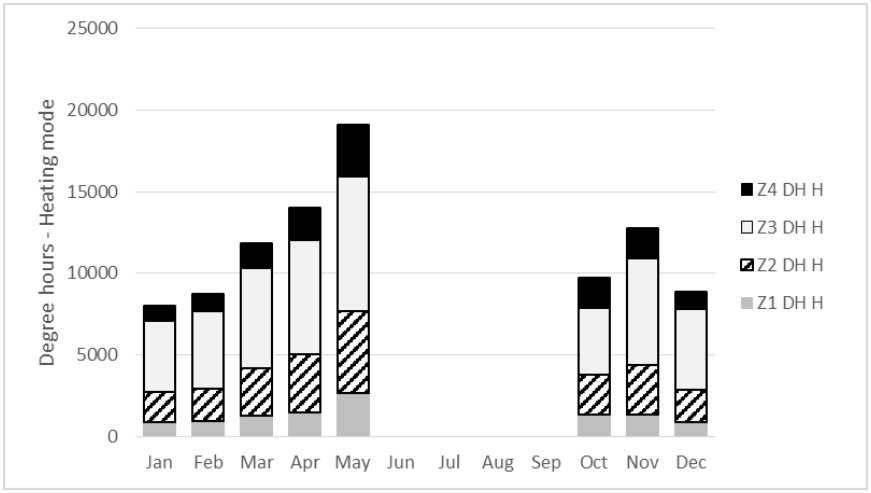

Figure 18 – Baseline results. Degree hours in heating mode

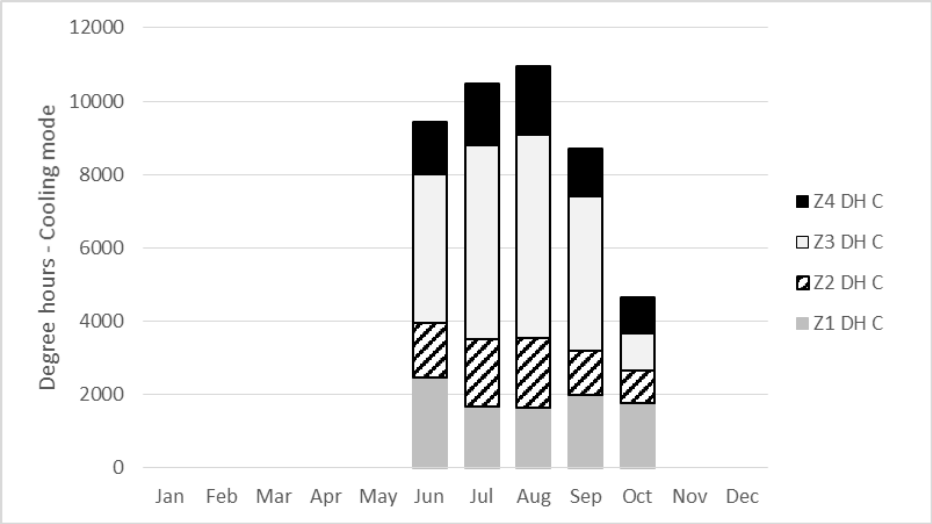

Figure 19 – Baseline results. Degree hours in cooling mode

Table 21: Degree hours of thermal discomfort. Baseline results

		Z1 DH	Z2 DH	Z3 DH	Z4 DH
	Jan	887	1847	4343	923
	Feb	948	2003	4724	1080
	Mar	1276	2876	6153	1519
	Apr	1507	3528	7031	1971
Heating	May	2681	5011	8246	3186
	Jun	2452	1489	4051	1447
	Jul	1653	1852	5282	1694
	Aug	1627	1913	5549	1870
	Sep	1979	1201	4234	1304
Cooling	Oct	1768	893	1003	990
	Oct	1339	2419	4149	1837
	Nov	1340	3014	6549	1841
Heating	Dec	882	1956	4954	1056

The figures above show increasing thermal discomfort in the shoulder seasons (i.e., near the mode-change dates), which is typical of 2-pipe systems. It must be noted that these periods correspond to the lowest thermal energy contributions of the second conditioning coil. This suggests that the lower flexibility of the system to adjust supply air temperatures results in increased thermal discomfort.

Monthly values of degree-hours are high, and generally larger in the heating season. Interior zones (Zones 2 and 3) are the most uncomfortable.

4.2.3.2 Control logic 1 Results

Figure 20 and Figure 21 show cumulative values of heating thermal energy use and degree-hours in heating mode, respectively. Both figures compare baseline (BL) vs. control 1 strategy results for a variety of combinations of plenum temperature setpoints (PHC ranges 10-14ºC, RHC ranges 26-30ºC).

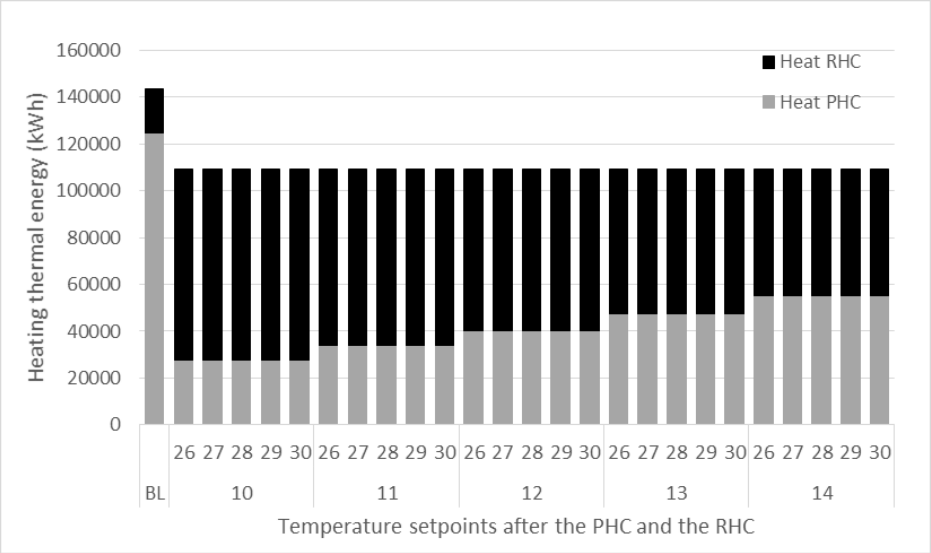

Figure 20 – Control logic 1 results. Heating thermal energy use. PHC is energy use in the preheating coil (1st stage of conditioning), RHC is energy use in the reheating coil (2nd stage of conditioning)

While the relative energy contributions of the two stages of conditioning largely vary with PHC temperature setpoint, the total thermal heating energy use with control strategy 1 is basically constant across the tested spectrum of PHC and RHC setpoints. Total heating energy use is roughly 110,000kWh/yr, which translates into 24% savings compared to the baseline scenario. It must be noted that, compared with the baseline, all the tested combinations show a much lower contribution of PHC to the overall heating thermal energy use.

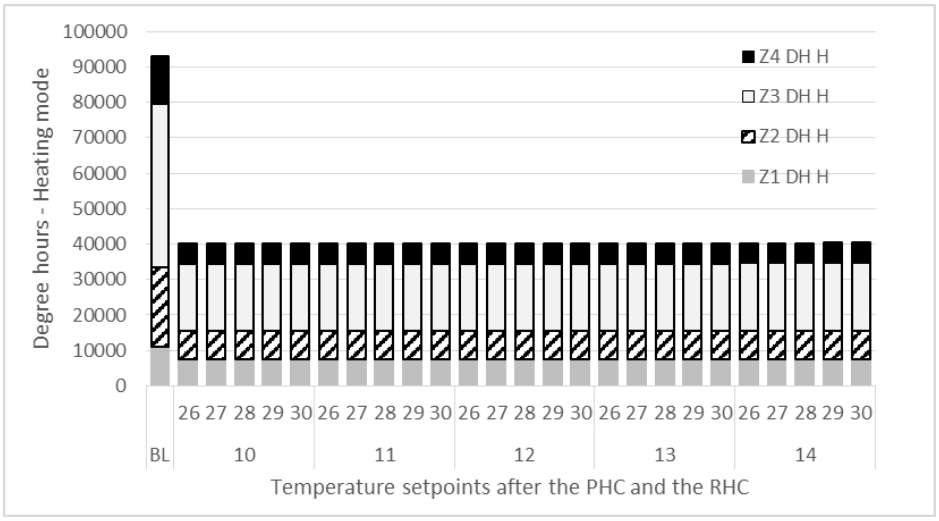

Figure 21 – Control logic 1 results. Degree hours in heating mode

Simulation results show that (within the tested ranges) temperature setpoints in the two plenums seem to have almost no impact on thermal comfort in heating mode. The overall degree-hours with control strategy 1 in heating mode drop from roughly 93,000 in the baseline to 40,000, which is a very significant (55%) reduction.

Figure 22 and Figure 23 show cumulative values of cooling thermal energy use and degree-hours in cooling mode, respectively. Both figures compare baseline vs. control 1 strategy results for a variety of combinations of plenum temperature setpoints (PCC ranges 23-27ºC, RHC ranges 13-14ºC).

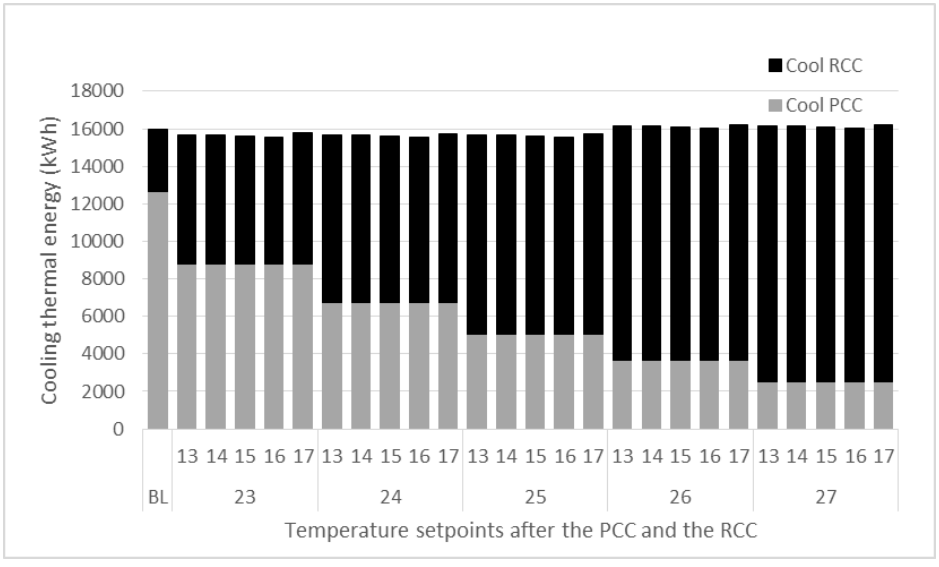

Figure 22 – Control logic 1 results. Cooling thermal energy use. PCC is energy use in the precooling coil (1st stage of conditioning), RCC is energy use in the recooling coil (2nd stage of conditioning)

Unlike in heating mode, overall cooling energy use does not see a substantial reduction with control 1 strategy, and even slightly increases in high PCC setpoints. This result suggests that the “not controlled” waterflow rates better match the cooling loads that they do the heating loads.

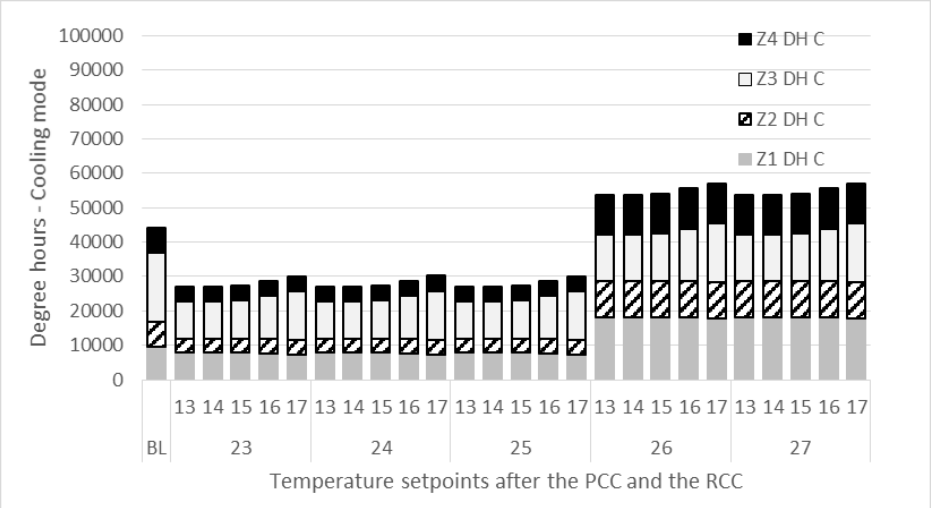

Figure 23 – Control logic 1 results. Degree hours in cooling mode

Similarly, degree-hours in cooling mode with control logic 1 do not see the consistent drop that was found in heating mode. It must be noted that with high PCC temperature setpoints degree hours with control logic 1 increase above the baseline. The sharp increase of degree-hours at the 25-26ºC boundary is the result of the internal control logic of supply air temperature as a function of room air temperature difference with its setpoint (see “baseline model”) and the constant 1ºC deadband. Nevertheless, results suggest that control logic 1 provides more benefits in heating mode than it does in cooling mode.

Although it cannot be seen in the above results, it must be noted that, unlike the baseline case, control logic 1 guarantees minimum supply air temperature equal to or above PCC setpoint (13-17ºC depending on the case), which avoids local thermal discomfort (draught). This is an additional comfort benefit of control strategy 1.

4.2.3.3 Control logic 2 Results

The controller is tested connected to the developed TRNSYS model. The new supply air temperature set-points are provided every 15 min to the TRNSYS model based on temperature readings of this time step. Figure 24 and Figure 25 show monthly profiles of heating and cooling thermal energy use, respectively. Both figures show the relative contributions of the 2 conditioning stages.

Total heating and total cooling energy monthly profiles are similar than in the baseline scenario. However, total heating demand with control strategy 2 is reduced, while total cooling demand is

slightly higher. The share of heating energy supply by the reheat coil is much larger with control strategy 2 than it was in the baseline scenario.

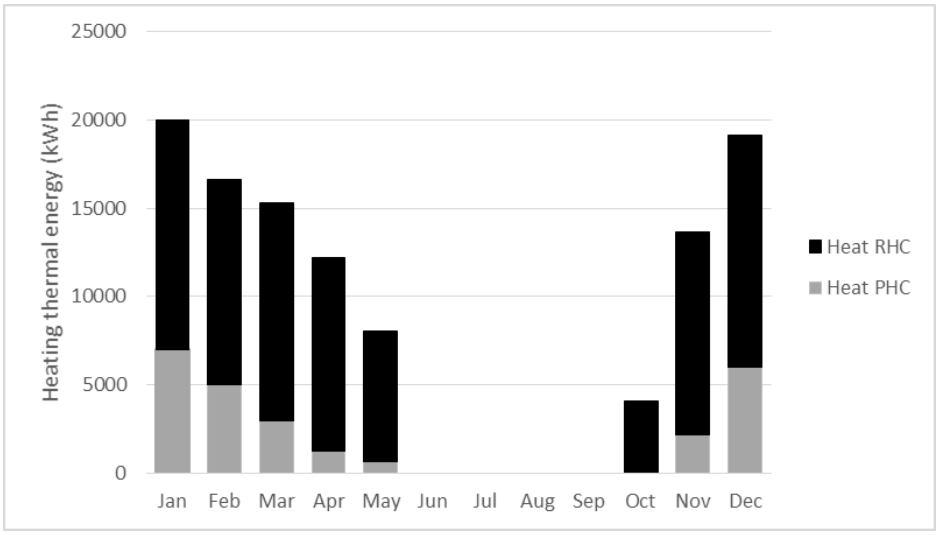

Figure 24 – Control logic 2 results. Heating thermal energy use. PHC is energy use in the preheating coil (1st stage of conditioning), RHC is energy use in the reheating coil (2nd stage of conditioning)

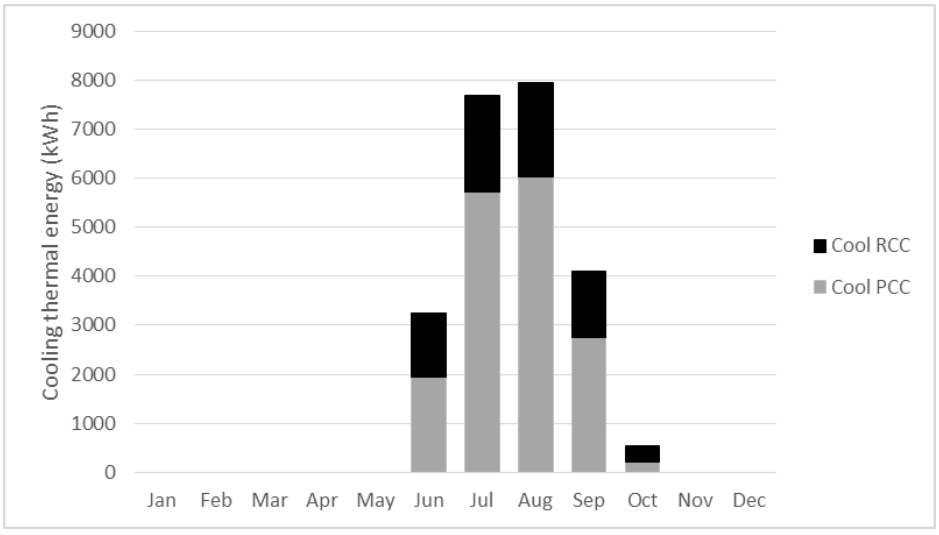

Figure 25 – Control logic 2 results. Cooling thermal energy use. PCC is energy use in the precooling coil (1st stage of conditioning), RCC is energy use in the recooling coil (2nd stage of conditioning)

Figure 26 and Figure 27 show monthly profiles of degree-hours (cumulative deviation between air temperature and room temperature setpoint) in heating and cooling season, respectively. Both figures show the degree-hours break-down by zone. Table 22 provides the numerical summary.

Both figures show similar profiles than the baseline scenario equivalents (with outstanding discomfort peaks close to the season-change dates), however, control strategy 2 provides much lower absolute values of degree-hours both in heating and cooling modes.

