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Abstract

Background: The performance of ventilation system in operating rooms (ORs) is closely related to the indoor environment quality, since it not only controls the concentration of bacteria and particles around the wound area, but also dedicates to create an appropriate indoor environment for patients and surgical staff. However, high energy consumption and costs caused by the high ventilation rate are also challenges to the users and the energy-saving department.

Objective: Develop a comprehensive evaluation framework on the suitability of different ventilation strategies for existing operating rooms by setting indices from the aspects of ventilation effectiveness, energy consumption and users' satisfaction.

Methods: Analytic hierarchy process (AHP) based on expert survey and fuzzy comprehensive evaluation (FCE) methods are adopted in this framework for the purpose of weight distribution and comprehensive evaluation result calculation, respectively. Operating rooms with laminar air flow (LAF) and mixing ventilation (MV) system in St. Olavs Hospital, Norway are used as case studies to verify the applicability of this evaluation framework. To obtain evaluation index values, measurements of microbial and particle concentration, air temperature and relative humidity have been conducted through mock surgeries; calculation and multi-linear regression method are used in electricity consumption while user's satisfaction questionnaires are also distributed to surgical team members.

Results: Through expert questionnaire survey, ventilation effectiveness, user satisfaction and energy consumption were weighted 0.49, 0.35 and 0.16, respectively. The bacteria, particles concentration and temperature of the two case operating rooms OR1 (mixing ventilation system) and OR2 (laminar air flow ventilation system) in St. Olavs Hospital 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. For OR 1, the calculated energy consumption does not reach the median value among all the operating theaters, therefore it belongs to "improper", while electricity consumption of OR2 belongs to "moderate". In addition, OR1 has a higher dissatisfaction rate whose priority is second only to bacteria and a noise value exceeding standard requirement. All these together make the comprehensive evaluation value obtains the comments of "unsuitable" for OR1 and "suitable" for OR2.

Conclusions: The suitability evaluation framework for OR ventilation systems in this study has reasonable and meaningful weight distribution for 3 aspects and 7 indices; with flexibility, the evaluation dimension can be added or subtracted from the framework, also the index benchmark can be adjusted according to actual needs. From case ORs at St. Olavs Hospital and the analysis of energy consumption influencing factors, OR ventilation system should pay attention to energy consumption and comfort based on cleanness. At the same time, the design and selection of ORS ventilation system may try to focus on appropriate air volume, rational adoption of heat recovery technology and setback strategy in addition to safety requirements.

Sammendrag

Bakgrunn: Utførelsen av ventilasjonssystemet i operasjonssalene er nært knyttet til kvaliteten på operasjonen, da det ikke bare styrer konsentrasjonen av bakterier og partikler rundt sårområdet, men også dedikerer til å skape et passende innemiljø for pasienter og leger. Høyt energiforbruk og kostnader forårsaket av den store ventilasjonshastigheten er imidlertid også problemer som truer brukerne og energisparingsavdelingen.

Mål: Utvikle et omfattende evalueringsramme for egnethet til ulike ventilasjonsstrategier for eksisterende operasjonsrom ved å sette indeksene fra aspektene av ventilasjonseffektivitet, energiforbruk og brukernes tilfredshet.

Metoder: Analytisk hierarkiprosess (AHP) basert på ekspertundersøkelse og fuzzy omfattende evaluering (FCE) metoder er vedtatt i dette rammen for formålet med vektfordeling og omfattende evalueringsresultatberegning, henholdsvis. Driftsrom med laminatluftstrøm (LAF) og blandingsventilasjon (MV) i St. Olavs Hospital, Norge, brukes som case-studier for å verifisere anvendeligheten av denne evalueringsrammen. For å oppnå evalueringsindeksverdier, måles målinger av mikrobiell og partikkelkonsentrasjon, lufttemperatur og relativ luftfuktighet gjennom mock operasjoner; beregning og multi-lineær regresjonsmetode brukes i strømforbruket mens brukerens tilfredsstillende spørreskjema også distribueres til kirurgiske lagmedlemmer.

Resultater: Gjennom ekspert spørreskjemaundersøkelse ble ventilasjonseffektivitet, brukertilfredshet og energiforbruk vektet 0,49, 0,35 og 0,16, henholdsvis. Bakteriene, partikalkonsentrasjonen og temperaturen i de to saksoperasjonene OR1 (blandingsventilasjonssystemet) og OR2 (laminatluftventilasjonssystem) i St. Olavs Hospital under ventilasjonseffektivitetsaspektet er "riktig siden de er innenfor det rimelige området anbefalt av standard. Fuktigheten til de to ORene er i feilområdet fordi det ikke er fuktighetskontroll, men tar bare 0,05 av den totale evalueringen. For OR 1, når det beregnede energiforbruket ikke medianverdien blant alle Operasjonsteatrene er derfor "feil". Mens energiforbruket til OR2 tilhører "moderat". I tillegg har OR1 en høyere misnøye-hastighet, hvis prioritet er andre bare for bakterier og en støyverdi som overstiger standardkravet. Alle disse sammen gjør den omfattende evalueringsverdien får kommentarene til "uegnet" for OR1 og "egnet" for OR2.

Konklusjoner: Evalueringsrammen for OR ventilasjonssystemer i denne studien har rimelig og meningsfull vektfordeling for 3 aspekter og 7 indekser; Med fleksibilitet, evalueringsdimensjon kan legges til eller trekkes fra rammen, kan også referanseindeksen justeres i henhold til de faktiske behovene. Fra tilfelle OR i St. Olavs Hospital og analyse av energikonsekvenspåvirkende faktorer, bør OR ventilasjonssystem være oppmerksom på energiforbruk og komfort på grunnlag av renhet. Samtidig kan utformingen og utvalget av ORS ventilasjonssystem prøve å fokusere på passende luftvolum, rasjonell bruk av varmegenvindingsteknologi og retrettstrategi i tillegg til sikkerhetskrav.

Preface

This master thesis was finished at the Department of Energy and Process Engineering at the Norwegian University of Science and Technology (NTNU) in Trondheim during the spring semester of 2019. The thesis has gained great support and collaboration with the project of The Operating Room of the future (FOR) at St. Olavs Hospital in Trondheim.

At the completion of this thesis, I would like to first express my sincere gratitude to my supervisor at NTNU, Professor Guangyu Cao, he has walked me through the stages of writing this thesis with his kindness, patience and tireless guidance during my stay at NTNU.

Then I would like to offer my special thanks to the staffs at FOR who have provided us great help. Especially Liv-Inger Stenstad for her hard work to coordinate between our measurement plans and the possibility to realize them in the hospital. Also, Tor Emil Giske, Morten Uv at the service center of St. Olavs Hospital.

Furthermore, I would also like to thank all the other master students and PhD candidates who worked together with me during the measurement in operating rooms, they are Christoffer Pedersen, Helena Kuivjõgi, Yixian Zhang, Jakub Wladyslaw Dziedzic and Masab Khalid Annaqeeb. I am so lucky to meet and work with you all.

Besides, I also want to thank my supervisor from Tianjin University in China, Professor. Shilei Lv. I really appreciated that he gave me financial support to cover my travel expense and offered me this wonderful opportunity to go abroad and broaden my academic horizons. This experience will certainly have an important impact on my future career choice.

Finally, I am so grateful to my family for their emotional and financial support throughout the duration of my studying at NTNU. Thank you all.

Minchao Fan

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List of Abbreviations (or Symbols)

AHP	Analytic hierarchy process
APD	Actual percentage of dissatisfaction
AHU	Air Handling Unit
ASHE	American Society of Healthcare Engineers
ASHRAE	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
CFU	Colony Forming Units
DIN	Deutsches Institut für Normung
EQI	Environment Quality Indices
FCE	Fuzzy comprehensive evaluation
HTM	Health Technical Memoranda
HVAC	Heating, ventilation and air conditioning
ISO	International Organization for Standardization
LBNL	Lawrence Berkeley National Laboratory
LAF	Laminar air flow
MV	Mixing airflow ventilation
OR	Operating Room
PMV	Predicted mean vote
PPD	Predicted percentage dissatisfied
SSI	Surgical site infections
WHO	World Health Organization

1 Introduction

1.1 Background

Operating room (OR) is one of the most indispensable parts in hospital that closely related to patients' life conditions. As there are usually opened wounds during operations, the clean environment is an important guarantee to reduce the rate of postoperative surgical site infections (SSIs), which account for nearly 36% of nosocomial infections in hospitals [1]. The ventilation system is responsible for providing a healthy indoor air environment for the patients as well as a comfortable working atmosphere for the surgical team [2]. The required parameters that affected by the ventilation system in operating rooms are usually air temperature, relative humidity, air velocity, bacteria level and particle concentration etc., while ideal working environment for the surgical team may include thermal comfort and acoustic comfort.

Traditionally, there are two types of ventilation system used in providing an air environment that meets the requirements according to different type of surgeries. For turbulent mixing airflow ventilation (MV) system, the supply air is quickly and evenly mixed with air in the environment to dilute pollutants in the room volume; while in laminar airflow (LAF) ventilation system, a unidirectional, low-turbulence downward displacement of air is delivered by large surface over the operating area, which is intended to create protective airflow around the patient. It is generally believed LAF system has better ability to remove bacteria [3], therefore are 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. [4] However, to achieve a clean environment can cost a lot, because of the high requirement in air change rates which are usually 20–40 times higher than in typical building spaces, operating rooms have become one of the most energy intensive part in hospital. High initial cost and maintenance cost also give a lot of pressure on hospitals and administrators. Although designers have been struggling to make it a perfect system, complaints from patients and surgeon or nurses about the discomfort environment still exist during operation. Through this, it is true that all we expected the ventilation in operating rooms is to use the minimum energy consumption and lifecycle cost to meet both the requirement of safety and satisfaction for site personnel. From this, overall evaluation is needed from a holistic view including ventilation effectiveness, energy efficiency as well as user's satisfaction.

1.2 Objective and scope of the study

The main objective of this study is to develop a comprehensive evaluation framework on the suitability of different ventilation strategies for existing operating rooms in hospitals. By setting indices from the aspects of ventilation effectiveness, energy consumption and users' satisfaction, LAF and MV system are mainly investigated in this study. Field measurements for case studies were performed in St. Olavs Hospital. The following substasks are chosen in order to achieve the study objective of this thesis:

- Literature review regarding the energy-efficient ventilation strategies in hospital.
- Create a comprehensive benchmark of energy use for the objective hospital operating rooms.

- Conduct field measurements of the indoor environment (temperature, relative humidity, airflow velocity, particle concentration, cfu level etc.) as well as thermal comfort survey and calculation in operating room with different ventilation systems at St. Olavs hospital.
- Evaluate the measured indoor climate data and energy consumption data.

The technical route of the paper is given in the following figure.

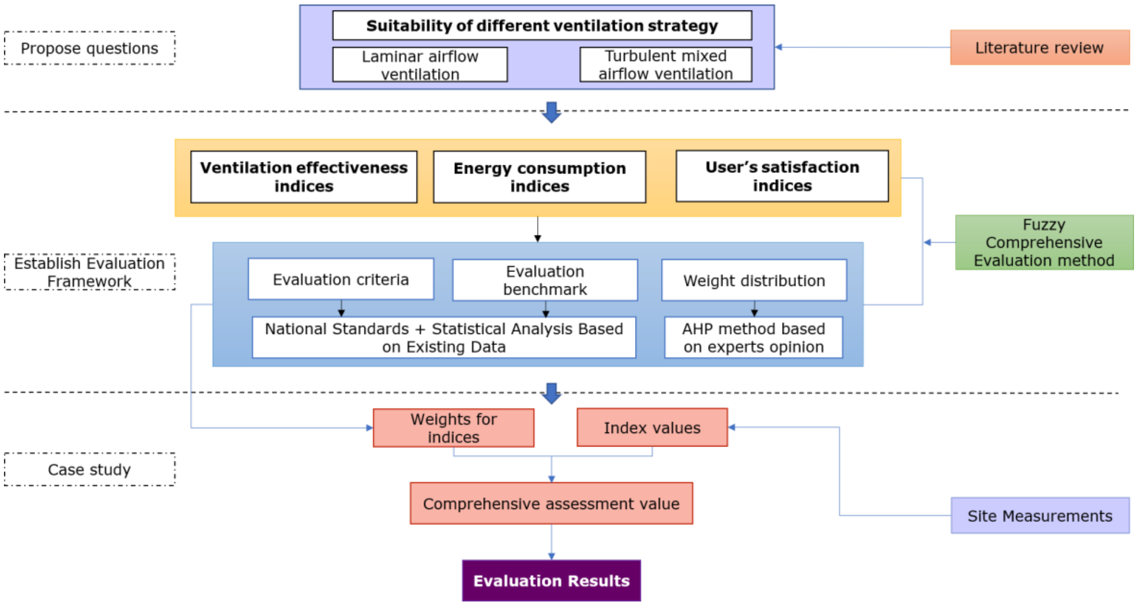


Figure 1.1: Technical route of this thesis

2 Literature review

From the above background information, this chapter presents the main research directions about of different ventilation strategies and their evaluation in operating rooms, then make summary and put forward the focusing point of this thesis.

2.1 Studies on the evaluation of different ventilation strategies

2.1.1 Rrequirements for OR ventilation in national standards

To regulate a reasonable design of OR and ensure the rationality of its indoor environment, national standard and guidelines are developed. On the selection of ventilation strategies, most of other countries do not give limits on the selection of different ventilation systems, but also some provisions give suggestions based on previous studies. ASHRAE 170-2017 [5] requires airflow in surgical cystoscopic rooms and caesarean delivery rooms shall be unidirectional, downwards. In German standard DIN 1946/4 [6], 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, with the controversy of SSI and LAF ventilation mentioned above, 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"* [7] issued in 2016. Comparison and analysis about the different national standards for the ventilation in ORs are used in thermal comfort, air change rates and setback studies [4, 8, 9]. General parameter requirements for operating rooms are briefly listed in Table 2.1 which usually including temperature, humidity and air velocity and pressure requirements.

Country	Standards	Temperature	Relative humidity	Pressure difference	Minimum Total ach
The U.S.	ASHRAE 170	20-24℃	20-60%	4 Pa	20 ach
The U.K. [10]	HTM 03-01	18-25℃	35-60%	25 Pa	25 ach
Germany	DIN 1946/4	19-26℃	30-50%	——	12 ach
Norway [11]		——	——	5-10 Pa	20 ach
China [12]	GB 50333	22-25℃	40-60%	——	12 ach
Spain [9]	UNE100713	22-26℃	45-55%	——	20 ach

Table 2.1: Parameter requirement in different standards for operating rooms

2.1.2 Evaluation or analysis from specific aspects

Studies related to the ventilation evaluation can include cost-benefit analysis of different air change rates, Thomas Gormley et al. in their paper estimate the cost for 1 air change per OR per year based on the cost of per kWh electricity [13] and 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. It may be true that simply increasing air change rates in the operating rooms tested did not necessarily provide an overall cleaner environment but did substantially increase energy consumption and costs. Thomas's research team also [14] selected environment quality indices (EQI) from the aspect of particle and microbial contamination, air velocity temperature and humidity. As the indices are measurable and repeatable, therefore this method can be safely used to evaluate air quality within the health care environment to provide guidance for operational practices and regulatory requirement. As the indoor environmental quality in an OR affects not only the patient health but also the satisfaction of the surgical staff, thermal comfort of surgical team is another direction that scholars are concerned about. It was found that surgeons and nurses feel different thermal sensations for the same surgical room through questionnaire surveys and PMV index calculation and it is suggested that ventilation conditions should be revised accordingly to the number of persons in the room and the type of activity performed [8, 15].

2.2 Studies on energy consumption of ORs

Being one of the most energy intensive departments in hospitals, operating room energy consumption are always concerned by organizations and scholars. Beier, a scholar from German measured air handling units electricity consumption in operating theaters could reach 364 kWh/(m^2·yr) with extremes of up to 1275 kWh(m^2·yr) for continuously operated AHUs [16]. M A Melhado et al. [17] simulated annual thermal consumption in three layouts of ORs with in orthopedic surgery in different cities and found that the layout with a hallway and a surgery room had the highest energy consumption as 530.20 kWh/m^2; the studied consumption of ORs are ranging from 358.70-530.20 kWh/m^2. In the research of S.C. Hu et al. [18], electricity consumption in unit area value for air-conditioning in operating theater is three times (45.06 kWh·m^{-2}month^{-1} / 15.97 kWh·m^{-2}month^{-1}) higher than that in general area and it takes about 3.02% of the total electricity consumption of the whole building. To reduce energy use, American Society of Healthcare Engineers (ASHE) [19] also recommend adopting setback strategy, which means to reduces the amount of air supplied when the room is not in use. Generally, for the evaluation of energy consumption for ventilation in ORs, an evaluation benchmark is needed. Dale Sartor et al. from Lawrence Berkeley National Laboratory [20] reviewed four techniques used for building energy performance benchmarking of cleanroom and laboratory buildings, including statistical analysis like ENERGY STAR Building Label in the U.S., point-based rating systems which is usually used in green building assessment systems like LEED and BREEAM, model-based benchmarking from simulation and also hierarchical end-use performance metrics. Although there are not many studies especially for energy consumption of OR ventilation system, statistical analysis can be used based on real operation data.

