Energy saving opportunities in operating theatres: a literature study

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Operating theatres are very strictly-controlled environments where any changes that are being introduced can have a direct impact on people's lives. The challenge of this research lays in providing solutions for energy savings which do not disturb the infection prevention measures and help maintain high quality of the surgery.

Keywords: Energy Savings, Hospitals, nZEB, Operating Theatres, Ventilation, Sustainable Healthcare, Infection Prevention

The health care sector is highly energy intensive. Worldwide, circa 6% of the total energy consumption in the buildings sector is represented by energy usage in medical centres. For this reason, hospitals strive to reduce their consumptions and CO_2-emissions. In order to meet the requirements, set by the European Union Energy Performance of Buildings Directive (EPBD), all buildings (residential and utility) need to comply to Nearly Zero Energy Building requirements according the EPBD [1]. Previous study [2] has looked into energy consumptions of various spaces within a hospital and concluded that for Dutch hospitals the energy reduction potential seems to be the highest in isolation rooms and operating theatres (OTs). For the OTs the highest energy consumption is attributed to the amount of supplied air, energy used for fans and the time that surgery rooms are in operation.

Methodology

In this study the possibility to reduce energy consumption in the OTs is investigated, using an approach that puts the human and his safety in the centre of attention. Most important factors in infection prevention are therefore categorized into four groups, the so called 'four Ps': pathogens, people, practice and place (**Figure 1**).

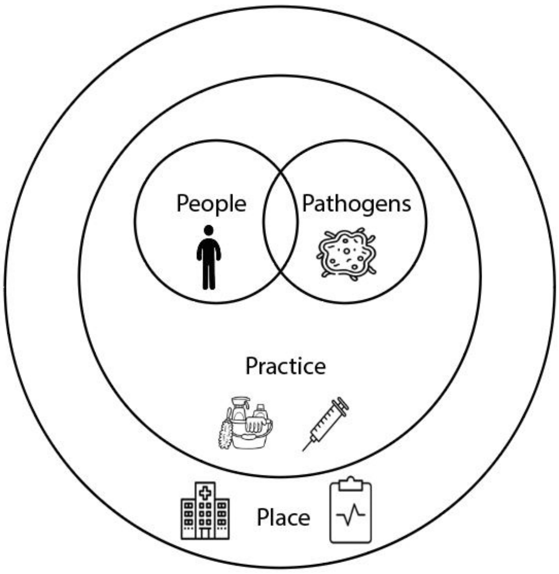

Figure 1. Four "Ps" of infection prevention.

In the Netherlands, a commonly used approach for an energy-efficient building design is the three-step strategy called 'Trias Energetica' [3]. Due to increasing concern and evolution of techniques, the 'Trias Energetica' has been upgraded to a 'Five-Step Method' [RHDHV], as can be seen in **Figure 2**. The additional steps to the original approach are: user demand and behaviour (point 1) and energy exchange and storage systems (point 4). The former step implements the 'user-oriented' concept through smart building designs and controls. The focus on the user and his primary process results in possibilities for improvements of indoor climate as well as productivity. Furthermore, it can substantially decrease energy use. This idea is further developed in this research. By investigating the parameters needed to create a safe environment, starting from the most basic layer such as bacteria transmission, the project aims to draw conclusions on the actual requirements for a healthy indoor environment in the OT, questioning the current standards. Is such a high air exchange rate necessary? Are current systems the most efficient infection prevention methods? How can the OT be optimized for a high surgical performance? These questions can only be answered by understanding the actual needs of this specific environment, therefore the focus on user demand and behaviour is crucial.

