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Performance assessment of an operating theatre design using CFD simulation and tracer gas measurements

MGLC Loomans^{a,*}, W van Houdt^b, AD Lemaire^c and JLM Hensen^a

^aEindhoven University of Technology, PO Box 513, 5600 MB, Eindhoven, The Netherlands.

^bHospital Tergooiziekenhuizen, Rijksstraatweg 1, 1261 AN Blaricum, The Netherlands

^cEfectis Nederland BV, PO Box 1090, 2280 CB Rijswijk, The Netherlands

Short title

Performance based assessment methodology ventilation operating theatres

Keywords

Performance assessment, Methodology, Ventilation efficiency, Operating theatre, CFD, Measurement

Abstract

The paper advocates the application of the performance based approach to arrive at improved, innovative and more functional buildings. It does so by describing the development of a performance assessment methodology for the assessment of the efficiency of a ventilation system in an operating theatre. This assessment is performed in the design and use phase to adhere to the performance based approach definition. The developed methodology is tested in a real case study with an innovative downflow plenum. Focus is on the low infection rate functional requirement.

The results from the case study indicate that the assessment methodology functions and that the innovative downflow systems that was the topic of the case study adheres to the requirements set. Some parts of the methodology, however, allow openings for further research. On the other hand, a similar assessment can be extended to other requirements, such as thermal comfort, hypothermia, etc.

1. Introduction

The basic concept of Performance Based Building (PBB) and its methodology already have been described in 1982 in the CIB-Report 64 [1]. The approach focusses on what a (part of a) building should do and not on how it is to be constructed. Furthermore, it requires an objective evaluation of the performance (in the design as well as in the use phase).

Focussing, as an example, on the ventilation system of an operating theatre, how is the assessment currently performed? In The Netherlands until now the performance of a ventilation system in an

* Corresponding author. Tel.: +31-40-247-4651, fax: +31-40-243-8595. E-mail address: M.G.L.C.Loomans@tue.nl.

operating theatre generally is assessed indirectly, with a focus on the use phase. The supply velocity, the temperature difference between supply and exhaust air and the air quality (i.e. number of particles per m^3) of the supply air are the main prescribed parameters to be tested. For the design phase these prescriptive requirements generally are the point of departure without any further considerations.

Nevertheless, assessment of the performance of the operating theatre requires an integral approach, where the focus should be on, e.g., a low surgical site infection rate. The significance of this infection risk has been quantified, in costs as well as personal consequences [2]. The air is one of the routes (direct and indirect via implants and instruments) for the contamination of a wound, resulting in surgical site infections. The air quality near the wound and the positions where implants and instruments are situated therefore should remain as high as possible. Humans form the most important contaminant source in an operating room, therefore an efficient ventilation of operating rooms is required. The currently applied prescriptive approach hampers application of possible innovative systems and may not guarantee good functioning of the total system or a further optimization. The performance based approach provides an answer to these notions. This topic has recently gained more interest in the Netherlands, as results have come available from applying surgery with a warranty in the USA [3]. Meaning that costs for additional treatment due to complications after the surgery are paid for by the hospital.

Assessment of the ventilation efficiency in an operating theatre in the design phase is possible when applying the Computational Fluid Dynamics (CFD) technique. In literature several references are available that describe the use of CFD for determining the ventilation efficiency in operating theatres. An extensive numerical study in which different cases, i.e. designs of ventilation systems for an operating theatre, are compared can be found in literature [4]. Amongst others, specific attention is given to the modeling of particles. A similar study is described by [5]. [6] present a CFD-study towards the thermal comfort environment and the contamination risk as a function of the medical lamp position and the diffuser supply velocity. [7] also present a numerical study with respect to the particle concentration in an operating theatre. In all cases no reference is made to measurements. Extensive validation of CFD models for application at operating theatres is described in [8] and [9]. Their full-scale experimental investigations included the air flow distribution under different configurations, contamination sources and measurement of Colony Forming Units (CFU).

Recently new developments have evolved in current practice in Western Europe. In The Netherlands an updated guideline for building operating theatres was issued in 2004 [10]. A prescriptive design

solution for all types of operating theatres is provided by minimizing the supply area for a downflow plenum to around 9 m². This agrees with developments in Switzerland, Germany and Austria and builds, amongst others, on a literature research [11]. This may however have important consequences for the optimal functioning of the total system. Despite the prescriptive nature, the Dutch guidelines do recommend to perform a CFD study to demonstrate the feasibility of the plenum design. However, no information is provided on how to perform such a study and assess the results. The equivalence principle would require a similar assessment for innovative systems.