2.3 Literature review summary

From the above literature, the requirements of different national standards for operating room mostly include temperature and humidity, pressure difference, ventilation rate and air velocity etc., but there is a lack of regulations for energy consumption of ventilation system as well as personnel comfort. Especially, a benchmark of OR energy consumption for ventilation system should be established for the assessment of consumption level. What's more, the existing evaluation is often carried out from one aspect, which has one-sidedness as there are several aspects to focus at the same time. Therefore, this study is designed to conduct an evaluation from a holistic view on the suitability of different ventilation strategies for ORs. Suitable ventilation strategy should use as relatively less energy consumption to create an environment which perfectly meets the standard requirements of clean rooms, at the same time ensure the staffs' and patients' coziness. The significance is to help provide guidance for the adjustment of ventilation system in operating room and the selection of reasonable ventilation system for future designers.

3 Research Methodology

This part including framework development, field measurement, experts survey and questionnaires. The following sections will explain each part in detail.

3.1 Evaluation framework

3.1.1 Analytic hierarchy process method for weight distribution

The analytic hierarchy process (AHP) method is originally developed by Thomas L. Saaty in the 1970s in the book *Decision Making for Leaders: The Analytic Hierarchy Process for Decisions in a Complex World* [21] and has been extensively studied and refined since then. AHP method is a structured technique in analyzing complex decisions, based on people's subjective judgment as well as mathematics. As the problem of suitability assessment is essentially a comprehensive evaluation problem with various kind of indices, AHP method with its natural simplicity is a good choice to help sort out the structural levels of the problem and assign weights to the indices at different levels. The procedures of using AHP method to determine weights can be summarized as follows:

(1) Build hierarchical structure

Explicit the evaluation objectives and decomposed the problem into different levels of elements, forming a hierarchical structure as shows in Figure 3.1.

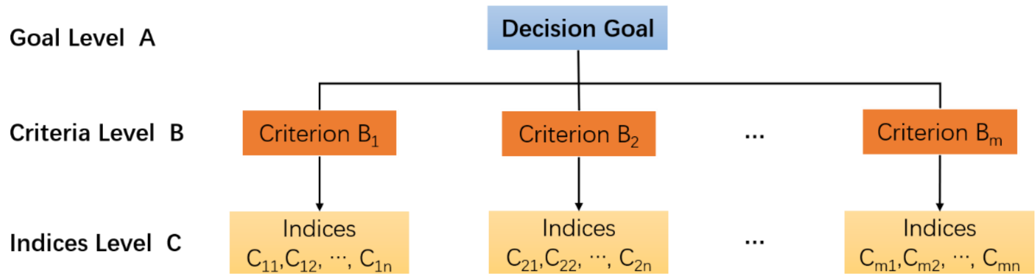


Figure 3.1: Hierarchical structure of general questions

(2) Develop comparison matrix

According to the hierarchical structure from the top to the bottom, develop the comparison matrix through the pairwise comparison between related factors in this level. Table 3. 1 gives an example of the comparison matrix between goal level A and criteria level B, where B_{ij} is the importance scale of the two-criteria comparison considering the goal. The scaling method adopted in this thesis is the commonly used 1-9 scale developed by Saaty as shows in Table 3. 2.

A	**B_1**	**B_2**	**B_3**	**...**	**B_{m1}**
B_1	1	b_{12}	b_{13}	...	b_{1m}
B_2	b_{21}	1	b_{23}	...	b_{2m}
B_3	b_{31}	b_{32}	1	...	b_{3m}
...	...	...	...	1	...
B_{m1}	b_{m1}	b_{m2}	b_{m3}	...	1

Table 3. 1: Comprehensive matrix

Scale	Compare I and j
1	I and j are equally important
3	I is weakly more important than j
5	I is more important than j
7	I is strongly more important than j
9	I is absolutely more important than j
2, 4, 6, 8	Intermediate scale
Reciprocal	if I compare to j, the scale is a_{ij}, then $a_{ji} = 1/a_{ij}$

Table 3. 2: 1-9 scale of the relative importance

Suppose the judgement matrix is $\mathrm{B} = (b_{ij})_{m\times m}$, there are three characteristics of matrix B.

- $b_{ij} > 0$ (I, j=1, 2, …, m) —— every element in the comparison matrix is positive.
- $b_{ij} = 1$ (i=1, 2, …, m) —— value on the diagonal line of the matrix is always 1, which means equally important as it is compare to itself.
- $b_{ij} = 1/b_{ji} (\mathrm{i} \neq \mathrm{j})$ —— off-diagonal elements are reciprocal.

(3) Conduct consistency check

Consistency of the judgement matrix means the judgment results are in uniformity and there are no contradictory results. As the matrix is derived from the subjective preferences of individuals, the inconsistency is unavoidable especially when there are many criteria in one layer. Therefore, in AHP method, the consistency ratio (CR) is defined and calculated from the consistency index (CI) of the judgement matrix (the one with our judgments) divided by the consistency index of a random-like matrix (RI) as shows in Eq. 3-1.

$$CR = \frac{CI}{RI} \qquad 3\text{-}1$$

$$CI = \frac{\lambda_{max} - m}{m - 1} \qquad 3\text{-}2$$

Where, λ_{max} is the largest eigenvalue of the judgement matrix; m is the number of criteria. To check the consistency of matrix B, when $\lambda_{max} = m$, CI=0, the judgement is perfectly consistent; while the more CI deviates from zero, the worse the consistency of the matrix is. Saaty also provided the calculated RI value for matrices of different sizes as shown in Table 3. 3. According to Saaty, if the calculated CR is less than 0.10, then it is acceptable to continue the AHP analysis, otherwise, the judgement matrix needs to be adjusted.

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Table 3. 3: Consistency indices for a randomly generated matrix

(4) Local priorities for indices

After the consistency check, the next step is to calculate the relative priority of hierarchical factors to the indices in the next level, which is called local priority. In specific cases, MATLAB may help to calculate the maximum eigenvectors and conduct standardization. For a judgement matrix B (eg. A three-order matrix), input the complete matrix in MATLAB

```
>>B = [b11, b12, b13; b21, b22, b23; b31, b32, b33];
>>[V, D] = eig(B);    % calculate eigenvalue and eigenvector
```

```
>>V = V(:,1);     % obtain the eigenvector which is corresponding with the eigenvalue
>> W = V/sum(V)   % obtain weight from standardization
```

(5) Overall priorities for indices

According to the sequence from top to bottom, the relative importance of each index at the lowest level to the goal level is calculated, which is demonstrated in Table 3. 4.

Local priorities	Criteria weights	Overall priority
$\boldsymbol{w(C_{11})}$	$w(B_1)$	$w(C_{11}) \times w(B_1)$
$\boldsymbol{w(C_{12})}$		$w(C_{12}) \times w(B_1)$
…		…
$\boldsymbol{w(C_{1n})}$		$w(C_{1n}) \times w(B_1)$
$\boldsymbol{w(C_{21})}$	$w(B_2)$	$w(C_{21}) \times w(B_2)$
…		…
$\boldsymbol{w(C_{2n})}$		$w(C_{2n}) \times w(B_2)$
…	…	…
$\boldsymbol{w(C_{mn})}$	$w(B_m)$	$w(C_{mn}) \times w(B_m)$

Table 3. 4: Calculation of overall priorities

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. It also 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. But one of the problems is the difficulty to ensure the inconsistencies in the final matrix of judgments, as numeric values are derived from the subjective preferences of individuals. In the hierarchy of the decision model, people's subjective factors have a great influence during the whole process which makes one person's decision of the pair-matrix hard to be persuasive. Of course, the method of expert group judgment is a way to overcome this shortcoming, which is considered in this thesis.

3.1.2 Fuzzy comprehensive evaluation method

Considering the evaluation problem in this study, suitability seems to have no obvious conceptual boundaries. Fuzzy comprehensive evaluation (FCE) method is an approach that considers the fuzziness of evaluation index and classification. According to the theory of membership degree of fuzzy mathematics, FCE method can be qualitative evaluation is transformed into quantitative evaluation. Procedures of FCE method are as follows [22]:

(1) Determining the set of evaluation factors

Suppose the number of evaluation factors to the evaluation objective is m, represented by $u_1, u_2, \dots, u_m$, therefore, the set of evaluation factors can be wrote as $\mathrm{U} = \{u_1, u_2, \dots, u_m\}$.

(2) Determining the set of comments

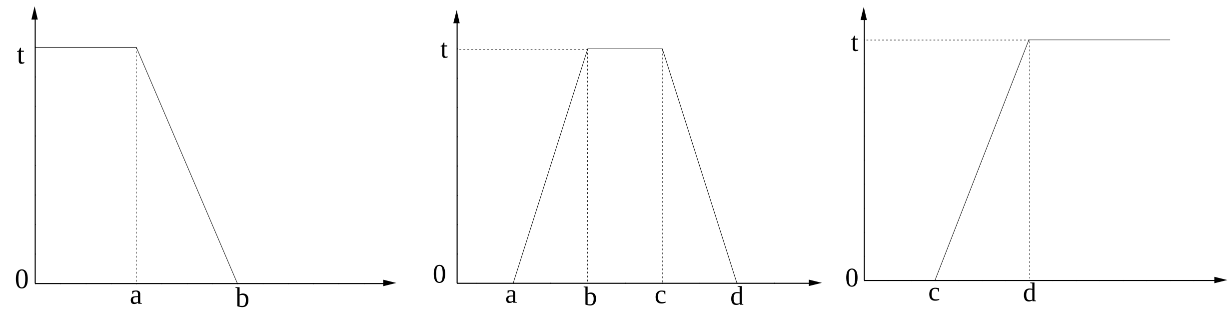
Each factor u_i has its corresponding appraisal grades v_j, then the set of comments which forms $\mathrm{V} = \{v_1, v_2, \dots, v_m\}$. For example, in this study m=3, $\mathrm{V} =$ {unsuitable, tolerable, suitable}.

(3) Setting the fuzzy mapping matrix

The mechanism of FCE method is to obtain the membership degree of the evaluation factors to appraisal grades. In the membership degree vector $R_i = \{r_{i1}, r_{i2}, \dots, r_{im}\}$, r_{im} represents the fuzzy membership in each grade; m is the number of levels in the evaluation. Generally, the membership degree vector of all factors can be derived and together form an evaluation matrix R:

$$R = \begin{bmatrix} r_{11} & \cdots & r_{1n} \\ \vdots & \ddots & \vdots \\ r_{m1} & \cdots & r_{mn} \end{bmatrix}$$

There are two methods to determine the degree of membership, according to qualitative index and quantitative index. For qualitative indicators, fuzzy statistics method is usually adopted based on expert opinions, then count the frequency of each index belonging to each evaluation level. For quantitative indicators, hierarchical membership function method can be used to determine the membership degree. It means to build corresponding membership functions according to policy provisions, quantitative standards, historical data or industry experience of the target index, then the level of each index division can be determined. Since different index has different characteristics, possible membership functions can be triangle-type functions, ladder shape functions as well as Gaussian membership functions. For example, ladder shape functions are shown in Figure 3.2.



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

(a)

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

(b)

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

(c)

Figure 3.2: Ladder shape membership functions

(4) Determination of weight distribution for evaluation indices

Weight distribution for indices can be obtained followed by AHP method mentioned above. The comparison matrix development is based on expert survey. The weight vector is represented as $W = (w_1, w_2, \dots, w_m)$.

(5) Getting the final evaluation result

By synthesizing the fuzzy matrix and weight vector as shows in Eq.3-3, the membership degree of the evaluated object to each evaluation grade can be obtained, that is, the overall evaluation result.

$$S = W \circ R \qquad 3\text{-}3$$

Where, $\circ$ is the symbol of fuzzy operator, which may represent different possible evaluation models. Commonly used operators are Zadeh operator, weighted averaging operator and bounded operator etc. Then the vector of FCE $S = (s_1, s_2, \dots, s_n)$ is obtained, where s_j is the membership degree which the evaluation objective belongs to the grade s_j. After the standardization, $\sum s_j = 1$, and the largest s_j value corresponding comment us the final evaluation result of the decision problem.

3.2 Evaluation indices and their benchmarks

3.2.1 Ventilation effectiveness

To ensure a safety environment for operation, the effectiveness aspect is commonly believed as one of the most important aspects of ventilation system in ORs. Four specific indices are chosen under this aspect according to related standards and they are bacterial concentration, particle concentration, temperature and relative humidity.

(1) Bacterial concentration (BC)

Colony-forming unit (cfu) is a commonly adopted to estimate the number of viable bacteria and is used as an index in the assessment of microenvironment quality around wound area during operation. This index is regulated in some national standards: Norwegian Board of Health Supervision require that general operating theatres should keep the number of airborne microbes beneath 100 cfu/m^3, while ultra clean rooms requires 10 cfu/m^3 which is the same in Chinese standard "Hygienic standard for disinfection in hospitals" GB 15982 and the U.K. standard HTM 03-01. As most ultra clean rooms are equipped with LAF systems and general operating rooms equipped with MV systems, in this paper we may set the evaluation grades for bacteria concentration separately for LAF and MV system according to the standards. For LAF systems, it is proper if BC≤6 cfu/m^3, moderate if 6<BC≤10 cfu/m^3 and improper if BC>10 cfu/m^3. For MV systems, it is proper if BC≤60 cfu/m^3, moderate if 60<BC≤100 cfu/m^3 and improper if BC>100 cfu/m^3.

(2) Particle concentration (PC)

Particle matter concentration is also an important parameter to judge air cleanliness and studies have shown that particles may be responsible for some postoperative complications [23] like adhesion and granuloma. Because there is no standard in the current building codes related to particle counts in an ORs, ISO standard 14644 which is used for classifying cleanroom and associated controlled environments is adapted in the application in this study. The size of controlled particles can be 0.1 μm, 0.2 μm, 0.3 μm, 0.5 μm, 1.0 μm, 5.0 μm. 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, since it is considered to be the size that begin to causes cell phagocytosis reactions [24]. According to literature [14], the air cleanliness class for normally LAF rooms is Class 5 which limit the suspended particulate number within 3520/m^3, for the MV system ORs the Class can be 6 or 7, which means the particle concentration should within 35200/m^3. Therefore, possible grading range for LAF is proper if PC≤352/m^3; moderate if 352<PC≤3520/m^3; improper if PC>3520/m^3 and for MV is proper if PC≤35200/m^3; moderate if 35200<PC≤3520000/m^3; improper if PC>352000/m^3.

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

Temperature and humidity are important parameters of ventilation and air conditioning system control. The reason for the special requirement of temperature and relative humidity in ORs is that patient often has large open wounds, warm temperature and high humidity environment may provide conditions for rapid reproduction of some bacteria and bring other hazards, at the same time may cause doctors and patients to sweat, which is not conducive to the sanitation of wound area and the smooth operation process; while low temperature may cause shivering for surgeons and hypothermia for patients, and low relative humidity may result in uncomfortable nose and throat as well as the dehydration of wound if the operation process lasts long. There are slightly different requirements for temperature and humidity in ORs in different national standards as shows in Table 2.1. As Norwegian standard does not specify some parameters, evaluation for these criteria in this study comprehensively considers this part in other European national standards[9] and choose their overlapped range as the proper range in this evaluation and the range outside the overlapping region but still within the limit value are considered as moderate. Therefore, a possible evaluation grades for these two parameters can be: proper if 22≤T≤24℃, 40%≤RH≤50%; moderate if 18≤T<22 ℃ and 24<T≤26 ℃ , 30%≤RH<40% and 50%<RH≤60%; improper if T>26 and T<18℃, RH <30% and RH >60%.