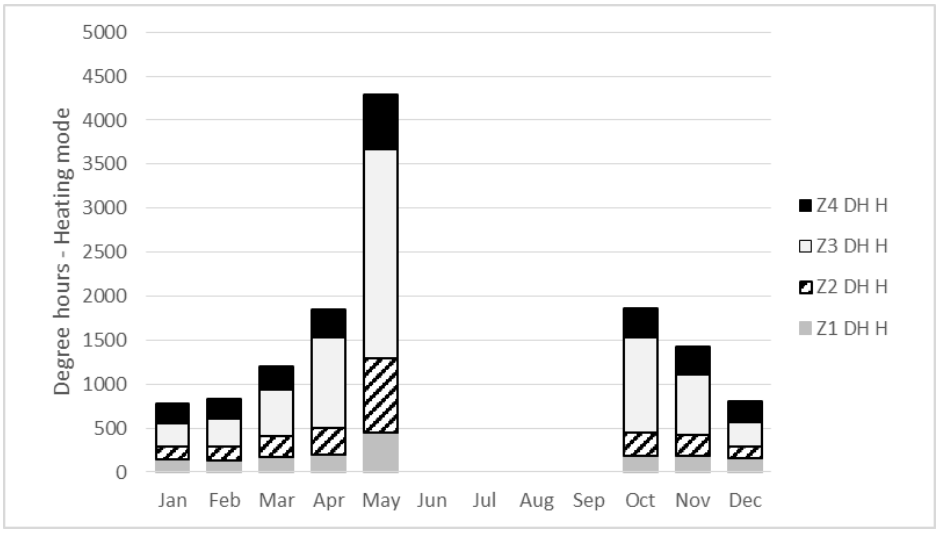

Figure 26 – Control logic 2 results. Degree hours in heating mode

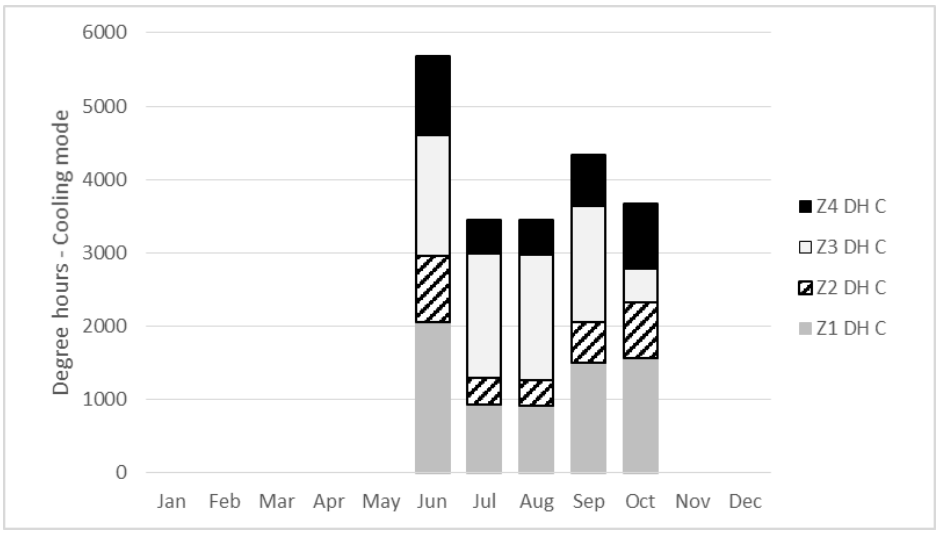

Figure 27 – Control logic 2 results. Degree hours in cooling mode

Table 22: Degree hours of thermal discomfort. Control logic 2

		Z1 DH	Z2 DH	Z3 DH	Z4 DH
	Jan	149	144	260	226
	Feb	137	157	313	226
	Mar	171	234	525	275
	Apr	199	309	1029	308
Heating	May	452	842	2370	628
	Jun	2052	905	1645	1073
	Jul	934	360	1689	472
	Aug	906	364	1704	471
	Sep	1503	554	1580	706
Cooling	Oct	1562	763	460	889
	Oct	189	256	1088	326
	Nov	186	230	696	318
Heating	Dec	153	141	280	237

Table 23 summarizes the main energy and degree-hour results of the 2 control strategies, and compares them against the baseline case. Results of control 1 strategy correspond to the best performing case in the parametric analysis.

Table 23: Summary results. Energy use, degree hours, and relative improvement (%) vs. baseline

	Baseline	Control Strategy 1		Control Strategy 2	
Total heating energy (kWh)	143000	109000	24%	109000	24%
Total cooling energy (kWh)	15900	15500	3%	23500	-48%
Total heating DH	93000	40200	57%	13100	86%
Total cooling DH	44500	27100	39%	20600	53%

Control strategies 1 and 2 result in very similar energy savings in heating mode (24%), however, control strategy 2 achieves much larger comfort benefits, as it reduces degree hours in heating mode by 86%. In cooling mode, control strategy 1 performs slightly better than the baseline in terms of energy, while control strategy 2 uses more energy. However, control strategy 2 achieves much larger comfort benefits compared to the baseline.

4.2.4 CONCLUSIONS

Simulation results show that the AHU installed at Hospital Virgen de las Nieves currently performs poorly both in terms of energy use and thermal comfort (particularly in heating mode). Reliability

of the baseline results is somewhat limited due to the lack of data of waterflow rate though the conditioning coils. Nevertheless, baseline results are a good illustration of the performance limitations of the currently implemented control system.

Control strategy 1 (fixed plenum setpoints) provides a better balance between the relative contributions of the 2 conditioning coils. Results show that in heating mode thermal energy use decreases by 24% and degree-hours decrease by 57%. Benefits in cooling mode are smaller.

Control strategy 2 (variable plenum setpoints) has a similar energy performance than control strategy 1 in heating mode, but achieves much better comfort results. In cooling mode this strategy uses more energy than control strategy 1 and even the baseline, however it does so in benefit of comfort.

Overall, both control strategies show large benefits compared to the baseline, both in terms of energy savings and thermal comfort. Control strategy 2 should be the choice to better satisfy comfort needs.

5 VENTILATION AIR CONDITIONING THERMAL ENERGY REQUIREMENTS

5.1 INTRODUCTION

The efficiency measures explored in Chapter 4 focus on control strategies that do not require hardware modifications to the air handling units. However, energy/heat recovery from exhaust air could potentially contribute to improving surgery room energy performance. As discussed in Chapter 2, heat recovery use in surgery rooms is accepted within the Spanish mandatory standards. The standards, however, do not provide tools to assess the convenience of energy/heat recovery units.

As discussed in Chapter 2, supply of outdoor air for surgery room ventilation is required to dilute anesthetic gases and other indoor generated contaminants. The Spanish mandatory outdoor airflow requirement for surgery rooms is 1200m^3/h (AENOR 2005). While other international standards require lower values relative to the Spanish code, outdoor airflow requirements in surgery rooms are substantially larger than conventional spaces (Ministerio de Industria Turismo y Comercio 2007).

Outdoor air that is introduced in the space (surgery room) has to be conditioned to the temperature and relative humidity levels in the room, which carries an associated use of thermal energy. In the winter months outdoor air is generally cooler and dryer (in absolute terms) than indoor air, requiring sensible heat to increase temperature and latent heat to increase humidity. On the other hand, in the summer months outdoor air is generally warmer and more humid than indoor air, requiring sensible cooling to reduce temperature and latent cooling to reduce humidity. While these statements are conceptually true for virtually any location in Catalonia and Spain (including the two case studies, Mollet and Granada), the absolute value of the thermal energy uses associated to ventilation air conditioning largely vary depending on the local climate conditions.

The thermal energy use associated with ventilation air conditioning is the key parameter to assess the convenience of energy recovery ventilators. Furthermore, the breakdown of the energy use into heating/cooling and sensible/latent components is necessary to evaluate the potential benefits of an energy recovery ventilator (which transfers both sensible and latent heat) relative to a heat recovery ventilator (which transfers only sensible heat).

The objective of this chapter is to evaluate the thermal energy use required for ventilation air conditioning in the two case study locations (Mollet and Granada). The thermal energy use is broken down into sensible heating (temperature increase in winter), latent heating (humidification in winter), sensible cooling (temperature decrease in summer) and latent cooling (dehumidification in summer) to facilitate the performance assessment of different types of energy recovery systems. The same assessment is replicated in a representative city of each region in Catalonia in order to provide a tool to assess the potential benefits of different types of heat recovery units in different locations. While the motivation for this chapter is to aid the assessment of energy recovery for surgery room systems, the results are valid for any other air handling unit application.

5.2 METHOD

Hourly values of ambient air temperature and relative humidity for Mollet and Granada are obtained from “Typical Meteorological Year” (TMY) files (METEOTEST 2014). TMY provide “a reasonably sized annual data set that holds hourly meteorological values that typify conditions at a specific location over a longer period of time” (Wilcox and Marion 2008). Instead, temperature and relative humidity data is obtained via personal communication with (Servei Meteorologic de Catalunya 2012). The data provided by the SMC corresponds to 2008, which according to the same source “was a statistically standard year” (Servei Meteorologic de Catalunya 2012). Based on indoor setpoints for temperature and relative humidity, and hourly values of ambient air temperature and relative humidity, the thermal energy calculations are developed as follows:

- Absolute humidity (grams of water/grams of dry air) of ambient and indoor air
- Enthalpy of ambient and indoor air
- During “heating mode” periods
    - Sensible heating requirements
    - Latent heating requirements
- During “cooling mode” periods
    - Sensible cooling requirements
    - Latent cooling requirements
- Hourly enthalpy results are integrated over a year

Indoor air temperature and relative humidity setpoints are 21ºC, 40% and 25ºC, 60% for winter and summer, respectively (Ministerio de Industria Turismo y Comercio 2007).

Psychrometric calculations in the aforementioned steps are performed by applying the equations in ASHRAE Fundamentals (ASHRAE 2009). Absolute humidity and enthalpy calculations are adjusted with the atmospheric pressure that corresponds to the elevation of the specific locations (Institut Cartografic de Catalunya 2012). The calculation process is as follows:

1- Known outdoor air dry bulb temperature t (ºC, from the weather dataset), the saturation pressure of water vapor (Pa) is calculated solving for p_{ws} in the following equation:

$$\ln p_{ws} = \frac{C_8}{t} + C_9 + C_{10}t + C_{11}t^2 + C_{12}t^3 + C_{13}t$$

Equation 7

Where:

C_8 = -5800.2206C_9 = 1.3914993

C_{10} = -0.048640239

C_{11} = 0.000041764768

C_{12} = -0.000000014452093

C_{13} = 6.5459673

2- Known outdoor air relative humidity RH (%, from the weather dataset) and p_{ws}, the pressure of water vapor (Pa) is calculated solving for p_w in the following equation:

$$RH = \frac{p_{ws}}{p_w}$$

Equation 8

3- Total pressure p (Pa) in a given location is calculated based on the elevation h (m) according to the following equation:

$$p = -11.45h + 101279$$

Equation 9

4- Known p, p_w, and p_{ws} (Pa), the humidity ratio (kg of water/kg of dry air) is calculated as follows:

$$W = 0.621945 \frac{p_w}{p - p_{ws}}$$

Equation 10

5- Known outdoor air dry bulb temperature t (ºC) and humidity ratio W (kg of water/kg of dry air), the moist air specific enthalpy h (kJ/kg of dry air) is calculated:

$$h = 1.006t + W(2501 + 1.86t)$$

Equation 11

6- The moist air specific volume v (m^3/kg of dry air) can be calculated based on temperature t (ºC), humidity ratio W (kg of water/kg of dry air) and total pressure (kPa) as follows:

$$v = 0.287042(t + 273.15)(1 + 1.607858W)/p$$

Equation 12

In order to allow the calculation of the sensible and latent components of the thermal energy requirements, an intermediate psychrometric point is defined as follows:

- In heating mode
    - Temperature t = Interior temperature setpoint in heating mode
    - Humidity ratio W = Humidity ratio or the outdoor air
- In cooling mode
    - Temperature t = Dry bulb temperature of the outdoor air
    - Humidity ratio W = Humidity ratio of the interior (setpoint in cooling mode)

Specific enthalpy h of the indoor air, outdoor air, and the intermediate psychrometric point are calculated with Equation 11. Finally, the sensible and latent components of thermal energy requirements are calculated:

In heating mode:

$$Qheat_{sensible} = \frac{(h_{intermediate} - h_{exterior})}{v}$$

Equation 13

$$Qheat_{latent} = \frac{(h_{interior} - h_{intermediate})}{v}$$

Equation 14

In cooling mode:

$$Qcool_{sensible} = \frac{(h_{intermediate} - h_{interior})}{v}$$

Equation 15

$$Qcool_{latent} = \frac{(h_{exterior} - h_{intermediate})}{v}$$

Equation 16

The functional unit of this study is a 1m^3/h constant outdoor airflow rate. Thermal energy results presented in this chapter shall be multiplied by the design airflow rate in a specific system. The constant rate hypothesis is consistent with the currently standard practice in surgery rooms in Catalonia and Spain (CatSalut and Corporació Sanitària de Barcelona 2012; Abad Baig 2013).

The “heating to cooling” and “cooling to heating” mode change dates are June 1st and October 1st, respectively. The differentiation between heating and cooling modes is required to properly account for the “favorable loads” (i.e., cool temperatures in summer nights are not considered as a heating load, warm temperatures in winter sunny days are not considered a cooling load). Figure 28 depicts the ambient air temperature profile for Barcelona and illustrates the datapoints considered in the calculations of sensible heating and cooling thermal energy.

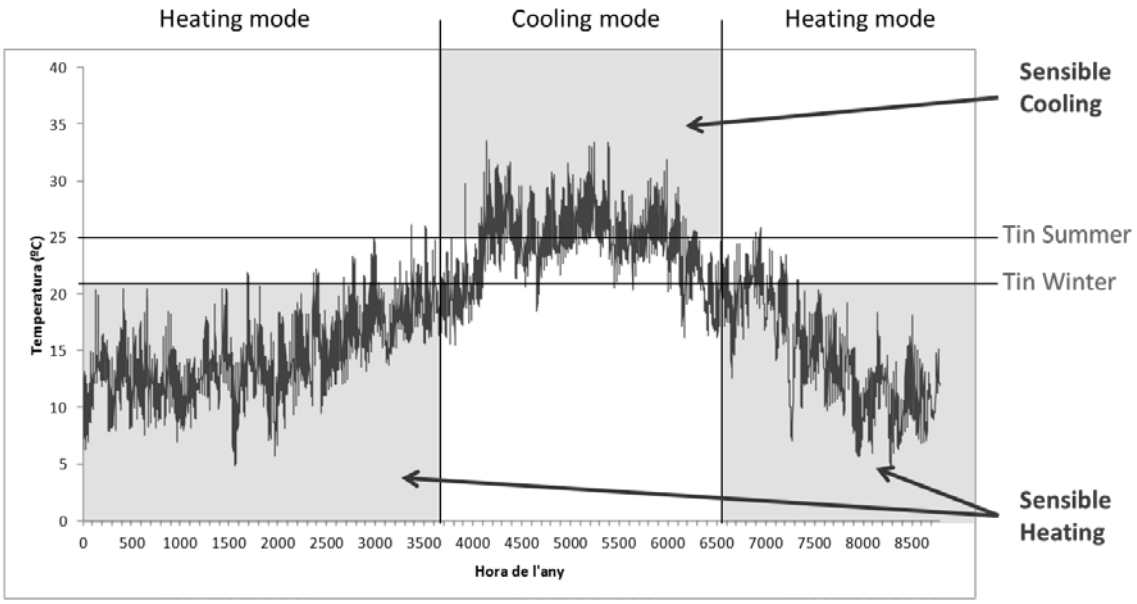

Figure 28 - Sensible heating and sensible cooling calculations

5.3 RESULTS

Table 24 shows the thermal energy requirements for outdoor air conditioning in the case study locations. Results are presented both on a per m^3/h supply airflow basis and assuming a constant $1200m^3/h$ outdoor airflow rate, as per the mandatory requirement in (AENOR 2005).

Table 24 Thermal energy for ventilation air conditioning. Mollet and Granada

Location	Sensible Heating (kWh per m^3/h)	Latent Heating (kWh per m^3/h)	Sensible Cooling (kWh per m^3/h)	Latent Cooling (kWh per m^3/h)
Mollet	15.4	3.5	0.5	1.2
Granada	20.7	6.0	0.9	0.0
	Assuming a $1200m^3/h$ constant outdoor airflow supply			
Location	**Sensible Heating (kWh)**	**Latent Heating (kWh)**	**Sensible Cooling (kWh)**	**Latent Cooling (kWh)**
Mollet	18,500	4,200	600	1,400
Granada	28,800	7,200	1,100	10

Figure 29 and Figure 30 depict the monthly profile of thermal energy use for ventilation air conditioning in Mollet and Granada, respectively. Both figures assume a constant $1200m^3/h$ outdoor airflow rate. Assessment of heat recovery options can be performed by applying the recovery efficiency factor of a given unit to the corresponding component (sensible or latent) in

Figure 29 and Figure 30 (e.g., a 60% efficient sensible heat recovery unit would reduce the sensible components for both heating and cooling by 60%).