In Germany, recently a concept standard has become available (VDI 2167; [12]). This is based on Swiss practise and assesses existing operating theatres with respect to the ventilation efficiency, expressed in a protection class. This standard applies a performance approach as it does not prescribe the design of the operating theatre, though implicitly reference is made to the design solution. This standard was specifically developed for in-situ assessment, i.e. not for the design phase.

Following the above state-of-the-art, the objective of this study was to develop a fully performance based approach for the assessment of the ventilation efficiency in operating theatres, establishing a low surgical site infection rate. Application was envisaged for the design as well as the use phase. The developed assessment methodology was evaluated for the case of an innovative design of a 'laminar' downflow plenum applying three different temperature planes. The methodology however may also be used for other designs. In-situ assessment of the investigated and actually built operating theatre was possible after completion. This work has evolved parallel to the above described developments.

After a short description of the purpose of the study and the methods applied, the assessment methodology will be described. The translation of the methodology to a practical case study is included alongside to elucidate the considerations. Actual results for the case study will be presented next. The paper will finish with a discussion on the developed methodology.

2. Purpose of the study

At the time of research, no fixed and mandatory guidelines or assessment procedures were available with respect to the performance criterion and related target values for minimizing the risk of surgical site infection in an operating theatre. Instead prescriptive information was provided for application of (standard) downflow plenums. The study should provide for an objective performance based assessment methodology for the assessment of (innovative) ventilation designs for operating theatres.

3. Methods

As described in the introduction, the performance based approach has been the point-of-departure for the development of the assessment methodology. This evaluation procedure encompasses; (1) problem description, (2) solver procedure and (3) results analysis. The assessment is based on a performance criterion, which should be decided upon as well. For each item a recipe has been developed to perform the assessment. In a case study the developed methodology has been verified.

Literature review, interviews with national experts in the field and earlier own research, as summarised in [13], have been used to develop the assessment methodology. For performing the actual case study numerical and experimental techniques have been used. For the numerical results the CFD-technique has been applied. The presented results have been obtained with the CFD-code WISH3D. This code has been validated in several international research projects [14]. For the operating theatre a special validation research has been performed [9]. For the experimental work the tracer gas technique was applied. The explanation for this is presented in the description of the methodology.

In the case study that was used the question should be answered whether an innovative design of a three temperature (3T) downflow plenum is applicable for an operating theatre and provides sufficient protection from surgical site infections for high risk surgery, such as orthopaedic surgery. The functional requirement with respect to the ventilation of operating theatres was defined as: The ventilation of an operating theatre should be performed in such a way that the risk of surgical site infection is as low as possible.

The design problem consists of a 3T plenum that differs in size from the standard small downflow plenum ($1.20 \text{ m} \times 2.40 \text{ m}$) as applied in older operating theatres in The Netherlands and from the large plenum (square $\sim 8\text{-}9 \text{ m}^2$) as prescribed, e.g., by the Dutch guideline [10]. Figure 1 presents the original lay-out of the 3T plenum. The temperature distribution over the plane is such that the surgical site is positioned under the coldest plane (T1). The operating personnel is situated under the planes indicated with T2, which supply temperature is higher. Finally, the highest temperature is supplied at plane T3, i.e. the position of the anaesthetist. The (near final) design of a complete operating theatre was the point-of-departure.

>> Figure 1.

4. Assessment methodology

4.1 Performance criterion and target value

In The Netherlands, as for many other countries, no fixed performance criteria are set that directly relate to the surgical site infection rate. As indicated in the introduction, they generally refer to prescribed design parameters that should guarantee minimum supply conditions. Operating theatres nevertheless can be classified with respect to the amount of CFU (reference with clean room). Three classes generally are defined; Class 1: $< 10 \text{ CFU/m}^3$ [ultraclean operating theatres]; Class 2: $< 200 \text{ CFU/m}^3$ [low infection risk medical procedures]; Class 3: $< 500 \text{ CFU/m}^3$ [treatment rooms]. The CFU concentration in this case has a direct relation with the infection rate in an operating theatre [15], where Class 1 generally relates to design solutions with laminar downflow systems.

The Class 1 performance requirement is advised in, e.g., England, for an area close to the wound (0.3 m). Also in the Netherlands orthopaedic surgeons advice this high quality standard [16]. These requirements are set and assessed for operating theatres in use. For assessment of new designs or innovative solutions no guidance is available from these requirements.

Given the fact that in orthopaedic surgery implants are used, high requirements should also account for the instrument tables, where instruments and implants are placed and exposed during the operation. Therefore, the performance requirement should extend to these areas as well when deciding on the performance criterion and target value.