3.2.2 Energy consumption

As the increasingly serious energy problems all over the world, it is of great significance to pay attention to energy in every industry even in a very small point. The HVAC system used in OR in hospital is one of the most energy consuming part due to several certain factors: nearly 24 hours constant operation, complete air-conditioning and the three stages of filtration in terminal devices and air handling units as well as high ventilation rates [25]. Not only the indoor air temperature, relative humidity and air cleanliness needs to be controlled, pressure and air velocity also needs to be in a reasonable range. Therefore, in the comprehensive evaluation for ventilation system, energy consumption should be one important aspect. However, OR ventilation system energy consumption is not specified in standards, building a benchmark is of great importance in comprehensive evaluation.

Although most of todays' public buildings have energy monitoring system, however, it is still hard to directly obtain such detailed energy consumption data, but it is possible to know logged parameters of important places like fresh and supply air temperature and humidity, air volume, heat recovery efficiency etc.

3.2.2.1 Energy calculation

This study considers the consumed electricity from fans used to deliver air and the energy consumption of treating outdoor air to the required state. Generally, energy consumption of fans W_f can be calculated according to Eq. 3-5 as well as Eq. 3-6 and air handling energy consumption W_h may base on Eq.:

$$W_s = \frac{P}{3600\eta} \quad \text{3-4}$$

$$W_f = W_s \times Q \times T \quad \text{3-5}$$

where W_s is the electricity consumption per unit volume air, kWh; P is the full pressure of the fan, Pa; η is the efficiency of the fan, %; Q is the air flow volume delivered by the fan; T is the calculation period of each situation.

$$W_h = Q \times (h_{supply} - h_{outdoor\ air}) \times T \quad \text{3-6}$$

where W_h is the electricity consumption of the target OR; h_{supply} is the enthalpy of the supply air; $h_{outdoor\ air}$ is the enthalpy of fresh air.

For this study, ventilation systems of ORs in St. Olavs hospital are with different type of format as shows in Figure 3.3, which needs to be considered differently during energy calculation.

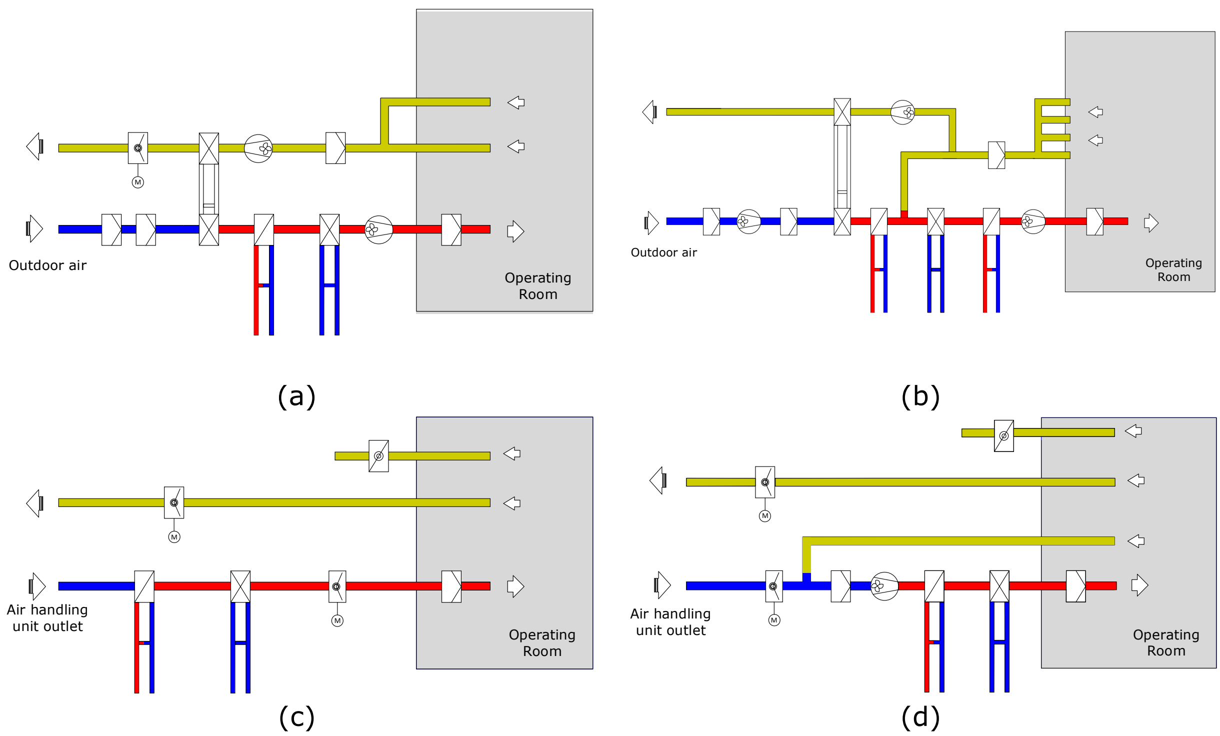


Figure 3.3: Different ventilation system formats in St. Olavs Hospital

(1) Separately treat air in full fresh air system with heat recovery as shows in Figure 3.3(a)

This system adopts all the exhaust air recovery to preheat outdoor air. The temperature of fresh air after heat recovery can be calculated as Eq. 3-7, then the energy consumption of air dealing can be calculated according to the Eq. 3-8.

$$T_{recovery} = T_{fresh\ air} - \eta \times (T_{fresh\ air} - T_{exhust\ air}) \qquad 3\text{-}7$$

$$W_h = Q \times (h_{supply} - h_{recovery}) \times T \qquad 3\text{-}8$$

Where η is the efficient of heat recovery equipment; $T_{recovery}$ is the supply air after heat recovery; $h_{recoveery}$ is the enthalpy of the supply air after heat recovery.

(2) Separately treat air in one turning air with heat recovery as shows in Figure 3.3(b)

This system format is normally adopted in LAF rooms, which part of the room air is used in exhaust air recovery to preheat fresh air and the other part is returned. Therefore, except for the temperature after heat recovery, the temperature after mixing with the return air also needs to be calculated, which is shown in Eq. 3-9.

$$h_{mix} = h_{returning\ air} + \frac{Q_{fresh\ air}}{Q_{returning\ air}} \times (h_{recovery} - h_{returning\ air}) \times T \qquad 3\text{-}9$$

Where, h_{mix} is the enthalpy of mixed air; $h_{returning\ air}$ is the enthalpy of mixed air; $Q_{fresh\ air}$ and $Q_{returning\ air}$ are the air volume of fresh and returning air, respectively.

(3) Centralized treatment air in full fresh air system as shows in Figure 3.3(c)

This system centralizes the primary treatment of fresh air and exhaust air through large scale air handling units (AHUs) and further treatment will be carried out at the terminal devices of each room. Therefore, calculating the energy consumption of each OR needs to share the energy consumed by AHU treating air and fans delivering air according to the proportion of air volume as shows in Eq.3-11.

$$W_{terminal} = Q \times (h_{supply} - h_{AHU\ outlet}) \times T \quad 3\text{-}10$$

$$W_h = W_{terminal} + \frac{Q_{supply\ air\ in\ one\ OR}}{Q_{air\ \ volume\ AHU\ provide}} W_{AHU} \quad 3\text{-}11$$

Where, $W_{terminal}$ is the energy consumed by terminal devices of each OR; $h_{AHU\ outlet}$ is the enthalpy of AHU outlet air; W_{AHU} is the energy consumed of AHU; $Q_{supply\ air\ in\ one\ OR}$ and $Q_{air\ \ volume\ AHU\ provide}$ are the air volume of supply air in the target OR and the total air volume supply of the AHU.

(4) Centralized treatment air in one turning air with heat recovery as shows in Figure 3.3(d)

This kind of system is also used in LAF operating theaters, which 1/3 of the room air volume is exhausted while 2/3 of the room air volume is returned. Therefore, calculations can be conducted based on the above illustration.

3.2.2.2 Multi-linear regression

From the above description of how to calculate the energy consumption value, ventilation system energy consumption may be influenced by a lot of factors. Therefore, in this paper, a multi-regression analysis method is used to establish a prediction model between energy consumption and possible variables of ventilation system in ORs. For example, variables affecting energy consumption in the OR may include outdoor temperature, supply air volume, heat recovery strategy, ventilation area, setback strategy, built year, etc.

In 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:

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

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

Multi-linear regression is realized by using SPSS statistics 25, which can easily achieve correlation analysis and partial correlation analysis. The process of linear regression adopted enter method which means 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.

3.2.2.3 Determine evaluation benchmark

Due to the time limitation of collecting energy consumption data in different weather conditions in the target hospital, determining the evaluation benchmark has lots of difficulties. Based on the calculation data and the prediction equation model above, local average outdoor temperature in April is introduced into the equation, then energy consumption can be transformed into the value at about the same test time, which makes it meaningful for comparison. According to the method of setting benchmark of building energy consumption the lower quartile or median of energy consumption level can be selected as the baseline.

3.2.3 User's satisfation

Ventilation system in ORs defines not only the air flow, but also creates an environment to ensure the comfort of surgical team during surgeries. Therefore, the satisfaction of operating room users is also an indispensable part in the comprehensive suitability evaluation. In this thesis, thermal comfort and acoustic environment are considered.

(1) Thermal comfort

For thermal comfort, PMV-PPD model has been adopted in ISO 7730 [26] 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) is chosen as an index to reflect the degree of dissatisfaction of the thermal environment though questionnaire survey. Then the grades of assessment can be proper if APD⩽10%; moderate if 10%<APD⩽25%; improper if APD>25%.

(2) Acoustic environment

With the large air flow and higher resistance in air ducts, noise caused by ventilation system also has 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 operating rooms can be selected as the assessment index for acoustic environment. Evaluation baselines proper if SPL⩽40 dB; moderate if 40<SPL<50 dB; improper if SPL⩾ 50 dB.

3.2.4 Evaluation indices summary

Based on the above analysis, the suitability evaluation indices for ventilation strategy in ORs are determined and summarized in Table 3.1.

Criteria level (B)	Indices level (C)	Assessment criteria	
Effectiveness (B_1)	BC (C_{11})	Proper	$BC \leq 6$ cfu/m^3 (LAF)
			$BC \leq 60$ cfu/m^3 (MV)
		Moderate	$6 < BC \leq 10$ cfu/m^3 (LAF)
			$60 < BC \leq 100$ cfu/m^3 (MV)
		Improper	$BC > 10$ cfu/m^3 (LAF)
			$BC > 100$ cfu/m^3 (MV)
	PC (C_{12})	Proper	$PC \leq 352/m^3$ (LAF)
			$PC \leq 35200/m^3$ (MV)
		Moderate	$352 < PC \leq 3520/m^3$ (LAF)
			$35200 < PC \leq 352000/m^3$ (MV)
		Improper	$PC > 3520/m^3$ (LAF)
			$PC > 352000/m^3$ (MV)
	T (C_{13})	Proper	$22 \leq T \leq 24$℃
		Moderate	$18 \leq T < 22$℃ and $24 < T \leq 26$℃
		Improper	$T > 26$℃ and $T < 18$℃
	H (C_{14})	Proper	$40 \leq RH \leq 50\%$
		Moderate	$30 \leq RH < 40\%$ and $50 < RH \leq 60\%$
		Improper	$RH < 30\%$ and $RH > 60\%$

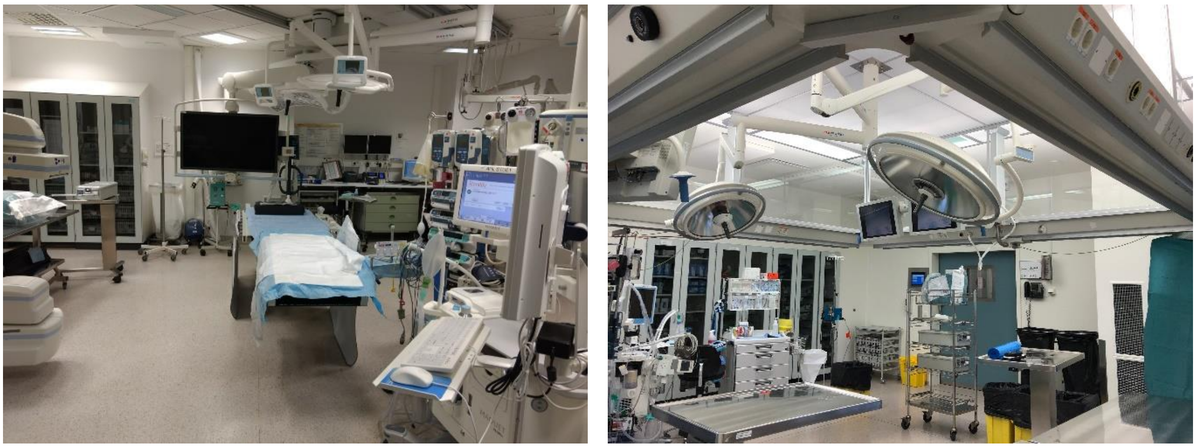
Energy consumption (B_2)	(C_{21})	Based on measured and calculated value	
User's satisfaction (B_3)	TC (C_{31})	Proper	APD⩽10%
		Moderate	10%<APD⩽25%
		Improper	APD>25%
	NL (C_{32})	Proper	SPL⩽40 dB
		Moderate	40<SPL<50 dB
		Improper	SPL⩾50 dB

Table 3.1: Suitability assessment factors/sub-factors summary

3.3 Exprimental measurements

3.3.1 Operating rooms at St. Olavs Hospital

The evaluation objectives in this study are the ventilation system in two ORs of St. Olavs hospital in Trondheim, Norway. Through the assessment of the suitability of them, validation and demonstration of how does the whole evaluation work can be carried out. The chosen ORs are OR1 in Emergency and Heart-Lung center and OR 2 in Orthopedic center respectively equipped with MV system and LAF ventilation system as shows in Figure 3.4 (a) and (b). The area of OR 1 and OR 2 is 53 m^2 and 51.84 m3, respectively.



(a) (b)

Figure 3.4: Layout of the two case operating rooms

3.3.2 Equipment

To obtain index value, site measurements need to be carried out in real operating rooms. From the chosen indices above, parameters that need to be tested include bacteria concentration, particle concentration, temperature and relative humidity etc.

(1) Microbial sampler

The concentration of microbial contaminants is measured mainly by the method of reading colony number on the agar plates after collecting air samples. To test the planktonic bacteria, air samples were collected by a calibrated active air sampler (Air Ideal 3P from Biomerieux) as shows in Figure 3.5(a). This sampler sucks in air with 100 L/min and uses an 85mm agar plate to achieve bacteria collection according to the impaction principle. The device was set to draw air for 10 minutes for each sample during measurements. Deposit bacteria are also tested by setting passive agar plates on the floor as shows in Figure 3.5(b). After the exposure, the agar plates are covered with lids and incubate for 2 days at 35±2℃ and one day at 23±2℃. Final results are from a microbiologist who works in the laboratory of St.Olavs Hospital.

(2) Particle counter

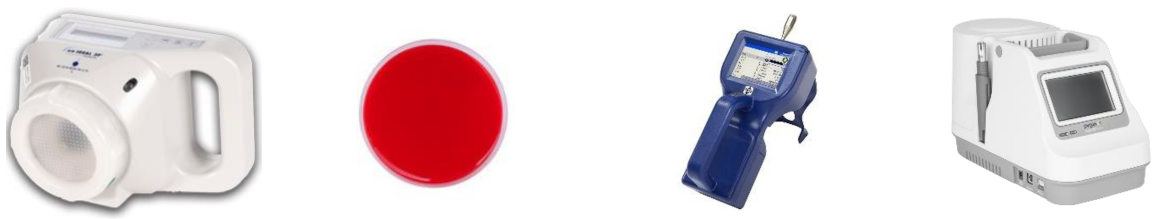
In this study, particle concentration in ORs are measured by using the calibrated TSI AEROTRAK^{TM} Handheld Particle Counter Model 9306-V2 as shows in Figure 3.5(c). With six channels, the measuring range is 0.3~10.0μm and the accuracy is $\pm 5\%$. Before the measurement starts, zero calibration is needed by using a zero-check filter and the calibration is completed when the number of any particle size within 5 minutes of sampling does not exceed 1. According to ISO14644, single sample volume (V_s) per sampling location is determined by using Eq. 3-12. In this study, as the estimated ISO classification is 5 in LAF room and class 6 or 7 for MV and the particle size considered is and D⩾0.5μm, the minimum single sample volume can be calculated as 5.68L. As the particle counter in the measure has a flow rate of 2.83L/min, then 2 min single sample count would be required.

$$V_s = \left(\frac{20}{C_{n,m}}\right) \times 1000 \qquad \text{3-12}$$

Where, V_s is the minimum single volume per location; $C_{n,m}$ is the class limit (number of particles per cubic meter) for the largest consideration particle size specified for the relevant class; 20 is the number of particles that could be counted if the particle concentration were at the class limit.