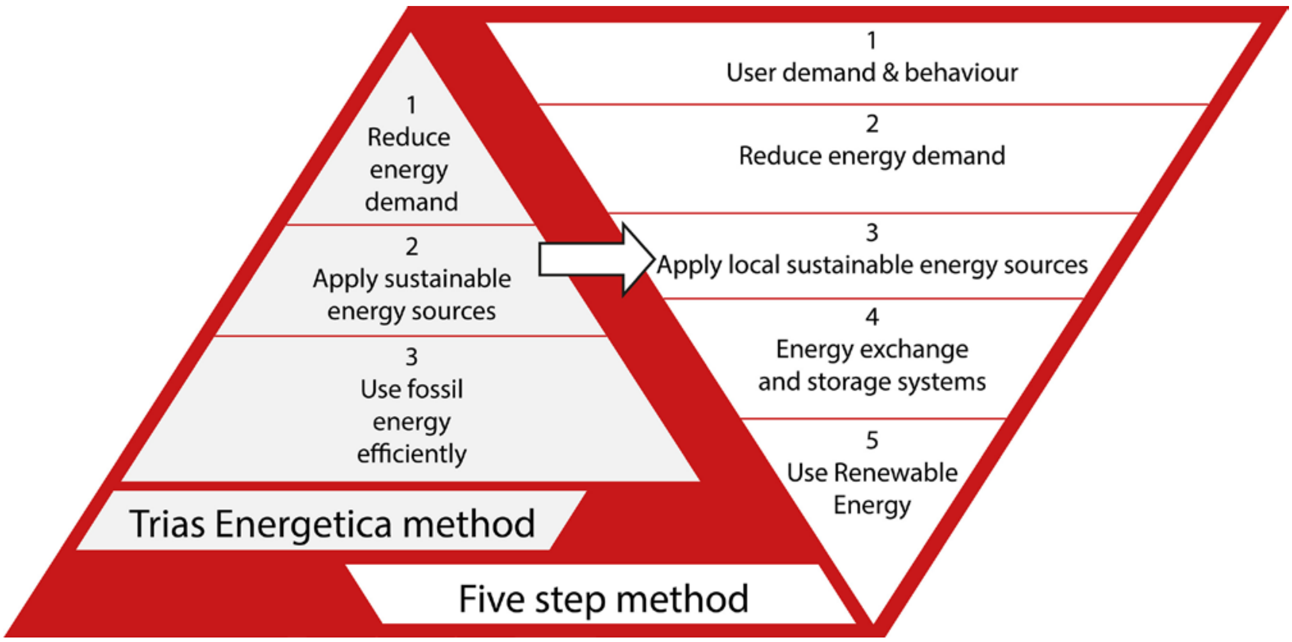

Figure 2. Building design approaches: 'Trias Energetica' versus the upgraded 'Five Step Method'.

Pathogens

The total annual number of patients that suffer from surgical site infections (SSIs) amounts to 1.12% for European hospitals [4]. Inside the operating theatre, bacteria can reach the wound either by dislocation within patient's own microbiota, through air or from poorly disinfected tools. The shedding of bacteria from staff's skin is considered one of the biggest potential sources of wound contamination [5]. Each person sheds around 10,000 skin particles per minute into the air while walking. Approximately 10% of these are estimated to carry bacteria [6]. Skin fragments carrying bacteria have an average size of 12 µm (range between 4–60 µm). Surgical-site contamination by airborne particles is ascribable in 30% of cases to direct settling of the particles on the wound and in 70% of cases to settling on the instruments and surgeon's hands followed by transfer to the wound [7].

There are several environmental factors that may impact the infection acquisition, from which four are of relevance in the operating theatre: relative humidity (RH), temperature, air speeds and movement intensity of the particles. There is research showing that maintaining the humidity levels in the range between 40 and 60% can be related to decreased infection rates in hospitals [8],[9]. This is due to lower possibility of droplets to remain suspended in the air for prolonged periods of time, prevention of mucous membrane from drying out, shorter life span of bacteria and viruses in such conditions and lack of accumulation of static electricity with higher humidities [10],[11].

On the other hand, professionals argue that relative humidity is not of such importance and there is no need to pay close attention to its levels.

People

While the primary focus of indoor environment in operating theatres is on infection prevention, thermal comfort of the workers tends to be generally overlooked. Study performed by Ilse Jacobs focused on the thermal sensation of surgical staff members in OTs equipped with different ventilation systems [12]. The conclusion of the research was that surgeons tend to feel from slightly warm to hot, anaesthetists and nurses from slightly cool to cold, and the patient from slightly cool to very cold. Only the surgery-assistant experiences a comfortable environment with the current environmental and clothing parameters according to Van Gaever et al. [13].