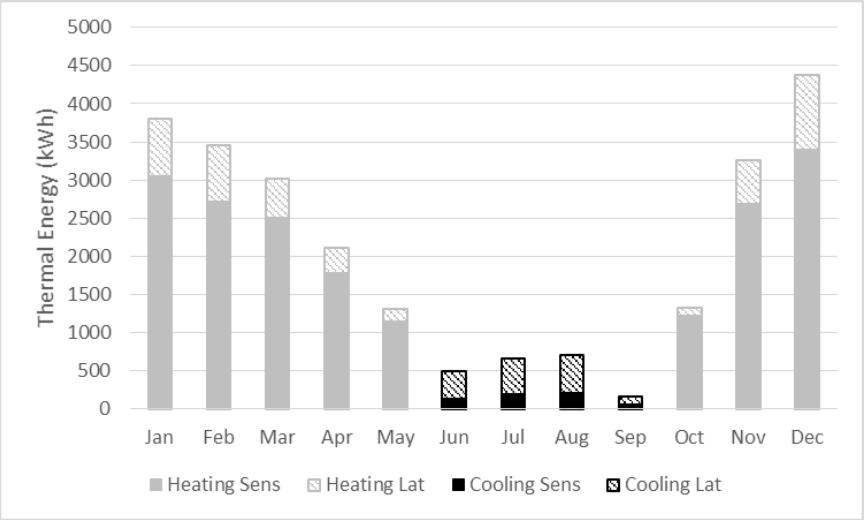

Figure 29 – Monthly profile of thermal energy use for ventilation air conditioning. Mollet

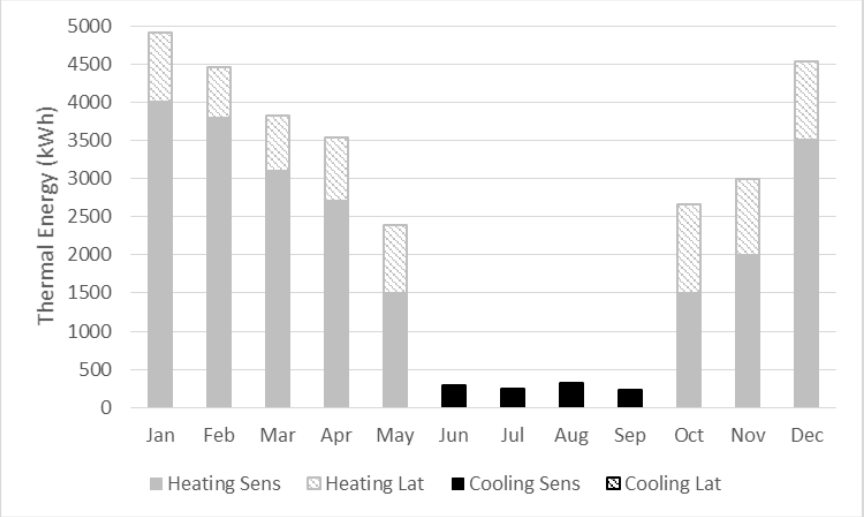

Figure 30 – Monthly profile of thermal energy use for ventilation air conditioning. Granada

The thermal energy associated with heating loads, both sensible and latent, is dominant over cooling both in Mollet and Granada. Sensible heating is the largest thermal energy user in both locations, particularly Granada. The sensible component is also dominant in cooling mode in Granada, where there is virtually no dehumidification required. However, the latent component is larger than sensible in terms of cooling in Mollet.

Results of the Catalonia-wide assessment are presented in Table 25, Figure 29 and Figure 30.

Table 25 Thermal energy for ventilation air conditioning. Region-specific results

		Thermal Energy (kWh per m^3/h)			
Region	**Location**	**Sensible Heating**	**Latent heating**	**Sensible cooling**	**Latent cooling**
Alt Camp	Vilarodona	18.4	5.2	0.6	2.3
Alt Empordà	Castelló d'Empúries	18.9	4.1	0.5	0.8
Alt Penedès	Sant Martí Sarroca	19.9	4.8	0.6	2.0
Alt Urgell	La Seu d'Urgell	26.2	8.4	0.5	0.0
Alta Ribagorça	Pont de Suert	28.6	8.7	0.6	1.3
Anoia	Òdena	21.2	5.6	1.0	3.0
Bages	St. Salvador de Guardiola	24.0	6.0	0.9	2.9
Baix Camp	Vinyols i Arcs	16.8	3.5	0.4	1.8
Baix Ebre	Aldover	16.2	4.7	1.1	2.6
Baix Empordà	La Bisbal d'Empordà	19.4	5.6	1.2	5.5
Baix Llobregat	Vallirana	18.2	4.4	0.7	2.0
Baix Penedès	El Vendrell	18.0	4.0	1.0	2.8
Barcelonès	Barcelona	13.7	3.6	0.9	2.3
Berguedà	La Quar	26.4	6.2	0.2	1.3
Cerdanya	Das	29.1	8.6	0.3	0.7
Conca de Barberà	L'Espluga de Francolí	21.5	4.2	0.7	2.7
Garraf	St. Pere de Ribes	17.6	3.6	0.7	2.0
Garrigues	Castelldans	21.7	6.0	1.0	3.1
Garrotxa	Olot	22.9	5.6	0.8	2.6
Gironès	Fornells de la Selva	22.9	5.2	0.9	2.5
Maresme	Cabrils	15.8	2.7	0.6	2.1
Montsià	Amposta	15.3	2.7	0.6	2.5
Noguera	Vallfogona de Balaguer	22.3	6.1	1.2	3.6
Osona	Gurb	24.8	6.0	0.7	2.4
Pallars Jussà	La Pobla de Segur	25.9	8.8	1.1	2.6
Pallars Sobirà	La Pobla de Segur[6]	25.9	8.8	1.1	2.6
Pla de l'Estany	Banyoles	19.2	4.8	1.0	2.4
Pla d'Urgell	Castellnou de Seana	22.5	6.2	1.2	3.7
Priorat	Falset	20.1	5.3	0.7	2.2
Ribera d'Ebre	Benissanet	18.9	5.2	1.2	3.0
Ripollès	St. Pau de Segúries	27.6	6.4	0.2	0.8

[6] There was no data available for any location in Pallars Sobirà. La Pobla de Segur is located at 27 km from Sort (capital of Pallars Sobirà), and is considered the best possible proxy.

		Thermal Energy (kWh per m^3/h)			
Region	**Location**	**Sensible Heating**	**Latent heating**	**Sensible cooling**	**Latent cooling**
Segarra	Cervera	23.0	6.9	0.7	3.2
Segrià	Lleida	22.5	6.7	1.1	3.0
Selva	Vilobí d'Onyar	22.5	4.8	0.8	2.6
Solsonès	Lladurs	25.3	6.8	0.5	2.0
Tarragonès	Constantí	17.8	4.1	0.6	1.9
Terra Alta	Batea	20.6	5.2	0.7	2.5
Urgell	Tàrrega	22.5	7.1	1.0	2.9
Vall d'Aran	Viella	28.8	8.3	0.2	1.0
Vallès Occidental	Cerdanyola	19.5	4.9	0.9	2.2
Vallès Oriental	Parets	19.4	4.8	0.9	2.3

Figure 31 Total heating thermal energy requirements map. Darker colors correspond to regions with larger heating requirements (kWh per m^3/h)

Figure 32 Total cooling thermal energy requirements map. Darker colors correspond to regions with larger cooling requirements (kWh per m^3/h)

The thermal energy results for Mollet are slightly lower than the results for Cerdanyola, which is the closest location in the Catalonia-wide assessment set. This is likely due to the difference in the data sources (synthetic TMY files for Mollet and Granada versus 2008 values for the Catalonia-wide assessment).

The maps of total heating and cooling requirements are generally symmetric, suggesting that the locations with the highest heating requirements are usually among the locations with the lowest cooling requirements, and vice versa.

Similarly to the results for Mollet and Granada, the general trend in Table 25 shows a dominant role of heating thermal energy over cooling thermal energy, even in the warmest regions. In heating mode, sensible heating is dominant, while latent heating is approximately 20% of the total thermal heating energy. On the other hand, the latent component is usually dominant in cooling mode, representing a 75% of the total cooling thermal energy, on average.

Overall, the results suggest that the primary target for a heat/energy recovery unit in both cases should be sensible heating. However, the ultimate assessment should account for:

- The efficiencies of the heating and cooling energy plants, respectively
- The price of the energy carriers (electricity/fossil fuels) used in the heating and cooling plants, respectively

The sensible and latent efficiencies, pressure drop and capital cost of the energy/heat recovery units in the market

6 CONCLUSIONS AND OUTLOOK FOR FUTURE RESEARCH

The objective of this thesis is to identify and evaluate energy efficient ventilation strategies in surgery rooms that maintain acceptable indoor air quality and cleanliness while reducing the associated energy use. Surgery rooms are chosen because they are the spaces with the most stringent IAQ requirements in hospitals (and derived high energy use), and they often have a dedicated system that can be operated independently.

The associated specific objectives of this thesis are:

- To perform a comprehensive and critical review of the indoor environmental quality and infection control requirements in surgery rooms.

This objective has been fulfilled in Chapter 2.

- To identify novel energy efficient ventilation strategies for surgery rooms.

Energy efficient strategies are generally defined in Chapter 2, and more specifically in the case studies of Chapter 4.

- To define an assessment method to consistently assess control strategies in surgery room ventilation control through computer-based energy models.

The assessment method is developed in Chapter 3, and applied in the two case studies in Chapter 4.

- To evaluate the ventilation strategies in terms of indoor environmental quality and energy use.

This objective is accomplished in Chapter 4.

This thesis builds on the existing knowledge in the areas of HVAC control, surgery room design and operation requirements, and thermal energy systems performance analysis. The main contributions of this thesis are:

1. A comprehensive and critical review of the indoor environmental quality and infection control requirements in surgery rooms.
2. A general method to adjust system operation (outdoor airflow rate, total supply air, indoor air temperature, and indoor air relative humidity) to meet IEQ performance goals while reducing energy use

3. Calibrated energy models of two surgery room systems.
4. Identification and assessment of control strategies for two surgery room settings (Hospital de Mollet and Hospital Virgen de las Nieves).
5. The assessment of a ventilation control strategy based on real time measurement of particle concentration in the surgery room.
6. The assessment of the thermal energy use for ventilation air conditioning in the two case study locations as well as all the regions in Catalonia.

The critical review in Chapter 2 identifies the basic mandatory IEQ requirements (and their respective motivations) for surgery rooms in Spain, which can be summarized as follows:

- Outdoor airflow rate requirement: meant to reduce occupant exposure to anesthetic gasses and other indoor generated pollutants. UNE 100713:2005 sets the mandatory minimum outdoor airflow rate requirement (1200m^3/h).
- Total airflow rate requirement: along with filtration requirements, it is meant as an indirect means to reduce infection risk for the patient. The purpose of the total airflow requirement is to reduce germ concentration by increasing air filtration rate, thus reducing particle and germ concentrations. UNE 100713:2005 sets minimum total airflow rate requirements depending on surgery room type (2400-3600m^3/h); however, it is unclear as to whether these requirements are mandatory.
- Overpressure requirement: Surgery rooms are required to maintain a higher pressure than the adjacent spaces to avoid particle infiltration. There are no mandatory pressure differential values in the Spanish code, although UNE 171340:2011 uses 6Pa as the validation threshold.
- Temperature and relative humidity requirements: meant to provide thermal comfort to occupants. Apparently, there are no quantitative mandatory thermal comfort requirements in surgery room operation, but rather design values.

The most salient regulatory ambiguities identified in Chapter 2 are found in 1) the total supply air requirements (method to proof concentration levels μ_s for non-mixing systems), 2) the justification for the mandatory outdoor air requirement, 3) the allocation of applications (i.e., types of operations) in surgery room classes, and 4) the requirement to perform the surgery room particle test in “at-rest” mode.

The review in Chapter 2 identifies the performance goals associated to the prescriptive requirements, and proposes a method to adjust system operation (outdoor airflow rate, total supply air, indoor air temperature, and indoor air relative humidity) to meet IEQ performance goals while reducing energy use. Easily applicable energy efficiency measures that follow this method and would comply with most of the reviewed standards (including the mandatory code in Spain) include:

- Temperature and relative humidity reset when the room is unoccupied: to widen temperature and relative humidity deadbands to minimize space conditioning when the surgery room is not in use.

- Use recirculated air in operational mode: provide the minimum outdoor air as required in the corresponding standard, and use recirculated air to meet the total airflow requirement. This measure is particularly suitable for laminar flow systems, as these carry an associated 3- to 4-fold total supply airflow requirement compared to conventional mixing systems.

- Outdoor and total supply airflow reset when the room is unoccupied: to reduce airflows when there are no sources of germs and contaminants in the room.

The review also concludes that, thanks to recent developments in commercially available sensors, total supply airflow could be controlled based on real time measurements of particle concentration in the surgery room. This measure does not comply with the current prescriptive code requirements, but addresses the performance motivation in the codes (infection control).

Chapter 4.1 quantifies the potential benefits of surgery room ventilation control strategies in a standard Air Handling Unit (AHU), using a surgery room in Hospital de Mollet as the case study. This section uses a calibrated energy model of a surgery room to assess the potential environmental and cost benefits of a variety of control strategies.

- Reset of temperature and relative humidity setpoints and deadbands when the surgery room is not in use

- Air recirculation

- Reset of supply airflow when the surgery room is not in use

- Supply airflow control based on real time measurements of particle concentration

These strategies are assessed individually and in combinations.

Results show that control strategies could reduce primary energy use and associated CO_2 emissions and energy costs by up to 86% (case #10, Particle + Air Reset + T and RH reset + Rec) relative to the baseline case (standard continuous operation according to the requirements and recommendations in the Spanish standards). Except for the particle-based airflow control case, these control strategies could be implemented at no cost. Due to the very stringent space conditioning requirements during operation and the relatively low operation time of surgery rooms (30% in the studies room), temperature and relative humidity reset is the strategy that offers the largest environmental and cost benefits (73% savings). Airflow reset is the second best performing strategy (54% savings), followed by air recirculation (24% savings) and particle concentration based airflow control (9% savings). Combining control strategies have the potential to further reduce energy use, although the marginal benefit of adding a strategy decreases as the system performance improves. However, the practical application of reset-based strategies strongly depends on finding means to effectively and reliably assess surgery room occupancy for the purposes of air handling unit control.

The benefits associated with particle concentration based airflow control are modest compared to other control strategies. This is probably due to the relatively “conservative” infection control performance target and airflow setpoint with low particle concentration readings used in this thesis. Further research should define infection control targets during surgery room operation as a function of surgery type. It must be noted that particle concentration based airflow control is the only control strategy that specifically addresses energy use reductions during operation

Chapter 4.2 explores the potential thermal comfort and energy performance benefits of control strategies applied to a much older facility equipped with a highly non-standard system. Chapter 4.2 uses a calibrated model of a surgery room in Hospital Virgen de las Nieves (Granada) as a case study. While the system studied in this chapter may not be representative of the stock of surgery room systems in Catalonia or Spain, it illustrates the potential application of controls as to retrofit in existing systems.

The control strategies evaluated in Chapter 4.2 are case-specific, and very much custom made to the specific characteristics of the system in Hospital Virgen de las Nieves. The two studied strategies control air temperature in the plenums (prior to being individually mixed in the 4 supply airstreams), the first one uses constant setpoints while the second strategy resets plenum setpoints dynamically. Results show that controls can reduce heating thermal energy use by up to 24% while improving thermal comfort in the occupied spaces both in heating and cooling modes. The two tested strategies provide similar energy results in heating. However, the strategy

that dynamically resets plenum temperature setpoints requires a larger cooling energy use but provides better overall comfort results.

Finally, Chapter 5 evaluates the thermal energy use required for ventilation air conditioning in the two case study locations (Mollet and Granada). The thermal energy use is broken down into sensible heating (temperature increase in winter), latent heating (humidification in winter), sensible cooling (temperature decrease in summer) and latent cooling (dehumidification in summer) to facilitate the performance assessment of different types of energy recovery systems. The same assessment is replicated in a representative city of each region in Catalonia in order to provide a tool to assess the potential benefits of different types of heat recovery units in different locations. The total thermal energy use for ventilation air conditioning in Mollet is 23MWh/yr and 2MWh/yr in heating and cooling modes, respectively. The equivalent values for Granada are 32MWh/yr and 1MWh/yr.

Results show that ventilation air conditioning energy use is dominated by heating thermal energy over cooling thermal energy both in Mollet and Granada, and even in the warmest regions in Catalonia. In heating mode, sensible heating is dominant, while latent heating is approximately 20% of the total thermal heating energy. On the other hand, the latent component is usually dominant in cooling mode, representing a 75% of the total cooling thermal energy, on average. Overall, the results suggest that the primary target for a heat/energy recovery unit in both cases should be sensible heating. High efficiency sensible heat recovery units are recommended in surgery rooms.

6.1 RELEVANT FINDINGS

- The indoor environmental quality and infection control requirements for surgery rooms in the Spanish standards are prescriptive based (rather than performance based), often unclear, and not always scientifically justified. This leads to confusion in the sector. Engineering companies and facility managers often design and operate surgery rooms to meet the most stringent recommendations (not only the requirements) in the available standards and guides.

- The intrinsic performance motivations for the requirements for total supply airflow, outdoor airflow, temperature, and relative humidity are different. This brings the opportunity to individually control the different HVAC setpoints.

- A careful control of a standard surgery room air handling unit can reduce primary energy use and associated CO_2 emissions and energy costs by up to 83% while

meeting all the indoor environmental quality and infection control requirements in the standards. In view of the magnitude of the potential energy savings, control measures for surgery rooms should be strongly encouraged for their wide application.

- There are currently no performance infection control targets during operation. Surgery room particle concentration tests for ISO classification are performed in “at rest” mode (i.e., the air handling unit is ON but the room is unoccupied). Future research should define particle concentration targets during surgery room operation as a function of surgery type. It must be noted that the risk of infection depends on whether the particles are infectious or not, the type of microorganism (if they are infectious), and the dose (number of microorganisms). The particle concentration sensors currently available are not capable of distinguishing whether particles are infectious or not. Therefore, real performance-based infection control will not be possible until real-time sensors are capable of counting and identifying microorganisms

- When acceptable ranges of particle concentration during operation are defined, further energy savings would likely be possible by controlling supply airflow based on real time measurement of particle concentration. If sensor technology develops to the extent of identifying infectious particles, infection control targets will have to be defined in terms of acceptable dose.

- Control strategies can also be successfully implemented as a retrofit for old and non-standard systems, leading to significant energy savings and thermal comfort improvements. Due to the specific nature of system lay-out and characteristics of non-standard cases, the numerical results of the air handing unit in Granada presented in this thesis should not be generalized to all non-standard units.

- Due to the large volumes of outdoor air supply in surgery rooms, these would largely benefit from energy recovery from exhaust air. Ventilation air conditioning energy use is dominated by heating thermal energy over cooling thermal energy both in Mollet and Granada, and even in the warmest regions in Catalonia. High efficiency sensible heat recovery units are strongly recommended for surgery room applications.

Overall, this thesis demonstrates that energy efficient ventilation strategies can be implemented in surgery rooms within the limits of the currently available standards, and without compromising indoor environmental quality and infection control performance. These strategies have the potential to reduce surgery room energy use and CO_2 emissions by up to one order of magnitude.