(3) Thermometer and hygrometer

Air temperature and relative humidity were measured by using factory calibrated Pegasor AQ™ Indoor (Figure 3.5(d)), whose measuring range is -20℃~60 ℃ and 0~90% RH with accuracy $\pm$0.2 ℃ and $\pm$1.1%, respectively. Temperature and relative humidity were logged by this device every 10s during measurements.



(a) Air IDEAL® 3P™ (b) Agar Plate (c) TSI AEROTRAK^{TM} Handheld Particle Counter Model 9306 (d) Pegasor AQ™ Indoor

Figure 3.5: Equipment and devices in measurements

3.3.3 Mock surgery procedure

As most of the parameters cannot be measured during real operations, mock surgeries 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. Table 3.2 listed the procedures of movements of surgical team members. The mock surgery lasts altogether 2 hours including incision phase (50 mins), joint replacement phase (33 min) and wound closure phase (37 min).

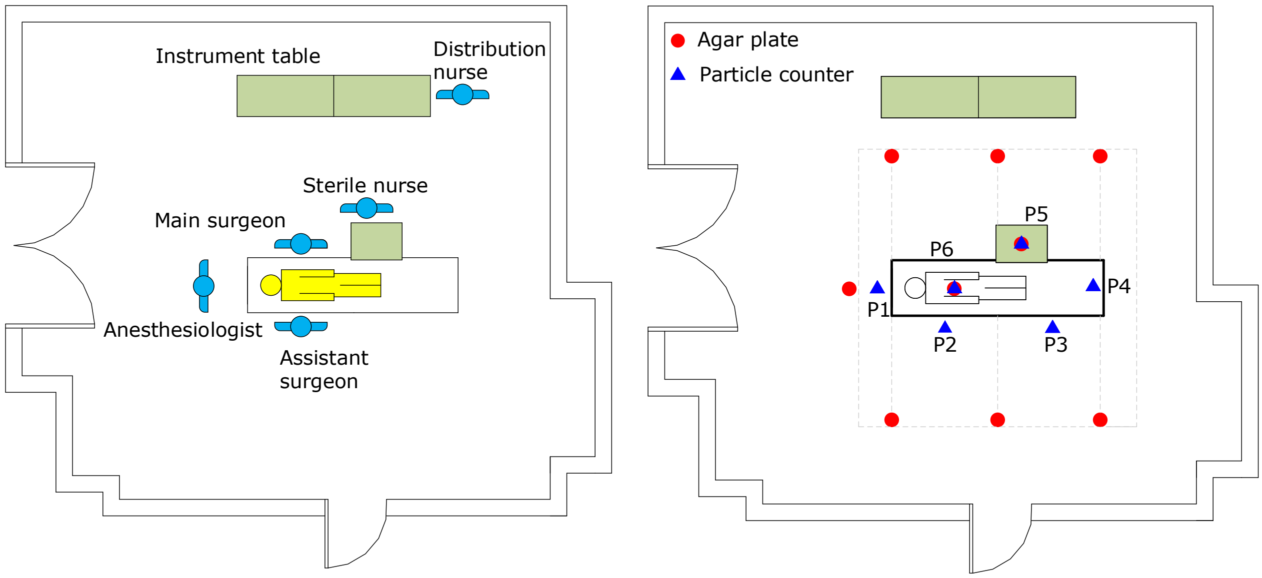
Phase	**Activities**				
Preparation	All surgical team member scrub hands			Patients lie down and draping	
	Main surgeon	Assistant surgeon	Sterile nurse	Distribution nurse	Anesthesiologist
Incision/ Joint replacement /Wound closure	Deliver instruments from/to sterile nurse	Use equipment near the patients wound	Pass and receive instruments to/from surgeon	Deliver and receive supplies to/from the sterile nurse	Observing the patient's health and inducing drugs
	Perform surgical actions inside the patients wound	Adjust the position of patients' leg	Deliver and receive supplies to/from the distribution nurse	Unpack supplies	
	Use surgical hammer and electric drill	Use equipment to assist main surgeon	Mix material	Gather equipment from cabinet	
	Rest for a few seconds	Rest for a few seconds	Rest for a few seconds	Rest for a few seconds	Rest for a few seconds

Table 3.2: Mock surgery procedures

Figure 3.6: During mock surgery process

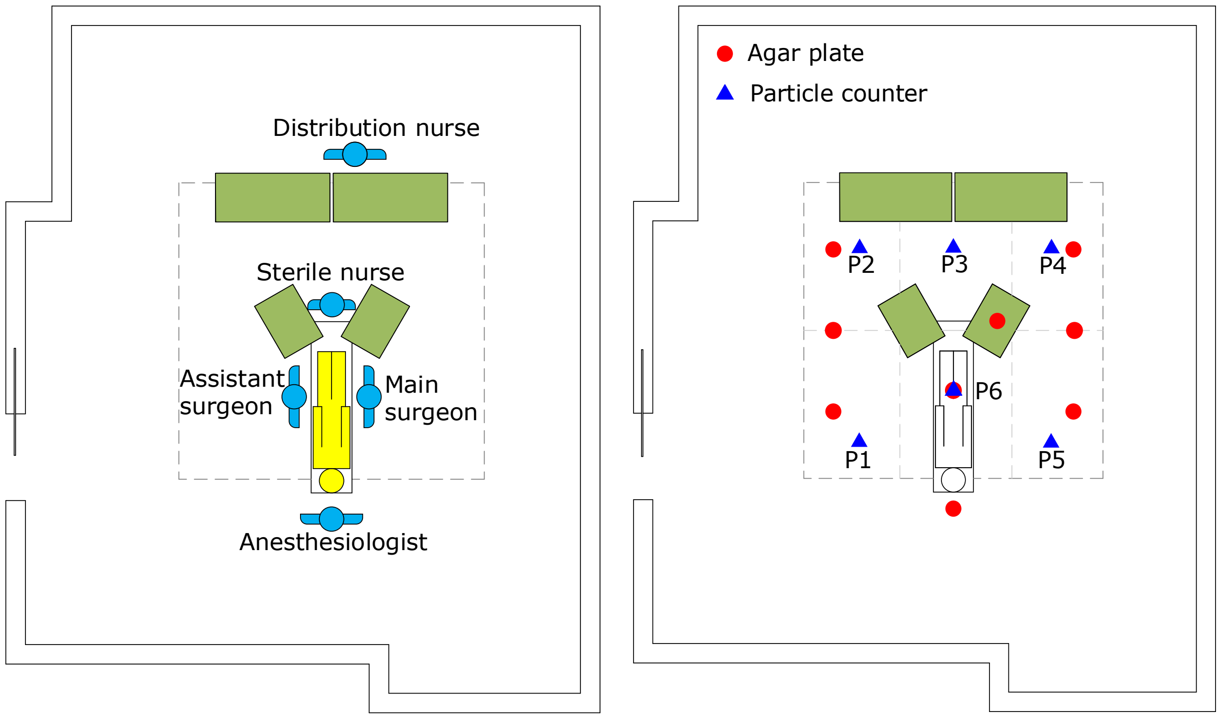
3.3.4 Measuring points set up

The position of participants during mock surgeries and measuring points arrangement of OR 1 (MV) and OR 2 (LAF) are shown in Figure 3.7 and Figure 3.8, respectively.



(a) (b)

Figure 3.7: Position of participants and measurement point arrangement in OR 1



(a) (b)

Figure 3.8: Position of participants and measurement point arrangement in OR 2

Figure (a) and (b) demonstrate that the position of surgical team members during operations. Bacteria measurement points are demonstrated with red circle in the above pictures. The point around wound area is used for planktonic bacteria concentration measurements, while the points around the 4m×4m sterile zone test the sedimentation bacteria. Particle measurement points are shown with blue triangles, the number of test points are determined according to the ISO standard requirement.

3.4 Expert survey and users' satisfaction questionnaire

Expert questionnaire are used to collect the opinion of relative importance of indications from professionals who have the experience of designing, operating or doing studies on OR ventialtion system. For the convenience of collecting data, expert survey was conducted online. Question list is designed and attached in Appendix 1.

Users' questionnaires were directly distributed to surgical team members who perform operations in the two chosen ORs. The questionnaire included two parts as shows in Appendix 2: thermal comfort questions based on their thermal sensations and degree of satisfaction; acoustic comfort questions asked about the percepetion of noise and if the noise may affect their work.

4 Results

4.1 Weights distribution result

Followed by AHP method mentioned in chapter 3.1.1, fifteen experts gave their opinions on determining the priority of indices. All these experts are professors and researchers, designers and engineers, operational management professionals whose works are closely related to ventilation. Through analysis and calculation of the expert survey, final weight distribution of all the indices are listed in Table 4.1.

Aspects	Priority	Indices	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

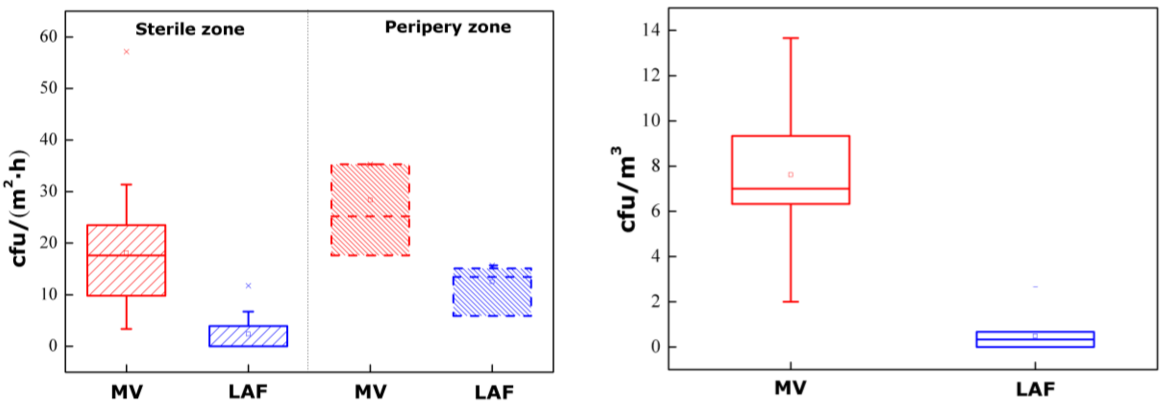
Table 4.1: Weigh distribution result summary

From the result, ventilation effectiveness is given the largest priority, followed by users' satisfaction and energy consumption. In terms of ventilation effectiveness aspect, compared with temperature and humidity, the concentration of bacteria and particles are major concerns. Finally, thermal comfort is stressed more than noise influence.

4.2 Indices' evaluation value results

4.2.1 Bacteria concentration

Figure 4.1 (a) is the comparison of the sediment bacteria measurement results between sterile area and periphery area in the two case ORs. It shows that in both ORs, periphery area has more bacteria than sterile area; operating theater with MV system has obviously higher concentration. Figure 4.1(b) demonstrates the bacteria measurement result from active air sampler, which is around wound area. In OR1 with MV system, the highest bacteria concentration during mock surgeries is up to 13.6 cfu/m^3, the lowest is 2 cfu/m^3 and the median value is 7 cfu/m^3. In OR2 with LAF system, the highest bacteria concentration is around 1.0 cfu/m^3 while the lowest is 0 and the median value is 0.3 cfu/m^3. For the purpose of evaluation, the median value of planktonic bacteria concentration number is chosen to represent the index value.

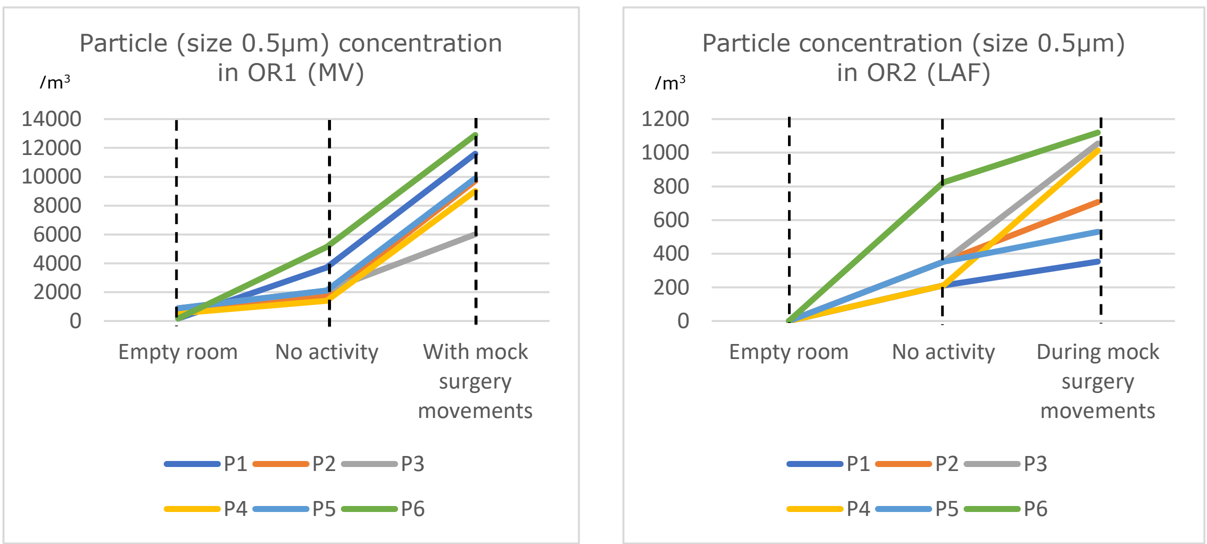


(a) (b)

Figure 4.1: Bacteria measurement results

4.2.2 Particle concentration

The results of particle concentration are shown in Figure 4.2, which shows the number of particles in different measurement points under the situation of empty room, no activity and with mock surgery movements. As can be seen from the figures, the particle concentrations of MV and LAF are very low when there is no person inside; when there is no movement, the number of particles near the wound is higher because the people gathering around. There was a further increase in the number of particles during simulated surgery, and the concentration of particles near the wound was still higher than that at other sites. 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.



(a) (b)

Figure 4.2: Particle measurement result in different locations of ORs

4.2.3 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 Figure 4.2. 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 to 27℃ or even higher. The measured relative humidity was between 11.01%-24.16% in both operating rooms, which was changing slightly with outdoor air humidity. To conduct evaluation, the index values adopt the average value from measurements, therefore, the index value of temperature and relative humidity in OR1 are 24.55℃ and 17.72%, respectively; in OR2 are 23.84℃ and 16.51%, respectively.

Mock surgeries	**OR1 (MV)**		**OR2 (LAF)**	
	Temperature	Humidity	Temperature	Humidity
No.1	23.99℃	15.11%	24.02℃	23.32%
No.2	24.85℃	14.41%	23.88℃	14.15%
No.3	24.81℃	23.64%	23.61℃	12.05%
Average	24.55℃	17.72%	23.84℃	16.51%

Table 4.2: Temperature and humidity measurement results in mock surgeries

4.2.4 Electricity consumption

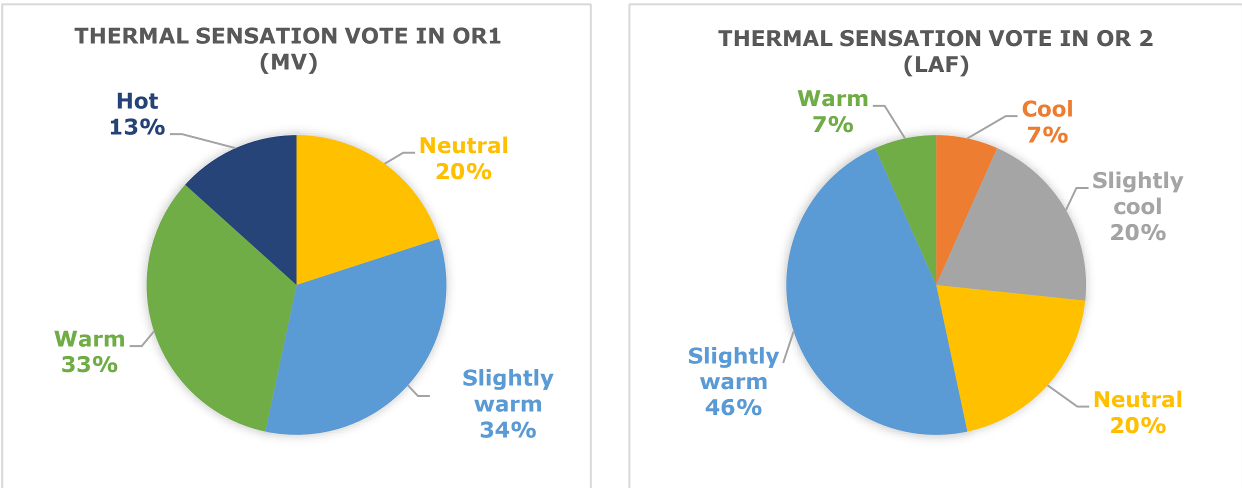
Based on the method of calculating energy consumption mentioned in the previous chapter, logged parameters of supply and exhaust air as well as the regression equation modified by the local average outdoor temperature in April (7.3℃), and the daily average energy consumption of OR1 and OR2 is obtained. Electricity consumption of OR1 is 4.50 kWh/m^2/day; while for OR2 with LAF is 5.17 kWh/m^2/day.