When it comes to the patient, a study by Khodakarami et al. stated that the temperature must not drop below 21°C [11]. However, a temperature above 23°C already becomes intolerable for the surgical staff. During an operation, body temperature is lowered due to open body wounds, infusion of cold fluids, inhalation of cold gases and lowering muscle activity or because of the pharmaceutical agents given to the patient. Even mild hypothermia can lead to numerous complications, which might lower the resistance to surgical wound infection [14]. A 36% decrease in infection rates was observed by Melling in patients who received some form of warming during the surgery [15].

Practice

In an environment where anaesthetic measures are suppressing immune system of a patient and a direct contact between him and OT staff is frequent, failure to maintain highest standards of (hand) hygiene can result in increased infection risk.

Table 1 summarizes factors associated with surgical-site infections. The icon representing a group of people means that a factor is related to discipline. Icon with a piece of paper shows the connection to rules and regulations. Icon with a light bulb means the relation with the skills of the operating team.

Table 1. *Factors associated with surgical-site infection.*

Operation characteristic	
	Inadequate surgical team preoperative hand and forearm antisepsis
	Inappropriate or untimely antimicrobial prophylaxis
	Inadequate sterilization of instruments
	Contaminated OT environment
	Inappropriate surgical attire and drapes
	Inadequate preoperative skin preparation
	Inappropriate preoperative shaving
	Poor surgical technique: excessive blood loss, hypothermia, tissue trauma, entry into a hollow viscus, devitalized tissues etc.
	Excessive duration of operation

Table 2 shows an overview of some of the factors that influence the occurrence of surgical site infections. It has to be noted that these values vary between studies and very often it is hard to estimate their role in reduction of SSI rates due to complexity of the surgical environment and too many factors that are mutually dependent. For some positions, for example surgical clothing, such an estimation was not possible, therefore these were not included in the table.

Place

Operating theatres can be classified depending on their performance as suitable for high-risk operations or not. Ventilation system which is installed in a given OT is responsible for providing clean air and maintaining the quality of the environment according to the class of the room.

In general, there are two main ventilation principles that are applied in OTs: mixing ventilation (turbulent mixed airflow TMA) and displacement ventilation (unidirectional flow UDF), as presented on **Figure 3**. Turbulent mixed airflow supplies turbulent streams of HEPA filtered air through diffusers on the ceiling, therefore creating a mixed ventilation in the whole space of an operating theatre. The system is based on dilution principle, which results in exponential decay of high concentrations of airborne microbes over time [19]. Second type is a system supplying conditioned air in a parallel stream to the surgical field. The streams of air move in parallel layers and, with equal speed of around 0.4 m/s, reach the operating table. This creates a sort-of protective curtain of airflow surrounding the surgical site. Apart from traditional systems, recent years have seen the emergence of new systems, based on mentioned principles. Halton Vita OT Space is a system that has been developed on mixing principle in the year 2015 and is presented on **Figure 4**.

Table 2. Influence of various factors on the decrease in surgical site infection rates [16],[15],[17],[18].

Influencing factor	Decrease in SSI rates
Hand hygiene	13-54%
Proper antibiotic use	26-92%
Occurrence of hypothermia	36%
Preoperative showering with chlorhexidine	24.4%
Type of intervention	up to 83.7%
Health state of the patient	up to 86.4%

The controlled dilution effect is created by circumferential air supply directed both inward towards the operating area and outward towards the room periphery. The emissions generated in the room periphery are diluted by additional air supplied to periphery zone. Based on room dimensions, operational needs and thermal comfort, airflow pattern can be adjusted. An example of a recently developed system working on the principle of UDF is Optimus Integrated Surgical Environment shown on **Figure 5**. In this approach the entire operating complex is integrated into one solution, including lighting, web cams, sensors, microphones and surgical cameras. The room air volume will be replaced 30 times per hour at very low velocities [21].

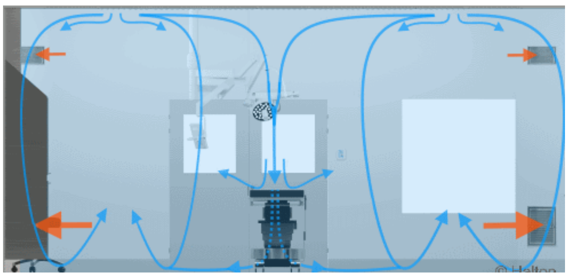

Figure 4. Halton - mixing ventilation principle [20].

