Highlights

- Develop a new suitability evaluation method for operating room ventilation systems.
- Considers ventilation effectiveness, energy consumption and users' satisfaction as a whole.
- Evaluation results may provide guidance for ventilation system commissioning.
- Proposed evaluation framework has flexibility and scalability on specific indicators.

Suitability evaluation on laminar air flow and mixing airflow distribution strategies in the operating rooms: A case study at St. Olavs Hospital

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Abstract

Operating room (OR) is an indispensable department in hospital, while the ventilation system is an important engineering solution ensuring adequate indoor air quality for surgical procedures. Suitable ventilation system in ORs should be defined as using the minimum energy consumption and lifecycle cost to meet both the requirements of clean air for safe surgeries and comfort for occupants. Therefore, the evaluation of the ventilation system performance in ORs should be carried out from a holistic view instead of one aspect only. This study aims to develop a flexible evaluation framework for the suitability evaluation for ventilation systems in ORs. To achieve the objective, we adopted analytic hierarchy process (AHP) and fuzzy comprehensive evaluation (FCE) methods and conducted suitability evaluation for two ORs with laminar air flow (LAF) and mixing ventilation (MV) system in St. Olavs Hospital, Norway. The evaluation includes seven indexes under three main aspects: ventilation effectiveness, energy consumption and users' satisfaction. The comprehensive evaluation results are obtained through site measurements during mock surgeries, data collection and calculation as well as the questionnaire survey. The evaluation result of the suitability performance of the OR with MV system was "unsuitable" while the one with LAF system was "suitable". Main reasons involve the unsatisfactory performance in energy consumption and thermal comfort indexes. The evaluation can provide basis for the commissioning of the ventilation system in the ORs of St. Olavs Hospital and provoke thinking of the ventilation system design and operation in the future.

Key words: air distribution strategy, operating room, suitability, evaluation

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Abbreviation		
MV	Mixing ventilation	
LAF	Laminar air flow	
AHU	Air handling unit	
OR	Operating room	
BC	Bacterial concentration	
NL	Noise level	
PC	Particle concentration	
RH	Relative humidity	
TC	Thermal comfort	
Notation	**Definition**	**Unit**
A	the area of OR	m^2
$G_{\text{AHU outlet}}$	the mass air flow rate from air handling unit (AHU) outlet into a room	kg/h
$G_{\text{return air}}$	the mass flow rate of return air	kg/h
G_{supply}	the mass air flow rate of supply air	kg/h
$G_{\text{total AHU provide}}$	the mass air flow rate that AHU provided	kg/h
$h_{\text{AHU outlet}}$	the specific enthalpy of the air from air handling unit outlet	kJ/kg
h_{mix}	the specific enthalpy of mixed air	kJ/kg
$h_{\text{outdoor air}}$	the specific enthalpy of outdoor air	kJ/kg
$h_{\text{return air}}$	the specific enthalpy of return air	kJ/kg
h_{supply}	the specific enthalpy of supply air	kJ/kg
P	the full pressure of the fan	kPa
Q_{f}	the air flow volume delivered by the fan	m^3/h
Q_{supply}	the air volume of supply air in the target OR	m^3/h
$Q_{\text{total AHU provide}}$	the total air flow rate provided by the AHU which may covers several ORs	m^3/h
$\text{R}_i = \{r_{i1}, r_{i2}, \dots, r_{im}\}$	the membership degree vector	
$\text{S} = (s_1, s_2, \dots, s_n)$	the fuzzy comprehensive evaluation vector	
t	the calculation period	h
$\text{U} = \{u_1, u_2, \dots, u_n\}$	the set of evaluation indexes	
$\text{V} = \{v_1, v_2, \dots, v_m\}$	the set of comments for each index	
$\text{W} = \{w_1, w_2, \dots, w_n\}$	the weight vector of evaluation indexes	
W_{AHU}	the electricity consumption of air handling process from AHU	kWh
W_{average}	the daily average electricity consumption of ventilation system in OR per square meter	kWh/m^2/day
W_{f}	the electricity consumption of fans in total	kWh

$W_{\mathrm{f}(i)}$	the electricity consumption of fans in the i-th 10-min data logging interval	kWh
W_{h}	the electricity consumption of air handling process	kWh
$W_{\mathrm{h}(i)}$	the electricity consumption of air handling process in the i-th 10-min data logging interval	kWh
W_{s}	the electricity consumption of fans per unit volume air	kWh/m^3
W_{terminal}	the electricity consumption of air treatment in terminal devices	kWh
W_{total}	the total electricity consumption of ventilation system in an OR	kWh
$W_{\mathrm{total}(i)}$	the total electricity consumption of ventilation system in the i-th 10-min data logging interval of the OR	kWh
η	the efficiency of the fan	%

1. Introduction

Operating room (OR) is one of the most essential departments in hospital that closely related to the health and lives of the patients. Among factors affecting surgical procedure, clean environment is the important guarantee to reduce the rate of surgical site infections (SSIs), which accounts for nearly 36% of nosocomial infections [1]. A research reported that the air in the ORs is considered as a route for microbes to enter surgical wounds [2]. Normally, there are two types of ventilation systems used in providing an adequate indoor environment that meets the requirements according to different type of surgeries. For mixing ventilation (MV) system, the supply air is quickly and evenly mixed with air in the indoor environment to dilute pollutants in the entire room; while for laminar airflow (LAF) ventilation system, an unidirectional, low-turbulence downward airflow is delivered by large surface over the operating area, creating protective airflow around the patient. It is generally believed that LAF system has better performance to remove bacteria [3,4], therefore it has been used in special types of surgeries which associates with a high risk of infection like prosthetic implant, organ transplantation, complex surgical oncology, neurosurgery, cardiovascular surgery etc. [5]. But the controversy of SSI and LAF ventilation exists in some literatures [6-8], and the World Health Organization (WHO) has required that the LAF ventilation systems should not be used to reduce the risk of SSI for patients undergoing arthroplasty surgery in the standard “Global guidelines for the prevention of surgical site infection” [9] issued in 2016.

On the selection of air distribution strategies, ASHRAE standard 170-2017 [10] requires airflow in surgical cystoscopic rooms and caesarean delivery rooms shall be unidirectional, downwards. In Germany standard DIN 1946/4 [11], ultra clean room class Ia requires supplying air with low turbulence air flow, while for room class Ib and II, turbulent air distribution can be adopted. However, regardless of the ventilation strategy adopted, the cleanliness, temperature and humidity of the indoor environment brought about by the ventilation in ORs often draw much attention. Among those aspects, bacteria concentration is a commonly adopted index in the assessment of OR environment and is specified in many related national standards. Colony-forming unit (cfu) is a unit used to estimate the number of viable bacteria or fungal cells in a sample. While, particle matter concentration is another important parameter in predicting wound contamination in clean surgery [2]. Studies have shown that particles may be responsible for some postoperative complications like adhesion and granuloma [12]. In ISO standard 14644 which is used for classifying cleanrooms and associated controlled environments, the size of controlled particles can be 0.1 μm, 0.2 μm, 0.3 μm, 0.5 μm, 1.0 μm and 5.0 μm. As patients often have large open wounds during operations, special requirements of temperature and relative humidity are necessary to avoid the wound dehydration, patient hypothermia or the uncomfortable nose and throat for surgical team members if the operation process lasts long. To ensure the rationality of ventilation design and indoor environment quality, most countries developed their own national standards and guidelines, which may include the above parameters as well as pressure difference, the minimum total air change rate as briefly listed in Table 1.

Table 1

Parameter requirement in different standards for operating rooms

Country	Standards	Temperature	Relative humidity	Pressure difference	Minimum air change rate	Applicable OR types
The U.S.	ASHRAE 170	20-24℃	20-60%	4 Pa	20 ACH[1]	Class B/C
The U.K. [13]	HTM 03-01	18-25℃	35-60%	25 Pa	25 ACH	General/UCV[1]
Germany	DIN 1946/4	19-26℃	30-50%	Not specified	2400 m^3/h	Class 1b
					9200 m^3/h	Class 1c
Norway [14]		Not specified	Not specified	5-10 Pa	20 ACH	Not specified
China [15]	GB 50333	22-25℃	40-60%	5-20Pa	18 ACH	Class III, II, I
Spain [16]	UNE100713	22-26℃	45-55%	5-20Pa	20 ACH	Type A/B
France [17]	NF S 90-351	19-26℃	Not specified	10-25Pa	——	Not specified

[1]ACH=air changes per hour [2]UCV=ultra clean ventilation

In addition to a safety indoor environment, the ventilation system in OR is also responsible for a pleasant working environment for surgical team members [18]. Although designers have been struggling to make it a perfect system, complaints from patients, surgeons or nurses about the discomfort environment during operation still exist [19,20]. A study conducted by Belgian scholars demonstrated that surgeons and nurses have different thermal sensations for the same surgical room; it is suggested that ventilation conditions should be revised according to the number of persons in the room and the type of activity performed. With similarities to thermal comfort, the energy consumption is also an negligible parameter but not included in most of the specifications. It is proved that ORs have become one of the most energy intensive parts in hospital [21,22], where the electricity consumption for air conditioning is three times higher than that in the general areas and can takes about 3.02% of the total electricity consumption of the whole building [23]. Reasons can be the nearly 24-hour running time, full air-conditioning, the three stages of filtration in terminal devices and air handling units (AHUs) as well as high ventilation rates [24], for example, the air change rate of LAF operating theater is usually 2–5 times higher than in typical building spaces [25]. Research also shows that the electricity consumption of AHUs in ORs could reach 364 kWh/(m^2·yr) with extremes up to 1275 kWh/(m^2·yr) for continuously operated AHUs [26]. Meanwhile, the high initial cost and maintenance cost also put great pressure on hospitals and administrators, as an increase of 24% in the building costs and of 34% in the annual operating costs for the ultraclean system versus the conventional one [27]; a decision to used 25 ACH to be safer rather than 20 ACH could cost the hospital an additional 7330 dollars per year per OR [28].