4.2.5 Theraml comfort and noise level

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

(1) Thermal comfort

From the questionnaires, thermal sensation votes for OR1 (MV) and OR2 (LAF) are shown in Figure 4.3. Thermal sensation is divided into 7-point scale from cold to hot. 34% of survey participants in OR1 and 46% in OR2 thought the environment is slightly warm, which takes the largest proportion. Then in OR1, the vote followed by warm, neutral and hot; in OR2 followed by neutral, slightly cool and equal percentage in warm and cool.



(a) (b)

Figure 4.3: Thermal sensation vote result

The actual percentage of dissatisfaction was obtained from questionnaire results. In OR1, 43% questionnaire participants thought it dissatisfied, while in OR2, no one was dissatisfied with the thermal environment in LAF operating room in the questionnaire survey.

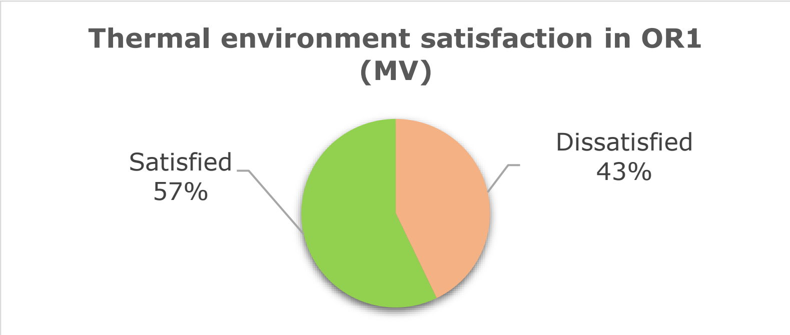


Figure 4.4: Thermal environment satisfaction in OR1 (MV)

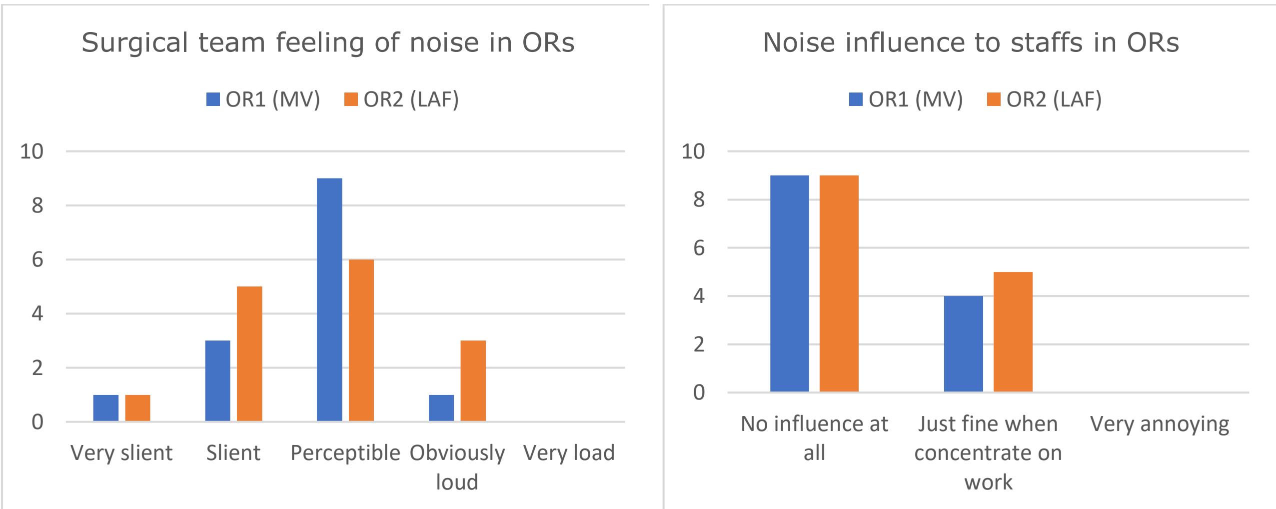
(2) Noise level

Noise level measurements were conducted in empty ORs and the result are listed in Table 4.3, which uses the average value of several positions as the index value.

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

Table 4.3: Sound pressure measurements result

Figure 4.5 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 about 60% considered it has no effect on them at all and the rest part thought it was just fine when they concentrated on work.



(a) (b)

Figure 4.5: Occupants feeling of noise and noise influence

4.3 Energy consumption benchmark

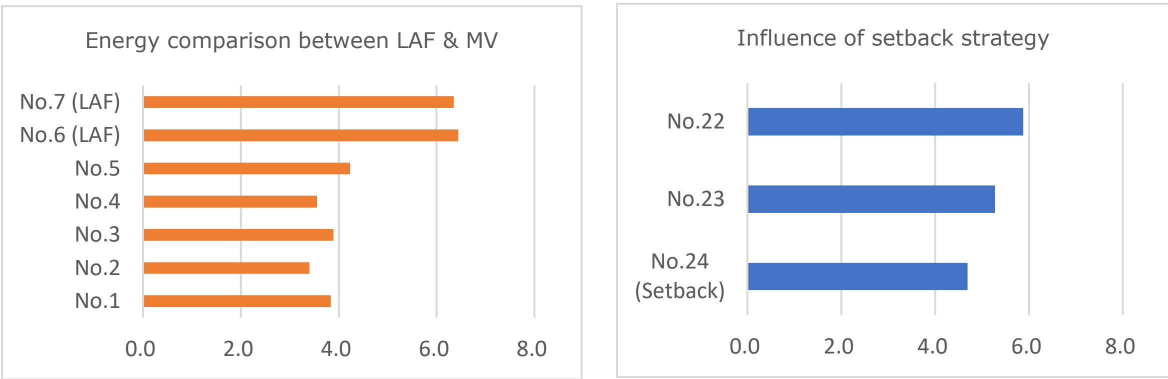
4.3.1 Electricity consumption calcualtion result

According to the previous analysis and illustration in Section 3.2.2, Table 4.4 shows the basic information and electricity consumption results of 42 ORs without temperature correction.

OR No.	Ventilation strategy	Supply air volume (m^3/h)	Heat recovery strategy	Electricity consumption per day (kWh/day)	Electricity consumption per day, per unit area ($kWh/m^2/day$)	Setback strategy
1	MV	2600	Y	158.48	3.84	N
2	MV	2600	Y	140.32	3.40	N
3	MV	2600	Y	160.54	3.89	N
4	MV	2600	Y	146.92	3.56	N
5	MV	3750	Y	235.27	4.23	N
6	LAF	11810	Y	264.38	6.44	Y
7	LAF	11810	Y	259.28	6.35	Y
8	LAF	8750	Y	288.67	5.19	N
9	MV	2320	Y	141.78	3.85	N
10	MV	1850	Y	176.71	3.59	N
11	MV	1900	Y	186.06	3.78	N
12	MV	2000	Y	205.75	4.18	N
13	MV	2100	Y	224.45	4.56	N
14	MV	2100	Y	223.96	4.55	N
15	MV	2660	Y	238.24	4.84	N
16	MV	2400	N	265.97	5.53	N
17	MV	2400	N	247.69	5.15	N
18	MV	2400	N	263.56	5.48	N
19	MV	2400	N	240.00	4.99	N
20	MV	2400	N	241.92	5.03	N
21	MV	3700	N	289.24	4.50	N
22	MV	3700	N	272.69	5.88	N
23	MV	3800	N	265.36	5.28	N
24	MV	3800	N	298.74	4.69	Y
25	LAF	12900	N	288.68	7.93	Y
26	MV	3800	N	282.90	5.02	Y
27	MV	3800	N	268.09	4.82	Y
28	MV	2700	N	152.57	3.56	Y
29	MV	2700	N	154.29	3.60	Y
30	MV	3800	N	219.53	3.88	Y
31	MV	3800	N	229.71	4.06	Y
32	MV	2700	N	138.86	3.24	Y
33	MV	2700	N	159.00	3.71	Y

34	MV	2700	N	156.86	3.66	Y
35	MV	2700	N	142.29	3.32	Y
36	MV	2700	N	187.71	4.38	Y
37	MV	2700	N	192.86	4.5	Y
38	MV	2700	N	162.00	3.78	Y
39	MV	2700	N	152.57	3.56	Y
40	LAF	12850	N	295.34	5.31	Y
41	LAF	12850	N	289.69	5.88	Y
42	LAF	12850	N	292.52	5.17	Y

Table 4.4: Electricity consumption result of ORs in St. Olavs Hospital



(a) (b)

Figure 4.6: (a) Comparisons on the energy consumption of LAF and MV system; (b) Influence of setback strategy on the energy consumption

The comparison in Figure 4.6(a) shows that the energy consumption of OR with LAF system in operating rooms of the same department is much higher than that with MV system. Setback strategy means to reduce air supply when there is no surgery and most operating rooms with LAF system adopt this strategy in St. Olavs Hospital. Figure 4.6(b) is the comparison of energy consumption for three MV operating rooms in the same department with and without setback strategy, which shows that setback strategy has a great effect on reducing energy consumption.

4.3.2 Linear regression

The following figures demonstrate the linear regression result. Preliminary screening requires that variables are linearly related with energy consumption, therefore, the final chosen variables are outdoor temperature (X_1), supply air volume (X_2), heat recovery strategy (X_3) and setback strategy (X_4).

The adjusted R^2 value in Figure 4.7 is the fitting degree of the estimated model to the observed values, which means that the regression can explain 85.2% variation of dependent variables. Figure 4.8 is the result of variance analysis which shows whether the whole regression equation is significant or not. If the significance value is less than 0.05, the regression equation can be considered useful.

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.931[a]	.866	.852	.38677

a. Predictors: (Constant), Setback strategy, Supply air volume, Heat recovery strategy, Outdoor temperature

b. Dependent Variable: Electricity consumption

Figure 4.7: Model summary

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	35.860	4	8.965	59.930	.000[b]
	Residual	5.535	37	.150		
	Total	41.394	41			

a. Dependent Variable: Electricity consumption

b. Predictors: (Constant), Setback strategy, Supply air volume, Heat recovery strategy, Outdoor temperature

Figure 4.8: Variance analysis result

In Figure 4.9, column "Unstandardized B" listed the coefficients in the regression equation; standardized coefficients indicate the relative importance each variable, t-test statistic, significance level Sig. and collinearity statistics. Tolerance and VIF factor are opposite to each other; VIF>10 means the variable has linear relationship with other variables, which is not allowed in the multi-linear regression equation and detailed collinearity diagnosis are also developed as shows in Figure 4.10.

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Correlations			Collinearity Statistics	
		B	Std. Error	Beta			Zero-order	Partial	Part	Tolerance	VIF
1	(Constant)	5.014	.156		32.054	.000					
	Outdoor temperature	-.101	.016	-.498	-6.270	.000	-.492	-.718	-.377	.573	1.746
	Supply air volume	.703	.061	.690	11.446	.000	.684	.883	.688	.994	1.006
	Heat recovery strategy	-.795	.137	-.384	-5.788	.000	-.131	-.689	-.348	.822	1.217
	Setback strategy	-.512	.157	-.255	-3.263	.002	-.386	-.473	-.196	.591	1.693

a. Dependent Variable: Electricity consumption

Figure 4.9: Coefficients in the regression equation

Collinearity Diagnostics[a]

Model	Dimension	Eigenvalue	Condition Index	Variance Proportions (Constant)	Outdoor temperature	Supply air volume	Heat recovery strategy	Setback strategy
1	1	3.493	1.000	.01	.01	.02	.01	.02
	2	.864	2.011	.00	.03	.00	.44	.05
	3	.387	3.003	.00	.04	.73	.14	.06
	4	.156	4.733	.13	.36	.05	.08	.85
	5	.100	5.910	.86	.57	.19	.32	.02

a. Dependent Variable: Electricity consumption

Figure 4.10: Collinearity diagnosis results

Besides, residuals were also checked. As shows in Figure 4.11 if the scatter points are gathering near the diagonal line, the residuals conform to the normal distribution.

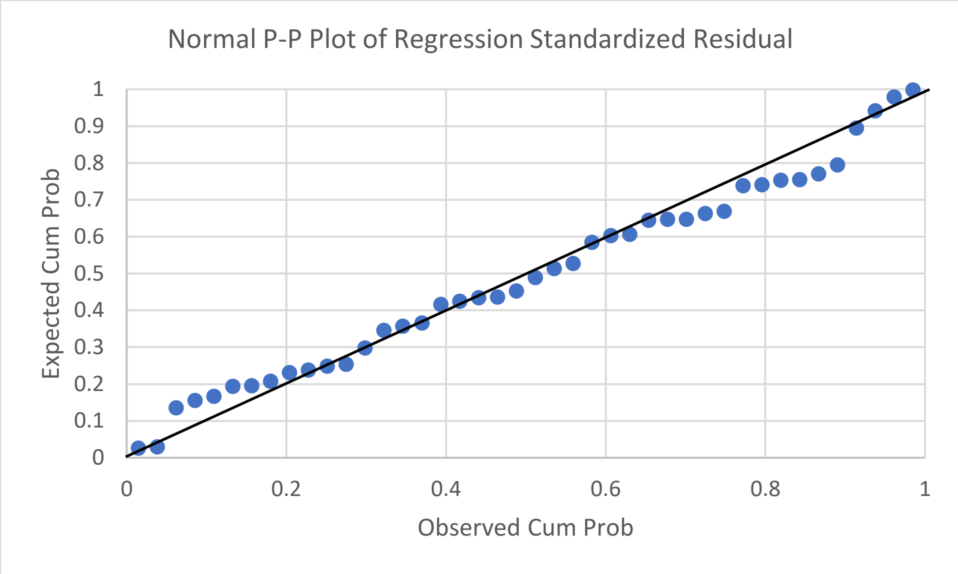


Figure 4.11: Regression Standardized Residual Plot

Based on the above analysis of regression model fitting situation, collinearity diagnosis and standardized residual analysis result from SPSS, the linear regression analysis equation of electricity consumption per unit area of ventilation in OR is as follows:

$$Y = 5.014 - 0.101X_1 + 0.703X_2 - 0.795X_3 - 0.512X_4$$

Where Y is the electricity consumption of ventilation in OR per unit area per day, X_1 is outdoor temperature,℃; X_2 is supply air volume, m^3/s; X_3 is heat recovery strategy, (0 represent no heat recovery, 1 represent heat recovery); X_4 is setback strategy (0 represent no using setback strategy, 1 represent using setback strategy).

4.3.3 Determine evaluation benchmark

Due to the time limitation of collecting energy consumption data in different weather conditions in the target hospital, determining the evaluation benchmark has lots of difficulties. Based on the calculation data and the prediction equation model above, local average outdoor temperature in April is introduced into the equation, then energy consumption can be transformed into the value at about the same test time, which makes it meaningful for comparison. The energy consumption of 42 ORs in St. Olavs Hospital is shown in Figure 4.12. According to the method of Cal-Arch setting benchmark of building energy developed by Lawrence Berkeley National Laboratory (LBNL), energy consumption within the range of top 25% of all same type buildings is considered low. Therefore, in this paper, the lower quartile or median of energy consumption level are selected as the baselines. The grades of energy consumption (EC) index in St. Olavs Hospital can be proper if EC⩽4.25 kWh/m²/day; moderate if 4.25<EC⩽5.18 kWh/m²/day; improper if EC>5.18 kWh/m²/day in LAF system ORs and proper if EC⩽3.76 kWh/m²/day; moderate if 3.76<EC ⩽4.50 kWh/m²/day; improper if EC>4.50 kWh/m²/day in MV system ORs.

