METHOD TO ASSESS THE PERFORMANCE OF VENTILATION SYSTEMS IN DWELLINGS CONSIDERING THE INFLUENCE OF UNCERTAINTIES

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ABSTRACT

Normally, the design of a ventilation system in a dwelling is based on national regulations, related design rules, building tradition and general knowledge about healthy indoor air quality, ventilation and air handling units. In practice, the actual performance of ventilation systems is determined by ventilation components, building properties, outdoor environment and occupant behavior. Unspecified items in the design rules and uncontrollable items in the design stage will bring uncertainties which may cause the actual performance deviating from the designed performance. In this research, an assessment method considering the influence of such uncertainties is proposed and developed. First, the method for defining criteria for assessing the performance of ventilation systems in houses is described. The basic idea is that the criteria should be defined based on the national ventilation regulations. Then, the process for estimating the uncertainties in four aspects (including ventilation components, building properties, outdoor environment and occupant behavior) is introduced based on the definition of 5 main uncertainty sources. The relevant parameters in each aspect and the main uncertainty sources for each parameter are figured out. A point which may be interesting is that we propose to explore the reaction of the system performance to certain occupant behavior rather than predicting the occupant behavior pattern. Later on, the uncertainty analysis techniques including uncertainty propagation technique and sensitivity analysis technique are introduced as Monte-Carlo simulation (with Latin-hypercube sampling) and Morris factorial sampling respectively. The uncertainties in ventilation components, building properties and outdoor environment are involved in both uncertainty propagation and sensitivity analysis while the occupant behavior is only analyzed via a sensitivity analysis. A pilot case study using the described method is given afterwards. The conclusions are that there is a necessity to integrate the influence of uncertainties in the assessment of ventilation systems in houses and that the introduced method could give a useful framework and approach for such assessment.

KEYWORDS
Uncertainties, performance assessment, ventilation system

1 INTRODUCTION
A common awareness regarding ventilation is that the proper amount of air change should be maintained while unnecessary air change should be minimized. For this aim, people realized that in a house a properly designed ventilation system was required and that this needed to be regulated. In order to obtain a properly designed ventilation system, two questions have to be answered, i.e. how much air flow is required and how to realize this amount of air change by

available measures. To answer these two questions, relevant required air flow rates and design solutions have been developed in different countries, including the required *performance requirements* and *design rules* (including prescriptive design requirements and generally accepted design rules) for ventilation systems. Many different types of ventilation systems for dwellings have been designed based on the same regulations and design rules within a country. But in practice, performance deviations can be found in two aspects, i.e. the performance difference between the same type of system equipped in the same or a similar type of building and the performance deviation between the actual and designed performance. A possible explanation is that such performance deviations could be partly due to the uncertainties existing in the development process of a ventilation system in dwellings which have not been well addressed in the design rules.

Several studies were already carried out for investigating the uncertainties in building performance analysis/simulation. Macdonald (2001) [1] compared and summarized the different uncertainty analysis techniques. De Wit (2002) [2] focused on modeling uncertainties in thermal performance predictions. Wouters et al. (2004) [3] gave a rough discussion about which parameters related to the performance of ventilation systems in houses should be considered as uncertain, focusing on the uncertainties in building properties and on scenarios (mainly including climate and occupant behavior). Generally speaking, in such researches, uncertainties related to the physical properties of building and the modeling were well addressed and the analysis techniques were also well illustrated. But deficiencies also exist, which were our main initiatives for conducting the current study, including the following aspects:

- The discussion of uncertainties mainly focused on the uncertainties in physical data, modeling uncertainties and scenarios (design boundaries, including e.g. climate and occupant behavior) based on a definitively designed building or system; but the uncertainties caused by a lack of specification in the design rules have not been well discussed.
- Researches were mostly conducted under specific conditions. But in different ventilation projects, different uncertainties may emerge. A general method for defining and estimating the relevant uncertainties in the development process of ventilation systems deserves attention.
- Although the uncertainties in occupant behavior and treatment method were discussed by several researchers, predicting future occupant behavior is still difficult because it involves a stochastic process. In our current research, we propose to explore the reaction of the system’s functions to occupant behavior instead of predicting the uncertainties in the system’s performances by predicting the uncertainties in occupant behavior.