Therefore, it can be seen that the performance of the OR ventilation system is multifaceted, the actual expectations of designers, surgical teams, operation and maintenance personnel for OR ventilation systems simultaneously include safety, comfort, and energy saving. However, many studies on the performance of OR ventilation system are still relatively one-sided and insufficient. Gormley et al. [29] and Wagner et al. [30] respectively proposed and applied the environmental quality indicators (EQIs), but only to assess the ventilation from the environmental aspect. Ozyogurtcu et al. [31] conducted the economical assessment of different HVAC systems for ORs in Turkey, where the life cycle cost (LCC) were considered and suggested that annual energy analysis should be performed before the final decision is made on the HVAC system. Swedish scholars Alsved et al. [32] evaluated three types of OR ventilation system which included a newly developed temperature-controlled airflow (T_cAF) technic from with respect to air cleanliness energy consumption and comfort of working environment (noise and draught), however, it failed to form a set of methodology as well as evaluation criteria to provide reference for future evaluation. Accordingly, there is an urgent need for a multi-dimensional decision making system when consider the performance of OR ventilation system especially in the context of building green.

This study aims to develop an evaluation method from a holistic view to assess the suitability of different air distribution strategies and take the ORs at St. Olavs Hospital in Norway as a case study. The method considers these following principles: cleaner surgical environment, more comfortable working environment and less energy consumption. With statistical analysis on actual operation data, benchmark for energy consumption level can be obtained [33]. The assessment model of the study may be used to provide guidance for the commissioning of ventilation system and the selection of reasonable ventilation system for future designers.

2. Methodology

2.1. Evaluation framework

Considering the evaluation problem in this study, the suitability assessment of ventilation performance could be considered as a multi-criteria decision making (MCDM) problem. Firstly, the evaluation object is the ventilation system in OR. Then, the core of this evaluation system is appropriate evaluation indicators under three selected aspects in this study; weight distribution of these indicators makes the decision making persuasive and evaluation benchmarks may come from national standards or other methods. According to the characteristic of the indicators, their evaluation value can be obtained through on-site measurements, data collection and calculation as well as the questionnaire survey. Finally, the comprehensive evaluation results will be obtained through multi-criteria evaluation method. Fig. 1 shows the components of the assessment framework.

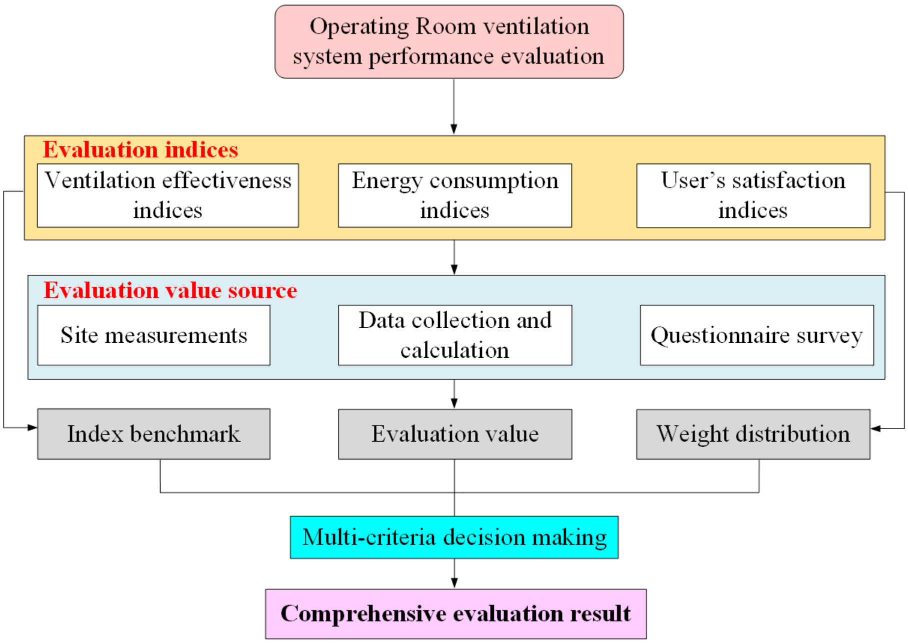


Fig. 1: Evaluation framework

2.1.1. FCE and AHP method

Since suitability seems to have no obvious conceptual boundaries, fuzzy comprehensive evaluation (FCE) method is a reasonable choice as it considers the fuzziness of evaluation index and classification and are able to transform qualitative evaluation into quantitative evaluation according to membership degree theory in fuzzy mathematics. Since several aspects are considered in this study and under each aspect there are sub-indicators, analytic hierarchy process (AHP) method is applicable to determine the weight distribution of each layer and indexes. The advantage of AHP method is that it only requires to compare a pair of elements at any time no matter how many factors are involved in the decision-making process and allows the inclusion of tangible variables (e.g., energy consumption) as well as intangible ones (e.g., user's satisfaction) as criteria in the decision. In order to make the weight distribution persuasive, a group of experts are invited to give judgements in this study.

2.1.2. Evaluation procedures

Procedures of using FCE and AHP method to realize the evaluation function are as follows:

(1) Determine the set of evaluation indexes which can be written as $U = \{u_1, u_2, \dots, u_n\}$.

(2) Determine the set of comments for each index. For example, u_i has its corresponding appraisal grades v_j, then the set of comments is $V = \{v_1, v_2, \dots, v_m\}$. In this study, m=3, V = {unsuitable, moderate, suitable}.

(3) Develop the fuzzy mapping matrix based on fuzzy membership of each index. In the membership degree vector $R_i = \{r_{i1}, r_{i2}, \dots, r_{im}\}$, r_{im} represents the fuzzy membership for each grade. Generally, the membership degree vector of all indexes can be calculated and form an evaluation matrix R.

$$R = \begin{bmatrix} r_{11} & \cdots & r_{1m} \\ \vdots & \ddots & \vdots \\ r_{n1} & \cdots & r_{nm} \end{bmatrix}$$

Two methods may be used to determine the membership degree: for qualitative indicators, fuzzy statistics method is usually adopted based on expert opinions, then the frequency of each index belonging to each evaluation level will be the membership degree; for quantitative indicators, the membership degree can be obtained by developing corresponding membership functions based on the level of each index division according to policy provisions, quantitative standards, historical data or industry experience of the target index. Since different index has different characteristics, possible membership functions can be triangle-type functions, ladder shape functions or Gaussian membership functions.

(4) Determine the weight distribution for evaluation indexes based on the expert survey and AHP method. Following the procedure of building hierarchical structure, experts give opinions to develop pair-wise comparison matrixes through 1-9 scales, consistency check and finally obtain the overall and local index weight distribution. The hierarchical structure of this study is shown in Fig. 2.

(5) Calculate the final evaluation result. By synthesizing the fuzzy matrix and the weight vector as shows in Eq.(1), the vector of fuzzy comprehensive evaluation $S = (s_1, s_2, \ldots, s_n)$ is obtained, where s_j is the membership degree that the evaluation objective belongs to the comment v_j. After standardization, $\sum s_j = 1$, and the largest s_j value corresponding comment is the final evaluation result of the decision problem.

$$S = W \circ R \tag{1}$$

where, $\circ$ is the symbol of fuzzy operator and the commonly used operators are Zadeh operator, weighted averaging operator and bounded operator etc.

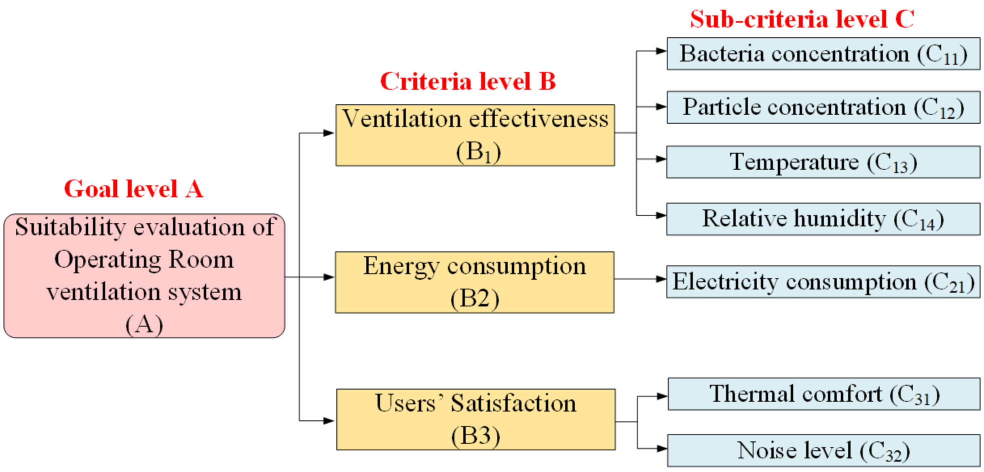


Fig. 2: Hierarchy structure of the suitability evaluation for OR ventilation system

2.2. Evaluation indexes and their benchmarks

Appropriate indexes with reasonable benchmarks are indispensable for evaluation. For the required indicators in national standards, the specified value can be considered as the evaluation benchmark directly; while for the indicators that have not yet been required, it is necessary to refer to the relevant research or the level of existing data according to the characteristics of the indicators.

2.2.1. *Ventilation effectiveness*

(1) Bacterial concentration (BC)

Norwegian Board of Health Supervision requires that general operating theaters should keep the number of airborne microbes beneath 100 cfu/m^3, while ultra clean rooms require 10 cfu/m^3. Therefore, according to the standards, the evaluation grades for bacteria concentration are set separately for LAF and MV system as listed in Table 3.