Based on the above, for the case study a performance requirement with respect to the air quality was set for the operating table and the instrument tables which is based on the concentration of CFU in the air. This number should be limited. For the case study the target value was set at a maximum of 10 CFU/m^3 at 0.05 m above the patient and instrument tables.

4.2 Evaluation procedure

4.2.1 Problem description.

The problem description for an operating theatre can be subdivided in three main items. The configuration to be investigated, the sources and the boundary conditions for which the evaluation should be performed. The configuration refers to the design and lay-out of the operating theatre. Besides design

information this must include the interior, i.e. a representation of the room in actual use including personell and equipment. This requirement can be derived from the research as presented in the introduction and from [13]. The representation of the room in actual use should be agreed upon with the surgical staff of the hospital in order to assess a, for the specific hospital and design lay-out, realistic situation.

The sources in the room refer to the personell and equipment which act as heat and contaminant sources. Heat sources are important as they influence the flow field. For a 'theoretical' mixing situation this may be neglected. In that case the CFU concentration can be calculated by hand based on the flow rate and the contamination source. However, when referring to a downflow situation, counteracting forces are present when heat sources are present under the downflow. This generally is the case and therefore will require the use of the CFD-technique. Furthermore, the heat load in the room determines the correct functioning of a downflow system. E.g., [13] found that, for a 'laminar' downflow to function optimally, the temperature difference between supply and exhaust air should be in the order of 1 to 2 K. Recent results indicate that for specific plenum designs this requirement may become obsolete [17].

Contaminant sources (expressed in CFU per time interval) are important as they determine the air quality in the room, which is the performance indicator for the case study under investigation. As absolute values are applied in the target value of the performance criterion, it is important that the sources that are incorporated in the problem description are realistic. The most important contaminant source in an operating theatre is the operating personnel. A person can spread between 1000 to 200.000 particles per second. An operating team therefore can spread several millions of particles per minute. Only a small part of these particles will carry a CFU. A fixed relation between the number of particles and the amount of CFU however has not been found [18]. Furthermore, the clothing worn will also significantly reduce the number of particles that is released to the air [19]. When different operating suits are worn, a differentiation should be made.

Based on the above information, Figure 2 represents the eventually investigated original design configuration for the case study. This included amongst others the ventilation design as proposed by the manufacturer. Besides the surgical staff near the operating table, also personnel in the periphery is foreseen with respect to the contaminant source. They however are not modelled physically. In the design at one side of the room also a preparation zone, with separate downflow system was foreseen, to be used prior to the operation. This zone is not in use during an operation. This configuration was decided upon

together with the surgical staff of the hospital. More information on the configuration is included in Appendix A.

>> Figure 2.

An overview of the heat and contaminant sources applied for the case study is given in Table 1.

>> Table 1.

The contaminant sources are released in a specific way. For the operating team, the source is positioned at the head of the individual person. This follows from [13]. For the periphery the contamination is modelled as a homogenous source to a height of 1.80 m. The periphery is defined as the area between the walls and the plenum. This difference in source modelling allows for the investigation of contamination from sources within and outside the plenum area or put more generally, nearby and further away from the operating area. This approach is similar to [12], but intends a more strict distinction between in- and outside the supply area. Remark that for other ventilation strategies the periphery may not be related to the supply area.

The remaining boundary conditions that are required to close the problem are provided by the design of the ventilation system of the operating theatre and the position of the room in the building and constructional aspects. Assuming a steady state approach, for the supply and exhaust conditions fixed values should be provided. For the investigated case study the walls were assumed adiabatic, with the exception of the radiant heat transfer (see Table 1). Table 2 presents an overview of the supply and exhaust conditions that have been assumed in the design phase.

>> Table 2.

4.2.2. Solver Procedure

The above presented first part of the methodology, the problem description, in principle should be fit for application in the design phase as well as for assessing an actually built operating theatre. This agrees with the performance concept. However for the different phases, different ‘solvers’ are applied. For the design phase airflow modelling (CFD) is the generally accepted technique. For testing the actually built room the tracer gas technique is applied. Both procedures will be explained below.

