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.

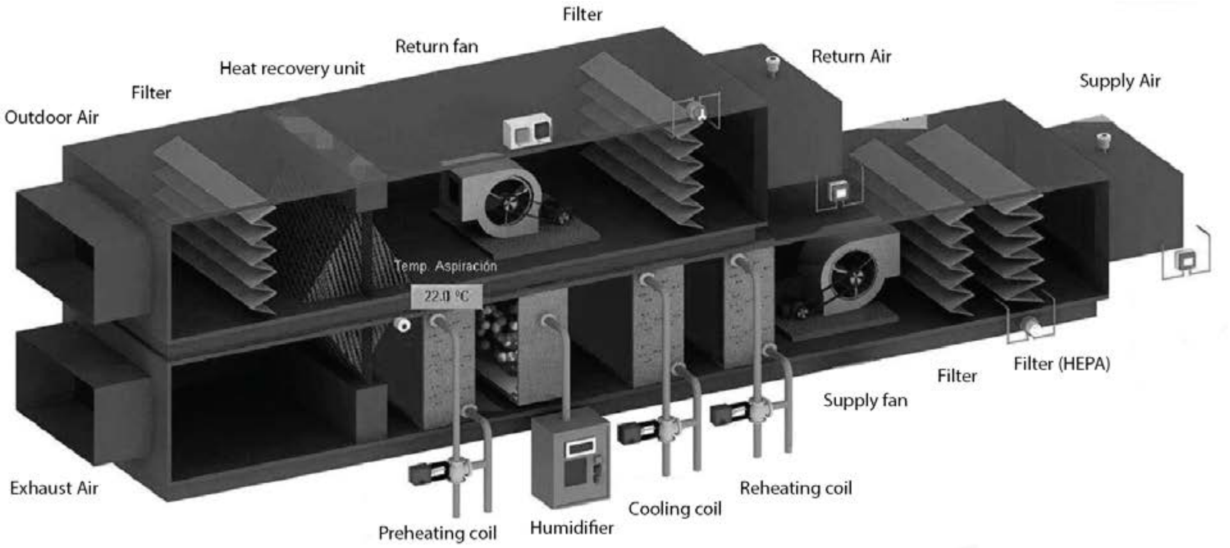

Figure 1- AHU schematic

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^{o}C-25^{o}C range (the default is 22^{o}C), however, the allowed temperature deadband is constant at ± 1^{o}C.

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 $20^{0}C \pm 5^{0}C$ 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 15-25ºC 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 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 = 22ºC ±1ºC	3,200m^3/h	3,200m^3/h

		Relative humidity = 50%±5% Continuous operation (24/7)	Continuous operation (24/7)	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)
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%	Occupied: 3,200m^3/h when particle concentration (0.3μm) is ≥10,200ppm. 1,600 m^3/h when particle concentration (0.3μm) is	Occupied: 3,200m^3/h when particle concentration (0.3μm) is ≥10,200ppm. 1,600 m^3/h when particle concentration (0.3μm) is

		Continuous operation (24/7)	≤3500ppm. Proportional airflow control in between limits Not occupied: 500m^3/h	≤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 = 22^0C ±1^0C Relative humidity = 50%±5% Not occupied setpoints: Temperature = 20^0C ±5^0C 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 = 22^0C ±1^0C Relative humidity = 50%±5% Not occupied setpoints: Temperature = 20^0C ±5^0C 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.

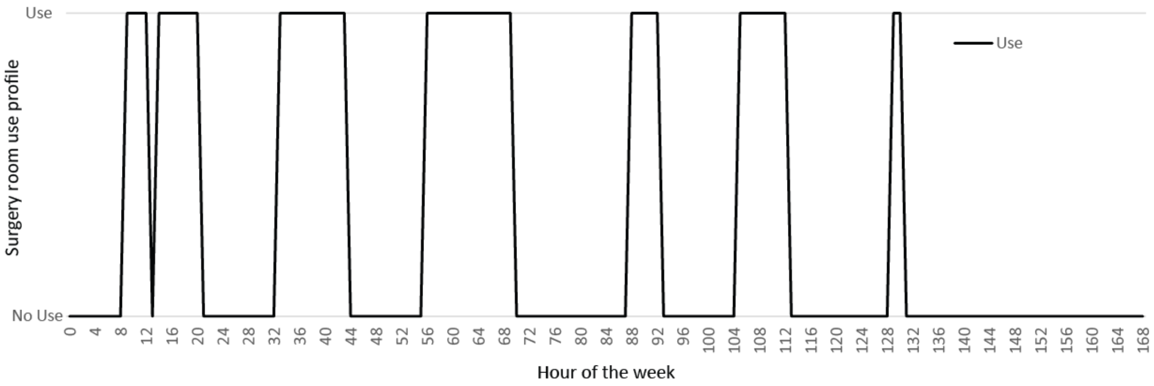

Figure 2- Surgery room occupancy profile (based on activity monitoring during the May 5-11, 2014 week)