(2) Particle concentration (PC)

For the convenience of comparison, this study focuses on accumulative number of particles per m^3 of the size 0.5 μm to evaluate the particle concentration in ORs, as it is also considered to be the minimum size to cause cell phagocytosis reactions [34]. The air cleanliness class for normal LAF rooms are Class 5 [29,32] and concentration of 0.5 μm particles need to be less than 3520/m^3; while for the MV system ORs, the class can be 6 or 7, which means the particle concentration shall be less than 35200/m^3.

(3) Temperature (T) and relative humidity (RH)

As shown in Table 1, the requirements for temperature and humidity for ORs in different national standards are slightly different. Since Norwegian standard does not specify these parameters, this study comprehensively considers temperature and humidity requirements in other European standards [16] and chooses their overlapped part as the proper range; the range outside the overlapping region but still within the limit value are considered as moderate.

2.2.2. *Energy consumption*

Different from the above parameters, OR ventilation system energy consumption (EC) has not been specified in standards yet. To develop the energy benchmark for OR ventilation system in St. Olavs Hospital, important parameters during its operation were logged every 10 mins, including fresh and supply air temperature and humidity, air volume, heat recovery efficiency, fan power etc. and the following parts are performed.

(1) Calculate electricity consumption for all 42 ORs in St.Olavs Hospital

In this study, it is considered that the energy consumed by OR ventilation system is the electrical demand and comes from two parts: the fans which are used for delivering air and the process of dealing with air to the required state. Generally, energy consumption of fans W_f can be calculated according to Eq.(2) and Eq. (3); air handling energy consumption W_h may base on Eq.(4):

$$W_\mathrm{s} = \frac{P}{3600\eta} \quad (2)$$

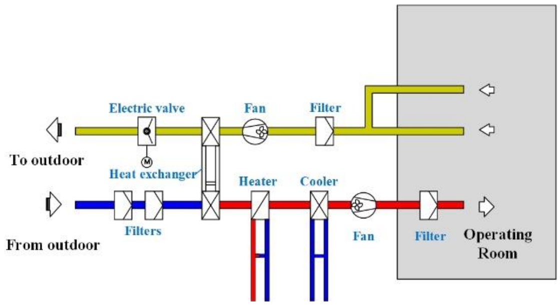
$$W_\mathrm{f} = W_\mathrm{s} \times Q_\mathrm{f} \times t \quad (3)$$

Where W_s is the electricity consumption per unit volume air, kWh/m^3; P is the full pressure of the fan, kPa; η is the efficiency of the fan, %; Q_f is the air flow volume delivered by the fan, m^3/h; t is the calculation period of each situation, h.

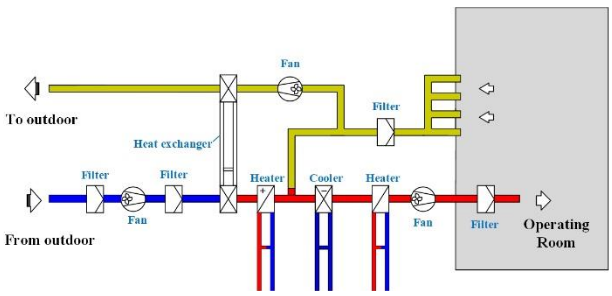
$$W_h = \frac{G_{\text{supply}} \times (h_{\text{supply}} - h_{\text{outdoor air}}) \times t}{3600} \quad (4)$$

Where G_{supply} is the mass air flow rate supplied to the OR, kg/h; h_{supply} and $h_{\text{outdoor air}}$ are the specific enthalpy of supply air and outdoor air, respectively, kJ/kg.

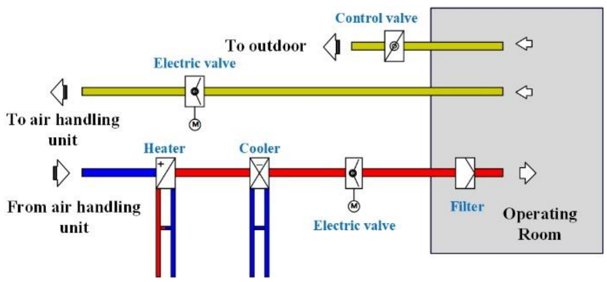
Fig. 3 demonstrates different types of ventilation system forms in St. Olavs Hospital, which should not be neglected during energy calculation.



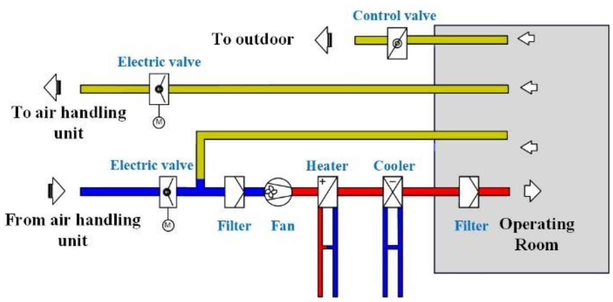
(a) Separately treat air in full fresh air system with heat recovery, being adopted in some MV ORs in St. Olavs Hospital.



(b) Separately treat air in one returning air system with heat recovery, being adopted in some LAF ORs in St. Olavs Hospital.



(c) Intensively treat air in full fresh air system, being adopted in some MV ORs in St. Olavs Hospital.



(d) Intensively treat air in one returning air system with heat recovery, being adopted in some LAF ORs in St. Olavs Hospital.

Fig. 3: Different ventilation system formats in St. Olavs Hospital

(2) Multi-linear regression

Since the energy consumption of ventilation system is influenced by a lot of factors including outdoor temperature, supply air volume, ventilation area, the adoption of heat recovery strategy, the adoption of setback strategy (to reduce the amount of air supplied when the room is not in use) [35], built year etc., multi-regression analysis method is used to establish a prediction model between energy consumption of ventilation in ORs and the affecting variables. This model can be used to estimate the energy consumption under different conditions to make up for the time limitation of collecting energy consumption data in different weather conditions in the target hospital. Local average outdoor temperature in data logging period can be introduced to achieve temperature correction, then the energy consumption results are able to adopt in benchmark determination.

In the multi-linear regression, assume random variables Y and independent variables $X_1, X_2, \ldots, X_p$ ($p \geq 2$) has linear correlations, then empirical model equation can be obtained as:

$$\mathrm{Y} = c_0 + c_1 X_1 + c_2 X_2 + \cdots + c_p X_p + \varepsilon \quad (5)$$

where, c_0 is constant and $c_1, c_2, \ldots, c_p$ are the coefficients of the corresponding dependent variables; ε represents error.

In this paper, multi-linear regression is realized by using software SPSS statistics 25, which can easily achieve correlation analysis and partial correlation analysis. The process of linear regression adopted enter method which directly takes all possible factors into account in the regression equation, then rationality can be judged by the parameters such as regression coefficient, significance coefficient, variance etc. Independent variable which has very weak linearity with dependent variable or who are collinear with other variables should be excluded.

(3) Determine evaluation benchmark

According to Germany standard VDI 3807 *Characteristic Consumption Values for Buildings* [36], the lower quartile mean value (the arithmetic mean value of the lowest 25% of the characteristic value given in ascending order) is considered as the reference value to lead the advancement of energy saving; besides, the median value, which demonstrates the general energy consumption level of most buildings, is also worth consideration. Therefore, this paper considers the average value of the lower quartile as well as the median of energy consumption level as the grading points to show the current energy consumption level among all the ORs in St. Olavs Hospital.

2.2.3. *User's satisfaction*

The ventilation system in OR defines not only the air flow, but also creates an environment to ensure the comfort of surgical team during surgeries. Therefore, thermal comfort and acoustic environment are considered under the aspect of users' satisfaction.

(1) Thermal comfort (TC)

PMV-PPD model has been adopted in ISO 7730 [37] to assess indoor thermal environment, recommending the limit value 0.5<PMV<+0.5, PPD<10%. However, due to the special environment in ORs, different thermal sensation of different roles in the ORs according to literatures, requirements for thermal comfort should be relaxed to some extent. Actual percentage of dissatisfaction (APD) [38] is chosen as an index to reflect the degree of dissatisfaction of the thermal environment, which based on the most specific answer from the participants.

(2) Noise level (NL)

With the large air flow and higher resistance in air ducts, noise caused by the ventilation system can also affect the satisfaction of the surgical team. According to related national standards also mentioned above (HTM 03-01, DIN 1946/4, GB 50333), sound pressure level (SPL) in empty ORs can be selected as the assessment index for acoustic environment.

Based on the above analysis, the suitability evaluation indexes for ventilation strategy in ORs are determined and summarized in Table 2.