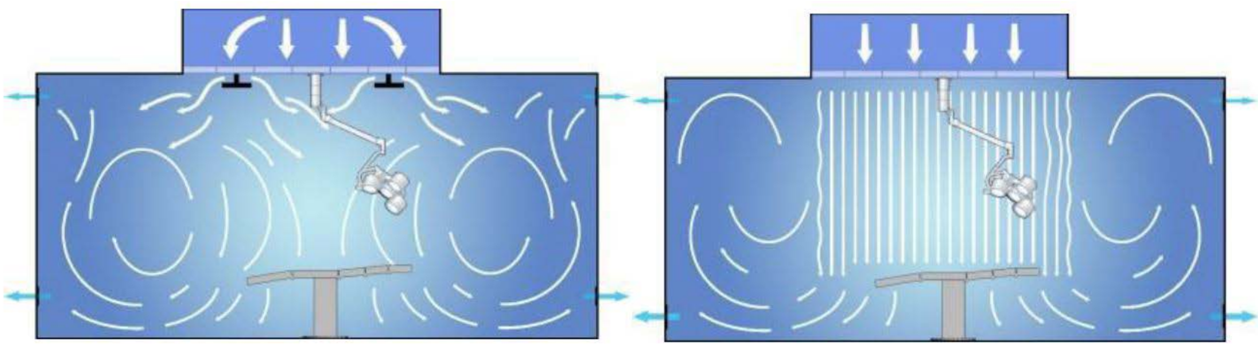

Figure 3. Flow patterns for the TMA (left) and UDF (right) ventilation systems [12].

A system called Opragon (**Figure 6**) is based on a modification of UDF - Temperature controlled Laminar Airflow (TAF). In this solution slightly chilled, HEPA-filtered air is introduced to the room and distributed by low impulse, half-spherically shaped air showers. They are mounted in a circle, creating an ultra-clean zone. Outside of the zone, eight additional diffusers are mounted on the ceiling, preventing stagnation zones in the periphery of the room. Higher density of chilled air causes it to fall to the floor at a speed controlled by the difference in temperature between the added air and the air at the level of the operating table. The temperature difference of −1.5 to −3°C between the added ultra-clean air and the surrounding air in the room at the operating table level needs to be maintained in order to guarantee a speed of around 0.25 m/s at the operating table level [22].

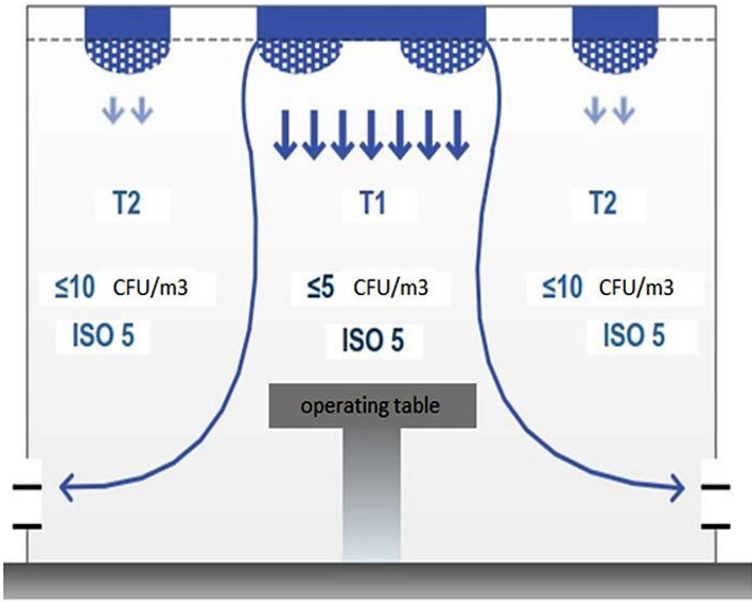

Figure 6. Opragon ventilation system based on TAF principle.

Figure 5. Optimus Integrated Surgical Environment – UDF ventilation principle [21].

