VENTILATION OPERATION IN HOSPITAL ISOLATION ROOM : A MULTI-CRITERION ASSESSMENT CONSIDERING ORGANIZATIONAL BEHAVIOUR

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ABSTRACT
Guidelines for isolation rooms in hospitals require keeping these rooms at negative pressure differential, but the guidelines do not impose a particular ventilation strategy how to achieve this. In principle, one could use variable ventilation regimes responding to interventions that cause a potential contamination risk such as the opening of doors. The variable ventilation regime would temporarily increase the volume offset and hence induce a higher negative pressure differential, whereas during other times the negative pressure differential would be kept at an acceptable minimum. In practice, however, VAV boxes (i.e. damper) are often set to deliver constant air volume. In this paper an adaptive VAV operation is introduced in response to the complaint that current operation is not adequate as it leads to excessive fan energy consumption. The paper evaluates the current practice while demonstrating efficiencies of the adaptive VAV operation, and supporting a rational selection of ventilation operation through a set of objective performance criteria. The chosen criteria relate to potential exposure of contamination, energy consumption and thermal comfort. It is shown that the two operation modes do not make a noticeable difference in the potential spread of contaminant and thermal comfort. However, the adaptive VAV mode consumes significantly less energy. It is also inspected whether the transition between low and high pressure differential is fast enough to reduce the temporary contamination exposure. To guarantee a safe transition, nurses may have to wait until the pressure control system gets settled. Hence, an additional performance aspect concerning the potential of delayed direct care is added on to the multi-criteria decision-making framework. A Bayesian decision theory is applied to compare two options given the stakeholders' environment. This reinforces the finding that the ultimate decision should be based on the multi-criteria comparison of building operational and organizational outcomes.

INTRODUCTION
Preventing nosocomial infection is a challenge to the healthcare facility. Active containment is required, hence patients are often placed in isolation rooms. Guidelines (ASHRAE 2003; CDC 1994; Department of Veteran Affairs 2006; NFPA 1987; AIA 2001) for isolation room ventilation specify that a negative air pressure in the room needs to be maintained to prevent the spread of airborne microorganisms. These guidelines do not specify a particular ventilation strategy, as long as the chosen strategy can be shown to satisfy the requirements.

In this situation, VAV boxes (i.e. dampers) are typically used for their energy saving features. In practice, however, these VAV boxes are often set to deliver a constant air volume, de facto rendering the VAV system into a CAV (constant air volume) system. This may be attributed to a lack of confidence in the controllability of VAV to prevent contamination exposure. In response to this, our work develops an improved VAV operation strategy in response to the inadequacy of current CAV operation in terms of fan energy consumption. This improved operation should secure the prevention of contamination to the same degree as the CAV, while taking advantage of energy saving features of the VAV. The details will be elaborated in the following sections.

The objectives of our work are: a) to develop and demonstrate an improved VAV operation strategy that is capable of preventing contamination exposure, b) to support a rational selection of ventilation options by suggesting a set of objective and the most relevant performance criteria, and c) to offer a re-evaluation opportunity to study whether the current practice of controlling VAV as CAV is really necessary given the proposed operation strategy.

The proposed VAV operation
Exhaust VAV boxes are set to modulate the air volume to maintain negative 2.5 Pa dP (pressure difference) during the time that the door is closed (Figure 1). When a nurse visiting isolation room presses a button before entering, the proposed VAV operation increases the exhaust volume to achieve negative 9 Pa dP a short time before the door opens. Nurses are allowed to enter the isolation room when the pressure difference sensor indicates -9 Pa dP. It is maintained at this level until nurses leave the

isolation area. After the door completely closes and the door sensor lets the controller know this event, the exhaust volume is decreased to reach the closed door pressure differential setpoint (- 2.5 Pa dP). If the door sensor detects that the door has not been completely closed, -9 Pa dP is sustained.