Given the high energy intensity of surgery rooms and the substantial benefits of control strategies, these should be strongly encouraged.

6.2 FUTURE WORK

Due to the lack of detailed data on the stock of surgery rooms in Catalonia (air handling unit type, vintage, heating and cooling plant characteristics, and geographical distribution), this thesis cannot assess the potential benefits in terms of energy and CO_2 savings of a Catalonia-wide application of the suggested efficiency measures. Should this data become available, future research could assess the potential benefits and challenges of the practical application of these strategies in the stock of surgery rooms in Catalonia.

Strategies that reset temperature and relative humidity (strategy 1 in 4.1.2.2) or supply airflow (strategy 3 in 4.1.2.2) based on room occupancy rely on an occupancy signal. Experience in Hospital de Mollet suggests that a manual switch for physicians to indicate surgery room use is not sufficient to provide an accurate and reliable occupancy signal. Future research should address appropriate systems to assess room occupancy for the purpose of air handling unit control. Occupancy assessment could be based on automatic systems such as presence or motion sensors, or on a manual system that better fits the physicians' standard processes and routines before and after a surgery intervention.

In addition to a reliable occupancy signal, reset strategies could only be applied in emergency surgery rooms if these have short enough room recovery times (i.e., the time required by the system to bring the room back to the standard IEQ and infection control performance). Acceptable room recovery times are not currently defined. Future research should address recovery time requirements, and compare them against the performance of the surgery rooms in Catalonia. In the meanwhile, reset strategies are only recommended for non-emergency surgery rooms.

This thesis provides the first assessment of ventilation control based on real-time measurement of particle concentration. The particle concentration targets used in this thesis are based on the limits for ISO 5 classification under Standard UNE 171340:2011, which is performed in occupancy state "at rest" (i.e., system running without occupation). Due to the absence of particle generation in the room, "at rest" is a more favorable condition than "operational". No references to particle concentration targets during operation were found during the comprehensive literature review. Future research should work towards a definition of acceptable particle concentration ranges during surgery room operation as a function of surgery type.

A challenge of the previous point is that “particle concentration” is only a proxy for “risk of infection”, however, it does not capture all the shades of infection control. In addition to particle concentration, the risk of infection depends on whether the particles are infectious or not, and the type of microorganism in case they are infectious. A high concentration of non-infectious particles poses no infection risk, while a low concentration of highly virulent microorganisms can be lethal. Real performance-based infection control will not be possible until real-time sensors are capable of counting and identifying microorganisms. Future sensor research and development should address real time identification of microorganisms.

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ANNEX A – ENERGY EFFICIENT VENTILATION CONTROL STRATEGIES FOR SURGERY ROOMS

Cubi, Eduard, Jaume Salom, and Nuria Garrido (2014). “Energy Efficient Ventilation Control Strategies for Surgery Rooms”. HVAC&R Research. (Accepted)

Energy Efficient Ventilation Control Strategies for Surgery Rooms

Surgery room specific energy use is among the highest in the built environment due to the stringent indoor environmental quality (IEQ) and infection control requirements. This study uses a calibrated energy model to evaluate the environmental and economic performance of a variety of ventilation control strategies that reduce surgery room energy use while maintaining IEQ and infection control performance. The individual control strategies evaluated in this study are 1) Temperature and relative humidity reset, 2) Air recirculation, 3) Airflow reset, and 4) Particle concentration based airflow control. Combinations of these strategies are also evaluated.

The best performing combinations of control strategies can reduce surgery room primary energy use, CO_2 emissions and energy costs by up to 86% relative to the standard practice. Temperature and relative humidity reset is the strategy that offers the largest benefits. Particle concentration based airflow control shows modest results partly due to the conservative infection control performance target. Future research should define infection control performance thresholds during operation.

Introduction

Energy use in hospitals is one of the highest in the building sector (Energy Information Administration, 2008, ASHRAE, 2003). Energy use associated with surgery rooms is particularly high due to the stringent infection control and indoor environmental quality (IEQ) requirements. The present article follows up on a critical review of the currently available indoor environmental quality and infection control standards for surgery rooms (Cubí Montanyà et. al. , 2014). The review article compared the requirements in selected international standards and guidelines (AENOR, 2005, American institute of Architects (AIA), 2001, ASHRAE, 2003, ASHRAE, 2008, Deutsches Institut fur Normung (DIN), 2008, Ministerio de Industria Turismo y Comercio, 2007, Department of Health - Estates and Facilities Division, 2007, Working Party on Infection Prevention (WIP- The Netherlands), 2005, Instituto Superiore per la Prevenzione e la Sicurezza del Lavoro (ISPESL), 2009, Ministry of Health - Greece, 2010, Regioni ed alle Province autonome di Trento e Bolzano, 2000, Servizi Sociali Sanità ed Assistenza, 1997, Technical Chamber of Greece, 2010, European Committee for Standardization (CEN), 1999) against their intrinsic performance motivation as stated in the standards themselves, or found in relevant literature such as (Hermans, 2000, Kowalski and Bahnfleth,

1998, Sterling et. al. , 1985). The review article identified the basic performance motivation behind the IEQ-related requirements:

- The minimum outdoor airflow rate requirement is meant to reduce occupant exposure to anesthetic gasses and indoor generated pollutants.
- The total airflow rate requirement is, in combination with filtration, meant to reduce the concentration of infectious airborne particles in the surgery room and, therefore, the risk of patient infection.
- The overpressure requirement is meant to prevent contamination from adjacent spaces.
- The temperature and relative humidity requirements address the comfort needs of physicians and patients (who are often weaker and more easily challenged by uncomfortable environments).

The different motivations for the requirements brings the opportunity to individually control HVAC setpoints for total supply airflow, outdoor airflow, temperature, and relative humidity. Control strategies to reduce surgery room energy use while meeting IEQ and infection control performance goals were identified in (Cubí Montanyà et. al., 2014). However, these strategies were not quantitatively evaluated. The objective of the present study is to quantify the potential benefits of surgery room ventilation control strategies.

Method

This study uses monitored data of a surgery room in Hospital de Mollet (Barcelona, Spain) to calibrate a TRNSYS (University of Wisconsin et. al. , 2013) energy model. The calibrated baseline model of the surgery room (i.e., a model of the current configuration and control strategy) is modified to assess the performance of the alternative control strategies.

System description

The surgery room under study is $37m^2$ in floor area and $118m^3$ in volume. It is located in the Hospital of Mollet (Barcelona, Spain). The Air Handling Unit (AHU) is a dedicated unit that provides ventilation and space conditioning to the surgery room space through a laminar flow diffuser. The AHU is equipped with a 60% efficient static sensible heat recovery unit with plate heat exchangers to comply with the Spanish mandatory energy standard (Ministerio de Industria, 2007). The AHU includes a heating coil, a cooling coil, and a reheating coil. The cooling

and reheating coils can be used simultaneously to meet both the temperature and relative humidity requirements of the surgery room. The AHU also features a humidifier. The AHU includes a supply and a return fan. The supply airflow rate is higher than the return airflow rate to guarantee overpressure in the surgery room (which is a required condition for infection control purposes). High Efficiency Particulate Air (HEPA) filters are installed in the supply airflow stream for infection control purposes. Figure 1 depicts the schematic of the AHU installed in the Hospital of Mollet. This AHU is a 100% outdoor air system, and does not allow air recirculation. As discussed in (Cubí Montanyà et. al., 2014), air recirculation in surgery rooms is allowed (and even encouraged) but seldom used in the Spanish surgery rooms. Although air recirculation cannot be implemented in the AHU in the Hospital of Mollet, this strategy is still assessed through modeling as a potential energy efficiency measure for AHUs that do have air recirculation capability.

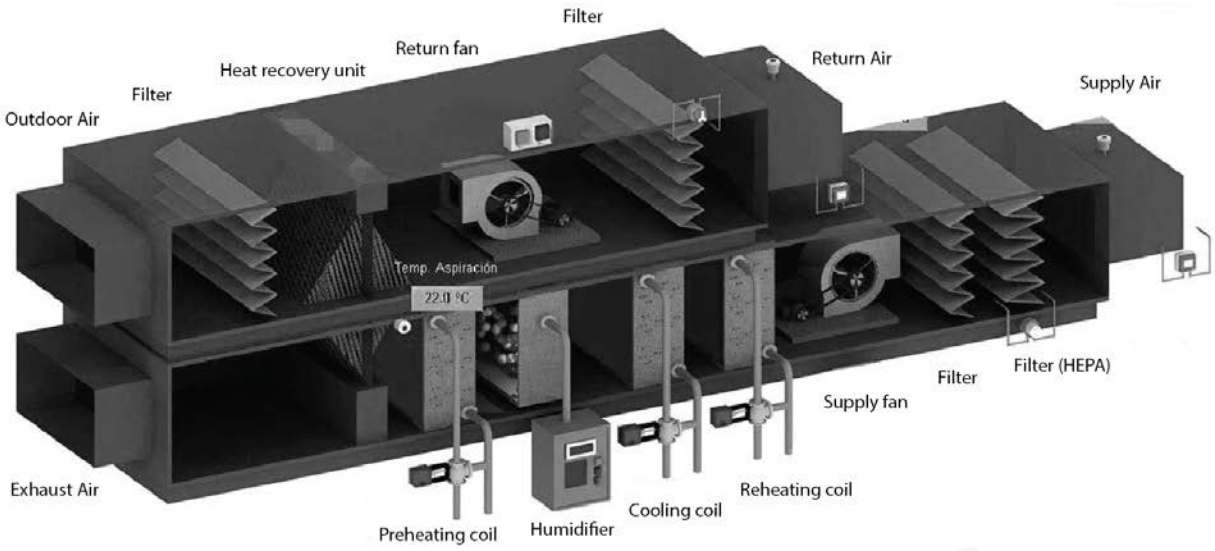

Figure 1- AHU schematic

The standard operation setpoints in the surgery room are 3200 m3/h supply airflow rate and 50% ± 5% relative humidity. The return fan is controlled to maintain a 10 Pa overpressure in the surgery room, which in the studied surgery room corresponds to 2500 m^3/h exhaust airflow rate when the doors are closed. The temperature setpoint can be manually adjusted by the user (physician) within the 18^0C-25^0C range (the default is 22^0C), however, the allowed temperature deadband is constant at ± 1^0C.

Energy efficient control strategies

The energy efficiency control strategies assessed in this study are: 1) Temperature and relative humidity reset, 2) Air recirculation, 3) Airflow reset and 4) Airflow control based on real time measurement of particle concentration.

1) Temperature and relative humidity setpoints and deadbands can be reset to less stringent values when the surgery room is not in use. This strategy reduces the amount of heating and cooling energy used for space conditioning (temperature and relative humidity control). To assess temperature and relative humidity reset this study uses $20^0C \pm 5^0C$ and 50%±5% as the setpoints and deadbands for temperature and relative humidity when the surgery room is not in use.

2) Since the requirements for total supply airflow and outdoor airflow derive from different motivations (infection control and dilution of anesthetic gases and contaminants, respectively), a fraction of the return air from the surgery room can be recirculated. To assess air recirculation this study uses 1200m3/h as the outdoor airflow supply setpoint, which is the minimum outdoor airflow requirement in Spain (AENOR, 2005, Ministerio de Industria Turismo y Comercio, 2007). Air recirculation in surgery rooms is allowed under the Spanish standard (AENOR, 2005) if the recirculated air comes from the same space to which will be supplied and flows through the same filtering stages as the outdoor air does. Similarly, ASHRAE (ASHRAE, 2003, ASHRAE, 2008) allows air recirculation in surgery rooms provided that HEPA filters are used.

3) The airflow reset strategy lowers both total supply and outdoor airflows when the surgery room is not in use. During non-use periods there is no generation of anesthetic gases or infectious particles in the room, however, the air handling unit must still maintain surgery room overpressure to avoid contamination from adjacent spaces (ASHRAE, 2003, AENOR, 2005). Since recirculated air does not contribute to room overpressure, the system is set to 100% outdoor air during non-use periods in the airflow reset strategy. Test results of the monitored surgery room in the Hospital of Mollet show that a $300m^3/h$ supply airflow are enough to maintain a 6Pa surgery room overpressure (threshold used for room validation in UNE 171340:2011 (AENOR, 2012)). This study uses 500m3/h as the supply airflow rate to assess airflow reset when the surgery room is not in use.

4) The potential use of real-time measurement of concentration of infectious particles for ventilation control was first introduced by Hermans (Hermans, 2000). Sensors of infectious particles are not commercially available, however there are sensors capable of reading real-time particle concentration (infectious or not) in

a variety of particle size ranges that could be used for ventilation control. To the authors' knowledge, this is the first field test of surgery room airflow control based on particle concentration. Due to the lack of previous studies, performance targets (particle concentration during surgery room operation) in the current standards, and a clear regulatory framework for surgery room airflow control in Spain (Cubí Montanyà et. al., 2014), the particle-based airflow control strategy tested in this study was defined in coordination with the infection control committee of the Hospital of Mollet and an external indoor environmental quality assurance consulting and certification body (Cruceta, 2014). Based on the precautionary principle, the field test reported in this study targets a very high infection control performance during operation, and allows only a limited airflow reduction with low particle concentration readings. This study uses the threshold values for ISO Class 5 (European Committee for Standardization (CEN), 1999) as the target for airflow control during operation. It must be noted that ISO Class 5 is the highest standard for surgery room classification in (Rosell Farrás and Muñoz Martinez, 2010, CatSalut and Corporació Sanitària de Barcelona, 2012). Furthermore, surgery room classification under Standard UNE 171340:2011 (AENOR, 2012) is performed in occupancy state "at rest" (i.e., system running without occupation) which, due to the absence of particle generation in the room, is a more favorable condition than "operational". Total supply airflow rate is set to the maximum fan capacity (3200m3/h) when the 0.3µm particle concentration reading approaches 10,200ppm (ISO Class 5 limit). Total supply airflow setpoint proportionally decreases with particle concentration up to a lower limit of 1600m^3/h and 3500ppm. The minimum 1600m^3/h is maintained for particle concentration readings lower than 3500ppm. The 3,500ppm lower limit is arbitrary. Concentration of 0.5µm particles is also monitored in real time, however readings never approach the ISO Class 5 limit for this size (3,520ppm) and, therefore, this reading does not affect airflow control. Particle sizes 0.3µm and 0.5µm are considered the most likely to be infectious in general surgery interventions (Cruceta, 2014). Larger particles are generated in traumatology interventions, but these are not likely to be infectious. The minimum total supply airflow (1600m^3/h) is 33% lower than the suggested 2400m^3/h in Standard UNE 100713:2005 (AENOR, 2005), but still higher than the minimum mandatory 1200m^3/h outdoor airflow requirement in the same standard. The minimum supply airflow was not further reduced to guarantee the proper performance (supply air velocity) of the laminar flow diffuser.

Reset strategies 1) and 3) reduce the surgery room IEQ and infection control performance, respectively, when the room is not in use. A short surgery room recovery time (i.e., the time required by the system to bring the room back

to the standard IEQ and infection control performance) is critical for the viability of these strategies in case of urgent (unscheduled) surgery interventions. The Spanish standard (AENOR, 2012) provides guidelines to test infection control recovery time, however, neither this standard nor the other relevant standards in Spain (AENOR, 2005, European Committee for Standardization (CEN), 1999, Ministerio de Industria Turismo y Comercio, 2007) provide acceptable ranges of recovery time for temperature, relative humidity, or infection control performance. Room recovery time tests at the Hospital of Mollet could not be performed. Assuming ideal air displacement, a complete air change in a surgery room like these in Hospital of Mollet (118 m^3 in volume) would require 2.2 minutes at full fan capacity (3200 m^3/h), or 3 minutes at the standard airflow rate (2400m^3/h). It must also be noted that during "not occupied" periods, strategy 1 maintains temperature within the 15-25^{o}C range and relative humidity within 35-65%, and strategy 3) maintains overpressure and a 500m^3/h supply of filtered air in a surgery room with no sources of contaminants. Experience in Hospital of Mollet as well as other hospitals in Spain (Barrachina, 2012, Cubí, 2014, Prat, 2014) shows that in emergency interventions there is a minimum of 15-20 minute time-lag between operation notice and patient arrival to the surgery room. While the considerations above suggest that surgery room systems are likely capable of bringing the IEQ and infection control performance back to the standard conditions within the required response time, room recovery time tests should be performed before the practical application of reset strategies in emergency surgery rooms. It must be noted that the standard practice in small and medium size hospitals is to maintain only one of the surgery rooms prepared and equipped 24/7 for emergency operations, while the other surgery rooms are used for scheduled interventions. Large hospitals dedicate 10-20% of the surgery rooms to emergencies (Barrachina, 2012, Cubí, 2014, Prat, 2014). Reset strategies could be applied to non-emergency surgery rooms at a lower risk.

The above energy efficient control strategies were assessed individually and in the combinations shown in Table 1. All the scenarios were evaluated using the same assumptions of surgery room occupancy profile, internal gains, and heat recovery properties. Except for the particle counter in the particle-based airflow control strategy, implementing these control measures on a relatively new and standard air handling unit (similar to that depicted in Figure 1) would not require any investment costs.

Table 1 Control strategies evaluated in this study. Temperature, relative humidity, total supply airflow, and outdoor airflow setpoints.