4.2.2.1. CFD simulation

A flow field can be described by the conservation of mass, momentum and energy. Given the boundary conditions, the resulting flow pattern is determined by solving the combined Navier-Stokes and energy, or any other scalar, equations,

$$\frac{\partial(\rho\phi)}{\partial t} + \text{div}(\rho\phi\mathbf{u}) = \text{div}(\Gamma \text{grad}\phi) + S_\phi \quad (1)$$

where

ρ = density

ϕ = dependent variable

$\mathbf{u}$ = velocity vector

Γ = diffusion coefficient

S_ϕ = source term

The technique of solving these equations numerically is known as Computational Fluid Dynamics (CFD) and has already a long record list of successful applications in numerous type of flow problems. For the turbulence modelling the standard k- ϵ model until now most often has been applied. This model has robust capabilities and its applicability for a wide range of turbulent flow problems, also indoors, was verified. In due course however other type of turbulence models have been developed, e.g. RNG-k- ϵ , realizable k- ϵ or k- ω , to name some alternative two equation models that are available [20]. These models might present better results for specific flow fields, e.g. buoyant driven flows [21]. Depending on the flow problem, i.e. the design of the operating theatre and the expected flow field, another type of turbulence model might be preferred. For the investigated case study the standard k- ϵ model was applied, under reference to the earlier validation study [9].

In order to assess the CFU concentration, the contamination has to be modelled. Three options of contaminant modelling can be distinguished: the passive scalar, the Euler and the Lagrange approach. This is under assumption that the size of the particle is small compared to the smallest wave length present in the turbulence and that the particles do not interact with each other [22].

The main difference between the three approaches to calculate the contaminant distribution in a room lies in the complexity with which individual particles are tracked in the flow. The passive scalar and the Euler approach deal with the particles as if it were a gas. In the Euler approach however the gravity force that acts upon a particle is included in the calculation of the particle contaminant distribution. The Lagrange approach not only includes the gravity force, but all other possible forces that may act upon a

particle. It calculates individual particle trajectories instead of a bulk of particles. From the individual particle trajectories the contaminant distribution can be derived.

The most important difference between the passive scalar and the Euler approach and the Lagrange approach therefore is that inertial effects are only dealt with in the Lagrange approach. The other two approaches assume that a particle will follow the flow instantly. Inclusion of the gravity in the Euler approach is only possible through the fact that the gravity force is constant and in a constant direction. The resulting settling velocity nevertheless is imposed instantly on the particle.

As inertial effects are neglected the passive scalar approach and the Euler approach are not able to calculate the turbulent diffusion of the particles near the particle source, i.e. they ignore the correlation of the velocity fluctuations. Applying the analytical solution for a homogeneous turbulent velocity field with zero average velocity [22], one can derive that these approaches are only valid for time scales that are larger than the integral time scale (T_L) of the turbulent flow [23]. The Lagrange approach does not have this restriction, however the main disadvantage of the Lagrange approach is the calculation time.

The gravity force is normally the most important force that acts upon a particle in the indoor air flow. Use of the Euler approach therefore is attractive when many contaminant concentration calculations are required. The Passive Scalar approach gives an overall view for the range of particles that are not or to a less extend affected by their individual size and weight.

A comparison of the three approaches was presented in [24]. This comparison was made for two types of rooms, of which one was a validation with measurement results. [25] used a cleanroom configuration with two supplies in the ceiling and four exhausts in the wall. The air exchange rate was set at 40 h^{-1} . The particle source was modelled as a for the flow transparent 'source volume' ($0.13 \times 0.14 \times 0.13 \text{ m}$) in the centre of the room with its centre point at a height of 0.8 m. Particle density was set at 1000 kg/m^3 . Murakami et al. measured the particle concentration in the exhaust and the average concentration in the cleanroom. The contamination distribution was simulated applying the described approaches, assuming the same 'source volume' for each approach. Table 3 presents the normalised results for this comparison for three different particle diameters.

>> Table 3.

From the results in Table 3 it is clear that for the smallest particles there principally is no difference between the approaches. For a particle diameter up to 10 microns (μm) the difference between the passive

scalar and Euler or Lagrange approach is smaller than 10%. For larger particles the difference increases. The difference between the Euler and Lagrange approach remains small, also at larger particle diameters, indicating that the gravity force indeed is most dominant and that the inertial effects on average do not influence the result significantly. Comparison with the measurement results in this case presents a good agreement.

For other type of flow fields, e.g. office rooms, the difference between the passive scalar and the other two approaches may already be more prominent at smaller particle diameters. This of course results from the on average lower velocities that are present in such a room. For the investigated operating theatre in the case study, with an air change rate of 35 h^{-1} , a comparison can be made with the above investigated clean room. Following the results, and under reference to the in-situ measurement, it was concluded that the passive scalar approach presents a sufficient basis to determine the air quality in the operating theatre.

4.2.2.2. Measurement.

Following the performance based approach, the operating theatre should be tested in-situ after completion according to the (as much as possible) same configuration as is investigated in the design phase. The developed and applied measurement procedure is described below for the investigated case study. The approach however can be generalised for other configurations.