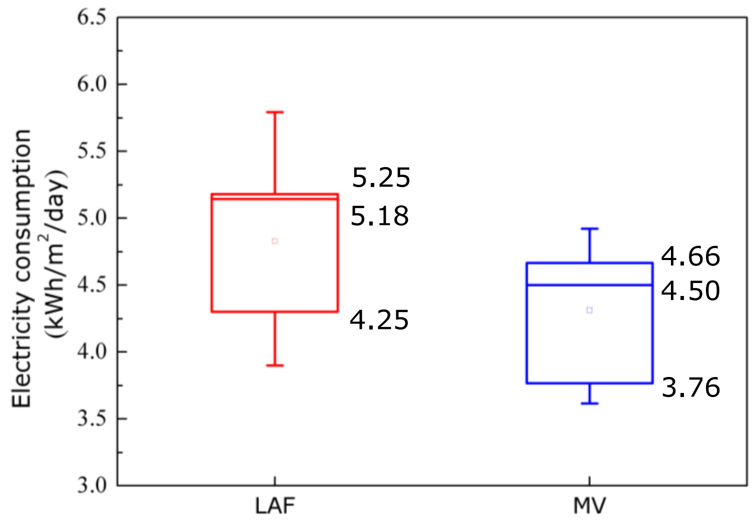


Figure 4.12: Energy consumption range after temperature correction

4.4 Evlaution score for indices

4.4.1 Membership function

The choice of membership function is determined by the property of indices. In this paper there are 7 indices and most of them the grades are expressed in range, therefore, ladder shape membership functions are suitable for them. The set of evaluation factors can be written as $\mathrm{U} = \{u_1, u_2, \dots, u_7\}$ corresponding to 7 indices; the comment sets $\mathrm{V} = \{0,1,2\}$ are defined as "unsuitable, tolerable, suitable". This section will try to develop membership function for each index.

(1) Bacteria concentration u_1

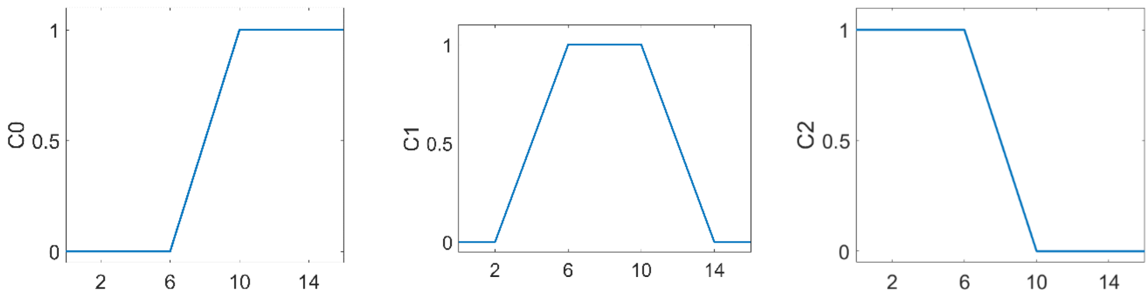
The membership functions of bacteria concentration in LAF operating theater to "0,1,2" are shown in Eq.4-1, Eq.4-2, Eq.4-3, respectively.

$$c_0(u_1)=\begin{cases} 0, & u_1 \le 6 \\ \dfrac{u_1-6}{10-6}, & 6 < u_1 \le 10 \\ 1, & u_1 > 10 \end{cases} \tag{4-1}$$

$$c_1(u_1)=\begin{cases} \dfrac{(u_1-2)}{(10-6)}, & 2 \le u_1 < 6 \\ 1, & 6 \le u_1 < 10 \\ \dfrac{(14-u_1)}{(10-6)}, & 10 \le u_1 \le 14 \\ 0, & u_1 < 2 \text{ or } u_1 > 14 \end{cases} \tag{4-2}$$

$$c_2(u_1)=\begin{cases} 1, & u_1 \le 6 \\ \dfrac{10\text{-}u_1}{10-6}, & 6 < u_1 \le 10 \\ 0, & u_1 > 10 \end{cases} \tag{4-3}$$

The corresponding function figures are listed in Figure 4.13(a), (b), (c).



(a) (b) (c)

Figure 4.13: Membership functions of bacteria concentration for LAF system

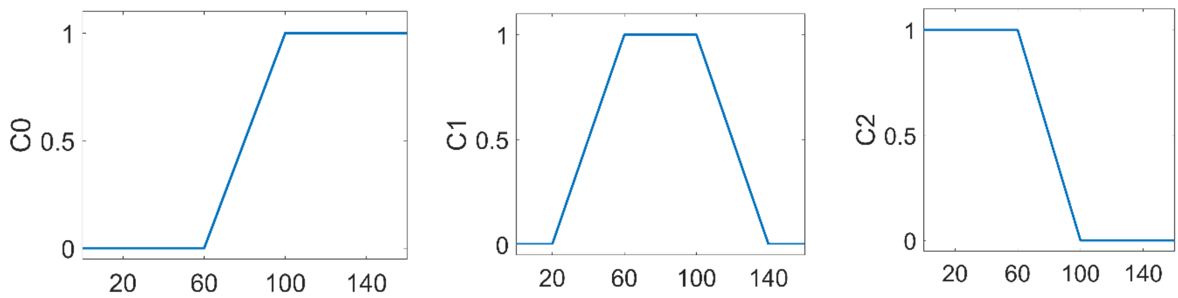
The membership function of bacteria concentration in MV operating theater to "0,1,2" are shown in Eq.4-4, Eq.4-5, Eq.4-6, respectively.

$$c_0(u_1)=\begin{cases} 0, & u_1 \le 60 \\ \dfrac{u_1-60}{100-60}, & 60 < u_1 \le 100 \\ 1, & u_1 > 100 \end{cases} \qquad 4\text{-}4$$

$$c_1(u_1)=\begin{cases} \dfrac{(u_1-20)}{(100-60)}, & 20 \le u_1 < 60 \\ 1, & 60 \le u_1 < 100 \\ \dfrac{(140-u_1)}{(100-60)}, & 100 \le u_1 \le 140 \\ 0, & u_1 < 20 \text{ or } u_1 > 140 \end{cases} \qquad 4\text{-}5$$

$$c_2(u_1)=\begin{cases} 1, & u_1 \le 60 \\ \dfrac{100\text{-}u_1}{100-60}, & 60 < u_1 \le 100 \\ 0, & u_1 > 100 \end{cases} \qquad 4\text{-}6$$

The corresponding function figures are listed in Figure 4.14(a), (b), (c).



(a) (b) (c)

Figure 4.14: Membership functions of bacteria concentration for MV system

(2) Particle concentration u_2

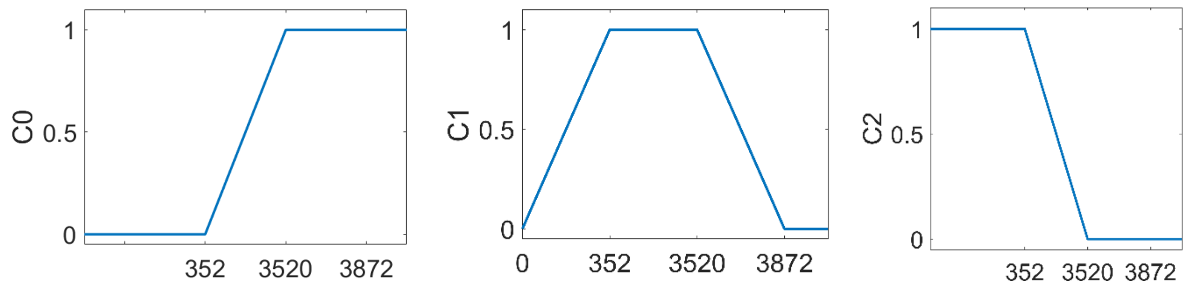
The membership functions of particle concentration in LAF operating theater to "0,1,2" are shown in Eq.4-7, Eq.4-8, Eq.4-9, respectively.

$$c_0(u_2)=\begin{cases} 0, & u_2 \le 352 \\ \dfrac{u_2-352}{3520-352}, & 352 < u_2 \le 3520 \\ 1, & u_2 > 3520 \end{cases} \qquad 4\text{-}7$$

$$c_1\left(u_2\right)=\begin{cases} \dfrac{u_2}{\left(3872-3520\right)}, & u_2 < 352 \\ 1, & 352 \le u_2 < 3520 \\ \dfrac{\left(3872-u_2\right)}{\left(3872-3520\right)}, & 3520 \le u_2 \le 3872 \\ 0, & u_2 > 3872 \end{cases} \qquad 4\text{-}8$$

$$c_2(u_2)=\begin{cases} 1, & u_2 \le 352 \\ \dfrac{3520\text{-}u_2}{3520-352}, & 352 < u_2 \le 3520 \\ 0, & u_2 > 3520 \end{cases} \qquad 4\text{-}9$$

The corresponding function figures are listed in Figure 4.15 **错误!未找到引用源。**(a), (b), (c).



(a) (b) (c)

Figure 4.15: Membership functions of particle concentration for LAF system

The membership functions of particle concentration in MV operating theater to "0,1,2" are shown in Eq.4-10, Eq.4-11, Eq.4-12, respectively.

$$c_0(u_2)=\begin{cases} 0, & u_2 \le 3520 \\ \dfrac{u_2-3520}{352000-3520}, & 3520 < u_2 \le 352000 \\ 1, & u_2 > 352000 \end{cases} \qquad 4\text{-}10$$

$$c_1\left(u_2\right)=\begin{cases} \dfrac{u_2}{\left(387200-352000\right)}, & u_2 < 35200 \\ 1, & 35200 \le u_2 < 352000 \\ \dfrac{\left(387200-u_2\right)}{\left(387200-35200\right)}, & 35200 \le u_2 \le 387200 \\ 0, & u_2 > 387200 \end{cases} \qquad 4\text{-}11$$

$$c_2(u_2)=\begin{cases} 1, & u_2 \le 35200 \\ \frac{35200\text{-}u_2}{352000-35200}, & 35200 < u_2 \le 352000 \\ 0, & u_2 > 352000 \end{cases} \qquad 4\text{-}12$$

The corresponding function figures are listed in Figure 4.16(a), (b), (c).

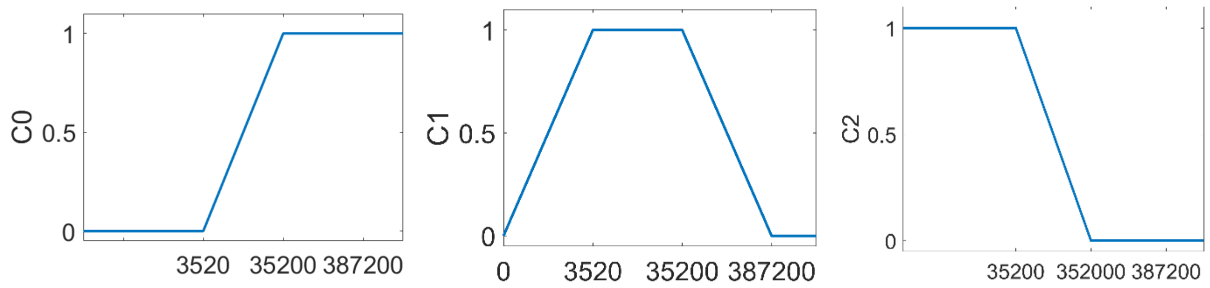


Figure 4.16: Membership functions of particle concentration for MV system

(3) Temperature u_3

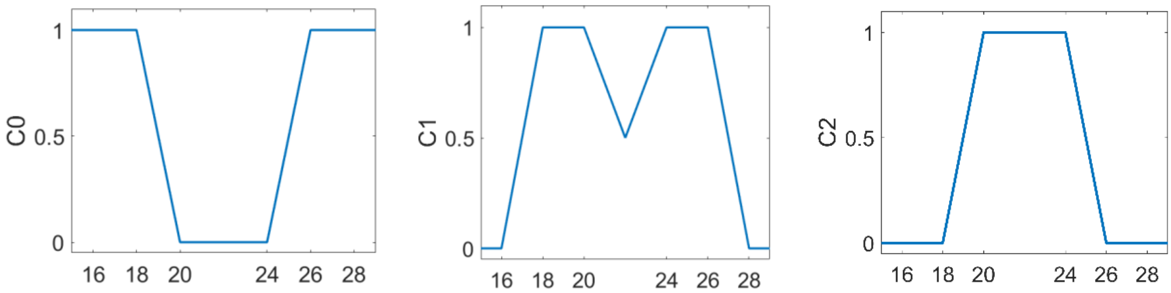
The membership functions of temperature operating theater to "0,1,2" are shown in Eq.4-13, Eq.4-14, Eq.4-15, respectively.

$$c_0(u_3)=\begin{cases} \frac{20-u_3}{20-18}, & 18 \le u_3 < 20 \\ 0, & 20 \le u_3 \le 24 \\ \frac{u_3-24}{26-24}, & 24 < u_3 \le 26 \\ 1, & u_3 < 18 \text{ or } u_3 > 26 \end{cases} \qquad 4\text{-}13$$

$$c_1(u_3)=\begin{cases} \frac{u_3\text{-}16}{18-16}, & 16 < u_3 < 18 \\ 1, & 18 \le u_3 < 20 \text{ or } 24 < u_3 \le 26 \\ \frac{1}{4}\left|u_3-22\right|+0.5, & 20 \le u_3 \le 24 \\ \frac{28-u_3}{28-26}, & 26 < u_3 \le 28 \\ 0, & u_3 < 16 \text{ or } u_3 > 28 \end{cases} \qquad 4\text{-}14$$

$$c_2(u_3)=\begin{cases} \frac{u_3-18}{20-18}, & 18 < u_3 < 20 \\ 1, & 20 \le u_3 \le 24 \\ \frac{26-u_3}{26-24}, & 24 < u_3 \le 26 \\ 0, & u_3 > 18 \text{ or } u_3 > 26 \end{cases} \qquad 4\text{-}15$$

The corresponding function figures are listed in Figure 4.17(a), (b), (c).



(a) (b) (c)

Figure 4.17: Membership functions of temperature

(4) Relative humidity u_4

The membership functions of relative humidity in ORs to "0,1,2" are shown in Eq.4-16, Eq.4-17, Eq.4-18, respectively.

$$c_0(u_4)=\begin{cases} 0, & 40\% \le u_4 \le 50\% \\ \dfrac{40\% - u_4}{40\% - 30\%}, & 30\% \le u_4 < 40\% \\ \dfrac{u_4 - 50\%}{60\% - 50\%}, & 50\% < u_4 \le 60\% \\ 1, & u_3 < 30\% \text{ or } u_4 > 60\% \end{cases} \tag{4-16}$$

$$c_1(u_4)=\begin{cases} 1, & 30\% \le u_4 < 40\% \text{ or } 50\% < u_4 \le 60\% \\ \dfrac{u_4\text{-}20\%}{30\% - 20\%}, & 20\% < u_4 < 30\% \\ \dfrac{70\% - u_4}{70\% - 60\%}, & 60\% < u_4 \le 70\% \\ \dfrac{1}{2}\left|u_4 - 45\%\right| - 0.5, & 40\% \le u_4 \le 50\% \\ 0, & u_4 < 20\% \text{ or } u_4 > 70\% \end{cases} \tag{4-17}$$

$$c_2(u_4)=\begin{cases} 1, & 40\% \le u_4 \le 50\% \\ \dfrac{u_4 - 30\%}{40\% - 30\%}, & 30\% \le u_4 < 40\% \\ \dfrac{50\% - u_4}{60\% - 50\%}, & 50\% < u_4 \le 60\% \\ 0, & u_4 < 30\% \text{ or } u_4 > 60\% \end{cases} \tag{4-18}$$

The corresponding function figures are listed in Figure 4.18(a), (b), (c).