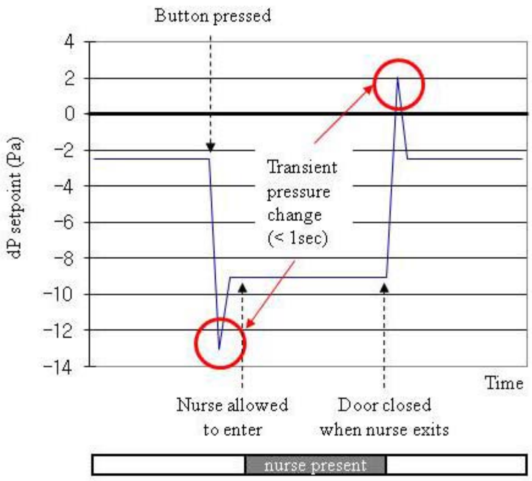

Figure 1 The proposed VAV operation

MULTI-CRITERION PERFORMANCE ASSESSMENT

This study aims to offer a decision-making support framework to choose an adequate ventilation operation for the isolation room in healthcare facilities. With the focus on making decisions during the building operation process, building performance assessment provides a common language to different stake holders with diverse expectations. To perform a rational and objective performance assessment from the perspectives of the facility manager, medical staff and patient, three building operational performance aspects are considered, i.e. energy consumption, potential exposure of contamination, and thermal comfort. An earlier paper (Kim et al., 2009), concluded that based on measures for the potential spread of contamination and thermal comfort, the current CAV operation and the improved VAV operation do not make a noticeable difference although the improved VAV operation consumes far less energy.

To confirm that the proposed VAV operation appears to be a reasonable selection, it has to be ascertained that enough settling time for the VAV to stabilize the pressure difference can be guaranteed. To do this, visitors and staff of the isolation room would have to wait long enough to allow the pressure difference to reach -9 Pa before opening the door. Therefore, another performance aspect is included quantifying the organizational effects of this procedure. One of the main effects is the waiting time. The facility manager would have to determine how much the organization (mainly nurses' group) can tolerate the waiting time. If this procedure is not appropriate for the organization, the selection of the improved operation may need to be reconsidered. The waiting time asks for a need of considering the potential of delayed medication. A summary of all considered performance aspects including those previously developed (Kim et al., 2009) is given below.

Performance aspect I : Energy consumption

Two operations are different in offset air volumes modulated through the exhaust damper in the room. In an isolation room, the exhaust fan takes the offset air out by controlling the exhaust duct static pressure. Hence, the exhaust fan energy consumption can be a critical indicator to distinguish the energy consumptions of the two operation modes.

Since the two operations run on the same set up of equipment specifications, except for flow volume rate, the fan law (Equation 1.a and 1.b) can be used to compare the fan power consumptions of the two operations. In particular, the fan law (Equation 1.b) relates flow volume rate and fan power consumption in a steady-state system, and relative fan power consumption of one operation (1) to another (2) is expressed as follows:

$$Bhp_1 = \left(\frac{P_1}{P_2}\right)^{\frac{3}{2}} \times Bhp_2 \qquad (1.a)$$

$$Bhp_1 = \left(\frac{cfm_1}{cfm_2}\right)^3 \times Bhp_2 \qquad (1.b)$$

where *Bhp* is horsepower, *P* is pressure and *cfm* is flow rate in terms of cubic feet per minute.

Performance aspect II : Potential exposure to contamination

Contaminant transmission towards the hall way is closely dependent on (1) contaminant distribution within a room, (2) the pressure differential between the isolation room and the hall way, and (3) door location. When the contaminant is concentrated further away from the door opening, contaminant transmission toward the outside is less likely. Particularly when the door is closed, the patterns of the contaminant distribution are similar irrespective of the pressure differentials that are imposed. This implies that the magnitude of the pressure differential does not affect the contaminant transmission in the closed door situation (Shih et al., 2007).