Table 2

Suitability assessment factors/sub-factors summary

Criteria level (B)	Indexes level (C)	Assessment criteria	
Ventilation Effectiveness (B_1)	BC (C_{11})	Proper	$\mathrm{BC} \le 6$ cfu/m^3 (LAF)
			$\mathrm{BC} \le 60$ cfu/m^3 (MV)
		Moderate	$6 < \mathrm{BC} \le 10$ cfu/m^3 (LAF)

			$60 < \mathrm{BC} \leq 100$ cfu/m^3 (MV)
		Improper	$\mathrm{BC} > 10$ cfu/m^3 (LAF)
			$\mathrm{BC} > 100$ cfu/m^3 (MV)
	PC (C_{12})	Proper	$\mathrm{PC} \leq 352/\mathrm{m}^3$ (LAF)
			$\mathrm{PC} \leq 35200/\mathrm{m}^3$ (MV)
		Moderate	$352 < \mathrm{PC} \leq 3520/\mathrm{m}^3$ (LAF)
			$35200 < \mathrm{PC} \leq 352000/\mathrm{m}^3$ (MV)
		Improper	$\mathrm{PC} > 3520/\mathrm{m}^3$ (LAF)
			$\mathrm{PC} > 352000/\mathrm{m}^3$ (MV)
	T (C_{13})	Proper	$22 \leq \mathrm{T} \leq 24$℃
		Moderate	$18 \leq \mathrm{T} < 22$℃ and $24 < \mathrm{T} \leq 26$℃
		Improper	$\mathrm{T} > 26$℃ and $\mathrm{T} < 18$℃
	RH (C_{14})	Proper	$40 \leq \mathrm{RH} \leq 50\%$
		Moderate	$30 \leq \mathrm{RH} < 40\%$ and $50 < \mathrm{RH} \leq 60\%$
		Improper	$\mathrm{RH} < 30\%$ and $\mathrm{RH} > 60\%$
Energy consumption (B_2)	(C_{21})	Based on the measured and calculated value.	
User's satisfaction (B_3)	TC (C_{31})	Proper	APD≤10%
		Moderate	10%<APD≤25%
		Improper	APD>25%
	NL (C_{32})	Proper	SPL≤40 dB
		Moderate	40<SPL<50 dB
		Improper	SPL≥50 dB

2.3. Experimental measurements in two case ORs

2.3.1. Operating rooms in St. Olavs Hospital

Field measurements of indoor environment were performed to obtain the evaluation values of some indexes in two ORs at St. Olavs Hospital. OR1 is equipped with MV system in Emergency and Heart-Lung Center and OR 2 in Orthopedic Center is equipped with LAF system, as shows in Fig. 4 (a) and (b). The area of OR 1 and OR 2 is 53 m^2 and 51.84 m^2, respectively. As most of the parameters cannot be measured during real operations, mock surgeries (shows in Fig. 5) need to be conducted to simulate real operating environment. To ensure the repeatability of measurements, mock surgery has its detailed, timed process for the possibility to control influencing factors. In this study, mock surgery movements are designed based on hip arthroplasty.

(a) OR1 (MV) (b) OR2 (LAF)

Fig. 4: Layout of the two case operating rooms

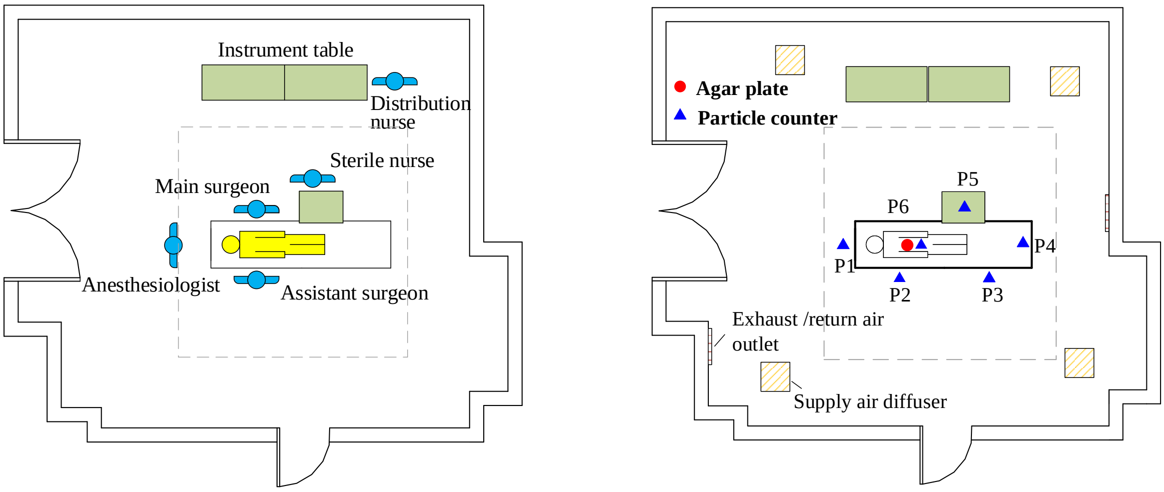
Fig. 5: Mock surgery in OR2 at St. Olavs Hospital

2.3.2. *Equipment*

From the chosen indexes, bacteria concentration is measured by reading colony number on the agar plates after collecting air samples from a calibrated active air sampler Air Ideal 3P (Biomerieux) which sucks in air with 100 L/min. The device was set to draw air for 10 mins for each sample during measurements. Then, the agar plates are covered with lids and incubate for 2 days at 35±2 °C and one day at 23±2 °C. Particle concentration in ORs are measured by using the calibrated TSI AEROTRAK™ Handheld Particle Counter Model 9306-V2. With six channels, the measuring range is 0.3~10.0 μm and the accuracy is ±5%. The particle counter has a flow rate of 2.83 L/min, then 2-min single sample count would be required for each measuring point according to ISO 14644 standard. Air temperature and relative humidity are measured by using factory calibrated Pegasor AQ™ Indoor device, whose measuring range is -20 °C~60 °C and 0~90% RH with accuracy ±0.2 °C and ±1.1%, respectively. Temperature and relative humidity were logged by this device every 10s during measurements. Noise level measurement adopted B&K 2245 Sound level meter, which has the measuring range of 15.2 dB to 140 dB from typical noise with the accuracy of 0.1 dB.

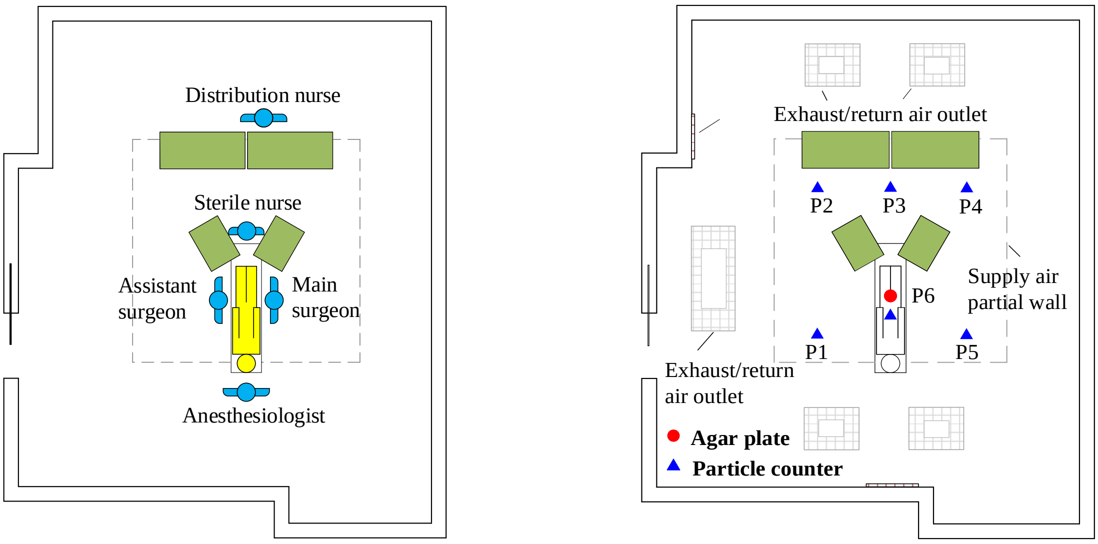
2.3.3. *Measuring points set up*

Fig. 6 and Fig. 7 demonstrate the position of surgical team members during mock operation, bacteria and particle measuring points for OR1 and OR2, respectively. Particle measurement points are distributed inside the 4m×4m sterile zone at the height of 1.1m and the number of points is determined according to the ISO standard.



(a) Position of participants (b) Measurement point arrangement

Fig. 6: Position of participants and measurement point arrangement in OR 1



(a) Position of participants (b) Measurement point arrangement

Fig. 7: Position of participants and measurement point arrangement in OR 2

2.4. Expert survey and users' satisfaction questionnaire

Expert survey was performed to collect opinion on the relative importance of indexes from professionals who have the experience of designing, operating or studying on OR ventilation. The experts were asked to determine which is more important through pairwise comparison according to 1-9 scale in AHP method. The details of the survey are attached in the Appendix A.

The users' satisfaction questionnaires were directly distributed to surgical team members who perform operations in the two chosen ORs. The questionnaire included two parts: thermal comfort questions was based on their thermal sensations and degree of satisfaction; acoustic comfort questions asked about the perception of noise and if the noise may affect their work. Details of the questionnaire are shown in Appendix B

3. Results and discussion

3.1. Indexes' evaluation value of the case ORs

3.1.1. Bacteria concentration

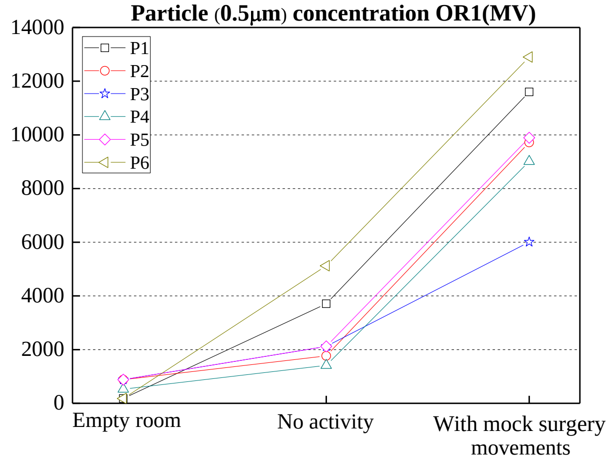
Table 3 demonstrates the planktonic bacteria measurement results from the active air sampler around the wound area. In OR1 with MV system, the mean bacteria concentration is 19 cfu/m^3 from 20 air samples in 3 mock surgeries, where the lowest value is 10 cfu/m^3 and the highest is 30 cfu/m^3. While in OR2 with LAF system, results are quoted from our previous study in the same operating room [39], which shows that the range of bacteria concentration is from 0-4 cfu/m^3 and the mean value 2 cfu/m^3 will be used in the evaluation. Therefore, compared to national standard requirements, both case ORs in St. Olavs Hospital performs good in removing bacteria. The reason why planktonic bacteria concentrations in the OR with LAF system were obviously lower than MV theater is that the large number of air exchange rates are more conducive to removing bacteria.