#	Description	Temperature and RH	Total Supply Airflow	Outdoor Airflow
0	Default values in Hospital of Mollet	Temperature = 22^0C ±1^0C Relative humidity = 50%±5% Continuous operation (24/7)	3,200m^3/h Continuous operation (24/7)	3,200m^3/h Continuous operation (24/7)
1	Baseline. Standard conditions in a Spanish hospital	Temperature = 22^0C ±1^0C Relative humidity = 50%±5% Continuous operation (24/7)	2,400m^3/h Continuous operation (24/7)	2,400m^3/h Continuous operation (24/7)
2	Temperature and relative humidity reset	Occupied setpoints: Temperature = 22^0C ±1^0C Relative humidity = 50%±5% Not occupied setpoints: Temperature = 20^0C ±5^0C Relative humidity = 50%±15%	2,400m^3/h Continuous operation (24/7)	2,400m^3/h Continuous operation (24/7)
3	Air recirculation	Temperature = 22^0C ±1^0C Relative humidity = 50%±5% Continuous operation (24/7)	2,400m^3/h Continuous operation (24/7)	1,200m^3/h Continuous operation (24/7)
4	Airflow reset	Temperature = 22^0C ±1^0C Relative humidity = 50%±5% Continuous operation (24/7)	Occupied: 2,400m^3/h Not occupied: 500 m^3/h	Occupied: 1,200m^3/h Not occupied: 500 m^3/h
5	Particle-based control, as tested in Hospital of Mollet	Temperature = 22^0C ±1^0C Relative humidity = 50%±5% Continuous operation (24/7)	3,200m^3/h when particle concentration (0.3µm) is ≥10,200ppm. 1,600 m^3/h when particle concentration (0.3µm) is ≤3500ppm. Proportional airflow control in between limits	3,200m^3/h when particle concentration (0.3µm) is ≥10,200ppm. 1,600 m^3/h when particle concentration (0.3µm) is ≤3500ppm. Proportional airflow control in between limits
6	Temperature and relative humidity reset + Air recirculation	Occupied setpoints: Temperature = 22^0C ±1^0C Relative humidity = 50%±5% Not occupied setpoints: Temperature = 20^0C ±5^0C Relative humidity = 50%±15%	2,400m^3/h Continuous operation (24/7)	1,200m^3/h Continuous operation (24/7)
7	Temperature and relative humidity reset + Airflow reset + Recirculation	Occupied setpoints: Temperature = 22^0C ±1^0C Relative humidity = 50%±5% Not occupied setpoints: Temperature = 20^0C ±5^0C	Occupied: 2,400m^3/h Not occupied: 500 m^3/h	Occupied: 1,200m^3/h Not occupied: 500 m^3/h

		Relative humidity = 50%±15%		
8	Particle-based control + airflow reset	Temperature = 22^{o}C ±1^{o}C Relative humidity = 50%±5% Continuous operation (24/7)	Occupied: 3,200m^3/h when particle concentration (0.3µm) is ≥10,200ppm. 1,600 m^3/h when particle concentration (0.3µm) is ≤3500ppm. Proportional airflow control in between limits Not occupied: 500m^3/h	Occupied: 3,200m^3/h when particle concentration (0.3µm) is ≥10,200ppm. 1,600 m^3/h when particle concentration (0.3µm) is ≤3500ppm. Proportional airflow control in between limits Not occupied: 500m^3/h
9	Particle-based control+ airflow reset + temperature and relative humidity reset	Occupied setpoints: Temperature = 22^{o}C ±1^{o}C Relative humidity = 50%±5% Not occupied setpoints: Temperature = 20^{o}C ±5^{o}C Relative humidity = 50%±15%	Occupied: 3,200m^3/h when particle concentration (0.3µm) is ≥10,200ppm. 1,600 m^3/h when particle concentration (0.3µm) is ≤3500ppm. Proportional airflow control in between limits Not occupied: 500m^3/h	Occupied: 3,200m^3/h when particle concentration (0.3µm) is ≥10,200ppm. 1,600 m^3/h when particle concentration (0.3µm) is ≤3500ppm. Proportional airflow control in between limits Not occupied: 500m^3/h
10	Particle-based control+ airflow reset + temperature and relative humidity reset + air recirculation	Occupied setpoints: Temperature = 22^{o}C ±1^{o}C Relative humidity = 50%±5% Not occupied setpoints: Temperature = 20^{o}C ±5^{o}C Relative humidity = 50%±15%	Occupied: 3,200m^3/h when particle concentration (0.3µm) is ≥10,200ppm. 1,600 m^3/h when particle concentration (0.3µm) is ≤3500ppm. Proportional airflow control in between limits Not occupied: 500m^3/h	Occupied: 1200m^3/h Not occupied: 500m^3/h

Particle concentration measurement. Experimental set up

An airborne particle counter was installed inside the surgery room, and connected to the existing AHU control system. The particle counter provides simultaneous readings of particle sizes 0.3µm and 0.5µm. The sensor is located above the operation table (where patients rest during operation), attached to the surgical light, to avoid interfering with the surgery activities. Since the surgery room under study has a laminar flow air diffusion system, the infection control committee of the Hospital of Mollet and an external indoor environmental quality consulting body (Cruceta, 2014) considered that this was the most representative location to measure septicity of air in contact with the patient. The particle counter runs continuously and is calibrated on a monthly basis.

Energy model and calibration

The energy model is developed in TRNSYS (University of Wisconsin et. al., 2013), and includes both the space (surgery room) and the air handling unit (AHU). The total heat gains/losses in the surgery room model result in a variation of interior temperature and relative humidity. The AHU model compares these room conditions with the

corresponding room setpoints and adjusts AHU operation accordingly. Constant space and system parameters (e.g., room geometry, AHU heat recovery efficiency) are embedded in the model. Variable model inputs (Table 2) are defined externally and linked to the model. Model outputs include room temperature and relative humidity as well as AHU performance variables such as thermal energy use in the heating/cooling coils and fan electricity use. The dynamic model does not include plant components (boilers and chillers), as the surgery room AHU uses thermal energy from generated in a central heating and cooling plant that serves the entire hospital. Seasonal boiler efficiency and chiller COP are 80% and 3.25, respectively (Catalonia Institute For Energy Research et. al. , 2012). Table 3 shows the conversion factors used for the environmental and cost analysis.

Table 2 Variable model inputs

Variable Input	Value / Source
Outdoor air temperature and relative humidity	Weather file for Mollet (METEOTEST, 2014)
Surgery room occupancy profile	Use of the surgery room was monitored by Hospital of Mollet personnel during a week (May 5-11, 2014) (Figure 2). This weekly occupancy profile is replicated throughout one year of simulation
Internal heat gains during operation	Heat gains associated to 7 occupants (including the patient) and 2000W of equipment
Supply airflow based on particle concentration monitoring	The particle concentration based airflow control is implemented and monitored in a surgery room at the Hospital of Mollet. Monitored supply airflow values are used as an input for the energy model (when this strategy is assessed)

Table 3 Electricity and Natural Gas conversion factors (Instituto para la diversificacion y ahorro de la energia (IDAE), 2012)

	Electricity	Natural Gas
Primary energy factor ($kWh_{primary}/kWh_{final}$)	2.35	1.07
Carbon intensity (kg CO_2/kWh_{final})	0.34	0.19
Cost (€/kWh_{final})	0.10	0.04

Model results are compared to monitored values for period of a week (April 28-May 4, 2014) with the system running under particle-based airflow control (strategy #5 in Table 1). Hourly values of simulated and monitored cooling thermal power correlate with a 0.84 r^2 factor, RMSE = 0.7kW (Figure 3). The difference between model results and monitored values of total (cumulative) cooling thermal energy use during the week is 10%. While a finer model calibration would likely be possible if sub-hourly monitored data were available, these results are considered acceptable for the purpose of this study (i.e., assess the relative benefits of different control strategies). Reliable monitored values of heating and fan energy use were not available for calibration.

The calibrated energy model was modified in order to assess the control strategies summarized in Table 1. The model variants only differ in AHU control strategy, and maintain the same input assumptions.

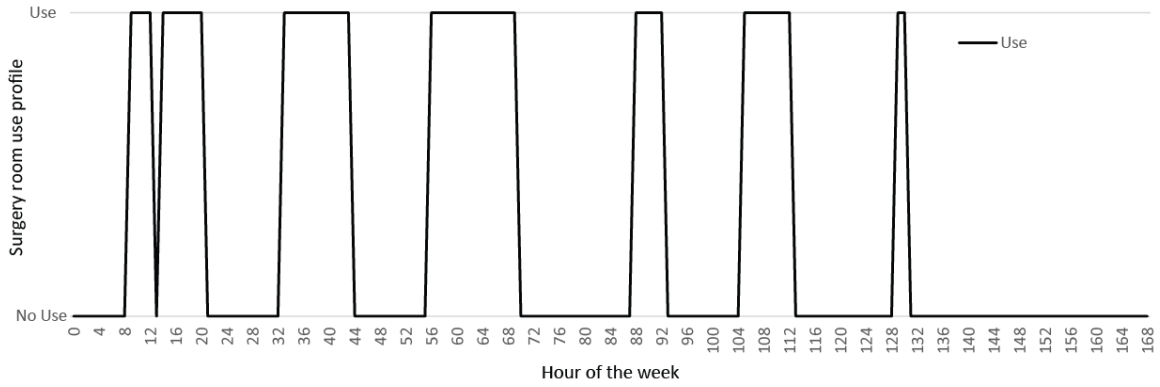

Figure 2- Surgery room occupancy profile (based on activity monitoring during the May 5-11, 2014 week)

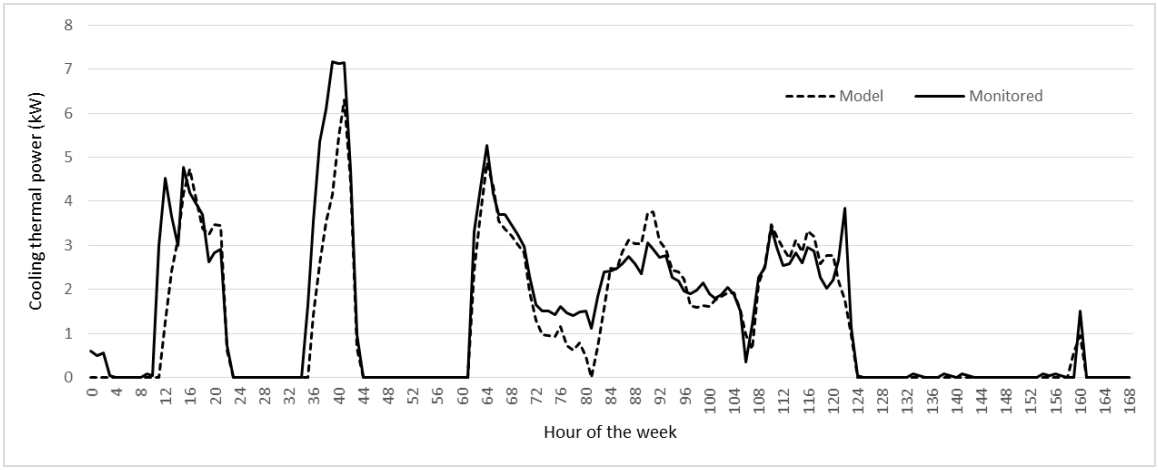

Figure 3- Cooling thermal power. Monitored values vs. model results (April 28-May 4, 2014)

Representativeness of the case study

Only one week of monitored surgery room occupancy is available for this study, and this occupancy profile (May 5-7, Figure 2) is replicated throughout the year in the energy model. However, the programs for the 6 surgery rooms in Hospital of Mollet for the whole month of May are available (6 rooms, 31 days). Occupancy profiles in surgery room programs are based on scheduled interventions and assumptions on intervention duration. The average monthly occupancy for the 6 surgery rooms according to the programs was 22% (i.e., on average, the surgery rooms were occupied 22% of the time). Monthly occupancy in the 6 surgery rooms ranged from 15% to 31%, with a 5% standard deviation. The monthly programs of the 6 surgery rooms showed scheduled interventions only during business hours,

Monday to Friday. The occupancy during the study week was 26% according to the program and 30% according to monitoring. This result suggests that the programs provide a reasonably accurate approximation of the actual occupancy. According to data derived from multiple field surveys, ASHRAE (ASHRAE, 2003) estimates that surgery rooms are occupied about 65 hours a week (39%). The occupancy rate used in this study is 9% lower than the estimated by ASHRAE, which may overestimate the benefits of the reset-based control strategies compared to an average American surgery room.

According to the Typical Meteorological Year (TMY) data file (METEOTEST, 2014), Mollet has 2220 SI Cooling Degree Days (CDD, base 10^0C) and 1450 SI Heating Degree Days (HDD, base 18^0C), which corresponds to Climate Zone 4 as defined in ASHRAE Standard 169 (ASHRAE, 2013). The highest and the lowest temperatures registered in the TMY file are 31^0C and 0^0C, respectively. Larger energy savings would be expected in surgery rooms located in more challenging climate zones.

The control strategies assessed in this study are applicable to relatively new and standard air handling units such as the one depicted in Figure 1.

Limitations

Evaluation of the particle concentration based control strategy is limited to the assessment of case #5 and its combination with other control strategies (cases #8, #9, #10). Variations of airflow reset as a function of particle concentration readings (e.g., a proportional airflow control with high and low particle and airflow limits different than these shown in Table 1, case #5) could not be tested. Further energy savings may be possible if infection control performance target (i.e., ISO Class) varied as a function of operation type or if total supply airflow was more aggressively reduced at low particle concentration levels. Particle concentration acceptable ranges during operation are currently not defined in the available standards. It must be noted that the risk of infection depends on whether the particles are infectious or not, the type of microorganism (if they are infectious), and the dose (number of microorganisms). “As few as 1-10 TB bacilli can be infectious for humans, while a total of 200 Rhinovirus virions may be required to cause a cold” (Kowalski and Bahnfleth, 1998). The particle concentration sensors currently available (such as the one used in this study) are not capable of distinguishing whether particles are infectious or not. Therefore, real performance-based infection control will not be possible until real-time sensors are capable of counting and identifying microorganisms.

This study assesses control strategies only. Further energy savings could be achieved by better adapting heat recovery properties as a function of climate. The results shown in this study apply to the climate characteristics of Mollet.

Results and discussion

Results of total annual thermal and final energy use for the different control strategies are presented in Figure 4. The individual contributions of heating, cooling, and fan energy use are shown in separate columns because they differ in energy carrier. Figure 5 compares the control strategies in terms total primary energy use. As shown in Table 4, CO_2 emissions and energy cost results follow the same pattern as total primary energy use results.

Energy use associated with air conditioning (heating and cooling) is dominant over fan energy use. Heating is the largest final energy user, partly due to the relatively higher efficiency of the cooling equipment. The contribution of cooling and fan energy use relative to heating increases in terms of primary energy use and carbon emissions due to the relatively larger conversion factors of electricity compared to natural gas (Table 3). However, heating remains the largest contributor to the total.

Fan energy use (and derived carbon emissions and costs) decreases with strategies that reset total supply airflow based on either occupancy or particle concentration readings. The contribution of fan energy use to the overall results is marginal across all cases and performance metrics. However, strategies that reduce fan use also result in a lower energy use for heating and cooling, as the amount of air to be conditioned is reduced. Total primary energy use, CO_2 emissions and energy costs could be reduced by 35% if the default total supply airflow in the Hospital of Mollet was reset to the requirements in Standard UNE 100713 (AENOR, 2005) (see cases #0 and #1).

Temperature and relative humidity reset when the surgery room is not occupied (case #2) shows the best environmental and economic performance among the individual strategies (cases #2 to #5). This is largely due to the very narrow temperature and relatively humidity window allowed during operation combined with an extended unoccupied time. The surgery room tested in Hospital de Mollet was occupied only 30% of the time, allowing relaxation of the temperature and relative humidity requirements during the remaining 70%. Similar occupancy rates are reported in (ASHRAE, 2003). Temperature and relative humidity reset alone result in 73% savings in primary energy use, CO_2 emissions and energy costs compared to the baseline (case #1).

Airflow reset (case #4) is the second best performing individual control strategy, saving 54% of the primary energy use, CO_2 emissions and energy costs compared to the baseline. Airflow reset also takes advantage of the extended unoccupied period of the surgery room. Air recirculation and particle concentration based airflow control result in 25% and 9% savings, respectively. The modest savings with the particle concentration based airflow control strategy are due to the "conservative" airflow reset with low particle concentration values. Total supply airflow with particle concentration based control range from 3200m^3/h to 1600m^3/h, while it is 2400m^3/h during occupied periods and 500m^3/h during non-occupied periods (70% of the time) with the airflow reset strategy. It is worth noting that air recirculation implemented on a continuous operation basis (case #3) requires hardware modifications in the AHU (a recirculation damper), but does not require any changes in the control settings.

Primary energy use, CO_2 emissions and energy costs can be further reduced if the control strategies are combined. Combinations of strategies that include temperature and relative humidity reset (cases #6, 7, 9, 10) result in savings ranging from 80% to 86% relative to the baseline (case #1). Savings are lower when temperature and relative humidity reset is not used (case #8). The best performing combination is case #10, which includes all the control strategies analyzed in this study. This combination uses strategies that reduce energy use when the surgery room is not used (temperature and relative humidity reset, airflow reset) and strategies that reduce energy use during operation (particle concentration based airflow control, air recirculation). It must be noted, however, that the incremental benefit of adding further control strategies tends to decrease.

Results show that the largest energy saving opportunities are associated with combinations of strategies that include temperature and relative humidity reset when the surgery room is not in operation. This study assumes an ideal use of the reset capability. However, experience in the Hospital of Mollet shows that physicians often forget to indicate a change in surgery room occupancy mode, making this strategy hard to implement in reality. Hospital of Mollet tried to implement temperature, relative humidity and airflow reset based on surgery room occupancy in the past. A manual switch was made available to physicians to indicate whether or not the surgery room was in operation. Hospital of Mollet decided to go back to continuous operation because physicians failed to properly indicate the surgery room operational status. If real time particle concentration measurements could be used to automatically identify occupancy, the savings associated with temperature, relative humidity, and airflow reset could be partially attributed to particle concentration airflow control. Alternatively, surgery room occupancy could potentially be automatically assessed with other systems such as presence or motion sensors. Future research should investigate appropriate technologies to assess surgery room occupancy for AHU control purposes.