Index contaminant concentration

Contaminants (or pathogens) emitted by a patient's respiration can be found everywhere in the isolation room, regardless of the magnitude of the pressure differential. A transmission of very low or almost nil concentration may not be so harmful since such concentration can be omnipresent. Here we need to set up a concentration index that differentiates the range between potentially harmful and almost harmless concentration. In this study, we choose 80%

of the cumulative contaminant concentration in a descending order as the index reference when 2.5 Pa dP is imposed (Figure 2).

To represent the contamination distribution in our study, the potential exposure $E_{potential}$ is introduced. It is used to indicate (Equation 2) the spread of the contaminant concentration. The contaminant distribution in a room with respect to the door movement can be obtained only through a CFD simulation of airflows. $E_{potential}$ is measured as the fraction over time and over the surface area on the horizontal plane at the patient bed level.

$$E_{potential} = \frac{\int_{A}\int_{t1}^{t2} C(t)dtdA}{A_{bed\_plane}} \qquad (2)$$

where C [ppm] is contamination concentration found to be above the index concentration, $E_{potential}$ [ppm·s] is the potential contaminant exposure, and A_{bed_plane} is the horizontal room section surface at the height of the patient bed.

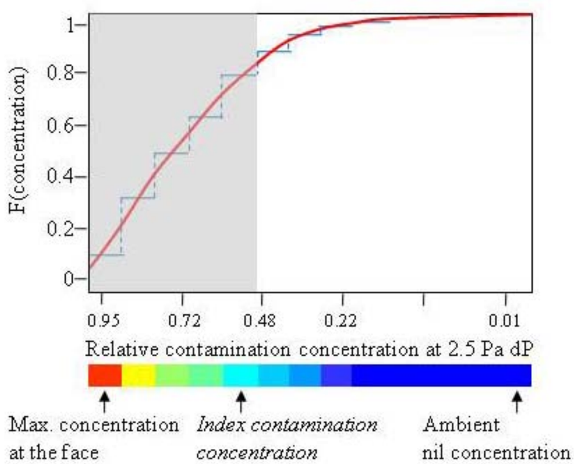

Figure 2 CDF of contamination concentration

Performance aspect III : Thermal comfort (PMV)

Predictive mean vote (PMV) is chosen for assessing thermal comfort of the patient. However, averaged PMV may not differentiate deviating PMV patterns caused by pressure differentials. It runs a risk of hiding poor local PMV values. A larger air volume offset can develop more eddies which can contribute to create a higher local air velocity, and affect air temperature and mean radiant temperature, thus PMV distribution would not be uniform for a space where airflow fluctuates strongly. This means occupants at different positions in the room actually could perceive very different thermal comfort. The patients in the isolation rooms spends most of their time in the bed. The CFD simulation will be used also to calculate the PMV values more precisely for each position in the room, particularly at the patient bed level.

Performance aspect IV : Potential of delayed direct care

CAV operation always provides continuous supply/exhaust air volume to maintain the design pressure differential. It is not needed to change pressure differential upon the door event. So there is no settling time that may interrupt nurses from entering the isolation room, to wait for a fully developed pressure differential.

VAV operation changes pressure differential when the door opens and closes. Nurses who get into the isolation room have to allow enough settling time for the fully developed pressure differential to establish before they open the door.

Step 1: Differential pressure sensors measure the pressure differential. Response time of differential pressure sensor is usually less than 5 seconds.
Step 2: If the measured pressure differential is not in the desired set point band, a local controller in the isolation room sends an actuation command to modulate the exhaust damper or to change the speed of the exhaust fan.
Step 3: The exhaust damper opening is modulated following the set point. Adjusting the damper opening following a change set point usually takes less than 30 seconds[1].
Step 4 : Depending on opening percentage of a terminal unit damper, the exhaust duct static pressure set point is reset upward or downward of the current system static pressure set point once every 10 minutes until certain conditions are satisfied. Please refer to Trane (2007) for the detail.
Step 5: The exhaust fan ramps up or down, and exhaust air volume changes depending on exhaust duct static pressure set point. The settling time for this step usually takes less than 2 minutes[1].
Step 6: Increased or decreased exhaust airflow is delivered throughout the duct. Since an independent exhaust fan drives airflow through the exhaust air duct to which isolation rooms are connected, air delivery time described in this step can be very short.
Step 7: The pressure differential in the space changes from one level to another level. Transient time for this step usually takes 1 second (Shih et al., 2007).