The investigated configuration with respect to the operating team, instrument tables, etc., was in agreement to the one applied for the CFD study. At the end of the design phase some details were changed with respect to the design, of which the most important one was a nearly 10% increase of the supply area (and air change rate to 40 h^{-1}). Figure 3 presents an impression of the investigated situation. The operating team near the operating table and the patient were represented by heated mannequins. The other two modelled persons in the room were represented by heated dummies. The remaining heat load in the room, e.g. the equipment and operating lamp, was provided for in order to arrive at the totally required heat load.

>> Figure 3.

The contaminant sources were introduced in the room via perforated small tubes that were positioned around the neck of the operating team near the operating table. The contamination from the periphery was

introduced via a perforated tube that was positioned at 1.20 m height in the centre of the periphery, surrounding the plenum. The latter source modelling was somewhat different than in the simulations. As contamination a tracer gas (SF_6) was applied¹. This is similar to the passive scalar approach as applied for the CFD-study. At a steady state situation the concentration level was determined. The measured tracer gas concentration in this case was recalculated to CFU/m^3 applying the ideal gas law.

>> Figure 4.

Tracer gas measurements have been performed at a limited number of discrete points, inherent to measuring. Figure 4 presents an overview of the applied measurement positions for the case study. In this case these positions have been fixed according to the performance considerations and the CFD results. They may however be determined following other, agreed on, considerations. In order to distinguish between contamination from the operating team and contamination from the periphery, tracer gas measurements were performed separately for the two locations of the source, the operating team and the periphery. For the performance assessment the combined result is of importance.

For the case study a recirculation air flow was applied. In order to perform the measurements this had to be changed so that 100% outdoor air was supplied. As a result the recirculation exhaust grilles in the corners of the room (final design) were not functioning for these measurements. This change resulted in an increased over pressure of the operating theatre to the adjacent rooms, approximately 25 Pa instead of the normally required 5 Pa. It is assumed that this pressure difference may have had an effect on the air flow, however mainly on the periphery and not near the operating and instrument tables.

Before and during the measurements, also the steady state boundary conditions need to be checked regularly, e.g. supply velocity and distribution over the plenum, in order to distinguish any malfunctioning of the system. For the investigated case study the average supply air velocity was 0.27 m/s. It was not fully homogeneous (deviation from the average nearly 20% at one measurement point) for one of the outer corners of the T3 plenum (see Figure 1). The supply temperature was measured over the total measurement time. The average temperature difference between T2 and T1 was 1.3 K and between T3 and T2 this was 0.6 K. In the CFD simulations the differences were both set at 0.7 K.

4.2.3 Results Analysis.

¹ The higher density of this tracer gas may introduce deviations at low air change rates in the order of 2 h^{-1} [26]. For the high air change rate (and related air velocity) in the case study this effect is negligible.

The applied result analysis is relatively straightforward. It of course largely depends on the performance criteria set at the start of the assessment. For the case study, in the CFD simulations, the calculated concentrations have been assessed for the individual tables, based on the performance requirement. A plane at 0.05 m above the individual tables was taken as the reference. For the measurements, the determined concentration levels for the individual measurement positions at the tables are assessed in a similar manner. Additionally, CFD-results and measurement results can be compared to assess the agreement between the two approaches. If differences arise this naturally would require a further analysis of the (differences in the) design and the realised situation. Nevertheless, in principle the separate assessments should be regarded independently.

4.3 results case study

The previous paragraph described the developed approach, with an explanation of the implications for the investigated case study. In this paragraph actual results from the case study (CFD and measurement) will be presented. After that the methodology will be discussed.

4.3.1 CFD simulation

Following the described configuration and boundary conditions, Figures 5 and 6 present the graphical results for the design configuration of the 3T plenum as discussed above. Figure 5 presents an example of the velocity vector field at a vertical cross-section of the room (at plenum part T3). Figure 6 presents contours of the contaminant concentration at two horizontal cross-sections at 0.05 m above the tables.

>> Figure 5.

>> Figure 6.

The calculated velocity field indicates some specific characteristics of the design. The intended downflow is present above the table and near the instrument tables. Furthermore, the disturbance of the operating lamp appears not to intrude the clean air near the patient. However, at a cross-section of the T3 plenum ($z = 4.50$ m, shown in Figure 5), the effect of the recirculation plenum is obvious. This is not intentional and should require an improvement of the design. It is explained from the temperature gradient that develops in the operating theatre, with the coldest air, from plenum part T1, penetrating to

the floor, whereas the momentum and the thermal force of the air from, specifically, the plenum part T3 are insufficient to reach that deep. This is combined with the high recirculation rate for the room.