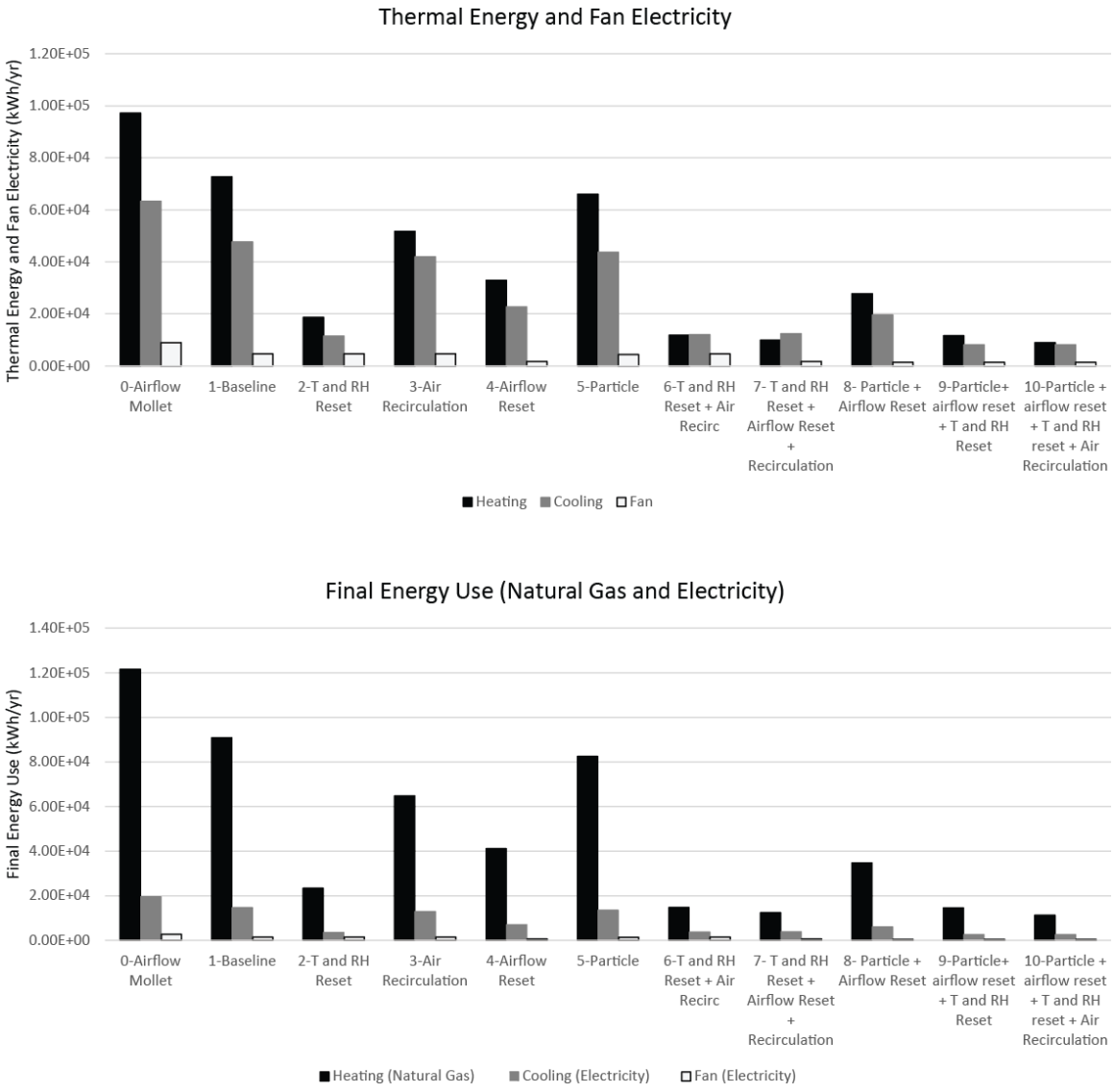

Figure 4- Thermal and final energy use

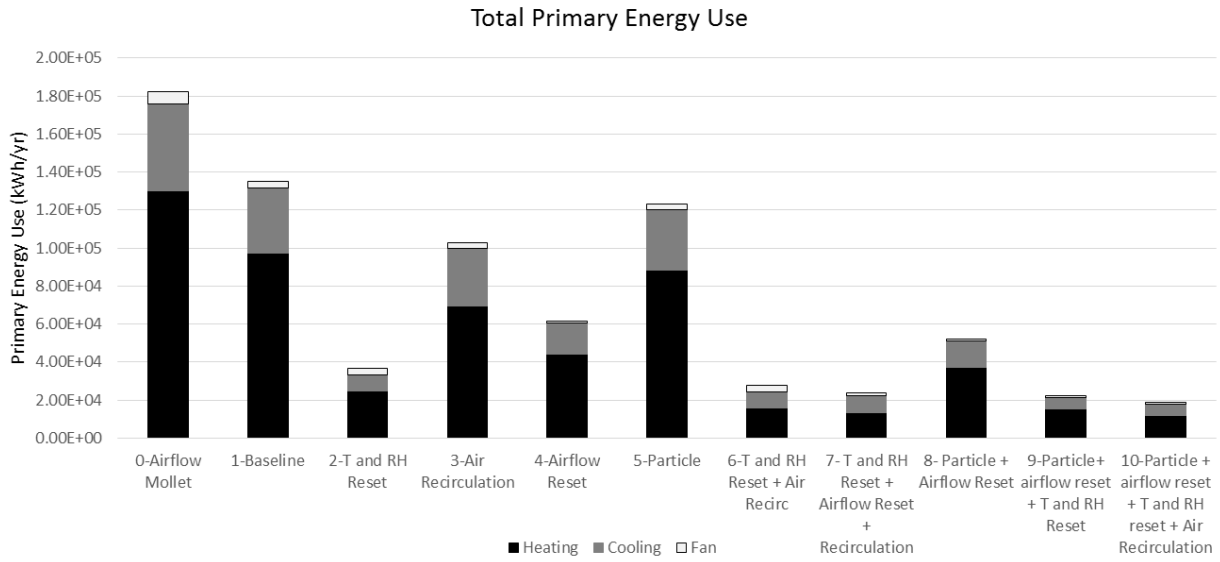

Figure 5- Primary energy use

Table 4 Primary energy use, CO_2 emissions, and Energy costs

	Primary Energy		CO_2 emissions		Energy Cost	
Case	**kWh/yr**	**Savings relative to baseline**	**kg/yr**	**Savings relative to baseline**	**€/yr**	**Savings relative to baseline**
0- Airflow Mollet	1.82E+05	-35%	3.12E+04	-35%	7.09E+03	-35%
1- Baseline	1.35E+05	0%	2.31E+04	0%	5.25E+03	0%
2- T and RH Reset	3.67E+04	73%	6.22E+03	73%	1.43E+03	73%
3- Air Recirculation	1.03E+05	24%	1.74E+04	25%	4.02E+03	23%
4- Airflow Reset	6.17E+04	54%	1.05E+04	54%	2.40E+03	54%
5- Particle control	1.23E+05	9%	2.10E+04	9%	4.78E+03	9%
6- T and RH Reset + Rec	2.79E+04	79%	4.61E+03	80%	1.10E+03	79%
7- T and RH Reset + Air Reset + Rec	2.36E+04	83%	3.90E+03	83%	9.34E+02	82%
8- Particle + Air Reset	5.23E+04	61%	8.92E+03	61%	2.03E+03	61%
9-Particle + Air Reset + T and RH Reset	2.24E+04	83%	3.81E+03	84%	8.74E+02	83%
10-Particle + Air Reset + T and RH reset + Rec	1.89E+04	86%	3.17E+03	86%	7.42E+02	86%

Conclusions

This study uses a calibrated energy model of a surgery room to assess the potential environmental and cost benefits of a variety of control strategies. Results show that control strategies could reduce primary energy use and associated

CO_2 emissions and energy costs by up to 86% relative to the baseline case (standard continuous operation according to the requirements and recommendations in the Spanish standards). Should these measures be applied to the 6 surgery rooms available in Hospital of Mollet, their combined annual energy bill could drop from 42,000€/yr (case 0 – Airflow Mollet) to 4,500€/yr (case 10 – Particle + Air Reset + T and RH reset + Rec). Except for the particle-based airflow control case, these control strategies could be implemented at no cost. Due to the very stringent space conditioning requirements during operation and the relatively low operation time of surgery rooms (30% in the studies room), temperature and relative humidity reset is the strategy that offers the largest environmental and cost benefits. Airflow reset is the second best performing strategy, followed by air recirculation and particle concentration based airflow control. Combining control strategies have the potential to further reduce energy use, although the marginal benefit of adding a strategy decreases as the system performance improves.

The benefits associated with particle concentration based airflow control (the most novel strategy included in this study) are modest compared to other control strategies. This is probably due to the relatively "conservative" infection control performance target and airflow setpoint with low particle concentration readings used in this study. The currently available standards classify surgery rooms based on particle concentration in "at rest" mode (system running without occupation), but do not provide acceptable particle concentration ranges during operation. Real performance-based infection control will not be possible until sensors are capable of assessing infectious agents. It must be noted that particle concentration based airflow control is the only control strategy that specifically addresses energy use reductions during operation.

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ANNEX B – INDOOR ENVIRONMENTAL QUALITY AND INFECTION CONTROL IN SURGERY ROOMS: CODE REQUIREMENTS VS. PERFORMANCE MOTIVATION. A CRITICAL REVIEW

Cubi, Eduard, Jaume Salom, and Nuria Garrido (2014). “Indoor Environmental Quality and Infection Control in surgery rooms: Code requirements vs. Performance motivation. A critical review”. HVAC&R Research. 20, 643-654. DOI: 10.1080/10789669.2014.929423

ATTENTION ¡

Pages 140 to 152 of the thesis are availables at the editor’s web

http://www.tandfonline.com/doi/full/10.1080/10789669.2014.929423#.VLPrZ3u2r0w

ANNEX C – 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

Cubi, Eduard, Sotiris Papantoniou, Davide Nardi Cesarini, Jesus Arbol, Jose Maria Fernandez, Jaume Salom (2014). “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, Canada).

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

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Abstract

Hospital Virgenlas Nieves currently features a multizone air handling unit (AHU) that provides ventilation and space conditioning to 4 spaces. It is a very old, non-standard unit with 2 stages of conditioning that heavily relies on manual control. The system will soon be upgraded with a connection to the main building management system, which will allow automatic control. A TRNSYS model was used to evaluate the potential benefits of AHU control strategies in terms energy use and thermal comfort. A control logic based on constant air temperature setpointsafter the 2 conditioning stages results in 24% heating energy savings and 57% decrease in overall heating degree-hours. Benefits in cooling mode are smaller.A second control strategy uses a fuzzy controller of Matlab to continuously set variable setpoints of plenum temperatures and supply air to the zones. While energy results are similar, comfort results are much more satisfactory.

1 Introduction

Hospital Virgen de las Nieves (hereafter referred to as HVN) located in Granada (Spain) uses a multizone air handling unit (AHU) as the sole means to provide ventilation and space conditioning to 4 zones (2 of which include a surgery room). The system is not currently connected to the main building management system, and heavily relies on manual control. The system operators receive frequent comfort complains from the occupants. The system is to be connected to main building automation system, which will allow implementing control strategies to improve thermal comfort and energy use. HVN has the exact same system set up in 5 additional floors in which the control solutions developed here could be easily replicated.

Objective

The objective of this study is to define control strategies for the air handling unit to improve system performance in terms of thermal comfort and energy use. Control strategies will be pre-evaluated using energy modeling tools (TRNSYS and Matlab).

2 Background

Advanced Air Handling Unit controls

Advanced control techniques of Air handling units have been developed in the latest years, and have been test based on experiments as presented by Kolokotsa et al. (Kolokotsa et al., 2002). In their publication fuzzy controllers are presented for controlling the air conditioning system and the dampers based on an interface using LON protocol.

A different application in a test chamber has been presented by Kolokotsa et al. (Kolokotsa et al., 2006), in which the internal conditions are controlled using a fuzzy controller which is installed in a computer and the commands are sent to the chamber's controller using an OPC Server. In the installation, the operation of the air handling unit and the external window are controlled based on inputs from temperature, humidity and air quality sensor.

A review on the available controllers for heating and cooling plants have presented by Dounis et al. (Dounis and Caraiscos, 2009) in which the classical controllers are compared to more advanced ones such as fuzzy based ones, and neural network controllers.

Dounis et al. (Dounis et al., 2011) have used the interconnection between TRNSYS and Matlab (type 155) to exchange information. Thus the TRNSYS thermal model has been used to verify the proper operation of the Matlab controller.

Thermal comfort assessment in surgery rooms

Indices to evaluate general thermal comfort in buildings found in literature are typically based on the Fanger model (Fanger, 1970), which introduced "Predicted Mean Vote" (PMV) and "Predicted Percentage of Dissatisfied" (PPD) as comfort indices. These indices are also used in standards EN ISO 7730:2005 (CEN European Committee for Standardization, 2005) and EN 15251:2007 (CEN European Committee for Standardization, 2007). Carlucci and Pagliano (2012) provided a detailed review of thermal comfort indices for general use spaces.

However, due to their unique characteristics, "Fanger-based" indices are not used in standards and guidebooks for surgery room design and operation. ASHRAE Standard 170 (ASHRAE, 2008) requires design temperature and relative humidity ranges to be 20-24ºC and a 30-60% respectively. The same values are recommended in the HVAC Design Manual for Hospitals and Clinics (ASHRAE, 2003), while and the Applications Handbook (ASHRAE, 1999) recommends a narrower range for relative humidity (45-55%) and a wider range for temperature (16.7-26º.7C) design. It must be stressed that these are system design ranges. However, this does not imply that their setpoints either during operation or when not in use must fall within these ranges.

3 Method

System description

The AHU in the surgery rooms of HVN is a multizone system that provides ventilation (fresh air) and space conditioning (either heating or cooling) to 4 zones (2 of which include surgery rooms). Figure 1 shows the SketchUp model of the spaces served by the AHU and the relevant shading elements.

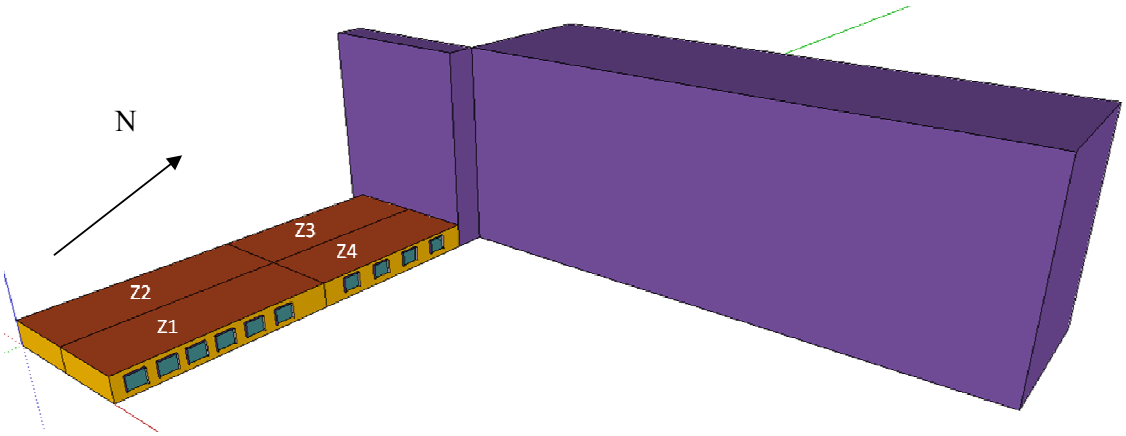

Figure 1 – SketchUp model - Zone layout

This AHU is a dedicated system (100% outdoor air) with no heat recovery. There is an independent supply duct for each of the 4 zones with an independent control damper for each of them. Figure 2 shows the AHU schematic.

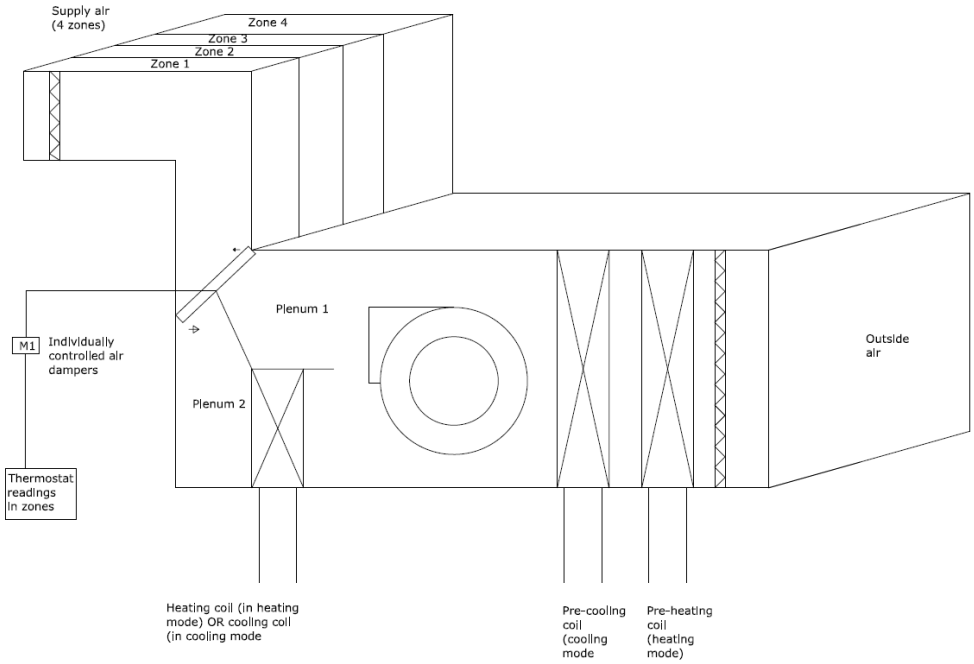

Figure 2 – Schematic of the multizone AHU in Hospital Virgen de las Nieves

The amount of supply air to the 4 zones is constant (constant volume system); the dampers change the ratio of air that comes from the 2 available plenums (at different temperatures): it could be 100% from one of the two sides, or a mix of the two. Air in Plenum 1 runs only through one pair of pre-conditioning coils ("1 stage conditioning", there are 2 coils heating/cooling in series, but only one active at a time), while air in Plenum 2 runs through an additional conditioning coil ("2-stage conditioning", 1 coil that is either heating or cooling depending on the season). This AHU is connected to a 2 pipe system - therefore, all the water in the coils is eitherheating or cooling.

The control system is currently not integrated in the central building management system.

- Room temperature set-points are manual control inputs by the occupants (through thermostats).
- Room temperature set-point drives the individual dampers position (through an internal control).
- Valve positions of the 3 coils (the 2 stages of conditioning) are manually operated. There is no automatic control over coil water flow rates, and therefore, no control over air temperature in the 2 plenums.

The air handling unit has no humidity control capabilities (neither humidification nor dehumidification) and the spaces have no humidity sensors. Therefore, none of the models considered humidity control (although outdoor air relative humidity was accounted for in the heating and cooling coils energy exchange).

The HVAC Design Manual for Hospitals and Clinics (ASHRAE 2003) recommends variable air volume (VAV) systems in spaces where there are significant unoccupied hours (such as surgery rooms). While a VAV would likely enhance energy efficiency in this case study, HVN is postponing measures that imply hardware purchase and installation.