Details on the sequence of operation are elaborated in (Kim 2008), where it is deduced that a pressure differential settling time for the isolation room would be around 3 minutes. Therefore nurses may have to wait to enter the isolation room up to 3 minutes after they press the door button.

3 minutes of delay in giving a care per visit may not look too serious. However, if nurses have to visit the isolation room more often, they also have to wait more often. Eventually it may lead to cause patients'

[1] Based on an interview with facility manger

complains or even pose a serious risk. Quantifying a negative effect to patients cannot be done simply without mentioning individual patient's illness and required level of intensive care. So in this study the potential of delayed direct care is assessed in terms of how much the waiting time takes nurses' general care time for each patient. A further case analysis in conjunction with a frequency of nurses' visiting will be discussed in the result section.

Discussion on air pressure balance controls

A negative pressure in the isolation room is formed by means of increasing exhaust air volume modulated by exhaust dampers. The increased offset air volume has to be supplemented and air would most likely flow in from the hall way. If the marginal air volume has not been spared at the central AHU level, it could impact the air balance in the corridor which may jeopardize the whole contaminant control of the floor.

To prevent this, the supervisory module of the local controllers of the sub-systems has to optimally control the ventilation system. This can be accomplished by combining local controllers of the sub-systems and optimal supervisory control of the building system. Particularly, the optimal supervisory control will result in less (or no) contentions or incongruity among controls of the sub-systems. Synchronization of the sub-control system is obtained through the design and implementation of an intelligent coordinator, which is the central supervisory controller. Existing research on supervisory control have shown promising results of the synchronized controls (Seem 1989; Seem et al. 1999; van Breeman and de Vries 2001; Salsbury 2005). One expected scenario would be depicted as the central AHU supplements the adequate amount of air volume needed by the increased offset volume before the supply fan gets bottled-necked or the deficient air gets supplied from the next door which finally breaks the air pressure balance. This can be implemented with setpoint manager type controls; boosting up of the flow volume setpoint proactively in AHU when a setpoint of the local damper controller shows an increasing tendency.

EXPERIMENT ENVIRONMENT

Case configuration and assessment method

An isolation room (Figure 3) in a hospital is selected as an exemplary case. To simulate the contaminant transmission, carbon dioxide is used to model and track the passive contaminant source in a CFD simulation (FloVENT 2008). The gas is released from the patients' mouth and is assumed to consist of air and carbon dioxide only (Shih et al., 2007). Supply air has 25°C and 50% RH. The patient activity level is 0.7 with 1.3 of clothing level. These are actual values in the observed isolation room. All boundary walls of the model are assumed to be adiabatic. Details on room configuration and simulation environment are elaborated in a previous paper (Kim et al., 2009).

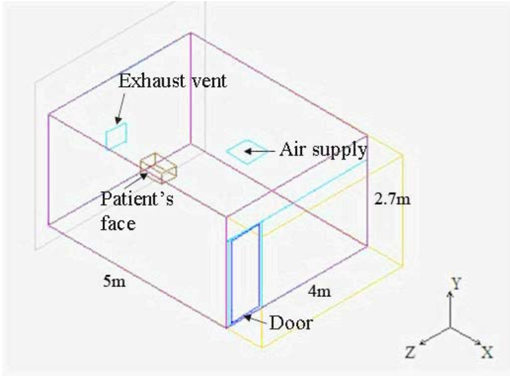

Figure 3 Exemplary isolation room

Operation schedule and offset air volume

Table 1 summarizes the operation schedule and relative supply/exhaust air volume of each operation. Supply air volume is calculated based on room volume and air leakage rate of the isolation room as recommended in guidelines (ASHRAE 2003; Department of Veteran Affairs 2006; AIA 2001). Exhaust air volume is calculated based on required pressure differential of each system.