The temperature gradient drives the central vertical flow of cooled air. The air showers located in the outside zone provide control of the room temperature, therefore there is no need for additional heating system, like in a laminar downflow. A comparison between three mentioned systems is presented in **Table 3.**

Conclusions and energy saving measures

Having conducted the literature research by starting from the human perspective it is possible to distinguish new strategies for energy reduction and process improvement. Traditionally the design of the operating theatres is based on many steady-state parameters, while in practice these values vary greatly. Aspects such as hand hygiene, skin shedding of the staff, parameters of the clothing (in case multi-use attire is used), movement of the staff etc. cannot be approximated with one number since they differ everyday depending on the team. Moreover, environmental factors such as relative humidity and indoor temperature can play a role in the spread of pathogens. When it comes to the systems themselves, their design parameters such as the location of inlets/outlets or location of heat sources in the room can greatly alter the way bacteria is transported within the OT.

It is therefore crucial for the engineers and designers of the OTs to be able to understand the way that bacteria travels in space and reaches the wound area of the patient. With better understanding of these mechanisms, ventilation systems could be adjusted to provide more precise and more energy-efficient solutions. However, before the research on the bacteria transmission is completed, there are several energy saving measures that can already be implemented in the hospitals:

- Airflow control based on particle concentrations,
- Variable temperature with the outdoor weather,
- Turning down the system for the night,
- Better planning of the use of OTs based on operation type,
- Removing humidification,
- Increased air recirculation.

One of the energies saving measures is airflow control based on particle concentrations. This energy saving measure at the same time provides increased infection prevention. By putting a real-time particle counter in the vicinity of the wound, it is possible to get an immediate feedback on the number of particles in that area. Although there is no direct correlation between the number of particles and the amount of colony forming units, bacteria always need a particle on which it can settle. Therefore, we can assume that if there is no or very little particles in the air, the chance of finding bacteria is also very low. Having a real-time feedback enables the system to reduce the amount of air if there are no particles in the air and increase it in case there is a significant of particles, thus improving infection prevention. This approach is in line with the statement that OTs design cannot be based on steady-state parameters. By the real-time measurement, the ventilation system can be adjusted to the current situation and its needs. Another measure is related to changing the absolute temperature inside the OT based on the outdoor conditions. Even though the temperature difference between the inlet and outlet air inside the room needs to be kept the same, the absolute values can vary with seasons, allowing for energy savings. Third measure is related to turning down the ventilation system for the night and it has been studied by Dettenkofer et al. [23]. The authors have concluded that shutting down OT ventilation during off-duty periods does not appear to result in an unacceptably high particle count or

Table 3. *Comparison of three ventilation systems [19].*

Description	Turbulent mixing	Unidirectional flow	Temperature controlled airflow
ISO class in the centre of the OR (steady-state)	7	5	5
ISO class in the periphery of the OR (steady-state)	7	7	5
Protected area	No	Yes	Yes
Recovery time <3 min	No	Yes	Yes
Type of flow	Turbulent	UDF	UDF
Acceptance for class Ia surgeries	No	Yes	Yes
Average airflow (m^3/h)	3 200 m^3/h	12 000 m^3/h	5 600 m^3/h
Recirculation of air	0%	70%	45%
Noise level in empty room	45 dBA	58 dBA	48 dBA
Ventilation power	2.8 kW	8.0 kW	5.7 kW
CFU/m^3 median(range)	10 (0-162)	0 (0-16)	1 (0-29)

microbial contamination and if the system is restarted 30min before the scheduled operation, high levels of air quality will be maintained. Fourth possibility is related to improved planning within the hospital management. Not all operations need to be conducted in the highest performance OTs, for which the energy consumption is very high in order to provide the highest levels of air cleanliness. If a classification of operation types is created, they could be distributed between two performance classes of the OTs, leading to energy savings. Last two measures are already being widely implemented in the USA with positive results regarding energy savings.

The article shows added value the approach was the focus on energy conservation begins primarily with the human needs and process conditions needed to supply a productive, healthy and comfortable indoor environment. Starting from the essential human and process needs it leads to an analysis resulting in relevant energy conservation possibilities. ■

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