Table 3
Planktonic bacteria measurement result

	MV (Mean (Range))	LAF (Mean (Range))
Planktonic bacteria (cfu/m^3)	19 (10-30)	2 (0-4)

3.1.2. Particle concentration

The results of particle concentration can be seen in Fig. 8, which demonstrates the number of particles in different measurement points under the situation of empty room, without activity and with mock surgery movements, respectively. From empty room to occupied room, the concentration of particles increased gradually. In the meantime, the highest particle concentration can always be seen near the wound area (P6), indicating that personnel is one of the sources of pollutant emission [40]. Index value of particle measurements adopts value with mock surgery movements, which is 12898/m^3 in MV room and 1120/m^3 in LAF room. According to ISO standard in Fig. 8, OR1 (MV) belongs to ISO 6 while OR2 (LAF) belongs to ISO 5 as expected.



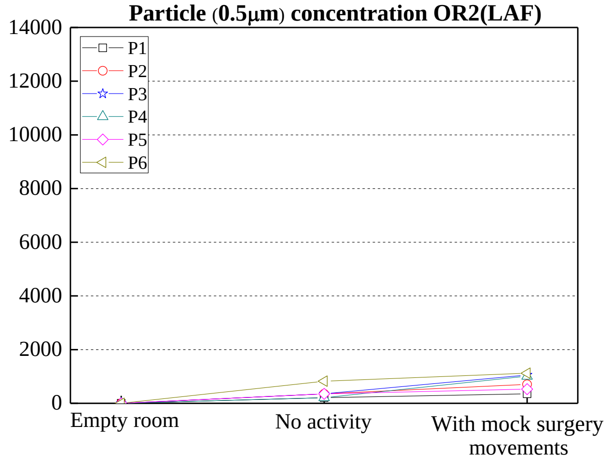


Fig. 8: Particle measurement result in different locations of ORs

3.1.3. Temperature and relative humidity

Air temperature and relative humidity in the two chosen ORs were also measured during the mock surgeries. When the room temperature was set at 23℃, the temperatures at the distance of 30 cm above the wound in 3 mock surgeries are shown in Table 4. In OR1, the temperature was around 23.46℃-25.21℃; in OR2 was around 23.16℃-24.34℃ and the temperature right under the operating lamp could reach 27℃ or even higher. The measured relative humidity was between 11.01%-24.16% in both ORs and it was changing slightly with the outdoor air humidity. To conduct evaluation, the average values from measurements is used as the index values, therefore, the index values of temperature and relative humidity in OR1 are 24.55℃ and 17.72%, respectively; in OR2 are 23.84℃ and 16.51%, respectively.

According to the evaluation grades of index set based on standards, the temperature measurement results in this study showed that the ambient temperature in OR1 and OR2 are within a reasonable range of 22-24℃. But this range can differ if it is going to be used in other special operating rooms like for new born babies who have poor ability to regulate their body temperature [41]. Without strict humidity control in Norwegian design codes, only two out of the six mock surgeries conducted in this study reached 20%, even when the outdoor humidity was between 60%-90% during the mock surgeries. The questionnaire issued in this study also asked about humidity perception, it showed that the 55% of the participants thought the environment in ORs was neutral while 45% of participants thought dry. Even though it may be acceptable to have humidity in the OR below 30%, it does not mean that OR should always maintain low humidity level. ASHRAE standard 170 had once lower the relative humidity level in ORs from 30% to 20% and this value was discussed by several organizations in the U.S. since low humidity concerns not only dryness of nose or throat, but the influence on some electronic medical devices [42]. What's more, from the hospital service center, it is learned that humidifying equipment is easy to breed bacteria, which may further affect the quality of air in the ORs. Therefore, it can be understood as avoiding risks and saving costs, while neglecting humidity control.

Table 4

Temperature and humidity measurement results in mock surgeries (30 cm above the wound)

Mock surgeries	OR1 (MV)			OR2 (LAF)		
	Temperature	Humidity	Date of measurement	Temperature	Humidity	Date of measurement
No.1	23.99℃	15.11%	4 March	24.02℃	23.32%	22 March
No.2	24.85℃	14.41%	15 March	23.88℃	14.15%	23 March
No.3	24.81℃	23.64%	25 March	23.61℃	12.05%	29 March
Average	24.55℃	17.72%	——	23.84℃	16.51%	——

3.1.4. Electricity consumption

OR1 (MV) is equipped with full fresh air ventilation system which centralizes the primary treatment of fresh air and exhaust air through large scale AHUs and further treatment is carried out at the terminal devices of each room, as shows in Fig. 3(c). Energy consumption of the ventilation system from the supply and exhaust fans are calculated according to Eq. (2) as well as Eq.(3). The energy consumption of the ventilation system due to air treatment process can be calculated by the following equations:

$$W_{\text{terminal}} = \frac{G_{\text{supply}} \times (h_{\text{supply}} - h_{\text{AHU outlet}}) \times t}{3600} \quad (6)$$

$$W_{\text{h}} = W_{\text{terminal}} + \frac{Q_{\text{supply air in OR}}}{Q_{\text{air volume AHU provide}}} W_{\text{AHU}} \quad (7)$$

where, W_{terminal} is the energy consumed by terminal devices of each OR, kWh; G_{supply} is the mass flow of the supply air, kg/h; t is the calculation period, h; $h_{\text{AHU outlet}}$ is the specific enthalpy of AHU outlet air, kJ/kg; W_{AHU} is the energy consumed of AHU during air treatment process, kWh; $Q_{\text{supply air in OR}}$ and $Q_{\text{air volume AHU provide}}$ are the air volume of supply air in the target OR and the total air volume supply of the AHU, respectively, m^3/h.

OR2 (LAF) consists of one-returning air system, which 1/3 of the room air volume is exhausted while 2/3 of the room air volume is returned, as shows in Fig. 3(d). Therefore, calculations can be conducted based on the following equations:

$$W_{\text{terminal}} = \frac{G_{\text{supply}} \times (h_{\text{supply}} - h_{\text{mix}}) \times t}{3600} \quad (8)$$

$$h_{\text{mix}} = \frac{G_{\text{AHU outlet}} \times h_{\text{AHU outlet}} + G_{\text{return air}} \times h_{\text{return air}}}{G_{\text{AHU outlet}} + G_{\text{return air}}} \quad (9)$$

$$W_{\text{AHU}} = \frac{G_{\text{total AHU provide}} \times (h_{\text{AHU outlet}} - h_{\text{outdoor air}}) \times t}{3600} \quad (10)$$

$$W_{\text{h}} = W_{\text{terminal}} + \frac{Q_{\text{supply air}}}{Q_{\text{total AHU provide}}} W_{\text{AHU}} \quad (11)$$

where, h_{mix} is the specific enthalpy of mixed air, kJ/kg; $h_{\text{return air}}$ is the specific enthalpy of return air, kJ/kg; $G_{\text{AHU outlet}}$ is the mass air flow rate from AHU outlet into an OR, kg/h; $G_{return\ air}$ are the mass flow rate of return air, kg/h; Q_{supply} is the volume flow rate of supply air in one specific OR, m^3/h; $Q_{\text{total AHU provide}}$ is the total air flow rate provided by the AHU which may covers several ORs, m^3/h.

Since there is a lack of separate energy consumption metering for OR ventilation systems, the above calculation is based on the recorded data of the ventilation system every 10 minutes during the operation period. For example, the i-th 10-minute calculation result is obtained as Eq. (12), where $W_{total(i)}$ is the total energy consumption in the i-th 10-minute data logging interval; $W_{h(i)}$ and $W_{f(i)}$ are the energy consumption from the air handling process and fans in the 10-minute interval, respectively.

$$W_{total(i)} = W_{h(i)} + W_{f(i)} \quad (12)$$

Therefore, the total electricity consumption of ventilation system W_{total} in the case ORs were calculated according to Eq (13). as:

$$W_{total} = \sum W_{total(i)} \quad (13)$$

Daily average electricity consumption per square meter of the two cases OR1 and OR2 during their data logging period are 5.32 and 5.06 kWh/m^2/day, respectively. After temperature correction $W_{average}$ of OR1(MV) is 4.86 kWh/m^2/day; while for OR2 with LAF system is 7.17 kWh/m^2/day, calculated as Eq. (14):

$$W_{average} = \frac{\sum W_{total(i)}}{A \times T} \quad (14)$$

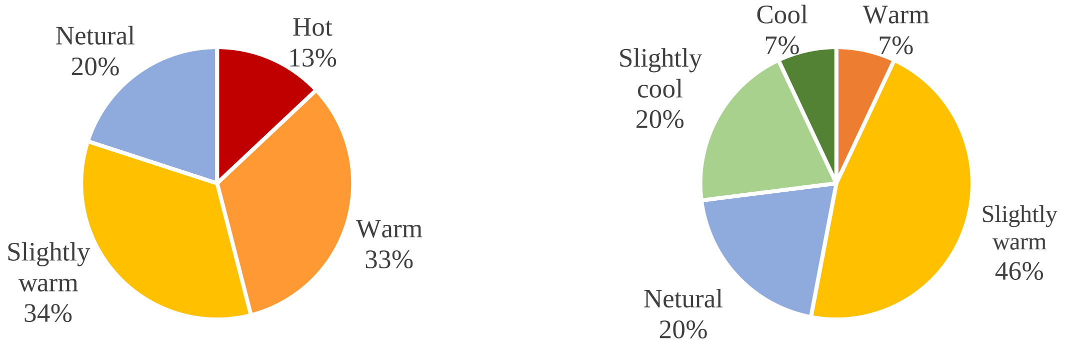
where, A is the area of the case OR, m^2; T is a value converted to daily average electricity consumption.