Table 1 Operation schedule and relative exhaust air volume with 100% of supply air volume

	Operation hour	Hours during the indoor climate exposed	Relative exhaust air volume	Volume offset
CAV-dP9	24hrs	0.2 hr(dP 9)	300%	-200%
VAV	1hr (dP9) 23hrs(dP2.5)	0.2 hr(dP 9)	300%(dP9) 204%(dP2.5)	-200% -104%

dP9 and dp2.5 mean 9 Pa dP and 2.5 Pa dP respectively.

Operation hour and exposure hours

The most frequent visitors of the patient room are nurses. From two reports (Lemonidou et al. 1996; Peter D. Hart Research Associates 2003), each nurse takes care of eight patients in average. Direct care [2] time for a patient would be about 459/8 = 57 minutes/day (about 1 hr) and the frequency of those nursing activities for a patient is about 48/8 = 6 activities/day.

When we assume that every nursing activity occurs during each visit, nurses visit the patient room 6 times per day. From an onsite observation of an

[2] Direct care includes the nurse care and interventions in the patient room. Other nursing activities such as indirect care and supplies&cleaning are typically done out of the patient room.

isolation room, it was found that the average duration that the hallway is exposed to the indoor climate is less than one minute for each door opening. Thus approximately during 12 minutes[3] per day (6 times x 1 min x in/out), at the maximum, the indoor climate is exposed to the hallway.

RESULTS

Energy consumption

The daily energy consumption of each operation is calculated based on the fan laws and ventilation operation schedule, as shown in Table 2. Note that the VAV operation consumes only a third of energy of the CAV-dP9.

Table 2 Relative daily energy consumption based on the fan laws

	Operation hour	Relative exhaust air volume	Relative daily energy consumption
CAV-dP9	24hrs	300%	648 Bhp_{op}hr (292%)
VAV	1hr (dP9) 23hrs(dP2.5)	300%(dP 9) 204%(dP2.5)	222 Bhp_{op}hr (100%)

Potential exposure to contaminants

Contaminant concentrations at both pressure differentials (dP 2.5 Pa and dP 9 Pa) are compared during the door being open. At dP 2.5, the contaminant does not seem to disperse to the hallway. However, unexpected movement by people, or unexpected influences caused by strong air induction from the hallway may introduce some contaminant transmission to the hallway when the door opens. This implies that a greater negative pressure differential is necessary when the door is opened. The CFD simulation for dP2.5 results in $E_{potential\_dP2.5}$ = 0.975, whereas the CFD simulation for dP9 results in $E_{potential\_dP9}$ = 0.3 (Figure 4 and 5).

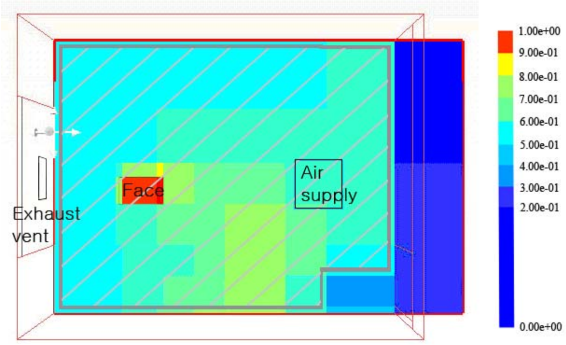

Figure 4 Contaminant concentration with dP2.5 when the door is open (the checked area is 97.5%)

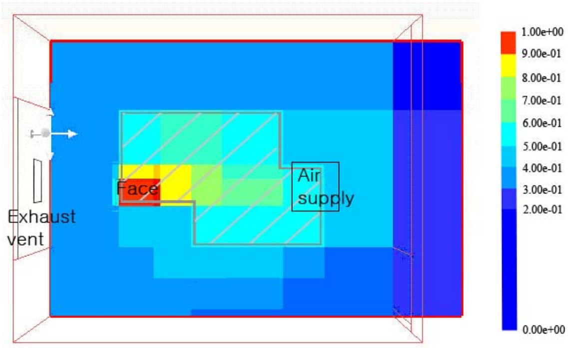

Figure 5 Contaminant concentration with dP9 when the door is open (the checked area is 30%)

If we assume that an improved VAV operation guarantees that the pressure differential is automatically increased to dP9 before the door opens, the relative daily potential exposure of both operations is equally low ($E_{potential\_dP9}$ = 0.3).