Based on the velocity vector field, however no conclusions can be derived with respect to the performance of the ventilation system design. Figure 6 presents the information for this. Focussing on the operating and instrument tables, one may conclude that the performance requirement is met for a large part of the table area. So despite the remarks to the flow field protection still is possible.

Based on the CFD results, changes were proposed to the original design and the configuration to improve the performance. Most important changes are:

- The recirculation plenums in the ceiling were brought to the open corners of the room, with a high-low distribution for the exhaust flow rate.
- A skirt was positioned at the combined side of the T1 and T2 plenum parts. The change was proposed in order to improve the stable clean air flow near the instrument table near the feet of the patient.
- The distance between the operating team and the instrument tables was enlarged (remark that this correction is not a design correction, but should affect the working conditions of the operating theatre in use).

The latter improvement indicates the importance of assessing the total configuration for this specific design problem. The changes are summarised in Figure 7. Based on these changes additional CFD simulations have been performed. The results of these simulations are shown in Figure 8 and 9.

>> Figure 7.

>> Figure 8.

>> Figure 9.

Based on the velocity vector field for the improved configuration, a flow field is established that is more in line with the downflow field that is expected. As a result the contaminant concentration near the instrument tables is reduced. Only a small part of the table does not satisfy the requirement.

Contamination from the operating team will not contaminate the wound area. By a careful positioning of the instrument tables the contamination of these tables may be minimised. Contamination from the

periphery will not reach the wound area as well. The instrument tables are affected, but generally the contamination level remains well below the specified requirement.

4.3.2 Measurement

A summary of the measurement results is presented in Table 4. The measurements were performed for the improved configuration as was developed and investigated in the design phase applying CFD. The presented results are the steady state values. For the measurements where the source was positioned in the periphery, at one point large fluctuations were measured. This was due to the fact that the measurement location was near the source location and may have resulted in short circuiting. Based on the results in Table 4 it is concluded that the total contaminant concentration above the operating and instrument tables (point 1 to 6) is well below the target value set.

>> Table 4.

4.3.3 Comparison

A comparison of the measurement results with the design values as obtained with CFD is given in Table 5. In this case the results for both source types are summed. The comparison shows a reasonable agreement. The main conclusion is that for both cases the performance requirement was adhered to.

>> Table 5.

Nevertheless, some difference are apparent. Most important difference is that at the operating and instrument tables contamination levels are measured that are larger than 1 CFU/m^3 . This difference is due to the fact that, because of the lay-out of the air handling unit, short-circuiting was possible. Additional particle measurements near the ceiling and at the operating table have indicated that zero particles are supplied into the room and that the contamination level remains negligible at the operating table, despite the presence of a particle source in the periphery. Therefore, the measurement results may be corrected for this.

Furthermore, comparison of the contamination levels in the periphery in an absolute sense is difficult, due to the fact that the source modelling was different, in combination with the difference in supply flow

rate and pressure hierarchy. The agreement of the average distribution over the periphery, in order of magnitude, nevertheless is reasonable.

5. Discussion Assessment methodology

The results indicate that the assessment methodology as developed and applied to the case study is functioning. I.e. for the innovative downflow plenum the performance could be assessed objectively in the design and use phase. It allowed for an objective design improvement and in both phases it was concluded that the inovative plenum can perform as required. Nevertheless, there are several remarks that can be made which may form a reference for further research.

Specifically for the operating theatre, an important aspect of the configuration that is to be investigated is that it should include the content of the operating theatre, i.e. personnel, patient, tables and equipment. This was already known from earlier work, such as [9]. It forms an integral part of the flow field that will develop and which performance is assessed. In principle the configuration is free and should be decided upon in consultation with the future users of the room, in order to agree to their standard working procedures. The results presented also indicate that the working procedure, i.e. position with respect to the instrument tables, may impede the optimal functioning of a system. An important remark is made with respect to the stationary (or ‘averaged’) situation that is investigated. One might assume that in the assessment different configurations should be investigated, e.g. where the physician has a different position with respect to the supply direction and the wound. Time weighting can be used in order to arrive at a weighted average contamination concentration. Naturally, such an approach is much more difficult to assess in an in-situ experimental situation and may compete with the practical applicability of the performance based approach. The same accounts for bringing in person movement [27].

In addition to the configuration, important considerations should be given to the applied sources and boundary conditions. Partly these result from the design plan. With respect to the contamination, sources have to be defined. This definition comprises the contaminant rate, the position where the contaminant is released and the type of contaminant. In this study, the contamination was assumed as a passive scalar (gas). Remark that this differs from the contaminant modelling as described in, e.g., [4]. Contaminant particles in operating theatres can have significantly larger diameters than 10 microns (μm) [19]. For these particles the passive scalar assumption does not hold as is shown in Table 3. In that case however

the position of release will become more important, as these larger particles will not follow the flow field present and the Lagrange approach will be required. This assumption would also require an adapted measurement approach where particles of similar size should be applied. Furthermore, the agreement in geometrical details in that case may become more important.

