APPLICATION OF STATISTICAL EXPERIMENTAL DESIGN FOR PARAMETRIC SIMULATION STUDIES IN BUILDING PHYSICS, WITH AN EMPHASIS ON INDOOR AIR

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ABSTRACT

Parametric studies have often been used for sensitivity analyses in the field of the pharmaceutical and agricultural sector. All such studies aims at bringing some kind of order out of complicated relationships between influencing factors and some response parameter(s). With experimental designs and statistical analysis methods, it is possible to trace and quantify influences of individual as well as combinations of input factors on the response parameter. This procedure has so far very seldom been used within the building sector. The paper describes an example within the area of indoor air quality, where a statistical experimental design procedure has been used. The purpose of the example was to analyse the fraction of time of the total heating season when the outdoor air ventilation flow rate was ≥ 4 litres/(s·person) in bedrooms. Four different ventilation systems were examined and seven parameters were chosen, suspected to influence the air flow rate. This kind of investigation calls for a large number of runs. In order to cover all combinations 4000 simulations have to be performed. With statistical experimental design and analysis methods the procedure can been reduced to 400 runs without significant loss in the quality of the results!

INTRODUCTION

Parametric studies are often used for sensitivity analyses. All such studies aims at bringing some kind of order out of complicated relationships between influencing factors and some response parameter(s). Fields of interest for such studies in indoor air quality and related areas include both experimental and computer simulation parametric studies. An example from the experimental field could be the problem of estimating drying-out conditions for concrete, influenced by a number of factors with different numerical values. Parametric studies by means of computer simulations can e.g. be performed within the area of indoor air quality, whereas the influences of a large number of parameters on the indoor air quality can be traced.

Unfortunately however, hitherto such studies have normally been performed in an unsophisticated way by building researchers. The normal procedure has been to establish some kind of base case value for each influencing parameter, and by keeping the value of all parameters but one at this base case level and changing the value of one parameter at a time, it is expected to be possible to see the relative importance of different parameters on some response parameters.

From a scientific point of view this approach makes little or no sense, since in "the real world", all different parameters can - and will - take different values, a number of them apart from the "base case" value, simultaneously. Correct planning of such experiments means that the values of all the input parameters must be changed in a systematic way, not only one parameter at a time. By means of correct experimental designs and statistical analysis methods, it is possible to trace and quantify influences of individual input parameters, as well as combinations of them, on the response parameters. Methods for planning large experimental studies to be performed in an efficient way with a minimum of number of experiments and known levels of uncertainty, have already been used for more than fifty years by now, in a lot of areas e.g. pharmacology and agricultural sciences. Only few correctly designed experiments with statistical evaluation have been performed within the building research area, e.g. [1] and [2].

This paper describes an example within the area of indoor air quality, where statistical experimental design and statistical analysis methods has been applied.

METHOD

Within the IEA Annex 27 project "Evaluation and Demonstration of Domestic Ventilation System", an indoor air quality study was performed. One of the purposes of the study was to analyse the *fraction of time of the total heating season when the outdoor air ventilation flow rate is ≥ 4 litres/(s·person) in bedrooms (As an average value for three bedrooms).* The target (the air flow rate) represents an internationally commonly used figure.

Four different types of ventilation systems were included: natural ventilation by window airing, natural ventilation by passive stack, mechanical exhaust ventilation, and finally, mechanical supply and exhaust ventilation.

Seven parameters were chosen, suspected to influence the air flow rate. These were:

1. Climatic conditions
2. Type of dwelling
3. Air tightness of the building envelope
4. Window airing patterns
5. Outdoor air supply devices (for natural and mechanical exhaust ventilation)
6. Central fan flow rate (for mechanical ventilation)
7. Local fans in kitchen and bathroom

The simulations of the air flow rates to individual rooms have been performed by means of a multi-zone air flow and ventilation computer model called COMIS [3].

Assumptions for the work are presented in [4]. The computer simulations have been performed by professor H Yoshino from Building Research Institute of Japan.

In order to perform the simulations with seven parameters and four ventilation systems, many runs would have to be performed. A "false" parameter study would vary one parameter per run, e.g. keep one value of all parameters but one at a base case level and changing the value of one parameter at a time. However, what happens if two parameters are changed at the same time to an extreme point in different directions, or if two parameters have a synergy effect?

Probably no answer can be given. Therefore, in order to cover all combinations, $3^5 \cdot 2^2 \cdot 4 =$ 3888 runs have to be performed.