Thermal comfort

As Table 3 and Figure 6 & 7 indicate, the PMV results for both operations are within the narrowly desired comfort range (from -0.5 to 0.5). Thus thermal comfort resulting from both operations results in similar patient perception of thermal comfort. But it has to be noted that the patient would perceive a slightly better thermal comfort in the dP2.5 operation mode, obviously attributable to lower air velocities.

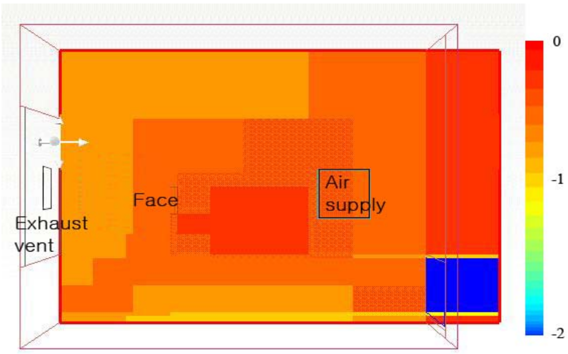

Figure 6 PMV distribution with dP2.5 (PMV -0.333 at the patient face)

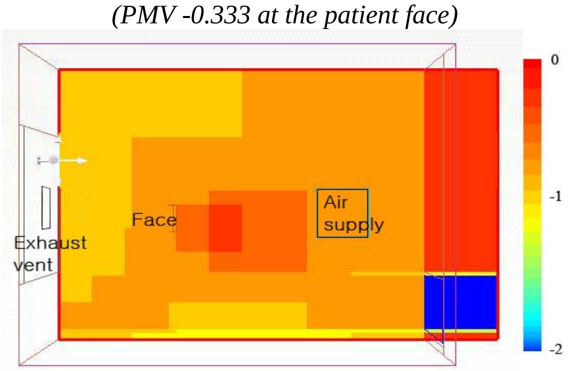

Figure 7 PMV distribution with dP9 (PMV -0.467 at the patient face)

[3] The period when the pressure differential fluctuates due to the door event can be estimated as 1 second (Shih et al., 2007), which is negligible compared to 12 minutes.

Table 3 Averaged PMV of each ventilation option

	Operation hour	PMV at the patient face	Time-averaged PMV
CAV-dP9	24hrs	-0.467	-0.467
VAV	1hr (dP9) 23hrs(dP2.5)	-0.467 -0.333	-0.339

Potential of delayed direct care

As reported earlier, one patient room is visited by nurses 6 times per day. This means that if the VAV is chosen, nurses have to spend, at the maximum, an extra 18 minutes (6 times x 3 minutes of settling time) per day per each patient room to give the same degree of direct care with the CAV operation. From a view of the patient, a patient takes 180 minute of nurses' general care (24 x 60 min / 8 rooms) in a day, thus 18 minutes that corresponds to 10% of general care time for each patient can be delayed.

Table 4 Potential of delayed direct care of each system option

	Operation hour	Potential of delayed direct care
CAV-dP9	24hrs	None (0%)
VAV	1hr (dP9) 23hrs(dP2.5)	18 minutes (10%)

DECISION MAKING

The comparative assessment is summarized in Table 5 and Figure 8. Findings and conclusions drawn from the assessment are illustrated below.

It is observed that as far as potential spread of contaminants and thermal comfort are concerned, the current CAV operation and the improved VAV operation do not make a noticeable difference. The VAV operation gives rise to 10% potential of delayed direct care compared to the CAV operation. But the more efficient VAV operation consumes far less energy.