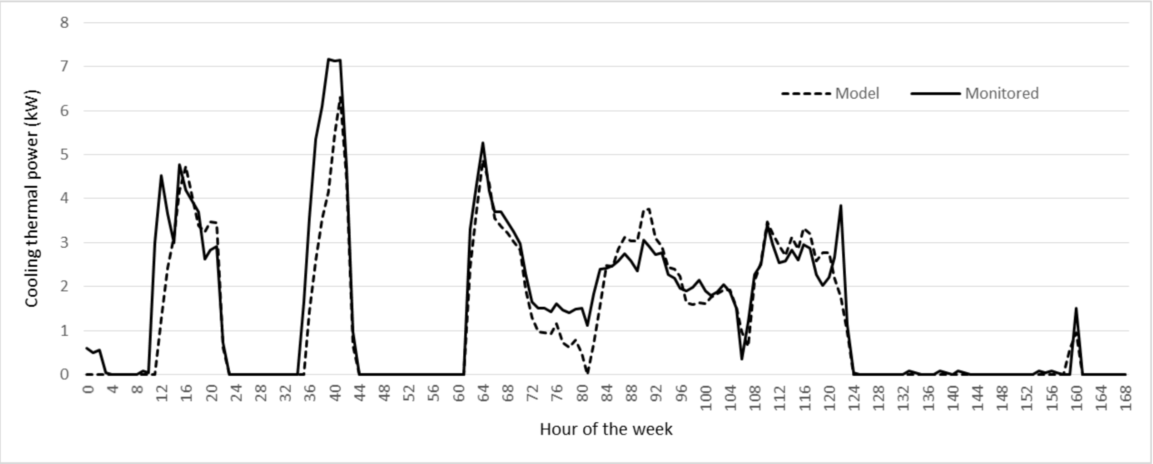

Figure 3- Cooling thermal power. Monitored values vs. model results (April 28-May 4, 2014)

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^{0}C) and 1450 SI Heating Degree Days (HDD, base 18^{0}C), 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^{0}C and 0^{0}C, 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.