3.1.5. *Thermal comfort and noise level*

The users' questionnaire was distributed to 14 surgical staffs who work in OR1 with MV system and to 15 staff who works in OR 2 with LAF system.

(1) Thermal comfort

Thermal sensation is divided into 7-point scale from cold to hot according to ASHRAE standard 55 [43]. From the thermal sensation vote results in Fig. 9, votes for OR1 were mostly on the "neutral" and "warmer" side, while the votes for OR2 were more inclined to "cool"; 34% of survey participants in OR1 and 46% in OR2 thought the environment is slightly warm, which takes the largest proportion in both operating theaters.



(a) Thermal sensation vote in OR1 (MV) (b) Thermal sensation vote in OR2 (LAF)

Fig. 9: Thermal sensation vote results

The actual percentage of dissatisfaction obtained from questionnaires is shown in Table 5. In OR1 (MV), 43% questionnaire participants were dissatisfied with the thermal environment, while no one was dissatisfied in OR2 (LAF) in the questionnaire survey.

Table 5

Thermal environment satisfaction questionnaire survey results

	OR1 (MV)	OR2 (LAF)
Percentage of satisfaction	57%	100%
Percentage of dissatisfaction	43%	0

This difference may first attribute to their wearing, as surgeons and nurses must wear special sterile clothing with masks, even with lead apron during the operations, which make them more likely to sweat, especially being in a state of extreme concentration. Besides, under the influence of the main heat source - operating lamp near the surgeons, uncomfortable feelings can easily occur. The biggest difference of the two ORs in this study is the air change rate. Larger air change rate is conducive to removing the heat around the body faster to some extent, therefore, questionnaire participants who work in the OR with LAF system will vote for a neutral or cool thermal sensation, since cooler environment is relatively comfortable for them.

(2) Noise level

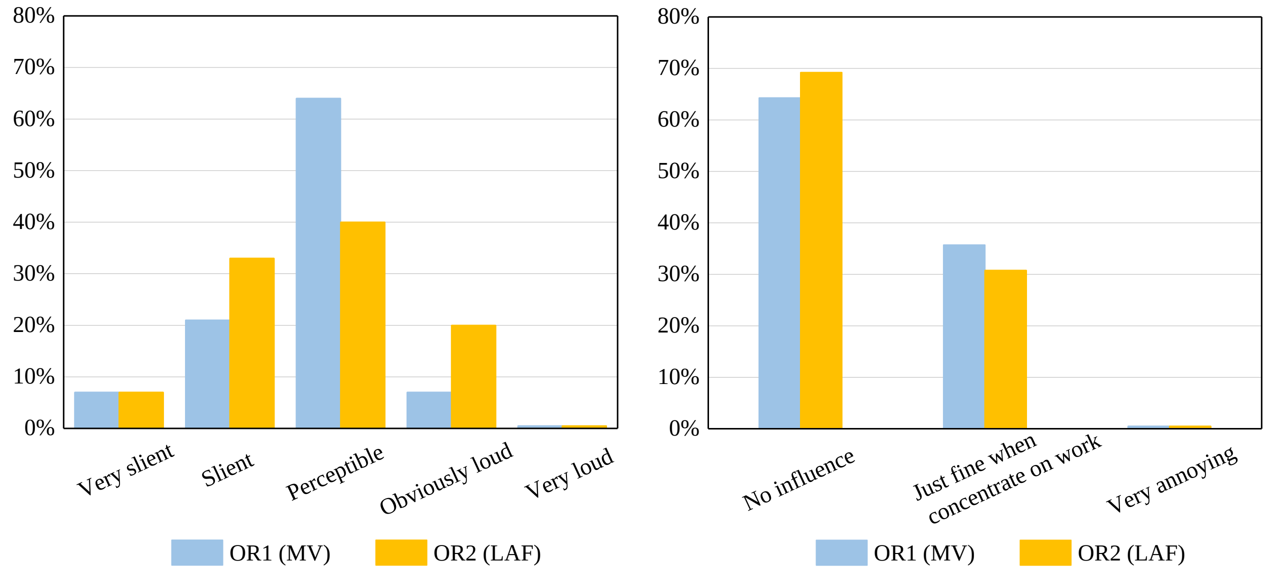
During the noise measurement, most of the medical equipment was turned off or not in the operation mode, therefore, the measured value in the empty room can be considered as the noise generated by the ventilation system. The noise may come from the fans and the transmission through the air ducts as well as the air flow passing through components with great resistance. Noise level measurement results are listed in Table 6, and the average value of all the measuring points in each OR is chosen as the index value used in the comprehensive evaluation.

Table 6

Sound pressure measurements results

Position	OR1 (MV)	OR2 (LAF)
Near surgeon	54.9 dB	52.7 dB
Near Anesthetist	55.2 dB	53.0 dB
Near sterile nurse	55.7 dB	54.5 dB
Near distribution nurse	57.7 dB	53.7 dB
Other points in the OR	54.3 dB	54.4 dB
Average	55.6 dB	53.7 dB

Fig. 10 is the statistical result of the questionnaire inquiring about the influence of noise. Surgical team participants in both operating rooms thought that the noise of ventilation system is perceptible, while over 60% considered it has no effect on them at all and the rest part thought it was just fine when they concentrated on work. Therefore, with higher fan power, more participants in OR2 (LAF) thought it was noisier than in OR1 (MV), although the test results seem on the contrary lower. The noise levels in both ORs were exceed the noise requirements in Germany standard DIN 1946/4, but within the range of 46-57 dB mentioned in literature [25] at John Hopkins Hospital. In the actual operation process, medical equipment will inevitably produce even more noise, which will affect the performance of surgical team members. Therefore, the hospital may need to further check the noise of ventilation system in each OR and strengthen the noise reduction material if necessary.



(a) Surgical team feeling of noise in ORs

(b) Noise influence to staffs in ORs

Fig. 10: Occupants feeling of noise and noise influence

3.2. Weight distribution result

Fifteen experts were invited to give their opinions on determining the priority of indexes. They are professors and researchers, designers and engineers, operational management professionals whose work are closely related to ventilation system. Through analysis and calculation, final weight distribution of all the indexes are listed in Table 7. Ventilation effectiveness takes precedence, followed by users' satisfaction and energy consumption. Ensuring the indoor cleanliness as the premise, appropriately sacrifice comfort and energy consumption is also the status quo of OR ventilation system. From the perspective of ventilation effectiveness alone, the concentration of bacteria and particulate matter is considered more important than temperature and humidity because people pay more attention to the infections after operation. Therefore, the weight vector is $W = [w_1, w_2, \ldots, w_7] = [0.23\ 0.15\ 0.06\ 0.05\ 0.16\ 0.22\ 0.13]$.

Table 7

Weigh distribution result summary

Aspects	Priority	Indexes	Local priorities	Overall priorities
Ventilation effectiveness	0.49	Bacteria concentration	0.47	0.23
		Particle concentration	0.30	0.15
		Temperature	0.13	0.06
		Relative Humidity	0.10	0.05
Energy consumption	0.16	Electricity consumption	1.00	0.16
Users' satisfaction	0.35	Thermal comfort	0.64	0.22
		Noise	0.36	0.13

3.3. Energy consumption benchmark

3.3.1. Electricity consumption calculation result

According to the previous analysis and illustration, basic information as well as electricity consumption results of 42 ORs were shown in Table 8.

Table 8

Electricity consumption result of ORs in St. Olavs Hospital

Air distribution strategy	Supply air volume range m^3/h	Total number of ORs	Number of ORs with heat recovery	Number of ORs with setback strategy	Energy consumption range $kWh/m^2/day$	Average Energy consumption $kWh/m^2/day$	Standard deviation
MV	1850-3800	35	12	14	2.42-5.74	3.66	0.94
LAF	8750-12900	7	3	6	5.06-7.40	6.00	0.60

There are 35 ORs equipped with MV system in this hospital and their electricity consumption per m^2 varies from 2.42 to 5.74 kWh per day; while in 7 ORs with LAF system, the electricity consumption varies from 5.06 to 7.40 kWh/m^2 per day. As shown in Fig. 11, the general energy use in LAF operating theaters (No.6-7) are higher than that of MV rooms (No.1-5) in the same department. In addition, Fig. 12 compares the energy consumption of ORs in the same department with and without setback strategy under the same air volume, it can be seen that energy consumption in No.24 OR is obviously lower than those without setback strategy.

However, one thing needs to be specified is that the logged data obtained from St. Olavs Hospital were from different time periods during March to May, 2019 (data logging in Neurology center, Women & children center were from Mar.25th-Apr.5th; data logging in Emergency & Heart and lung center was from Apr.5th-Apr.11th; data logging in Orthopedic center was from Apr.23rd-May.3rd.) and the data were also limited by the number of measuring points equipped with sensors as well as the actual functions of the energy monitoring platform.