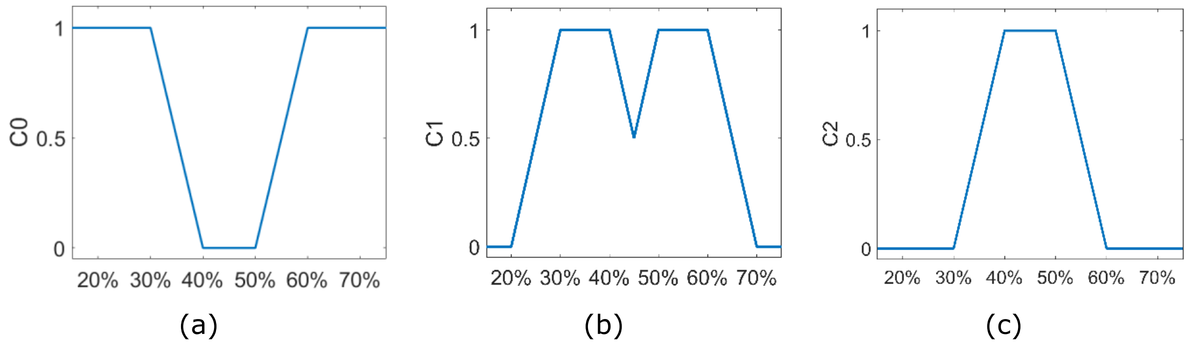


Figure 4.18: Membership functions of relative humidity

(5) Electricity consumption u_5

The membership functions of electricity consumption in LAF operating rooms to "0,1,2" are shown in Eq.4-19, Eq.4-20, Eq.4-21, respectively.

$$c_0(u_5)=\begin{cases} 0, & u_5 \le 4.25 \\ \dfrac{u_5-4.25}{5.18-4.25}, & 4.25 < u_5 \le 5.18 \\ 1, & u_5 > 5.18 \end{cases} \tag{4-19}$$

$$c_1(u_5)=\begin{cases} \dfrac{u_5-3.32}{(4.25-3.32)}, & 3.32 \le u_5 < 4.25 \\ 1, & 4.25 \le u_5 < 5.18 \\ \dfrac{(6.11-u_5)}{(6.11-5.18)}, & 5.18 \le u_5 \le 6.11 \\ 0, & u_5 > 3.32 \text{ or } u_5 > 6.11 \end{cases} \tag{4-20}$$

$$c_2(u_5)=\begin{cases} 1, & u_5 \le 4.25 \\ \dfrac{5.18\text{-}u_5}{5.18-4.25}, & 4.25 < u_5 \le 5.18 \\ 0, & u_5 > 5.18 \end{cases} \tag{4-21}$$

The corresponding function figures are listed in Figure 4.19(a), (b), (c).

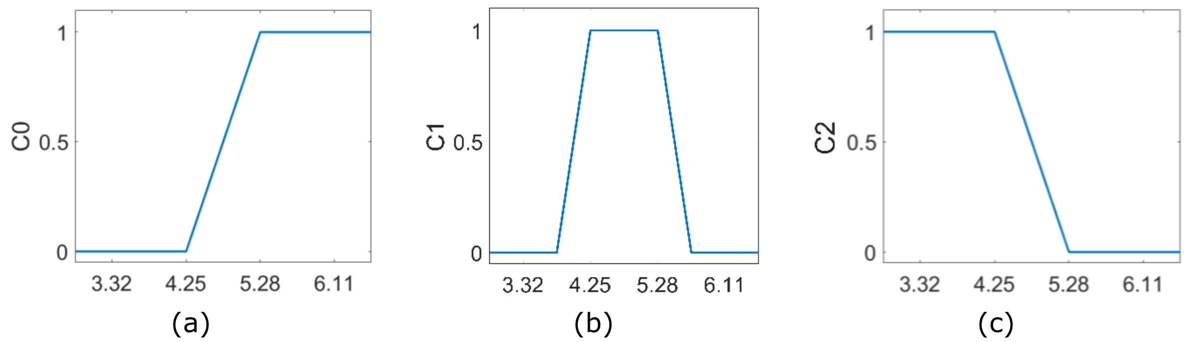


Figure 4.19: Membership functions of electricity consumption for LAF system

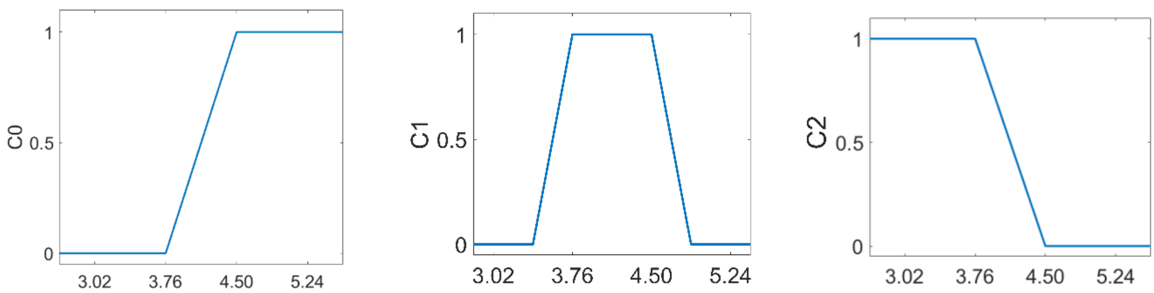
The membership functions of electricity consumption in MV operating rooms to "0,1,2" are shown in Eq.4-19, Eq.4-20, Eq.4-21, respectively.

$$c_0(u_5)=\begin{cases} 0, & u_5 \le 3.76 \\ \dfrac{u_5-3.76}{4.50-3.70}, & 3.76 < u_5 \le 4.50 \\ 1, & u_5 > 4.50 \end{cases} \tag{4-22}$$

$$c_1\left(u_5\right)=\begin{cases} \dfrac{u_5-3.02}{\left(3.76-3.02\right)}, & 3.02 \le u_5 < 3.76 \\ 1, & 3.76 \le u_5 < 4.50 \\ \dfrac{\left(5.24-u_5\right)}{\left(5.24-4.50\right)}, & 4.50 \le u_5 \le 5.24 \\ 0, & u_5 > 3.02 \text{ or } u_5 > 5.24 \end{cases} \tag{4-23}$$

$$c_2(u_5)=\begin{cases} 1, & u_5 \le 3.76 \\ \dfrac{4.50\text{-}u_5}{4.50-3.76}, & 3.76 < u_5 \le 4.50 \\ 0, & u_5 > 4.50 \end{cases} \tag{4-24}$$

The corresponding function figures are listed in Figure 4.20(a), (b), (c).



(a) (b) (c)

Figure 4.20: Membership functions of electricity consumption for MV system

(6) Thermal comfort u_6

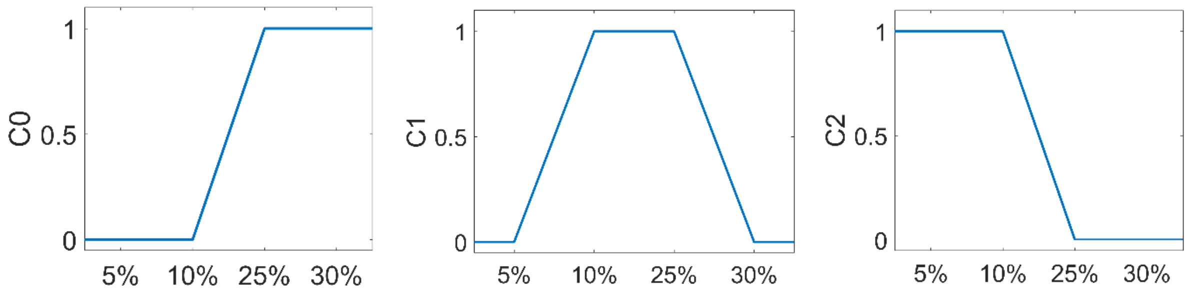
The membership functions of actual percentage dissatisfaction in LAF operating theater to “0,1,2” are shown in Eq.4-25, Eq.4-26, Eq.4-27, respectively.

$$c_0(u_6)=\begin{cases} 0, & u_6 \le 10\% \\ \dfrac{u_6-10\%}{25\%-10\%}, & 10\% < u_6 \le 25\% \\ 1, & u_6 > 25\% \end{cases} \tag{4-25}$$

$$c_1\left(u_6\right)=\begin{cases} \dfrac{u_6-5\%}{\left(10\%-5\%\right)}, & 5\% \le u_6 < 10\% \\ 1, & 10\% \le u_6 < 25\% \\ \dfrac{\left(30\%-u_6\right)}{\left(30\%-25\%\right)}, & 25\% \le u_6 \le 30\% \\ 0, & u_5 > 5\% \text{ or } u_6 > 30\% \end{cases} \tag{4-26}$$

$$c_2(u_6)=\begin{cases} 1, & u_6 \le 10\% \\ \dfrac{25\%\text{-}u_6}{25\%-10\%}, & 10\% < u_6 \le 25\% \\ 0, & u_6 > 25\% \end{cases} \quad \text{4-27}$$

The corresponding function figures are listed in Figure 4.21(a), (b), (c).



(a) (b) (c)

Figure 4.21: Membership functions of actual percentage of dissatisfaction

(7) Noise level u_7

The membership functions of noise level in operating theater to "0,1,2" are shown in Eq.4-28, Eq.4-29, Eq.4-30, respectively.

$$c_0(u_7)=\begin{cases} 0, & u_7 \le 40 \\ \dfrac{u_7-40}{50-40}, & 40 < u_7 \le 50 \\ 1, & u_7 > 50 \end{cases} \quad \text{4-28}$$

$$c_1(u_7)=\begin{cases} \dfrac{u_7-30}{(40-30)}, & 30 \le u_7 < 40 \\ 1, & 40 \le u_7 < 50 \\ \dfrac{(60-u_7)}{(60-50)}, & 50 \le u_7 \le 60 \\ 0, & u_7 > 30 \text{ or } u_7 > 60 \end{cases} \quad \text{4-29}$$

$$c_2(u_7)=\begin{cases} 1, & u_7 \le 40 \\ \dfrac{50\text{-}u_7}{50-40}, & 40 < u_7 \le 50 \\ 0, & u_7 > 50 \end{cases} \quad \text{4-30}$$

The corresponding function figures are listed in Figure 4.22(a), (b), (c).

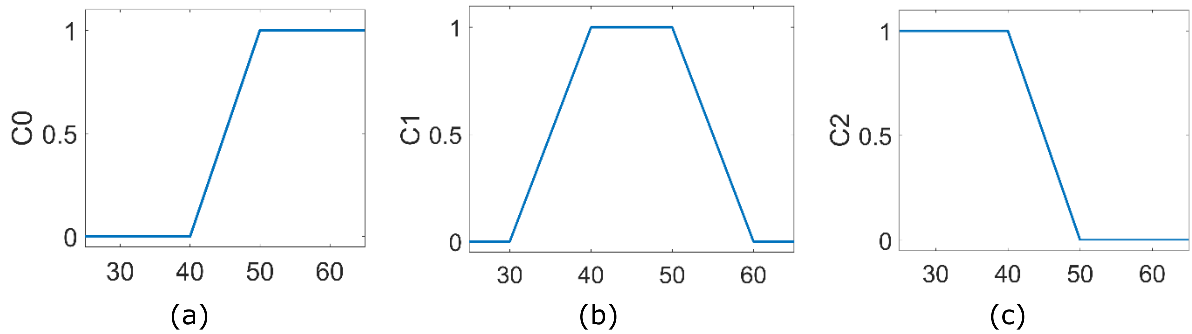


Figure 4.22: Membership functions of noise level

4.4.2 Index membership to comment set

Each index value of the two case ORs was substituted into the corresponding membership functions, and the evaluation matrices can be calculated as shows in Table 5.2.

	Items	U value	r	R
OR1 (MV)	Bacteria concentration u_1	7	$r_1=[c_0(u_1),c_1(u_1),c_2(u_1)]=[0,0,1]$	$R_1=\begin{bmatrix} r_1\\ r_2\\ r_3\\ r_4\\ r_5\\ r_6\\ r_7 \end{bmatrix}=\begin{bmatrix} 0 & 0 & 0\\ 0.30 & 0.37 & 1\\ 0.28 & 1 & 0.73\\ 1 & 0 & 0\\ 1 & 0.92 & 0\\ 1 & 0 & 0\\ 1 & 0.44 & 0 \end{bmatrix}$
	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	4.50	$r_5=[c_0(u_5),c_1(u_5),c_2(u_5)]=[0.86,1,0.08]$	
	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	0.3	$r_1=[c_0(u_1),c_1(u_1),c_2(u_1)]=[0,0,1]$	$R_2=\begin{bmatrix} r_1\\ r_2\\ r_3\\ r_4\\ r_5\\ r_6\\ r_7 \end{bmatrix}=\begin{bmatrix} 0 & 0 & 1\\ 0.24 & 1 & 0.76\\ 0 & 0.96 & 1\\ 1 & 0 & 0\\ 0.99 & 1 & 0.93\\ 0 & 0 & 1\\ 1 & 0.63 & 0 \end{bmatrix}$
	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 u_5	5.17	$r_5=[c_0(u_5),c_1(u_5),c_2(u_5)]=[0.99,1,0.93]$	
	Thermal comfort u_6	0	$r_6=[c_0(u_6),c_1(u_6),c_2(u_6)]=[0,0,1]$	
	Noise level u_7	53.7	$r_7=[c_0(u_7),c_1(u_7),c_2(u_7)]=[1,0.63,0]$	

Table 4.5: Calculation of the evaluation matrices

4.5 Comprehensive value

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

$$S_1 = W \circ R_1 = [0.23 \quad 0.15 \quad 0.06 \quad 0.05 \quad 0.16 \quad 0.22 \quad 0.13] \begin{bmatrix} 0 & 0 & 1 \\ 0.30 & 0.37 & 1 \\ 0.28 & 1 & 0.73 \\ 1 & 0 & 0 \\ 1 & 0.92 & 0 \\ 1 & 0 & 0 \\ 1 & 0.44 & 0 \end{bmatrix} = \begin{bmatrix} 0.62 & 0.32 & 0.42 \end{bmatrix} \qquad \text{4-31}$$

$$S_2 = W \circ R_2 = [0.23 \quad 0.15 \quad 0.06 \quad 0.05 \quad 0.16 \quad 0.22 \quad 0.13] \begin{bmatrix} 0 & 0 & 1 \\ 0.24 & 1 & 0.76 \\ 0 & 0.96 & 1 \\ 1 & 0 & 0 \\ 0.99 & 1 & 0.93 \\ 0 & 0 & 1 \\ 1 & 0.63 & 0 \end{bmatrix} = \begin{bmatrix} 0.37 & 0.45 & 0.77 \end{bmatrix} \qquad \text{4-32}$$

After normalization, $S_1^{'} = [0.45 \quad 0.24 \quad 0.31]$, $S_2^{'} = [0.24 \quad 0.28 \quad 0.48]$, which according to maximum membership principle means that OR1 is more likely to obtain the comment of "unsuitable" and OR2 obtains the comment of "suitable".

5 Discussion

5.1 Evaluaiton analysis

5.1.1 Rationality of weight distribution

The weighted results from the expert survey showed that the ventilation effectiveness takes precedence, followed by user satisfaction and energy consumption. It can be explained that a safety indoor environment during surgical process should be guaranteed first and foremost, while to a certain extent, users' satisfaction and energy may be sacrificed. This consideration is also what the ventilation system in OR is facing. In terms of ventilation effectiveness aspect, the concentration of bacteria and particulate matter are the main factors to be considered as they may be more closely related to post-operative infections compared with temperature and humidity. Finally, thermal comfort was given more attention than the noise level since people may tend to neglect part of white noise while concentrating on their work which is also shown in the questionnaire in this study, but it will seriously affect the working conditions if the feelings are too hot, cold or sweating, especially for surgeons whose work needs precision and extreme seriousness. Therefore, the weights determined in this paper based on expert questionnaire are understandable and reasonable.

5.1.2 Measurement result analysis

(1) Bacteria and particles

Since planktonic bacteria and sedimentation bacteria concentration have different units, they cannot compare together. This study separately chose the comparison between two case ORs on the planktonic bacteria concentration near the wound area and the comparison of sedimentation bacteria concentration in sterile and periphery areas in each OR under the same simulated operation movements. Both bacterial concentrations in LAF theater were lower than MV theater, because the larger number of air exchange rates are more conducive to removing bacteria. Normally in MV system ORs, the requirement for bacteria is 100 cfu/m^3, which means the chosen MV operating theater performs good in removing bacteria. For particle concentration, ISO standard 7730 gives the maximum allowable concentration of 0.5 μm particles for classification in Table 5.1. Therefore, OR1 (MV) which has 12898 particle/m^3 belongs to ISO 6 while OR2 (LAF) belongs to ISO 5. From the comparison of particle concentration in the situation of empty room, occupied but without activity and people doing mock surgery movements, the concentration of particles increased gradually. The highest particles concentration was always seen near the wound area, indicating that personnel is one of the sources of pollutant emission as expected and the type of particles were most likely to be epidermal impurities scattered by human body.

ISO Class number	Maximum allowable concentrations (0.5 μm, particle/m^3)
3	35
4	352
5	3520
6	35200
7	352000
8	3520000

Table 5.1: ISO classes of air cleanliness by particle concentration

(2) Temperature and humidity

The main function of controlling temperature in ORs is to ensure the patient's body temperature, skin evaporation rate and metabolic rate in a normal level under anesthesia. According to the evaluation grades of index set based on standards, the temperature measurement results in this study showed that the temperatures near the wound 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 [27]. Therefore, air temperature provided by the ventilation system is the basic guarantee for the performance of the ventilation system, doctors and nurses have the responsibility to adjust according to their needs.