It may not be a clear-cut case for the decision-maker to choose the VAV, since the waiting time may not be acceptable to the organization. To make a rational selection that is the most suitable for his isolation rooms, the organization (decision-maker) has to weigh his preferences between building operational measures (e.g. energy consumption) and organizational outcomes (e.g. potential of delayed direct care), and compare the two options based on these preferences. A rational way to do this can be based on Bayesian decision applied to multi criterion decision making as explained in French (1986).

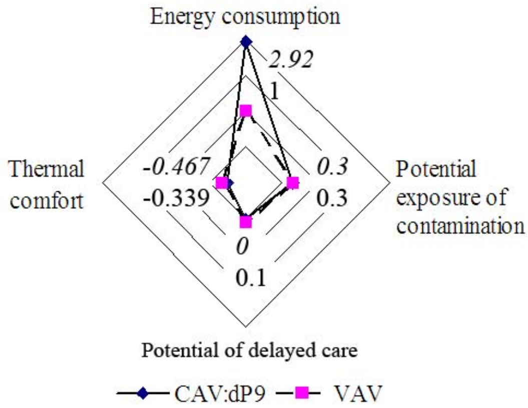

Figure 8 Radar map comparing performances of both operation modes

Table 5 Multi-criteria performance assessment of two operations

	Energy consumption	Potential of delayed care	Potential exposure of contamination	Thermal comfort PMV
CAV-dP9	292%	0%	30%	-0.467
VAV	100%	10%	30%	-0.339

Decision theory

Bayesian decision theory offers a normative approach to rank various options in order of preferences consistent in his decision-making tasks. The theory assumes that a decision is made only by decision maker's a-priori preferences and the quantified information delivered by results of performance assessments. Hence the highlight of this theory is that if a decision-maker embeds his rationality into its axioms, the preference of the decision maker also can be numerically expressed in terms of a utility function over multiple criteria.

The main principle of the utility function theory is that if a decision-maker prefers option y to option x, then the utility of option y is larger than the utility of option x (Axiom 1).

A utility function $u : X \rightarrow R$ rationalizes a preference relation $\preceq$ on X if for every $x,y \in X$, $u(x) \leq u(y)$ if and only if $x \preceq y$. (Axiom 1)

We assume that utility functions of each criterion exist, and can be generated from surveys or experiences of decision makers. Also utility functions of x and y are assumed to be *linear* and *additively independent*.

In this paper, the Bayesian decision theory is applied in the selection of ventilation operation for isolation rooms. There can be two decision makers with different attitudes towards the operation of isolation room operation: risk neutral (decision maker 1) and less risk incentive (decision maker 2). The first decision maker regards both less energy consumption and less delay in giving care as equally prefered. The second decision maker, however, emphasizes giving care without delay. In addition, if the potential delay in giving care is more than 5% (considered a tolerable loss), he is not willing to take much risk that nurses may wait longer. But if the loss of nursing time is less than 5%, he is encouraged to take such option.

Modelling of preference for decision-making

In our problem we assume that the decision maker has two objectives: (1) to minimize energy consumption (*X*) and (2) to minimize potential of delayed direct care (*Y*). A performance analysis has shown the quantified results for both options, and both are encoded into marginal utilities over *X* and *Y* respectively. Hence the decision maker's multi-criterion utility function can be described as:

$$U(x,y) = c_2x + c_1y + c_0 \qquad (3)$$

We can apply the fact that we can set the boundary of the function with:

$$U(0, 0) = 1 \qquad (4)$$

$$U(3, 0.2) = 0 \qquad (5)$$

Equation (5) can be interpreted as that allowances for the maximum energy consumption and potential of delayed direct care in this decision-making case are 300% and 20% respectively. In addition to these, we can give one more constraint where the decision-maker makes a trade-off between *X* and *Y*, i.e. equation (6). We assume here that for the decision-maker, the utility of 50% energy consumption and 30% potential of delayed direct care (lower energy consumption and higher potential of delayed direct care, i.e. the conventional VAV) is equal to the utility of 500% more energy consumption and 1% potential of delayed direct care (high energy consumption and practically no delay in giving care, i.e. CAV with very static controls). This statement implies that the decision-maker perceives equivalent satisfactions for these two operations. This numeric statement is, of course, only a hypothetical assumption based on the decision maker's assumed subjective preference.