Obviously, it is impossible or time-consuming to handle all combinations. A reduction of runs to a manageable experiment would be very convenient. This may be achieved by using a scientifically based experimental design and a statistical evaluation method. In this work the number of runs can then be reduced to $3^{5-2} \cdot 2^2 \cdot 4 = 432$ runs!

The number of runs or how much the number may be reduced depends on the goal of the investigation and the goodness of the model, based upon the factors and the responses.

The factors in the experimental design have been investigated with a linear and an interactive method, in order to determine the relationship (antagonism or synergy) between the factors. The responses have been analysed with partial least square method, since the work contained three responses (the air flow rate in three bedrooms). Another method is the least squares regression method, which e.g. fits *one* response at a time and hence assumes the factors to be independent.

The statistical analysis was performed by a computer program called MODDE [5], which stands for *mod*elling and *de*sign. It is a PC-Windows program, used for the generation and evaluation of statistical experimental designs.

In Table 1 the ranges of the selected factors, that were assumed to have an influence on the air flow rate, are presented. The assumptions for the ranges are also presented in [4].

Table 1. Influencing factors assumed, for computational simulations in an experimental design, for studying the fraction of time of the total heating season when the outdoor air ventilation flow rate is ≥ 4 litres/(s·person).

Factors	Ranges
Climatic conditions	Nice, London and Ottawa (warm, mild and cold climate)
Type of dwelling	detached house, ground and top floor dwelling
Air tightness of the building envelope	1, 2.5 and 5 *or* 2.5, 5 and 10 air change rate/h at 50 Pa differential pressure
Window airing patterns	no window airing or patterns determined by means of the outdoor climate: temperature and wind speed
Outdoor air supply devices (for natural and mechanical exhaust ventilation)	0, 100 and 400 cm²
Central fan flow rate (for mechanical ventilation)	15, 30 and 45 litres/s
Local fans in kitchen and bathroom	0-100 litres/s and 0-25 litres/s respectively

RESULTS

The results indicated that a dwelling with passive stack ventilation system has an outdoor air ventilation flow rate of ≥ 4 litres/(s·person) approximately 10-40 percent of the heating season, depending on what level/floor the apartment is situated on, see Table 2. In addition, the larger the outdoor air supply devices are the higher the air flow rate is.

A dwelling with mechanical exhaust air ventilation system and has an air flow rate ≥ 4 litres/(s·person) approximately 20-50 percent of the heating season; and, a dwelling with balanced mechanical ventilation system approximately 50-70 percent of the heating season. Thus, the type of ventilation system has a large influence on the fraction of time of the total heating season when the outdoor air ventilation flow rate is ≥ 4 litres/(s·person).

Finally, no apartment had an outdoor air ventilation flow rate of ≥ 4 litres/(s·person) during 100 percent of the heating season. The highest fraction of time when the air flow rate is ≥ 4 litres/(s·person) is for the case when having a balance mechanical ventilation system with local fans in kitchen and bathroom. This case gives ≥ 4 litres/(s·person) in bedrooms approx. 70 percent of the time.

Table 2. The table presents the *fraction of time (percent) of the total heating season* when the outdoor air ventilation flow rate is ≥ 4 litres/(s·person) in bedrooms. The table shows only a minor part of the original and entire table. The complete results are presented in [7].

		Passive stack		Mechanical exhaust air		Balanced mechanical ventilation	
	Outdoor air supply devices (cm^2)	100	400	100		-	
	Central fan flow rate (litres/s)	-		45		30	
	Local fans in kitchen and bathroom (litres/s)	no	yes	no	yes	no	yes
	Air tightness ($m^3/m^2 \cdot h$) at 50 Pa differential pressure						
Top floor dwelling	1	27	38	35	36	52	56
	5	33	38	47	49	66	70
Ground floor dwelling	1	19	30	26	28	52	57
	5	25	30	34	36	66	71
Detached house	2.5	11	22	18	20	53	57
	10	17	22	21	22	67	71

DISCUSSION

Experimental design is used to guide and plan experiments in order to extract the maximum amount of information from the collected data in the fewest number of experimental runs. The purpose is to vary relevant factors simultaneously over a set of experiments and then connect the results by means of a mathematical model. The model is then used for interpretation, predictions and optimisation.

The paper described an example within the area of indoor air quality where a statistical experimental design procedure has been used. The presented example would normally call for a large set of runs, but with the statistical experimental design and analysis method the procedure had been reduced from approx. 4000 to 400 runs, without significant loss in the quality of the results!

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