The applied CFD-technique shows to be capable for use in the design phase. Earlier research supports this. Consideration may be given to the type of turbulence model used. The standard k- ϵ model has been applied in this study and part of the other studies referenced. Little experimental data yet is available to support the use of other turbulence models. In [28] the effect of two different turbulence models towards the contaminant distribution in an operating theatre is compared. Based on the found differences it is concluded that the simpler turbulence model is valid. Actual comparison towards a specific performance indicator as assumed here was not performed, but the principle indicates that high level modeling may not provide other (integrated) answers. This certainly holds when other important parameters and boundary conditions are neglected or not well taken into account [27]. Generally an optimum will have to be searched for.

The presented experimental in-situ assessment for the case study indicated that parts of the design assessment were less straightforward translated to an in-situ assessment. Main difficulties were found in the source modelling for the periphery. Nevertheless, the approach chosen does represent reality more close than by modelling individual persons, assuming that the design evaluation is for an ‘averaged’ situation. The application of recirculation hampers the straightforward application of the tracer gas technique. Nevertheless, the air handling unit normally will be able to function at 100% outdoor air. Application of particles would overcome this problem as generally HEPA filters are used, allowing the recirculated particles to be filtered out. Considerations with respect to the particle size and source location already are indicated above.

The developed measurement methodology differs from the parallel developed approach described by [12]. This approach has most agreement with the intentions of this work. Major differences however are found in the source location and the type of contaminant source that is applied. VDI also assumes two source locations, one to investigate the protection from sources from the operating team within the downflow area, and one with respect to sources at the outer part of the downflow area. The lay-out is focussed on a large downflow plenum and a standard configuration. The here developed approach intends a more strict distinction between in- and outside the supply area. Furthermore, in VDI 2167 the sources all

are assumed to be positioned on the ground and are not combined with, e.g. the operating team. Finally, as contaminant source particles are used. In the draft version of [12] however no particle diameter is mentioned.

6. Conclusions

This paper wants to advocate the application of the performance based approach to arrive at improved and more functional buildings. It does so by describing the development of a performance assessment methodology for the assessment of the efficiency of a ventilation system in an operating theatre. This assessment should be performed in the design and use phase to adhere to the performance based approach definition. The developed methodology was tested in a case study with an innovative downflow plenum that is designed for an operating theatre. Testing was possible in the design phase and in the actually built situation. The assessment methodology in principle is generally applicable for operating theatres. Nevertheless, the case study has indicated several points for further research.

The performance assessment for this case study was focussed on the contamination concentration (expressed in CFU/m³). However, the assessment can be extended to other performance requirements, such as thermal comfort, hypothermia, etc. The hypothesis is that if the performance assessment for a room is performed in such an objective manner, based on performance requirements that are of direct interest (i.e. the contamination concentration in CFU/m³ has a direct relation with the surgical site infection rate), that the actual design result is more in line with client expectations. In addition the actually built result can be assessed accordingly. Currently, the assessment in practise has mainly been focussed on the boundary conditions and therefore generally prescribed solutions. The performance based approach does allow for innovative designs to be assessed and eventually applied.

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Appendix A

Additional geometry information with respect to the investigated configuration can be found in Table A-1.

>> Table A-1.

Figures as appear in Manuscript:

A performance based assessment methodology for the evaluation of ventilation strategies for operating theatres

MGLC Loomans, W van Houdt, AD Lemaire and JLM Hensen

Figure 1. Top view of the lay-out of the 3T plenum (temperature plane $T1 < T2 < T3$).

Figure 2. Investigated configuration of the operating theatre (6.0×7.7×3.1 m).

Figure 3. Impression of the investigated operating theatre.

Figure 4. Overview of measurement points for tracer gas (top view).

Figure 5. Front view of velocity vector field at $z = 4.5$ m.

Figure 6. Contaminant contour field (internal sources and sources in the periphery combined) at $y = 0.95$ m (left) and $y = 1.25$ m (right).

Figure 7. Improved design and assessment configuration.

Figure 8. Front view of velocity vector field of the improved configuration at $z = 4.5$ m.

Figure 9. Contaminant contour field (internal sources and sources in the periphery combined) improved configuration at $y = 0.95$ m (left) and $y = 1.25$ m (right).

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Figure 2. Investigated configuration of the operating theatre (6.0×7.7×3.1 m).

Figure 3. Impression of the investigated operating theatre.