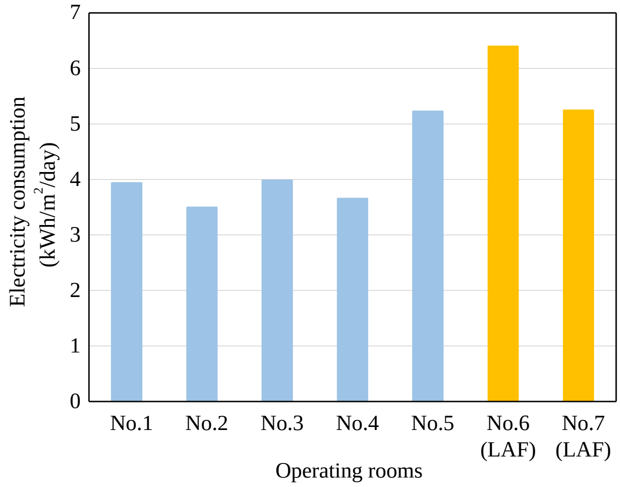


Fig. 11: Comparisons on the electricity consumption of LAF and MV system

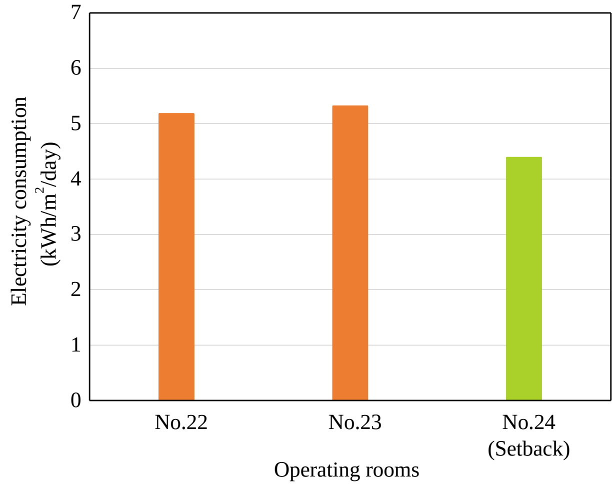


Fig. 12: Influence of setback strategy on the electricity consumption

3.3.2. Linear regression

Preliminary screening requires that variables are linearly related with energy consumption (Y, kWh/m^2/day), therefore, the final chosen variables are outdoor temperature (X_1, °C), supply air volume (X_2, m^3/s), heat recovery strategy (X_3, 0-without heat recovery, 1-with heat recovery) and setback strategy (X_4, 0-with setback strategy, 1-without setback strategy) and the linear regression analysis equation is as follows:

$$\mathrm{Y} = 4.647 - 0.149X_1 + 1.139X_2 - 1.110X_3 - 0.589X_4$$

From the report generated from SPSS software, the adjusted R^2 of the regression model is 0.867, which is the fitting degree of the estimated model to the observed values and it means that the regression can explain 86.7% variation of dependent variables. The result of variance analysis showed the whole regression equation is significant. In Table 9, column "Unstandardized B" listed the coefficients in the regression equation; the absolute values of standardized coefficients indicate the relative importance each variable. Collinearity tolerance and VIF factor are opposite to each other and they showed the collinearity between variables; VIF>10 means the variable has linear relationship with other variables, which is not allowed in the multi-linear regression equation.

Table 9

Coefficients in the regression equation

	Unstandardized B	Standardized Coefficients Beta	t	Sig.	Collinearity Tolerance	Statistics VIF

(Constant)	4.647		18.061	.000		
Outdoor temperature	-0.149	-0.570	-5.625	.000	0.316	3.160
Supply air volume	1.139	0.870	13.226	.000	0.753	1.328
Heat recovery strategy	-1.110	-0.419	-5.520	.000	0.564	1.772
Setback strategy	-0.589	-0.232	-2.299	.027	0.319	3.135

The energy consumption prediction equation involves several possible factors. From the coefficients in front of each variable, the relative influence of them can be seen from the standardized coefficients value above, which shows supply air volume has the largest contribution followed by outdoor air temperature, heat recovery strategy and set back strategy. Since the energy data failed to cover the whole year at the moment, the predicted model is only applicable during the transitional month between winter and spring. Therefore, the coefficient of outdoor temperature variable X_1 is negative, since the higher the temperature at the transitional season between winter and spring, the lower the energy consumption will be. The positive coefficient in front of air volume X_2 proves that their increase is in direct proportion to energy consumption; the negative coefficients of variables of heat recovery strategy X_3 and air volume reduction strategy X_3 show that the adoption of the strategy is conducive to reducing energy consumption.

3.3.3. Determine evaluation benchmark

Based on the local average outdoor temperature during March to May (5.2°C) [44], energy consumption range after temperature modification is shown in the box chart in Fig. 13. The lower quartile mean value and median value in operating theater with MV system are 3.40 kWh/m^2/day and 3.96 kWh/m^2/day, respectively; while those values for operating theater with LAF system are 5.73 kWh/m^2/day and 7.17 kWh/m^2/day, respectively. Therefore, the grades of energy consumption (EC) index in St. Olavs Hospital is classified as proper if EC⩽3.40 kWh/m^2/day; moderate if 3.40<EC⩽3.96 kWh/m^2/day; improper if EC>3.96 kWh/m^2/day in MV system ORs and proper if EC⩽5.73 kWh/m^2/day; moderate if 5.73<EC⩽7.17 kWh/m^2/day; improper if EC>7.17 kWh/m^2/day in LAF system ORs.

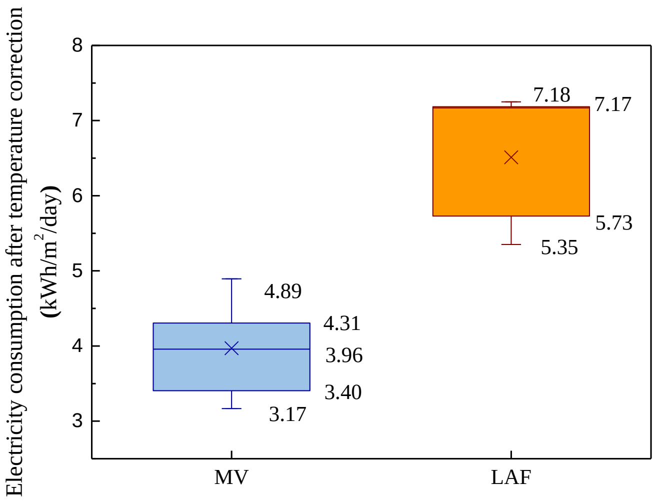
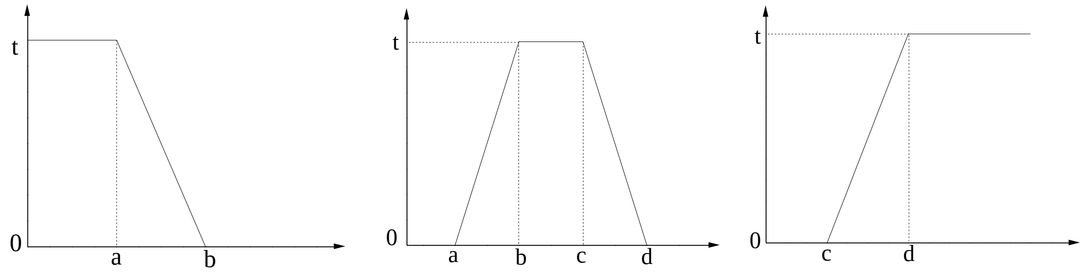


Fig. 13: Electricity consumption range after temperature correction

3.4. Comprehensive evaluation

According to the procedures of FCE method, the membership function should be constructed to obtain the membership degree of the index value for each comment. As the grades of all 7 indexes are expressed in range, ladder shape membership functions are more appropriate to determine the membership degree. Each index can be expressed with the figures and functions as shown in Fig. 14(a), (b) (c), which respectively indicates the membership degree of the index to the suitability comments. The set of evaluation factors can be written as $\mathrm{U} = \{u_1, u_2, \ldots, u_7\}$ corresponding to 7 indexes; the comment sets V are defined as {“unsuitable”, “moderate”, “suitable”}.



$$A(x)=\begin{cases}1, & x<a\\ \dfrac{b-x}{b-a}, & a\le x\le b\\ 0, & x>b\end{cases}$$

$$A(x)=\begin{cases}\dfrac{b-x}{b-a}, & a<x\le b\\ 1, & a\le x\le b\\ \dfrac{d-x}{d-c}, & c\le x\le d\\ 0, & x<a \text{ or } x>d\end{cases}$$

$$A(x)=\begin{cases}0, & x<c\\ \dfrac{x-c}{d-c}, & c\le x\le d\\ 1, & x>d\end{cases}$$

(a) (b) (c)

Fig. 14: General form of ladder membership functions

Each index value of the two case ORs was substituted into the corresponding membership functions, and the evaluation matrices can be calculated as shown in Table 10.

Table 10

Summary of the evaluation matrices

	Items	U value	r	R
OR1 (MV)	Bacteria concentration u_1	19	$r_1 = [c_0(u_1), c_1(u_1), c_2(u_1)] = [0,0,1]$	$R_1 = \begin{bmatrix} r_1\\ r_2\\ r_3\\ r_4\\ r_5\\ r_6\\ r_7\end{bmatrix} = \begin{bmatrix} 0 & 0 & 1\\ 0.30 & 0.37 & 1\\ 0.28 & 1 & 0.73\\ 1 & 0 & 0\\ 1 & 0 & 0\\ 1 & 0 & 0\\ 1 & 0.44 & 0\end{bmatrix}$
	Particle concentration u_2	12898	$r_2 = [c_0(u_2), c_1(u_2), c_2(u_2)] = [0.30,0.37,1]$	
	Temperature u_3	24.55	$r_3 = [c_0(u_3), c_1(u_3), c_2(u_3)] = [0.28,1,0.73]$	
	Humidity u_4	17.72	$r_4 = [c_0(u_4), c_1(u_4), c_2(u_4)] = [1,0,0]$	
	Electricity consumption u_5	4.86	$r_5 = [c_0(u_5), c_1(u_5), c_2(u_5)] = [1,0,0]$	
	Thermal comfort u_6	0.43	$r_6 = [c_0(u_6), c_1(u_6), c_2(u_6)] = [1,0,0]$	
	Noise level u_7	55.6	$r_7 = [c_0(u_7), c_1(u_7), c_2(u_7)] = [1,0.44,0]$	
OR2 (LAF)	Bacteria concentration u_1	1.25	$r_1 = [c_0(u_1), c_1(u_1), c_2(u_1)] = [0,0,1]$	
	Particle concentration u_2	1120	$r_2 = [c_0(u_2), c_1(u_2), c_2(u_2)] = [0.24,1,0.76]$	
	Temperature u_3	23.84	$r_3 = [c_0(u_3), c_1(u_3), c_2(u_3)] = [0,0.96,1]$	
	Humidity u_4	16.51	$r_4 = [c_0(u_4), c_1(u_4), c_2(u_4)] = [1,0,0]$	
	Electricity consumption	7.17	$r_5 = [c_0(u_5), c_1(u_5), c_2(u_5)] = [1,1,0]$	

u_5			
Thermal comfort u_6	0	$r_6 = [c_0(u_6), c_1(u_6), c_2(u_6)] = [0,0,1]$	$$R_2 = \begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ r_4 \\ r_5 \\ r_6 \\ r_7 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 \\ 0.24 & 1 & 0.76 \\ 0 & 0.96 & 1 \\ 1 & 0 & 0 \\ 1 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0.63 & 0 \end{bmatrix}$$
Noise level u_7	53.7	$r_7 = [c_0(u_7), c_1(u_7), c_2(u_7)] = [1,0.63,0]$	