Indoor air quality is generally determined by three factors: the functions of ventilation systems, indoor emissions (materials) and occupant behavior. Different from the traditional assessment of indoor air quality, which focuses on the concentrations of indoor air pollutants, in the current research we focus on only one factor, i.e. the functions of the ventilation system. More specifically, we focus on the functions required in ventilation regulations for a ventilation system in a house. In order to give a more clear explanation of our ideas, the structure of the current research is explained in below figure 1.

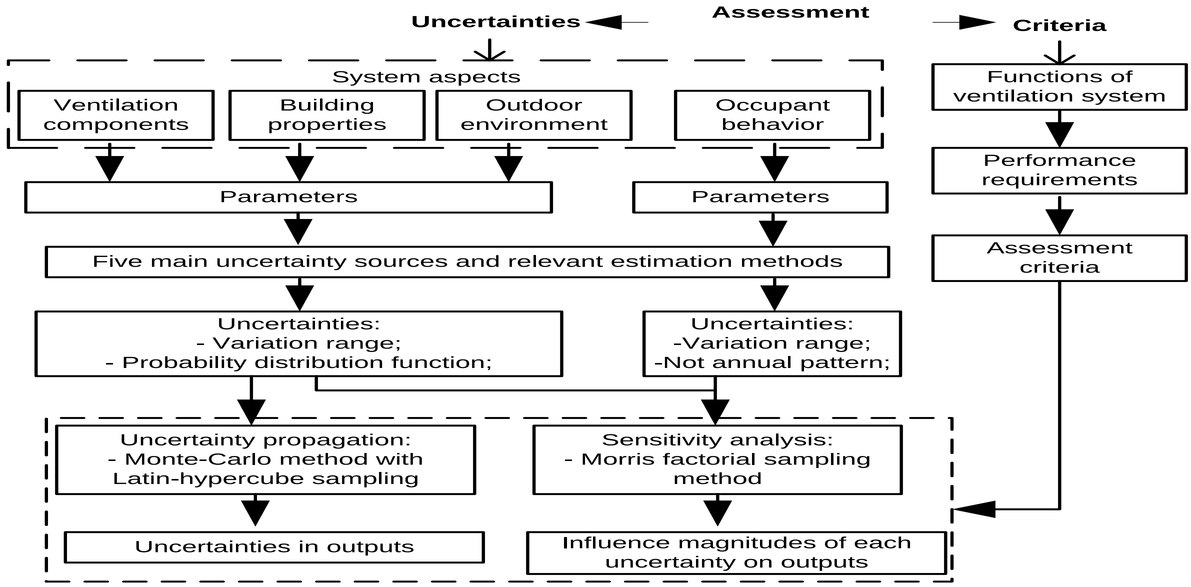


Figure 1 : Overview of the structure of the assessment method

2 ASSESSMENT CRITERIA

The required functionality or performance of a ventilation system in a dwelling is actually defined using performance criteria and required values derived from the national ventilation regulations in each country. Thus, assessment criteria and required values should also be defined based on specific national ventilation regulations. Various different performance criteria can be derived from different national regulations. A review of the ventilation regulations and standards of four countries, including Canada [4], Denmark [5], UK [6] and the Netherlands [7] was carried out to figure out the key criteria and aspects to be used generally for expressing the required performance of ventilation systems in houses. Consequently, the most relevant criteria to be considered in the current method are summarized with short description as:

- Minimum ventilation capacity;
- Air flow direction;
- And Controllability.

2.1 Minimum ventilation capacity

Ventilation capacity includes exhaust capacity and supply capacity. The corresponding criteria should be defined for both aspects based on local or national regulations. Defining criteria for minimum exhaust capacity is simple because they mostly can be straightforwardly derived from the relevant ventilation regulations. In ventilation regulations, such criteria are normally specified based on room type, and/ or room volume or space.

Criteria for minimum capacity should be divided into room/ space level and whole house level. Furthermore, four types of air flow elements could be considered as supply air, i.e. air flow from designed openings or grilles, infiltration from cracks, overflow from internal rooms, and recirculation flow. In different ventilation regulations, there are different considerations of the contribution of each of these air flow elements to the indoor air quality. For defining criteria, such contributions should be considered based on the relevant ventilation regulations and the researcher‘s interests.

Although normally not specified in regulations, the total designed exhaust rate and supply rate should be equal to each other. Besides, the whole house exhaust rate or supply rate should not be less than the higher value of the required minimum total exhaust and supply rate.