Although many European standards provide design parameters for OR ventilation system including both temperature and humidity, Norwegian design codes do not have strict humidity control. Only two out of the six mock surgeries conducted in this study reached to 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% as shown in Table 2.1 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. 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 is understandable that in order to avoid risks and save costs, the humidity control is neglected.

(3) Thermal comfort and noise

From the user's questionnaire thermal comfort part, the votes on thermal sensation for OR1 were mostly on the neutral and warmer side, while the votes for OR2 were more inclined to cool. Since the setting temperature is the same, this is more due to the large air change rate in OR2, which helps to remove the heat around human body.

During the noise measurement in this study, 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 only by the ventilation system. The noise generated by the ventilation system indoors often comes from the fans and the noise transmitted through the pipeline as well as the sound of air flow passing through components with greater resistance. Because of the large air volume in the operating room, power of fans was higher, then even the empty room will feel the noise is obviously loud as in the questionnaire. In the actual operation process, medical equipment will inevitably produce 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.

5.1.3 Energy consumption result analysis

For the energy consumption calculation, due to the limitation of time and other conditions, the logged data obtained from St. Olavs Hospital were from different time periods most in April, 2019 (Neurology center, women & children center from Mar.29th-Apr.5th; Emergency and heart and lung center from Apr.5th-Apr.11th; Orthopedic center from Apr.23rd-Apr.30th etc.) 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. Therefore, errors may occur because of the difficulties in collecting information. Errors may come from the inability to obtain real-time value of fan power and the lack of humidity and temperature sensor for some points like supply air outlet or behind heat recovery devices. Therefore, some of these values were obtained from the performance curve of fan brochures and measured by indoors for example near the supply air diffusers. At the same time, to compensate for the incomparable situation caused by different logging time, the temperature was corrected by the energy consumption regression equation. However, the unit of energy use intensity can only be expressed as kWh/(m^2·day) and the value may be since the data are not covered the whole year, only the transitional month between winter and spring.

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 from Figure 4.9, which shows supply air volume has the largest contribution the followed by outdoor air temperature, heat recovery strategy and set back strategy. The coefficient of outdoor temperature variable 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 proves that their increase is in direct proportion to energy consumption, and the negative coefficients of variables of heat recovery and air volume reduction strategies show that the adoption of the strategy is conducive to reducing energy consumption. The current limitation is that the predict model can only be applied for the OR ventilation energy consumption during the transitional season between winter and spring of St. Olavs Hospital, Norway, more data are needed to make it applicable to wider situation.

5.2 Comprehensive value result analysis

The suitability of OR ventilation system is defined in this thesis as using relatively less investment and energy consumption to create an environment which perfectly meets the standard requirements of clean rooms at the same time ensuring the comfort and safety of surgical team members and patients. The results of comprehensive evaluation were obtained according to the membership degree of each comment, which can be considered as hiring experts to grade the performance of the OR ventilation system in all the aspects and after weight assignments, the comments which wins the maximum number of votes will be the final evaluation results. Therefore, the evaluation results of OR1(MV) and OR2(LAF) ventilation suitability in the operating room selected in this paper are "unsuitable" and "suitable", respectively.

Each index value and its grades are shown separately in Table 5.2 according to their benchmarks mentioned in Chapter 3.2. The bacteria, particles 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. For OR 1, the calculated energy consumption does not the top 50% among all the operating theaters, therefore it belongs to "improper", while electricity consumption of OR2 belongs to "moderate". In addition, OR1 has a higher dissatisfaction rate whose priority is second only to bacteria and a noise value exceeding standard requirement. All these together make the comprehensive evaluation value obtains the comment of "unsuitable". Therefore, when "unsuitable" evaluation results appear, the first thing needed is to find the corresponding index value with the largest weight, then view other indices according to their priorities.

	OR1(MV)	Grades	OR2(LAF)	Grades
Bacteria concentration	7 cfu/m^3	Proper	0.3 cfu/m^3	Proper
Particle concentration	12898/m^3	Proper	1120/m^3	Proper
Temperature	23.8℃	Proper	22.7℃	Proper
Relative Humidity	13.0%	Improper	17.9%	Improper
Electricity consumption	4.50 kWh/m^2/d	Improper	5.17 kWh/m^2/d	Moderate
Thermal comfort	43%	Improper	0	Proper
Noise level	55.6 dB	Improper	53.7 dB	Improper

Table 5.2: Evaluation index value and belonging grades

5.3 Suggestion for OR ventialtion systems

From the above discussion, rough suggestions can be given to the ventilation system in ORs at St.Olavs Hospital:

(1) Design and selection of the ventilation system for ORs should focus on appropriate air volume on the basis of meeting the demand of safety, then make rational use of the heat recovery technology as well as setback strategy.
(2) Relevant cleaners and managers should adjust the ventilation system to rest mode in time after cleaning the operating room.
(3) Develop better controlling system based on high technologies for example adopting occupancy sensors which can combine audio, infrared and motion detection and switch an OR between unoccupied and occupied modes automatically, which do not require staff interaction. Combined controlling strategy together with manual switchover is also a good choice.
(4) Regularly test the air cleanliness, temperature, humidity and noise in the ORs, and timely understand the feelings of the operating team through investigation to provide the basis for possible system adjustment.

5.4 Limitation

In this study, several 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 [28], door openings etc. Secondly, due to the limitation of time and condition of data collection, this study mainly focused on St. Olavs Hospital. This evaluation system provides a framework for evaluating the performance of ventilation system in ORs from a holistic view, however, the evaluation criteria may not be necessarily reasonable for ORs in all kinds of hospitals worldwide. ORs in other countries can meet different standards or energy consumption levels.

5.5 Future work

In the future studies, energy consumption of ventilation system for ORs in St. Olavs Hospital can be further collected to obtain annual energy consumption level and form a more accurate prediction model. Also, collecting energy consumption in other hospitals or other areas is conducive to the establishing energy consumption evaluation benchmarks with wider scope of application. In addition, other aspects related to the performance of operating room ventilation system can also be added to the evaluation system, for example, the cost of ventilation system, including initial investment, annual operation and maintenance costs as well as environmental impact.

6 Conclusion

This study tried to establish a flexible suitability evaluation framework for the ventilation system of hospital ORs, which is used to evaluate the operation status of the ventilation system from a holistic view including ventilation effectiveness, electricity consumption and user's satisfaction. Different from the assessment only from a single aspect, it provides an overall reference for the facility manager or administrative manager of the ventilation system of the operating room. From the previous chapters' description and analysis, conclusions can be drawn as follows:

(1) The weights distribution obtained by AHP method and expert survey are 0.49, 0.35 and 0.16 corresponding to ventilation effectiveness, users' satisfaction and energy consumption aspect, respectively. The distribution meets the current requirements of ventilation which means it is reasonable and meaningful.

(2) The evaluation framework provides a basis for the suitability assessment of ventilation performance in operating theaters. The framework is flexible to add in more aspects such as ventilation system lifecycle cost and environmental impact etc., meanwhile, the benchmarks of evaluation indices are able to be adjusted according to different regions and countries applied.

(3) From the evaluation result of two case operating rooms OR1 (MV) and OR2 (LAF), only by satisfying indicators with large proportions, better assessment results can be obtained. Both case ORs had good performance on microbial, particle concentration and temperature under the ventilation effectiveness aspect, which ensured the safety of the operation process. However, the final comprehensive evaluation of OR1 (MV) is "unsuitable", as it gets more unsatisfactory votes in thermal comfort, the second most important aspects; and its calculated energy consumption exceeds the median energy consumption of all ORs. While OR2 (LAF) finally gets the comment "suitable" as it only has less satisfied index with relatively low importance such as humidity, noise performance and ultimately does not affect too much on the suitability result.

(4) Through the analysis on the influencing factors of energy consumption, design and selection of the ventilation system for ORs should focus on the appropriate air volume based on meeting the demand of safety and make rational use of the heat recovery technology as well as setback strategy. Professional staffs who are responsible for OR ventilation systems ventilation system need to make sure the system is in better situation of energy saving and regularly ask the needs of the surgical team members then try make adjustments to make possible adjustments to meet their satisfaction.

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Appendices

Appendix 1: Expert survey to obtain weight distribution

Appendix 2: Users' satisfaction questionnaire

Appendix 1: Expert survey to obtain weight distribution

Expert survey on the priority of the suitability indices for ventilation strategy in hospital operating rooms

This is a questionnaire survey used to ask for expert opinions on index weight distribution in comprehensive evaluation of operating room ventilation systems. It takes about 5-10 minutes to complete.

*Required

Preface

Dear professional participant,

I am currently undertaking my master thesis about a multi-criteria analysis to evaluate the performance of different ventilation strategies (eg. laminar airflow (LAF) and turbulent mixing ventilation (MV) system) for operating room at hospitals. The aspects including ventilation effectiveness, energy consumption as well as user's satisfaction are taken into consideration in this evaluation, which may help to provide guidance for the adjustment of ventilation system in operating rooms and the selection of reasonable ventilation system for future designers.

In the following pages, I would like to obtain your opinion as an expert through a survey questionnaire, in which you are required to prioritize some options with respect to the criteria and the project goal. Your answer will be used as a basis in AHP (Analytic Hierarchy Process) method for weights allocation.

The information you provide will be of great value for this research, and accordingly, your participation is anticipated and very much appreciated. We sincerely hope you can assist.

Minchao Fan
Master student
Department of Energy and Process Engineering
Norwegian University of Science and Technology
Email: minchaof@stud.ntnu.no

Skip to question 1.

Basic Information

The following information is only used for classification and I guarantee that your personal information will not be leaked to others. Please chose the option which best fits you.

1. **1.1 What is your occupation?** *

   Mark only one oval.

   - ◯ Professor or researcher
   - ◯ Designer or engineer
   - ◯ Operational management Professional
   - ◯ Others

2. **1.2 Is your research or work related to ventilation systems?** *

   Mark only one oval.

   - ◯ Yes, closely related.
   - ◯ Slightly related.
   - ◯ No, not related at all.

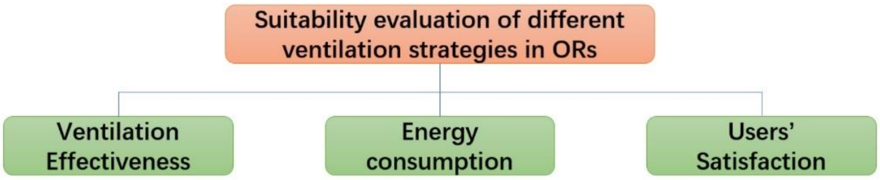
Skip to question 3.

Opinion collection

In this part, all the questions are based on pair-wise comparisons, which are the fundamental components of AHP method. Each participant is required to enter his/her judgements and makes a distinct, identifiable contribution to the issue. Participants do not have to agree on the relative importance of the criteria. In the following questions, we would like to have your opinions in order to assign weights for indices. Please choose the options which you think are appropriate.

Please give opinions to the following questions with respect to the goal: Suitable ventilation strategy in operating rooms

Criterion level



3. **2.1 How important is "ventilation effectiveness" compared to "energy consumption" of ventilation systems? (Ventilation effectiveness is ____________than energy consumption)** *

Mark only one oval.

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

4. **2.3 How important is "ventilation effectiveness" compared to "users' satisfaction" of ventilation systems? (ventilation effectiveness is ____________than users' satisfaction)** *

Mark only one oval.

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

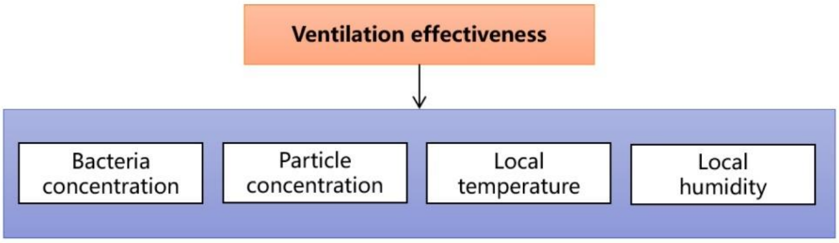
5. **2.4 How important is "energy consumption" compared to "users' satisfaction" of ventilation systems? (Energy consumption is ____________than users' satisfaction)** *

Mark only one oval.

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

Please give opinions to the following questions with respect to the goal: Ventilation effectiveness in operating rooms

Evaluation indices



6. **2.7 How important is "bacteria concentration" compared to "particle concentration" of ventilation systems? (Bacteria concentration is ____________than particle concentration)** *

Mark only one oval.

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

7. **2.8 How important is “bacteria concentration” compared to “local temperature” of ventilation systems? (Bacteria concentration is ____________than local temperature)** *
Mark only one oval.

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

8. **2.9 How important is “bacteria concentration” compared to “local humidity” of ventilation systems? (Bacteria concentration is ____________than local humidity)** *
Mark only one oval.

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

9. **2.10 How important is “particle concentration” compared to “local humidity” of ventilation systems? (Particle concentration is ____________than local humidity)** *
Mark only one oval.

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

10. **2.11 How important is "particle concentration" compared to "local temperature" of ventilation systems? (Particle concentration is ____________than local temperature)** *

Mark only one oval.

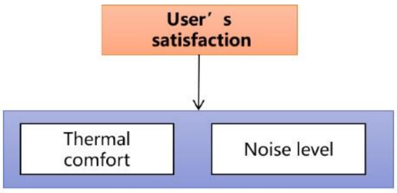
- 9-Absolutely more important
- 7-Strongly more important
- 5- More important
- 3-Weakly more important
- 1-Equally important
- 1/3-Weakly less important
- 1/5-Less important
- 1/7-Strongly less important
- 1/9-Absolutely less important

11. **2.12 How important is "local humidity" compared to "local temperature" of ventilation systems? (local humidity is ____________than local temperature)** *

Mark only one oval.

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

Please give opinions to the following questions with respect to the goal: User's satisfaction of the ventilation system in operating rooms



12. **2.13 How important is "thermal comfort" compared to "noise level" of ventilation systems? (Thermal comfort is ____________than noise level)** *

Mark only one oval.

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

Appendix 2: Users' satisfaction questionnaire

NTNU

Users' satisfaction Questionnaire about the Ventilation and Thermal Environment in Operating Rooms in St.Olavs Hospital

If you do not know what to answer, please leave the mark before questions number.

General information (following information is only used for research and will not be leaked to others who are not included in this research)

1. Your role in the operating room:

☐Surgeon	☐Assistant surgeon	☐Distribution nurse
☐Sterile nurse	☐Anesthesist	☐Other:

2. Gender

☐Male	☐Female

3. Age

☐under 20	☐20-30	☐31-40	☐41-50
☐51-60	☐61-70	☐over 70	

4. In which operating room you stayed?

☐OR1, (MV)	☐OR2, (LAF)

Thermal environment

Your answers should be based on sensation what you felt in operating room on the last surgical procedure you had.

5. a) What was your general thermal sensation in the operating room during the operation?

Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
☐−3	☐−2	☐−1	☐0	☐1	☐2	☐3

b) How often did you feel that?

Never	Seldom	Often	Very often	All the time
☐0	☐1	☐2	☐3	☐4

6. How was your skin wettedness* (*skin wetting caused by sweating)?

Dry	Neutral	Slightly wet	Wet	Very wet	Soaking wet
☐0	☐1	☐2	☐3	☐4	☐5

7. Please answer to following questions regarding to your sensation about cold draught in operating room:

a) Did you perceive a cold draught from the ventilation in the room?

Stagnant	Gently breeze	Breeze	Neutral	Slightly draught	Draught	Strong Draught
☐1	☐2	☐3	☐4	☐5	☐6	☐7

b) How often did you feel it during the operation?

Never	Seldom	Often	Very often	All the time
☐0	☐1	☐2	☐3	☐4

c) Where did you feel the cold draught mostly?

☐ feet	☐ knees	☐ hips	☐ chest	☐ head

8. What was your feeling about the humidity in the operating room during the operation?

Very humid	Humid	Slightly humid	Neutral	Slightly dry	Dry	Very dry
☐−3	☐−2	☐−1	☐0	☐1	☐2	☐3

9. Were you satisfied or not with the thermal environment in the operating room during operation?

Dissatisfied	Satisfied
☐	☐

Acoustic environment

Your answers should base on sensation what you felt in operating room in past several weeks.

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

Very silent	Silent	Perceptible	Obviously Loud	Very loud
☐−2	☐−1	☐0	☐1	☐2

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

☐ Yes, it makes me felt anxious.
☐ Did not notice the noise from ventilation system.
☐ No, no influence to me at all.