Baseline model

Both the building and the system were modeled in TRNSYS version 17 (University of Wisconsin et al., 2013). Version 17 features a new building model that contains 3D geometric surface information that is used for the detailed radiation calculations. The building model included only a single storey (which corresponds to the service space of the air handling unit), and assumed no heat transfer to/from the adjacent stories (which was considered a reasonable simplification, as the adjacent stories have the same space use and lay-out). Heating and cooling coils were modeled with TESS types 670 (heating) and 508 (cooling), which calculate outlet temperatures of air and water based on their respective inlet temperatures, flow rates, and a user defined by-pass factor (which was adjusted based on monitored data, as explained below). Zone geometry and envelope characteristics were modeled based on the documentation provided by Hospital Virgen de las Nieves. The weather file for Granada was obtained from the Meteonorm Database (METEOTEST).

Internal gains in the selected areas were calculated based on approximate values of occupancy density, lighting, and equipment use provided by Hospital Virgen de las Nieves personnel. Zones 1 and 2 have the same floor area (158m^2) and space type distribution; therefore, they also have the same (assumed) internal gains. The same is true for Zones 3 and 4 (floor area = 136m^2). Note, however, that total gains in the 4 zones are different due to the differences in orientation and exterior wall and window area. Table 1 summarizes the assumed internal gains in the zones. Table 2 summarizes zone characteristics.

Table 1 – Occupancy and internal gains in the zones

Time interval	Gains	Zones 1 and 2	Zones 3 and 4
Morning	Occupants (#)	9	4
(8:00-15:00)	Radiant (W)	2741	1852
	Convective (W)	1133	744
	Latent (W)	855	380
Afternoon	Occupants (#)	10	0
(15:00-22:00)	Radiant (W)	2773	1369
	Convective (W)	1191	152
	Latent (W)	950	0
Night	Occupants (#)	5	0
(22:00-8:00)	Radiant (W)	2615	1369
	Convective (W)	899	152
	Latent (W)	475	0

As part of the work developed within the EC-funded Green@Hospital project (Green@Hospital), the AHU was recently equipped with monitoring equipment that allowed for the adjustment of some of the system parameters in the model. An energy meter was installed in each of the heating and cooling coils of the AHU. According to the data sheet (Kamstrup), thermal energy metering error was:

$$Error = \pm\left(0.15 + \frac{2}{\Delta\theta}\right)\% \quad (1)$$

Where $\Delta\theta$ is the difference between inlet and outlet water temperature in the coil.

Model validation was basically done based on data corresponding to the period between October 4 and 7, 2013 (cooling season).

Total supply airflow rate was adjusted based on the heat transfer balance in the first conditioning coil (a monitoring input). The adjusted total supply airflow was 7700kg/h. It must be noted that this value is similar to the initial assumption, which was based on the results of air velocity spot measurements carried out by HVN personnel (8200kg/h).

The adjusted total supply airflow was used as a model input for the precooling coil. Precooling coil bypass factor was adjusted until the model outlet temperatures of both air and water showed close results compared to the monitoring values. The resulting by-pass factor (i.e., fraction of air that does not interact with the conditioning coil) was 75%, which is very large yet consistent with a very old air handling unit.

The same method was used to adjust the model of the second conditioning coil (recooling coil, in cooling mode), although only periods in which the 4 air dampers were fully closed could be used (necessary condition to know the corresponding airflow rate). The by-pass factor was adjusted to 85%, which provided a good match for both air and water side outlet temperatures.

Distribution of total supply airflow into the 4 zones was based on the relative size of duct section at the outlet of the AHU, which carries the implicit assumption that the pressure drop in the 4 distribution ducts is roughly the same.

Table 2 – Zone characteristics

Parameter	Zone 1	Zone 2	Zone 3	Zone 4
Floor area (m^2)	158	158	136	136
Exterior wall (m^2)	71	0	0	45
Window area (m^2)	16	0	0	11
Fraction of supply airflow (%)	52	26	7	15

Waterflow values for the two stages of conditioning were obtained from monitoring. There was only 12 days' worth of reliable data. Waterflow through the conditioning coils was not constant due to hydraulic instabilities (this AHU does not have a dedicated water supply loop), however, variations were relatively small (see Table 3). Because of the lack of more representative information, the 12-day waterflow profiles were used as a constant modeling input throughout the year (i.e., the same data series were repeated over and over). This assumption imposes a strong limitation on model reliability, as in reality the system operators would occasionally adjust coil valves based on comfort complains. Nonetheless, the authors decided to repeatedly use these waterflow profiles because they were not able to find more reliable data/method to describe operator's manual adjustments.Furthermore, while the results derived from this hypothesis may not accurately represent reality, they are a good illustration of the performance limitations of the currently implemented control system.

Table 3 – Water flow through conditioning stages. Monitoring results

Parameter	1st Stage	2nd Stage
Minimum flow (kg/h)	5460	1396
Average flow (kg/h)	6997	1772
Maximum flow (kg/h)	8436	2073
Standard Deviation (kg/h)	444	130

The supply air temperature control (i.e., damper position) was implemented in the model according to the following logic:

- Room air temperatures (readings from the building module) and room temperature setpoints (assumed 23ºC both for summer and winter, based on the expertise of HVN personnel) are compared. The default supply air temperature setpoints are set as the room air temperature setpoints (occupant input). When there is a >1ºC difference between room temperature reading and the corresponding temperature setpoint, a proportional control modifies supply air temperature setpoint to a lower or higher value depending on the zone cooling/heating requirements. This results in a set of "ideal" supply air temperature set-points for the 4 zones.
- The ideal supply air set-points are modified to fall within the feasible limits of the 2 stages of conditioning (in heating mode min = PHC Temp, max = RHC temp, where PHC is air at "preheating coil" outlet and RHC is air at the "reheating coil" outlet, the two plenums).
- The modified supply air temperature set-points for the individual zones are used as inputs for the flow diverters and mixers, which correspond to the air dampers in the multizone AHU.
- Supply air outputs of the AHU model are inputs for the zones in the building model.

Energy performance evaluation was based on the thermal energy use in the conditioning stages (both in heating and cooling). This is thermal energy (heating and cooling) provided by the conditioning coils, and does not account for the efficiency of the central heating and cooling plant. Fan electricity use was not included in the analysis because it is a constant volume system (i.e., fan energy use remains constant regardless of the control strategy).

In terms of thermal comfort, the difference between room air temperature and room air temperature setpoint was used to evaluate the effectiveness of the control strategy in delivering the desired comfort. The difference between delivered and desired supply air temperatures was integrated over time, and presented in terms of "degree-hours". As acknowledged in Section 2, thermal comfort in general use spaces is often evaluated with indices based on the work by Fanger. However, the authors chose to use degree-hours because 1) the system is only capable of controlling (and only to some extend) one of the comfort parameters: temperature, 2) surgery rooms do not have standard conditions of interior setpoints, clothing level, or metabolic rate that are required for the assessment of PMV and PPD, and 3) the purpose of the study is to assess how well the system can match the local temperature setpoints. Previous studies (Stephan et al., 2011) have used degree-hours to assess systems based on a single control parameter (temperature).

Control logic 1 – Constant plenum temperatures

The first improvement to the AHU control was to add control loops in the conditioning coil flow rates so that air temperature in the two plenums remained "constant". It must be noted that this is a 2-pipe system, and therefore, control capabilities of the AHU are limited: supply air temperature cannot be higher than outdoor air temperature in cooling mode, and cannot be lower in heating mode.

This strategy was modeled by using ideally controlled heating and cooling coils. These provide the required heating/cooling for the outlet air to exactly match a given temperature setpoint, however, they are still limited by the 2-pipe constraint (i.e., cooling is only possible in cooling season, and heating is only possible in heating season). A parametric analysis was run to evaluate the performance of the system under a variety of plenum temperature setpoints.

Control logic 2 – Dynamic plenum temperature setpoints based on readings from indoor temperature

An advanced controller is developed in Matlab's environment. The specific programming environment is selected because it contains several toolboxes for advanced control techniques development. In order to initiate an interface between Matlab & TRNSYS, type 155 is used. Using the specific type, data are exchanged between Matlab and TRNSYS, so that Matlab is called after the convergence of the TRNSYS model. This condition reflects the approach followed in real-time implementation when a sensor is reading a condition, and then the controller is sending a command to the systems. Each time-step, TRNSYS sends selected data to Matlab, which in return sends back control commands to TRNSYS. Inside Matlab's environment a smart controller for the surgery room air handling unit, based on fuzzy logic, is called.

Fuzzy logic architecture is selected because it contains, in the form of rules, the knowledge of the personnel which is currently adjusting the system manually. The input to the controller is the difference between the current temperature in each room separately from the defined setpoint. Thus, the controller is trying to minimize the error between these two values. Due to the installation and operation of a PID controller for basic control the smart controller is designed to adjust the supply air set-point of the 4 air streams. The architecture and the characteristics of the developed fuzzy controller can be seen in Table 4.

Table 4 - Architecture and characteristics of the fuzzy controller

Type of fuzzy controller	'Mamdani'
N. of inputs	4: error between current and desired indoor temperature
N. of outputs	4: change of supply air set-point
Fuzzification membership functions	5
De-fuzzification membership functions	5

The fuzzification parameters are similar for all 4 rooms and they can be re-adjusted if it required in case one of the rooms has different performance. Similarly, the de-fuzification parameters can be re-adjusted if required.

Moreover the system can only provide heating or cooling based on the season of the year (2 pipe system). Thus, the controller has to be adjusted in order to operate for both heating and cooling season. In order to prevent an un-normal operation of the controller, the supply air temperature set-points has to be limited between some upper and lower boundaries. The boundaries for the set-points can be seen in Table 5.

Table 5: Boundaries of supply air temperature set-point

Seasons	**Boundaries**	**Values**
Cooling mode	Upper limit	25°C
	Lower limit	13°C
Heating mode	Upper limit	30°C
	Lower limit	13°C

In cooling mode supply air temperature should be above 13 C to avoid local discomfort (draft). Similarly, the minimum setpoint for heating cannot be below 13 C. The upper limits are selected based on the response of the system to the controller's commands. Each time-step the output of the controller (positive or negative) is added to the previous stored value and the new one is sent to the TRNSYS model. Thus, if the upper limit for cooling mode is higher than 25°C, it will take more time-steps to find the required supply air temperature set point which will balance indoor temperature close to the set point.

Furthermore, the controller is adjusting the temperature set-point of the 2 chambers (pre-heating/cooling, re-heating/cooling). The values of these set-points depends on the minimum and maximum values of the new supply air set-points. For heating mode the pre-heating chamber is having as set-point temperature the minimum value of the supply air temperature and the re-heating chamber is having the maximum value. Thus, the rooms which require these temperature can be pleased while the other 2 rooms can be pleased adjusting the dampers internally. Similarly for cooling mode, the pre-cooling chamber is having the maximum value of new supply air set-points while the re-cooling chamber is having the minimum value.

4 Results and discussion

Baseline Results

Figure 3 and Figure 4 show monthly profiles of heating and cooling thermal energy use, respectively. Both figures show the relative contributions of the 2 conditioning stages. Since this is a 2-pipe system, there is no simultaneous heating and cooling energy use. Based on the experience of Hospital Virgen de las Nieves personnel, the heating/cooling mode change dates were assumed to be June 1st and October 15th (hence, there is both heating and cooling energy use in October).

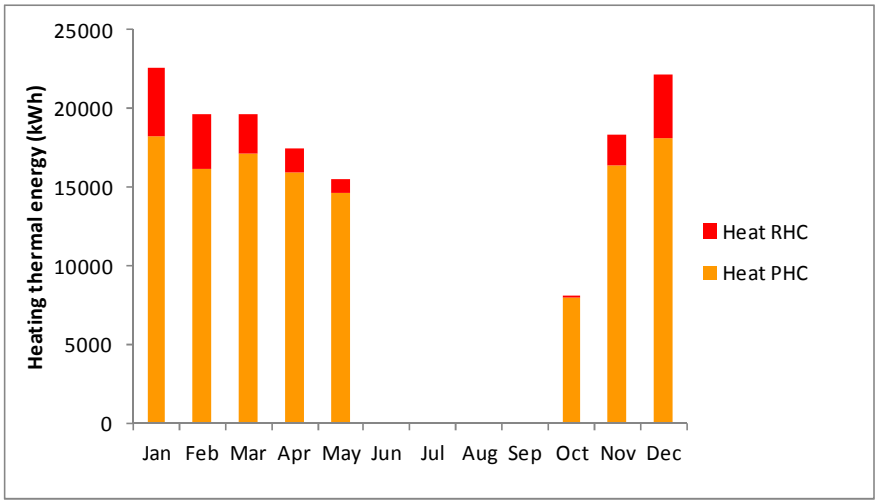

Figure 3 – Baseline results. Heating thermal energy use. PHC is energy use in the pre-heating coil (1st stage of conditioning), RHC is energy use in the reheating coil (2nd stage of conditioning)

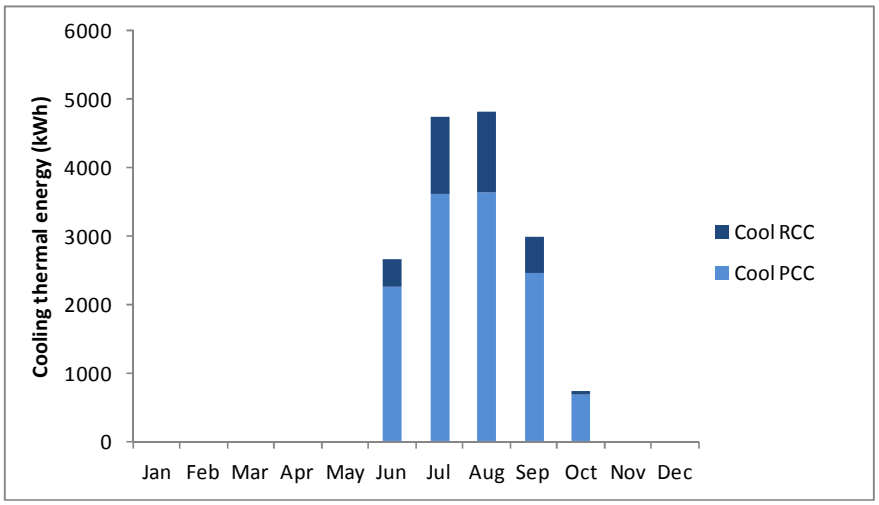

Figure 4 – Baseline results. Cooling thermal energy use. PCC is energy use in the pre-cooling coil (1st stage of conditioning), RCC is energy use in the recooling coil (2nd stage of conditioning)

Although total heating and cooling thermal energy use follow the expected profile (larger heating energy use in the coldest months, larger cooling energy use in the hottest), heating

energy use in the first stage of conditioning remains fairly constant throughout the heating season. The contribution of the first conditioning stage (both in heating and cooling) is largely dominant over the second stage of conditioning. Considering that the second stage of conditioning provides flexibility to adjust supply air temperatures according to the different requirements in the 4 zones, itsvery low energy contribution suggests that it is often by-passed due to a too hot (in heating mode) or too cold (in cooling mode) air temperature after the first stage of conditioning.

Figure 5 andFigure 6show monthly profiles of degree-hours (cumulative deviation between air temperature and room temperature setpoint) in heating and cooling season, respectively. Both figures show the degree-hours break-down by zone.

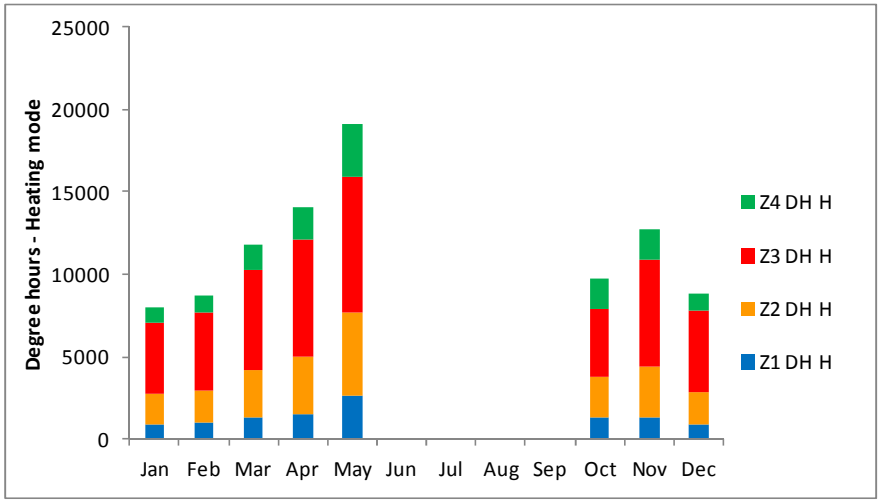

Figure 5 – Baseline results. Degree hours in heating mode

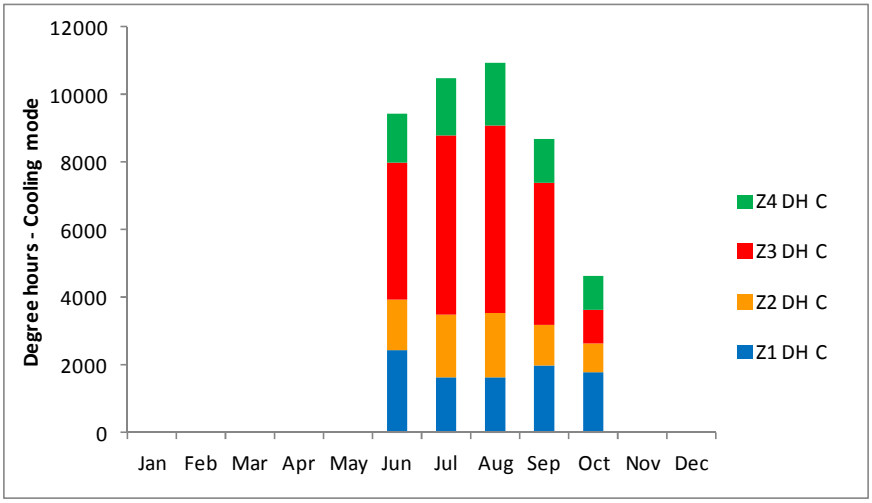

Figure 6 – Baseline results. Degree hours in cooling mode

The figures above show increasing thermal discomfort in the shoulder seasons (i.e., near the mode-change dates), which is typical of 2-pipe systems. It must be noted that these periods correspond to the lowest thermal energy contributions of the second conditioning coil. This suggests that the lower flexibility of the system to adjust supply air temperatures results in increased thermal discomfort.