In order to take account into all these factors, weighted average type operator M (·,+) were selected to calculate the final evaluation result $S = W \circ R$.

$$S_1 = W \circ R_1 = [0.23 \quad 0.15 \quad 0.06 \quad 0.05 \quad 0.16 \quad 0.22 \quad 0.13] \begin{bmatrix} 0 & 0 & 1 \\ 0.30 & 0.37 & 1 \\ 0.28 & 1 & 0.73 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \\ 1 & 0.44 & 0 \end{bmatrix} = [0.62 \quad 0.17 \quad 0.42] \tag{15}$$

$$S_2 = W \circ R_2 = [0.23 \quad 0.15 \quad 0.06 \quad 0.05 \quad 0.16 \quad 0.22 \quad 0.13] \begin{bmatrix} 0 & 0 & 1 \\ 0.24 & 1 & 0.76 \\ 0 & 0.96 & 1 \\ 1 & 0 & 0 \\ 1 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0.63 & 0 \end{bmatrix} = [0.38 \quad 0.45 \quad 0.62] \tag{16}$$

After normalization, as shown in the Section 2.1.2, fuzzy comprehensive evaluation vectors are obtained as $S_1' = [0.51\ 0.14\ 0.35]$, $S_2' = [0.26\ 0.31\ 0.43]$, which means that OR1 is more likely to obtain the comment of "unsuitable" and OR2 obtains the comment of "suitable" according to maximum membership principle.

From the evaluation results, the bacteria, particle concentration and temperature of the two ORs under ventilation effectiveness aspect are "proper" since they are within the reasonable range recommended by the standard. The humidity of the two ORs are in the "improper" range due to the lack of humidity control, however, it only takes up 0.05 of the total evaluation in this study. As the calculated energy consumption for OR1 is higher than the energy consumption median value among all ORs with MV system in St. Olavs Hospital, it belongs to "improper"; while that of OR2 belongs to "moderate". Besides, since OR1 received more unsatisfactory votes on the thermal comfort index, which is weighted second only to bacteria concentration, the final evaluation result of OR1 obtained is not as good as OR2. Therefore, when "unsuitable" evaluation results appear, the first thing needed is to find the corresponding index value with the largest weight, then view other indexes according to their priorities.

4. Practical limitations

From the above establishment process of the evaluation system, the evaluation framework is flexible to further add in more aspects such as ventilation system lifecycle cost and environmental impact etc., meanwhile, the benchmarks of evaluation indexes may be adjusted according to different regions and countries applied. However, there are some unavoidable limitations should be noted. Firstly, the measurements were performed during mock surgeries rather than real surgeries to avoid interfering with their normal work in ORs, after all, OR is a place concerning life and death. Although we try to perform similar actions, the value of bacteria and particles may differ from previous studies performed in the same operating rooms because of those recognized factors that may have an impact: the number of indoor personnel, gender, clothing, intensity of activities, location and type of surgical lamps [45], door openings etc. Secondly, due to the limited data, the evaluation framework established in this study has not been tested in other hospitals, further investigations are needed to evaluate ORs with MV and LAF in other hospitals. In addition, due to the limited feedback, the change of the weight of these parameters may also affect the evaluation results.

5. Conclusions

To address the problem of relatively one-sided evaluation on OR ventilation system performance, this study has endowed more connotations to the suitability of OR ventilation systems and proposed a new suitability evaluation framework. Based on the results, the following conclusions can be drawn:

(1) The suitability evaluation framework was established based on the consideration of fuzziness in suitability and weight distribution according to expert opinions. It comprehensively considers ventilation effectiveness, electricity consumption and users' satisfaction at the same time, which is an effective way for the quantified assessment of the performance of OR ventilation system during the operation stage. At the same time, the evaluation framework has flexibility and scalability on specific indicators.

(2) In this study, two case ORs with different ventilation strategies in St. Olavs Hospital were taken as examples to prove the availability and rationality of the proposed system. It reflects the current situation that the ventilation system in ORs performs better in ensuring the clean and safe operation environment, but to a certain extent sacrifices the energy consumption and the comfort of the surgical team members.

(3) Through the analysis on the influencing factors of energy consumption, design and selection of the ventilation system for ORs should focus on the appropriate airflow rate based on meeting the demand for safety and make rational use of the heat recovery technology as well as setback strategy. Suggestions can be provided to the management of ventilation facilities in ORs at St. Olavs Hospital and other hospitals:

   a. Regularly test the air cleanliness, temperature, humidity and noise in the ORs and keep tracking the comfort level of the surgical team to provide the basis for possible system commissioning.

   b. Develop better controlling system based on some frontier technologies. For example, by using the occupancy sensors combined with audio, infrared and motion detection technologies to switch the ventilation system in OR between unoccupied and occupied modes automatically. Combined controlling strategy together with manual switchover is also a good choice.

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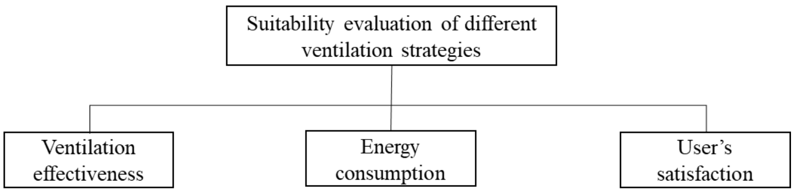
Appendix A Expert survey on weight distribution

In this part, all the questions are based on pair-wise comparisons, which are the fundamental components of AHP method. Participants are required to choose their judgement of the importance of the indexes based on the following table.

9	7	5	3	1	1/3	1/5	1/7	1/9
Absolutely more important	Strongly more important	More important	Weakly more important	Equally important	Weakly less important	Less important	Strongly less important	Absolutely less important

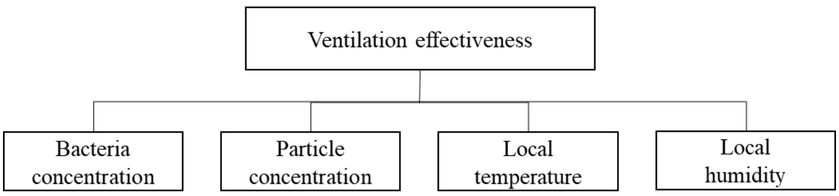
Criteria Level



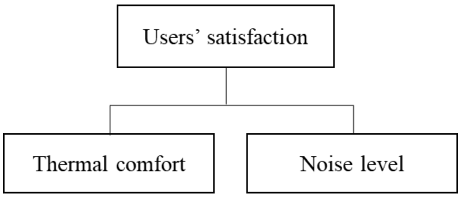
Ventilation effectiveness: The performance of providing a clean and healthy environment.
Energy consumption: The amount of electricity consumed by ventilation system.
User's satisfaction: The comfort feeling of site personnel including surgical team and patients.

1. How important is "**ventilation effectiveness**" compared to "**energy consumption**" of ventilation systems?
2. How important is "**ventilation effectiveness**" compared to "**users' satisfaction**" of ventilation systems?
3. How important is "**energy consumption**" compared to "**users' satisfaction**" of ventilation systems?

Sub-Criteria Level



4. How important is "**bacteria concentration**" compared to "**particle concentration**" under the ventilation effectiveness aspect of ventilation systems?
5. How important is "**bacteria concentration**" compared to "**local temperature**" under the ventilation effectiveness aspect of ventilation systems?
6. How important is "**bacteria concentration**" compared to "**local humidity**" under the ventilation effectiveness aspect of ventilation systems?
7. How important is "**particle concentration**" compared to "**local humidity**" under the ventilation effectiveness aspect of ventilation systems?
8. How important is "**particle concentration**" compared to "**local temperature**" under the ventilation effectiveness aspect of ventilation systems?
9. How important is "**local humidity**" compared to "**local temperature**" of under the ventilation effectiveness aspect ventilation systems?



10. How important is "**thermal comfort**" compared to "**noise level**" under the users' satisfaction aspect of ventilation systems?

Appendix B User's satisfaction questionnaire

Thermal environment

Your answers should be based on what you felt in operating room on the last several surgeries you had participated.

1. What was your general thermal sensation in the operating room during the operation?

☐ Cold	☐ Cool	☐ Slightly cool	☐ Neutral	☐ Slightly warm	☐ Warm	☐ Hot

2. How often did you feel that?

☐ Never	☐ Seldom	☐ Often	☐ Very often	☐ All the time

3. How you satisfied with the thermal environment during your work in the operating room?

☐ Satisfied	☐ Dissatisfied

Acoustic environment

4. What is your perception of the noise from the ventilation system in the operating room?

☐ Very silent	☐ Silent	☐ Perceptible	☐ Obviously loud	☐ Very loud

5. Did the noise from the ventilation affect you during the operation?

☐ Very annoying	☐ Just Fine when concentrate to the work	☐ No influence to me at all

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