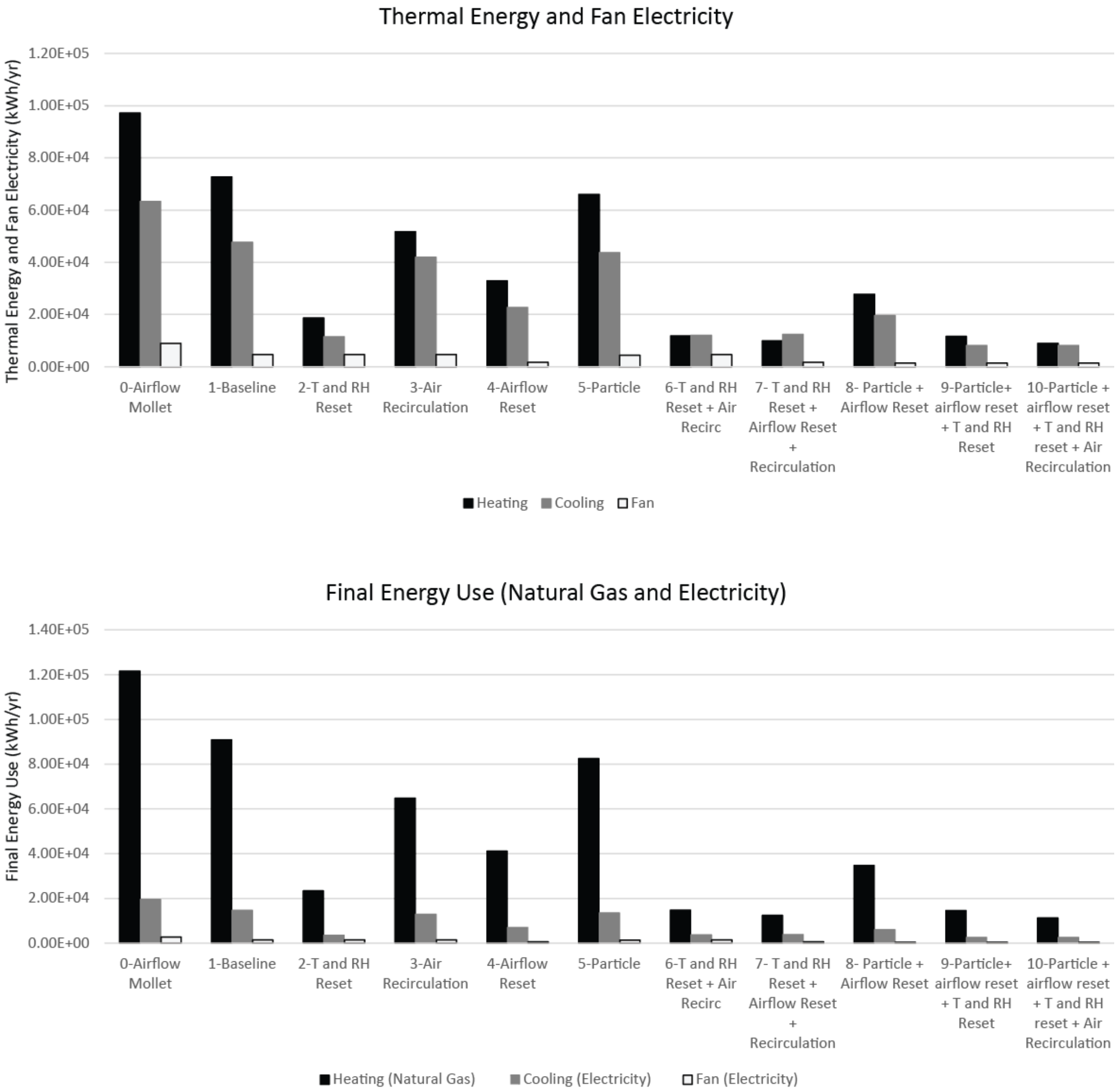

Figure 4- Thermal and final energy use

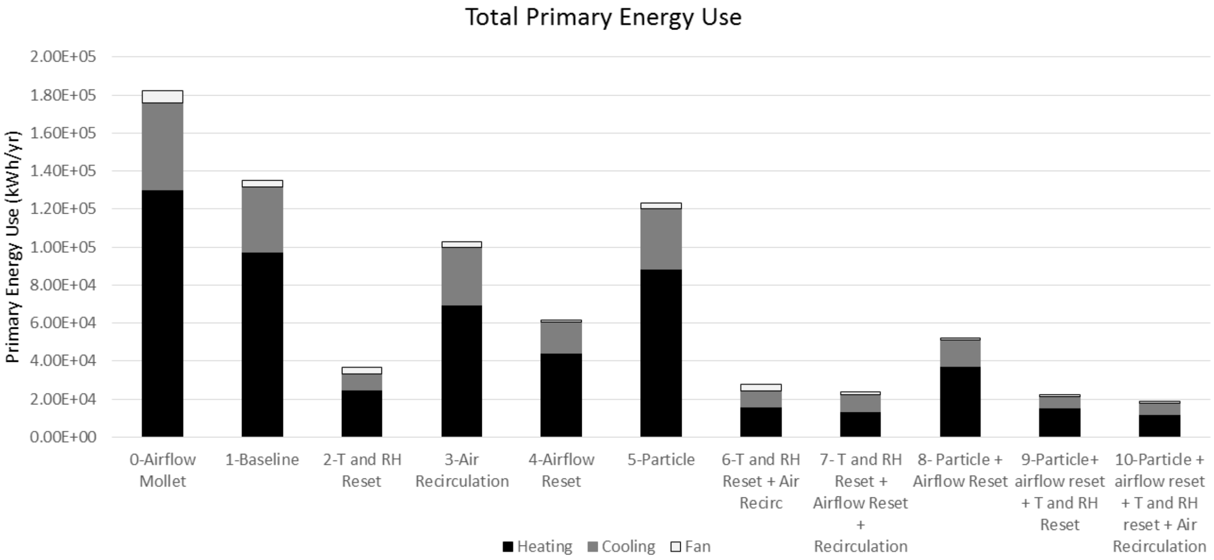

Figure 5- Primary energy use

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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