Monthly values of degree-hours are high, and generally larger in the heating season. Interior zones (Zones 2 and 3) are the most uncomfortable.

Control logic 1 Results

Figure 7 and Figure 8 show cumulative values of heating thermal energy use and degree-hours in heating mode, respectively. Both figures compare baseline (BL) vs. control 1 strategy results for a variety of combinations of plenum temperature setpoints (PHC ranges 10-14ºC, RHC ranges 26-30ºC).

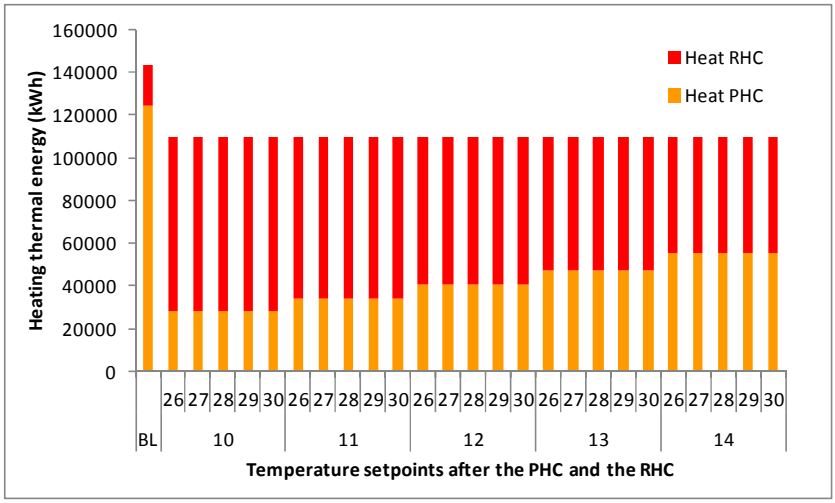

Figure 7 – Control logic 1 results. Heating thermal energy use. PHC is energy use in the preheating coil (1st stage of conditioning), RHC is energy use in the reheating coil (2nd stage of conditioning)

While the relative energy contributions of the two stages of conditioning largely vary with PHC temperature setpoint, the total thermal heating energy use with control strategy 1 is basically constant across the tested spectrum of PHC and RHC setpoints. Total heating energy use is roughly 110,000kWh/yr, which translates into 24% savings compared to the baseline scenario. It must be noted that, compared with the baseline, all the tested combinations show a much lower contribution of PHC to the overall heating thermal energy use.

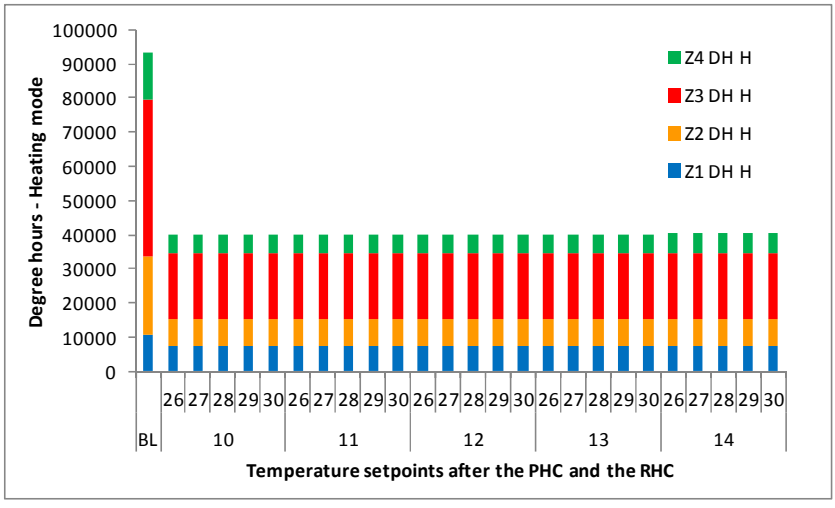

Figure 8 – Control logic 1 results. Degree hours in heating mode

Simulation results show that (within the tested ranges) temperature setpoints in the two plenums seem to have almost no impact on thermal comfort in heating mode. The overall degree-hours with control strategy 1 in heating mode drop from roughly 93,000 in the baseline to 40,000, which is a very significant (55%) reduction.

Figure 9 and Figure 10 show cumulative values of cooling thermal energy use and degree-hours in cooling mode, respectively. Both figures compare baseline vs. control 1 strategy results for a variety of combinations of plenum temperature setpoints (PCC ranges 23-27ºC, RHC ranges 13-14ºC).

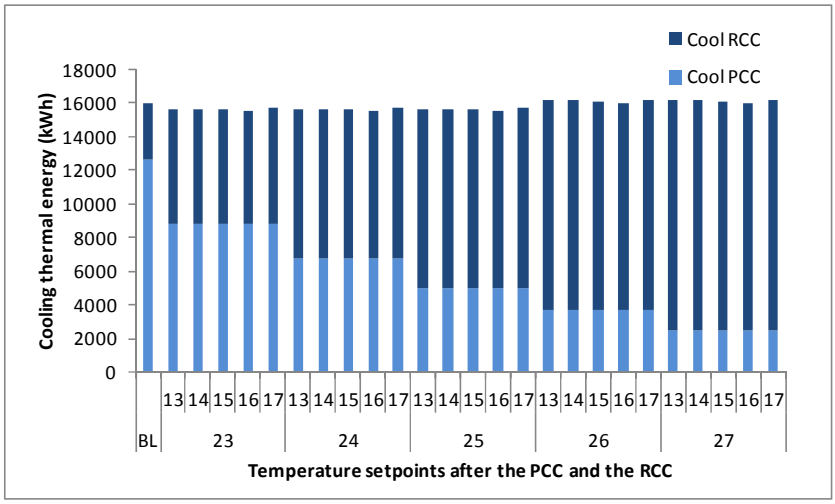

Figure 9 – Control logic 1 results. Cooling thermal energy use. PCC is energy use in the precooling coil (1st stage of conditioning), RCC is energy use in the recooling coil (2nd stage of conditioning)

Unlike in heating mode, overall cooling energy use does not see a substantial reduction with control 1 strategy, and even slightly increases in high PCC setpoints. This result suggests that the "not controlled" waterflow rates better match the cooling loads that they do the heating loads.

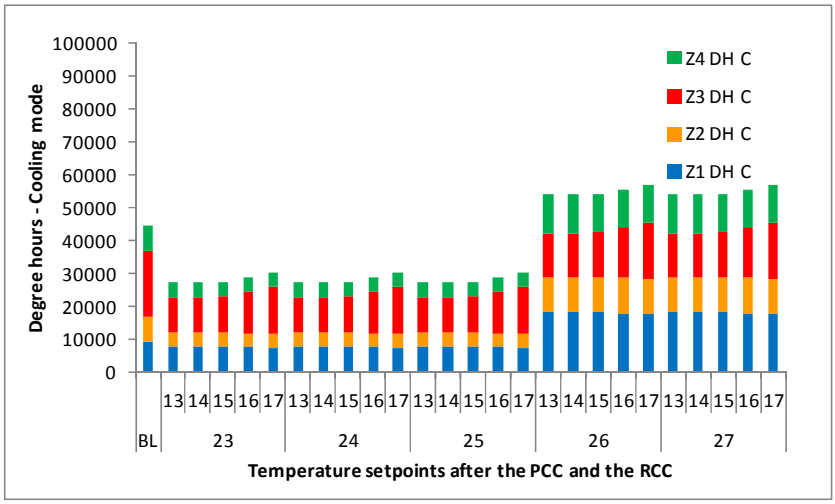

Figure 10 – Control logic 1 results. Degree hours in cooling mode

Similarly, degree-hours in cooling mode with control logic 1 do not see the consistent drop that was found in heating mode. It must be noted that with high PCC temperature setpoints degree hours with control logic 1 increase above the baseline. The sharp increase of degree-hours at the 25-26ºC boundary is the result of the internal control logic of supply air temperature as a function of room air temperature difference with its setpoint (see "baseline model") and the constant 1ºC deadband. Nevertheless, results suggest that control logic 1 provides more benefits in heating mode than it does in cooling mode.

Although it cannot be seen in the above results, it must be noted that, unlike the baseline case, control logic 1 guarantees minimum supply air temperature equal to or above PCC setpoint (13-17ºC depending on the case), which avoids local thermal discomfort (draught). This is an additional comfort benefit of control strategy 1.

Control logic 2 Results

The controller is being tested connected to the developed TRNSYS model. The new supply air temperature set-points are provided every 15 min to the TRNSYS model based on temperature readings of this time step. Figure 11 and Figure 12 show monthly profiles of heating and cooling thermal energy use, respectively. Both figures show the relative contributions of the 2 conditioning stages.

Total heating and total cooling energy monthly profiles are similar than in the baseline scenario. However, total heating demand with control strategy 2 is reduced, while total cooling demand is slightly higher. The share of heating energy supply by the reheat coil is much larger with control strategy 2 than it was in the baseline scenario.

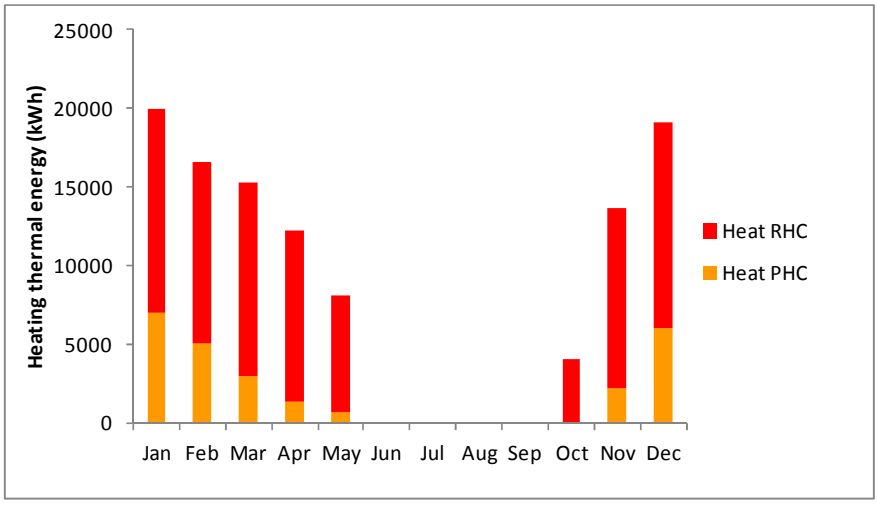

Figure 11 – Control logic 2 results. Heating thermal energy use. PHC is energy use in the preheating coil (1st stage of conditioning), RHC is energy use in the reheating coil (2nd stage of conditioning)

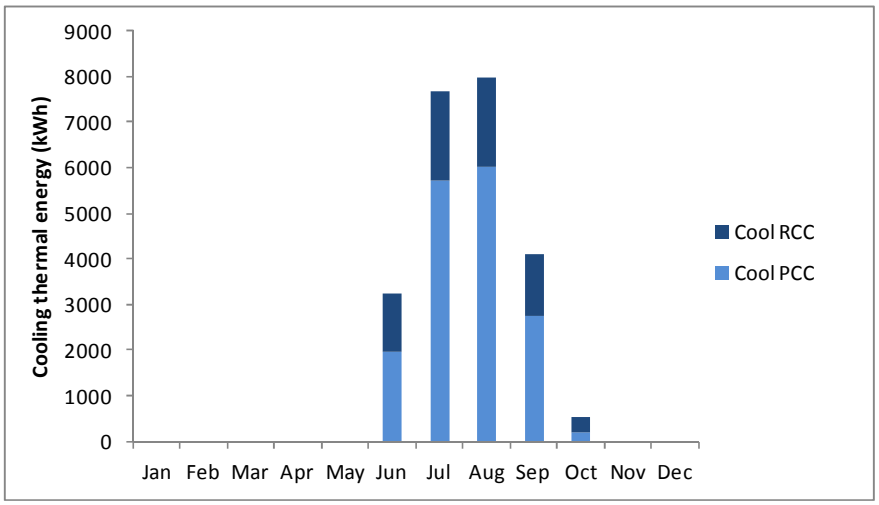

Figure 12 – Control logic 2 results. Cooling thermal energy use. PCC is energy use in the precooling coil (1st stage of conditioning), RCC is energy use in the recooling coil (2nd stage of conditioning)

Figure 13 and Figure 14 show monthly profiles of degree-hours (cumulative deviation between air temperature and room temperature setpoint) in heating and cooling season, respectively. Both figures show the degree-hours break-down by zone.

Both figures show similar profiles than the baseline scenario equivalents (with outstanding discomfort peaks close to the season-change dates), however, control strategy 2 provides much lower absolute values of degree-hours both in heating and cooling modes.

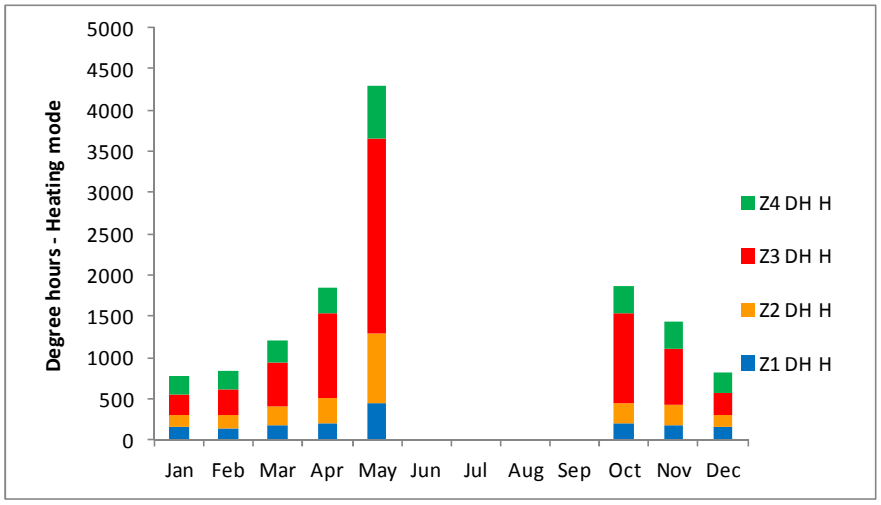

Figure 13 – Control logic 2 results. Degree hours in heating mode

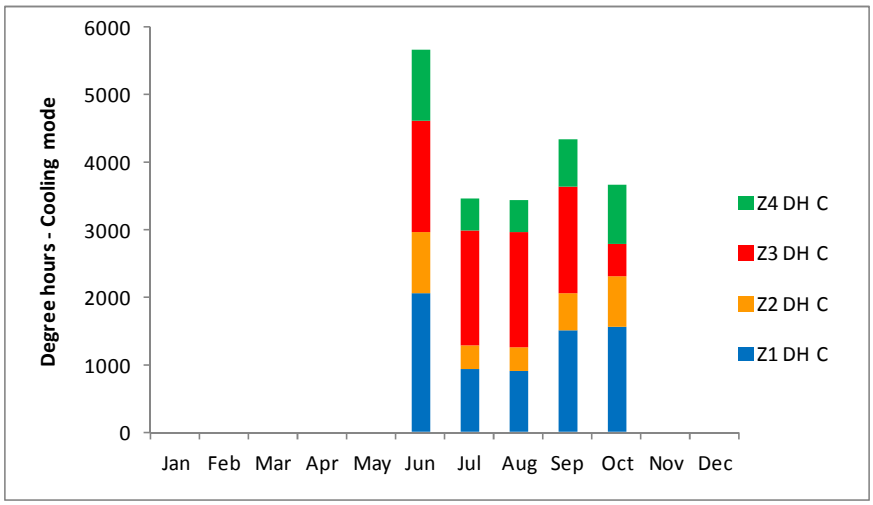

Figure 14 – Control logic 2 results. Degree hours in cooling mode

Table 6 summarizes the main energy and degree-hour results of the 2 control strategies, and compares them against the baseline case. Results of control 1 strategy correspond to the best performing case in the parametric analysis.

Table 6: Summary results. Energy use, degree hours, and relative improvement (%) vs. baseline

	Baseline	Control Strategy 1		Control Strategy 2	
Total heating energy (kWh)	143000	109000	24%	109000	24%
Total cooling energy (kWh)	15900	15500	3%	23500	-48%
Total heating DH	93000	40200	57%	13100	86%
Total cooling DH	44500	27100	39%	20600	53%

Control strategies 1 and 2 result in very similar energy savings in heating mode (24%), however, control strategy 2 achieves much larger comfort benefits, as it reduces degree hours in heating mode by 86%. In cooling mode, control strategy 1 performs slightly better than the baseline in terms of energy, while control strategy 2 uses more energy. However, control strategy 2 achieves much larger comfort benefits compared to the baseline.

5 Conclusions

Simulation results show that the AHU installed at Hospital Virgen de las Nieves currently performs poorly both in terms of energy use and thermal comfort (particularly in heating mode). Reliability of the baseline results is somewhat limited due to the lack of data of water-flow rate though the conditioning coils. Nevertheless, baseline results are a good illustration of the performance limitations of the currently implemented control system.

Control strategy 1 (fixed plenum setpoints) provides a better balance between the relative contributions of the 2 conditioning coils. Results show that in heating mode thermal energy use decreases by 24% and degree-hours decrease by 57%. Benefits in cooling mode are smaller.

Control strategy 2 (variable plenum setpoints) has a similar energy performance than control strategy 1 in heating mode, but achieves much better comfort results. In cooling mode this

strategy uses more energy than control strategy 1 and even the baseline, however it does so in benefit of comfort.

Overall, both control strategies show large benefits compared to the baseline, both in terms of energy savings and thermal comfort. Control strategy 2 should be the choice to better satisfy comfort needs.

6 Acknowledgements

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ANNEX D – ESTUDIO DE LAS PERDIDAS ENERGETICAS ASOCIADAS A CLIMATIZACION DEL AIRE DE RENOVACION

Cubi, Eduard, Josep Piquer, Marius Gamissans, Christoph Peters (2012). “Estudio de las perdidas energeticas asociadas a climatizacion del aire de renovacion”. El Instalador. 499, 18-26.

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