$$U(0.5, 0.3) = U(5, 0.01) \qquad (6)$$

The first decision maker's multi-criterion utility function is then described as:

$$U(x,y) = -0.164x - 2.54y + 1 \qquad (7)$$

On the basis of equation (7), we can calculate the utilities of both options:

CAV-dP9 : $U(2.92, 0) = 0.52$ (8)

VAV : $U(1, 0.1) = 0.58$ (9)

This result suggests that the improved VAV is preferred over the CAV, because the energy saving benefit of the improved VAV is apparently more dominant than the potential of delayed direct care, given this decision maker's risk neutral preference.

A less-risk incentive decision maker

The second decision maker can hold the following marginal utility of Y (Figure 9). He wants nurses to spend less time to wait before entering the isolation. In addition, he would be even happier if a ventilation operation holds a practically little potential of delayed direct care (less than 5%). He keeps the identical manner of the decision problem with the first decision maker and thus the boundary conditions of his utility function (Equation 4 and 5) are sustained, except for his marginal utility for loss in nursing time.

Following the same approach as above, the second decision maker's utility function is:

$$U(x,y) = \begin{cases} -0.175x - 10y + 1.5 & 0 \le y \le 0.05 \\ -0.175x - 3.157y + 1.158 & y > 0.05 \end{cases} \qquad (10)$$

Calculating the utilities using Equation (10),

CAV-dP9 : $U(2.92, 0) = 0.98$ (11)

VAV : $U(1, 0.1) = 0.67$ (12)

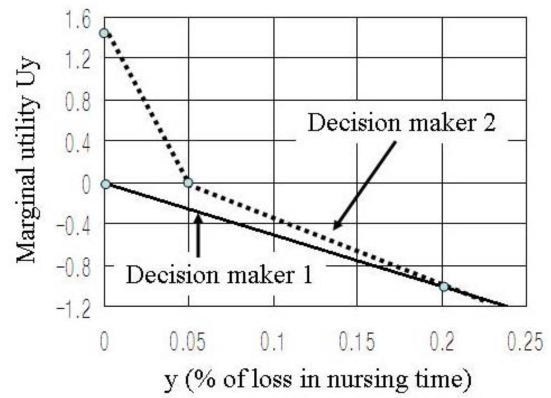

Figure 9 Marginal utility U_y for two decision makers

The second decision maker would choose the CAV-dP9 operation, since it offers the least potential of delayed direct care that is less than 5% care time range.

The conclusion is that different preferences by the decision maker may lead to a different preferred operation mode. The decision-making requires the quantification of all relevant performance criteria and the construction of a plausible utility function.

CONCLUSIONS

Despite its energy saving feature, the currently installed VAV systems often runs constant air volume in some isolation rooms in the healthcare facility. Hence in this paper an adaptive VAV operation is introduced in response to the complaint that current operation is not adequate as it leads to inefficient fan energy consumption. It turns out that the adaptive VAV mode consumes significantly less energy compared to the current CAV operation. It is also inspected whether the transition of the adaptive VAV between low and high pressure differential is fast enough to reduce the temporary contamination exposure. To guarantee a safe transition, nurses have to wait before entering. Hence, additional performance aspect concerning potential of delayed direct care added on to the multi-criteria decision-making framework.

The multi-criteria performance assessment reinforces again that a selection of suitable ventilation operation for isolation rooms should not place an emphasis only on building operational measures. The ultimate decision should be based on the multi-criteria comparison of building operational and organizational outcomes. To rationalize an objective decision making procedure, the Bayesian decision theory is introduced. Its application shows that a composite of identical information resulting from performance assessment, but with different preferences by decision makers may lead to a different preferred operation mode.

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