2.2 Air flow direction

Not every ventilation regulation defines the air flow direction as a performance criterion, but the importance of avoiding unwanted ventilation directions is obvious. Generally speaking, among the regulations in different countries, the unwanted air flow directions can be summarized into the following parts:

- Air flow from polluted/ wet rooms to habitable space;
- Air flow from combustion appliance or chimney into the habitable space;
- Back flow crossing the exhaust ducts/ grilles;
- Reverse air flow crossing the facade air inlets/ outlets (not for cross or single-sided natural ventilation systems).

2.3 Individual controllability

Individual controllability is typically not defined in ventilation regulations and is an indicator proposed by us. The employment of individual controllability is to describe the reactions of the performance of a ventilation system to certain individual occupant behavior. The following aspects are considered:

- The influence on the air flow in other rooms by a change in the position of the air inlet in one room;
- The influence on the air flow in other rooms by a change in the position of window openings in one room;
- The influence of a change in the position of internal doors on the overall air flow in the house.

If the individual behavior of an occupant could strongly affect the system performance, for example strongly reduce the supply air flow in other rooms, certain measures may be required to deal with such effects.

3 UNCERTAINTIES

The ventilation performance not only depends on ventilation components but also on other external factors. In each of these factors, uncertainties could be produced. We generally consider the uncertainties in the following aspects:

- Ventilation components;
- Building properties;
- Outdoor environment;
- Occupant behavior.

For identifying the uncertainties in such aspects, five uncertainty sources are defined. For an uncertainty analysis, certain information of each uncertainty may be required, including the variation range and probability distribution. The description of these five uncertainty sources and proposed estimation methods for each of them is given below:

- Specification uncertainty;
- Design alternative;
- Production deviation;
- Modeling uncertainty;
- Stochastic process.

Specification uncertainty means that not all relevant parameters which are needed as inputs for an assessment process or calculation model are specified in the design or required in the design rules. For example, in the selection of a fan, only the working point is considered but not the whole fan curve which also influences the practical performance of the fan. This uncertainty source is related to the lack of specification in design rules. To estimate this specification uncertainty, it is first important to know which parameters are not specified and then to ascertain the variation ranges of the values of such parameters. The most straightforward way is to use measurement data of such unspecified parameters.

Design alternative is the design choice which the designer has without conflicting with the design rules. For example, only the minimum requirements on the designed air flows are defined, meaning the designer could use the values higher than the minimum values. For the designer; if the designer has no preferred design choice yet and wants to know the influence of different design choices, the design alternative could be an uncertainty source. This type of uncertainty can also be considered as a kind of lack of specification in the design rules, but is different from specification uncertainty. The variation range should be estimated or defined based on the possible alternatives resulting from the design rules. For example, the air tightness level is specified; the designer may have alternatives from a high air tightness level to a medium air tightness level.

Production (construction) deviation is the difference between the practical properties of the products with the nominal/ theoretical properties of the products caused by the realization process. The reasons can be summarized as two aspects: nominally identical products that are produced or constructed by different machines or workers, and the random error that the same process may result in different results. In practice, it is difficult to completely separate these two aspects. Anyway, such uncertainties could be reflected in measurement data. Estimations are best made directly through measurement. For example, for a certain type of construction, like a window, the air leakage value could vary in a certain range. If measurement data is missing, estimation may be made based on the requirements in relevant standards and assumptions.

Modeling uncertainty involves the employment of various models to represent reality. Models are developed usually with simplifications and approximations. Arbitrarily speaking, no one model can 100% represent the reality. During the assessment of a ventilation system, many inputs not measurable are derived from models. In [2], the methods for estimating modeling uncertainty were discussed and proposed to be used. For a rough estimation, the scatter between different models could be used. If more a strict estimation is required, costly methods like expert judgment, experiments and measurements may be needed.

Stochastic process is related to the factors which actually require prediction, including e.g. future climate, occupancy and occupant behavior. Such stochastic process factors are normally assumed to be certain default values or profiles in the design. Therefore, uncertainties are introduced. Different treatments for climate and occupant behavior are used. For climate, we recommend to used different typical patterns of annual weather data to represent the climate variations; for example, typical average weather year, typical hot year and typical cold year. Except the indoor heating temperature, the other defined occupant behaviors are treated as part of a sensitivity analysis which only requires the variation range of the parameters but not the whole annual behavior pattern.