Measurement point	Height
1 to 6	0.05 m above the table
7 to 12	0.95 m

Figure 4. Overview of measurement points for tracer gas (top view).

Figure 5. Front view of velocity vector field at $z = 4.5$ m.

Figure 6. Contaminant contour field (internal sources and sources in the periphery combined) at $y = 0.95$ m (left) and $y = 1.25$ m (right).

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Tables as appear in Manuscript:

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Table 1. Sources

Table 2. A. Supply Conditions; B. Exhaust, Recirculation Conditions

Table 3. Normalized Concentration in the Exhaust and Averaged in the Room for Three Particle Diameters

Table 4. Overview of the Measured Values for Contamination Concentration at the Indicated Measurement Points (See Figure 4) for the Improved Configuration

Table 5. Overview of the Measured And Calculated Values for Contamination Concentration at the Indicated Measurement Points (See Figure 4)

Table A-1. Geometry information

Table 1. Sources

	Heat source (total; W)	convective ¹ (-)	Contaminant source (CFU/min)
Surgeon	160	0.6	200 CFU/min
operating team (3 persons near table)	123	0.6	200 CFU/min
operating team (1 persons in the periphery)	123	0.6	-
Anesthetist	86	0.6	-
operating team (4 persons periphery)	-	-	500 CFU/min
Patient	86	0.6	-
Equipment	400	1.0	-
Lamp	200	0.75	-

¹ For the CFD simulations, the radiant part is assumed to be transferred evenly to the walls.

Table 2. A. Supply Conditions

plenum	Volume flow rate (m ³ /h)	Temperature (°C)
T1 central	1200	19.3
T2 side (2×)	2×1300	20.0
T3 additional	1200	20.7
total	5000	

B. Exhaust, Recirculation Conditions

exhaust- / recirculation grille	Volume flow rate (m ³ /h)
recirculation ceiling (2×)	2×1300
exhaust low (2×)	2×515
exhaust high (2×)	2×260
overflow ceiling	850
Total	5000

Table 3. Normalized Concentration in the Exhaust and Averaged in the Room for Three Particle Diameters

Particle diameter, microns (μm)	in the exhaust Murakami et al. (1992) (-)	Passive Scalar (-)	Euler (-)	Lagrange (-)
0	1.0	1.0	1.0	1.0
10	0.91	1.0	0.93	0.96
50	0.11	1.0	0.11	0.14
in the room				
0	1.70	1.59	1.59	1.72
10	1.59	1.59	1.51	1.62
50	0.52	1.59	0.58	0.66

Table 4. Overview of the Measured Values for Contamination Concentration at the Indicated Measurement Points (See Figure 4) for the Improved Configuration

source: operating team,				source: periphery,			
Point	CFU/m ³	Point	CFU/m ³	Point	CFU/m ³	point	CFU/m ³
1	0.6	7	15	1	1.4	7	2.5
2	0.6	8	5	2	1.5	8	7.6
3	0.5	9	1	3	1.3	9	201*
4	0.6	10	1	4	1.4	10	20
5	0.6	11	5	5	1.6	11	8.9
6	0.7	12	15	6	1.5	12	26

* Large fluctuations measured (23 – 208 CFU/m³)

Table 5. Overview of the Measured And Calculated Values for Contamination Concentration at the Indicated Measurement Points (See Figure 4)

Measurement,				Simulation,			
point	CFU/m ³	point	CFU/m ³	point	CFU/m ³	point	CFU/m ³
1	2	7	17.5	1	<1	7	40
2	2.1	8	12.5	2	<1	8	30
3	1.8	9	201*	3	<1	9	50
4	2	10	20	4	<1	10	40
5	2.2	11	14	5	<1	11	25
6	2.2	12	40	6	5	12	35

* Large fluctuations measured (23 – 208 CFU/m³)

Table A-1. Geometry information

Description	Width, m	Length, m
supply ceiling		
central plenum (T1)	1.2	1.2
side plenums (T2; 2×)	1.0	1.6
additional plenum (T3)	1.2	1.2
exhaust		
exhaust (low, beveled corner; 2×)	0.4	0.4
exhaust (high, beveled corner; 2×)	0.3	0.3
overflow ceiling	1.0	1.0
design configuration (original)		
recirculation (ceiling; 2×)	0.7	1.6
design configuration (adapted)		
recirculation (low, beveled + straight corner; 2×)	0.4	0.4
recirculation (high, beveled + straight corner; 2×)	0.3	0.3
additional overflow door	0.1	0.4
operating lamp	diameter	0.7 m
instrument table (near feet)	height	1.2 m
instrument table (behind assistant; 2×)	height	0.9 m