The relevant parameters, uncertainties, dominant uncertainty sources and proposed estimation methods are summarized in table 2. The list in table 2 is considered to cover most of the uncertainties but is not exhaustive.

Parameters	Main uncertainty sources	Possible estimation methods
Ventilation components		
Geometry properties	Design alternatives; Production deviation;	Specified probable variations in design rules; Estimation from measurement data;
Flow coefficients & Flow exponents	Production deviation; Modeling uncertainties	Measurement or products data; Measurement data and interactions;
Duct leakage	Specification uncertainty; Production deviation;	Probable duct type or airtight levels; Measurement data;
Exhaust/supply grilles	Construction deviation;	Accuracy requirements on fittings; Measurement data;
Heat recovery efficiency	Production deviation;	Product information and measurement data;
Internal leakage	Production deviation;	Product information and measurement data;
Building properties		
Building direction	Specification uncertainty;	Probable directions and design limitations;
Building air tightness	Specification uncertainty; Construction deviation	Specified air tightness level; Measurement data.
Outdoor environment		
Climate data	Specification uncertainty; Stochastic process;	Probable climate regions; Using different typical weather data;
wind reduction factor	Modeling uncertainty	Estimation from calculation models; Expert judgment;
Wind pressure coefficients	Modeling uncertainty	Estimation from calculation models; Expert judgment;
wind direction	Modeling uncertainty	Estimation between different climate data; Expert suggestions;
Local temperature	Modeling uncertainty	Estimation from literature or data;
Occupant behavior		
Indoor setting temperature	Specification uncertainty	Estimation from survey data;
Control of air inlet	Stochastic process	Variation range of the position of air inlets;
Control of windows	Stochastic process	Variation range of the position of windows;
Control of doors	Stochastic process	Variation range of the position of doors;

(Note: Assumption is always a possible estimation method when other methods are not available.)

Table 2: parameters, uncertainties, dominant uncertainty sources and relevant estimation methods

4. ANALYSIS TECHNIQUES

4.1 Basic uncertainty quantification techniques

With uncertainty quantification studies, there are generally two different analysis purposes, i.e. quantification of the uncertainties in output results from uncertainties in inputs, and figuring out the individual influence or importance of each uncertainty on the outputs. The respective analysis techniques can be generally categorized as uncertainty propagation and sensitivity analysis.

For uncertainty propagation, there exist many techniques including a black box technique (Monte-Carlo method), a statistical method (Factorial regressions), and an internal method (integrating uncertainties into the model equations). Among such techniques, we propose the Monte-Carlo method with Latin-hypercube sampling to be used for uncertainty propagation. The main reason for this selection is that the Monte-Carlo method does not require particular knowledge of statistics and is suitable for calculations with complex models or software packages. Latin-hypercube sampling is a kind of improved stratified sampling method which divides each of the parameters into N disjoint intervals with equal probability mass. This technique could provide a good coverage of the parameter samples space with relatively small number of samples compared to random sampling. More detailed information about the Latin-hypercube sampling method can be found in Mckay et al. (1979) [8].

Sensitivity analysis can be divided in different levels, from addressing the important or influential parameters to addressing the interaction between parameters and the quadratic influence of a single parameter. For uncertainty quantification studies in engineering, normally a parameter screening process will be carried out first to address the influential parameters from a large set of parameters. For parameter screening, the Morris factorial sampling method is recommended to be used. The Morris method indicates which factors are important, and also gives information on the directions of the main effects and on the severity of these interactions or nonlinear effects. A more detailed introduction into the Morris sampling method can be found in [9].

4.2 Treatment of occupant behavior

Above, we have stated that the research is not going to predict the whole occupant behavior pattern during the usage stage but is going to explore the reaction of the system's performance to certain occupant behavior, as we defined the criteria of individual controllability. For the parameters related to occupant behavior we defined in section 3 that the variation ranges are all considered as (0, 1). A parameter screening analysis (sensitivity analysis) among such parameters is proposed to be carried out. Then the main influence on the performance and the interaction among such parameters can be estimated.

5. PILOT CASE STUDY

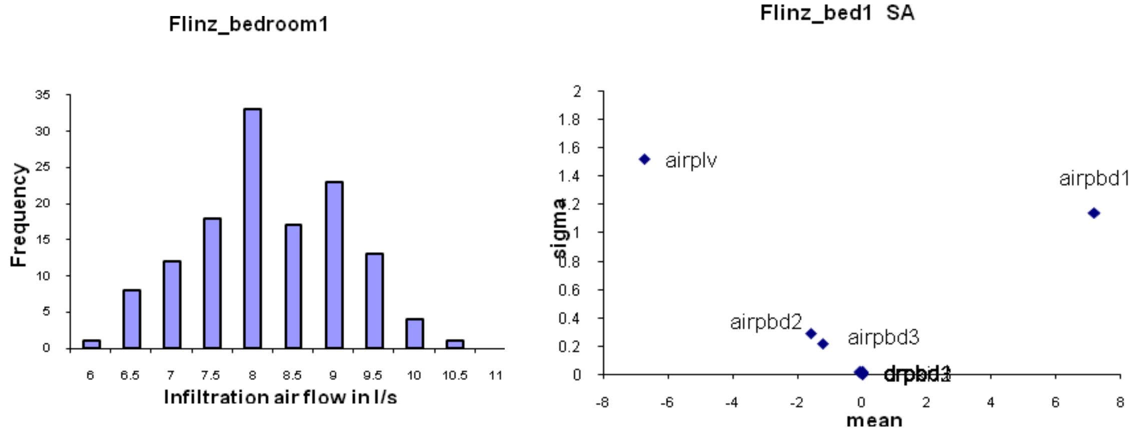
A pilot case study is carried out to show the application of above described assessment method. The case dwelling is assumed to be located in Delft in the Netherlands, identical to the reference Dutch single family house from Agentschap NL (Tussenwoning) which can be found in [10]. The ventilation system equipped in this reference house uses a central mechanical exhaust and natural supply of air (standard Dutch system C). The process of the assessment is described below.

Identification of assessment criteria. According to the Bouwbesluit 2003 (Dutch regulation), relevant assessment criteria are (for air flow rate, expressed in dm^3/s): the room exhaust rates for kitchen, bathroom and toilet, room supply air for living room and bedroom 1, 2, 3, whole house supply rate (we consider two conditions: with infiltration and without infiltration) and unwanted air flow direction, including the air flow from bathroom and toilet room to habitable space.

Estimation of uncertainties. The uncertainties estimated are related to the following components or parameters: facade air inlets, overflow components, positions of exhaust grilles, building air tightness, wind pressure coefficient, wind reduction factor and use of air inlets and internal doors.

Calculation process. Calculations are based on the model built in the simulation tool TRNFLOW (a combination of TRNSYS and COMIS). A whole year simulation is carried out, while the typical annual climate data for De Bilt is used. 130 runs were executed for uncertainty propagation of 26 parameters (the probability distribution of each parameter is divided into 130 non-overlapping intervals with equal probability mass and then each interval is sampled once) and 148 runs were executed for parameter screening among 35 parameters (each parameter is sampled 4 values; use of air inlets and internal doors are calculated separately from the other three aspects).

Results. Part of the results is shown in figure 2. The value in figure 2a is annually averaged hourly flow rate for bedroom1 (main bedroom), including ventilation and infiltration (when all air inlets are fully opened) which is even below the designed pure supply value 14.7 dm3/s (without infiltration). Figure 2b shows that the ventilation and infiltration rate of bedroom1 is actually highly determined by the position of the air inlet in the living room. This means the individual controllability of the air inlet in the living room is limited. Other results can be displayed in the same forms as shown in figure 2 a/b.



(Note: "airplv" and "airbd1" mean the positions of facade grille in living room and in bedroom1 respectively.)
Figure 2 a/b. Uncertainties in total ventilation in bedroom1 and influential factors

6. CONCLUSION

In this article, we introduced an assessment method of ventilation systems in dwellings considering the influence of uncertainties. The core objective of the method is to explore the performance of ventilation systems in houses expressed by performance criteria defined in ventilation regulations with considering the uncertainties in 4 categories (ventilation components, building properties, outdoor environment and occupant behavior). The relevant methods for defining criteria and estimating uncertainties are given. The pilot case study shows that uncertainties could have significant influence on the performance of ventilation systems in houses and the method described could give a useful framework and routine for carrying out such analysis.

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