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Empiricism in the Thermal Analysis of Naturally Ventilated Buildings

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Three thermal analysis methods with different degrees of empiricism are quantitatively investigated regarding the ease of use, efficiency, accuracy and redundancy of generated information. From this investigation it is concluded that, for design purposes, a sensitive interplay between experiment and theory can often lead to an optimum method.

NOMENCLATURE

ΣA total area of building's exposed shell [m^2]
ΣC total active thermal capacity of building per unit exposed shell area [kJ °C^{-1} m^{-2}]
q heat generation [W]
R_s thermal resistance of shell [°C m^2 W^{-1}]
T temperature [°C]
$TTTC$ total thermal time constant [hr]
t time of day [hr]

Greek symbols
α phase shift between forcing function and response [rad]
β phase angle of heat generation [rad]
Δ increment
ϕ phase angle of outdoor forcing temperature [rad]

Subscripts
ff forcing function
i indoor air
o outdoor air
sum summer
wint winter

Notation
$\tilde{}$ alternating part of alternating variable
$\bar{}$ mean part of alternating variable
$|\,|$ amplitude of alternating variable

1. INTRODUCTION

WITH THE advent of more computing power more complex thermal analyses of buildings are done. There is a growing tendency to eliminate the need for empiricism in the simulation procedures. The question is however, how successful are these theoretically based simulation procedures? How accurate, for example, can the modelling technique model natural ventilation, or are empirical data on natural ventilation flow rates needed in the prediction process? Are these methods efficient?

Excellent papers on the appropriate formulation of building environmental prediction models were published by Lord and Wilson [1, 2]. They discuss, in general terms, different aspects of prediction models, e.g. what level of empiricism is acceptable, what level of detail is necessary, is redundant information generated, ease of use and other important aspects. It is the purpose of this paper to investigate quantitatively the above-mentioned aspects for three different thermal analysis procedures, each with a different level of empiricism.

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2. BASIC OUTLINE OF THE THREE METHODS

2.1 *Empirical method*

The empirical method is described in more detail than the other methods in this paper, as information on this method is not readily available in the open literature. The method [3] is based on temperature measurements in more than 30 naturally ventilated buildings, ranging from low cost houses to hospitals and office buildings. The method can predict the maximum and minimum indoor air temperatures in a building. Data of the building construction as well as of the design outdoor air temperatures for a specific location are needed as input to the method.

The empirical equations for the method were derived from indoor air temperature measurements in naturally ventilated buildings, where direct sun penetration in summer was prevented. The method approximates the daily variation of outdoor and indoor air temperatures as sine waves. It is then possible to plot the measured ratios of the indoor and outdoor air temperature amplitudes as a function of the calculated total thermal time constants ($TTTC$) for different buildings. From this data an empirical equation for amplitude ratio can be written as follows [3]:

$$\frac{|\tilde{T}_i|}{|\tilde{T}_o|} = 49\, R_s (TTTC)^{-0.9} \qquad (1)$$

where $|\tilde{T}_o|$, the amplitude of the outdoor air temperature is known from design weather data and where the total thermal time constant ($TTTC$) and the shell resistance (R_s) for the building or design room can be calculated from design plans [3]. The empirical constant of 49 in equation (1) accounts for the fact that the real forcing temperature acting through the building shell is the sol-air and not the outdoor air temperature. As the amplitude of the sol-air temperature is larger than the amplitude of the outdoor air temperature, the constant of 49 is larger than would be the case if the sol-air temperature was used as the outdoor forcing temperature [4].

Empirical data [3] were used to derive the equation for the mean indoor air temperature. The equation for the mean indoor air temperature $\bar{T}_i$ is given by

$$\overline{T_i} = \overline{T_o} + \overline{\Delta T} \quad (2)$$

where $\overline{T_o}$ is the mean outdoor air temperature which is available from design weather data. The difference $\overline{\Delta T}$ between the mean indoor and outdoor air temperatures differs between summer and winter and is given by the following empirical equations [5]:

$$\left.\begin{aligned} \overline{\Delta T}_{\text{sum}} &= 2°\text{C} \\ \overline{\Delta T}_{\text{wint}} &= -40{,}4(SR)^4 + 89{,}7(SR)^3 \\ &\quad -85{,}3(SR)^2 + 45{,}6(SR) - 2{,}2 \end{aligned}\right\} \quad (3)$$

where SR is a function of the amount of direct solar penetration into the room [3].

The values of the mean indoor air temperatures were generally found to be higher than the mean values of the outdoor air temperatures. The empirical equations therefore partly account for the fact that the generally higher mean sol-air and not the lower mean outdoor air temperature is the mean forcing temperature for heat flow through the building shell [4].

The empirical method cannot predict the effect of exterior surface colour, internal heat generation or the time when the minimum and maximum temperatures are reached. As it is not theoretically based, it is difficult to extend this method to include these effects. The main advantages of this method are however its ease of application as well as the fact that the effect of typical rates of natural ventilation in conventional buildings is included in the empirical equations.

2.2 *Semi-empirical method*

A semi-empirical method was developed to alleviate the limitations of the empirical method. This method has all the advantages of the empirical method. It however has the added advantage that it is primarily based on theory and can therefore easily be extended to include special thermal effects. The method is derived from a simplified electrical analogue as well as measurements. The derivation of the relevant equations was described in detail in a previous article [6]. Only the final equation for indoor air temperature is given in this paper. By making the assumption that the forcing temperature T_{ff} as well as the heat generation term q can be simulated by first frequency sine curves, the following equation for the indoor air temperature T_i can be written for the semi-empirical method [6]:

$$\begin{aligned} T_i = {} & \frac{0.091\,\bar{q}}{\Sigma A} + \bar{T}_{ff} \\ & + \frac{75\,|\tilde{T}_{ff}|}{\Sigma C} \sin\left[\frac{2\pi}{24}t - \phi - \arctan\frac{\Sigma C}{150}\right] \\ & + \frac{6{,}8\,|\tilde{q}|}{\Sigma C \Sigma A} \sin\left[\frac{2\pi}{24}t - \beta - \arctan\frac{\Sigma C}{150}\right]. \end{aligned} \quad (4)$$

If more than one frequency components are necessary for the forcing temperature or for the heat generation term, equation (4) can be extended to include such effects [5]. Another possibility is to solve the electrical analogue numerically. The semi-empirical method is easy to use and ideal for the thermal analysis of naturally ventilated conventional buildings. It, however has the disadvantage that it may be necessary to extend the method for some analyses.

2.3 *Theoretical method*

The DEROB building thermal simulation system is the third method that was investigated. The theory of DEROB is fairly complex and comprehensive and is described elsewhere [7, 8]. Finite difference equations, derived from the differential equation for unsteady heat flow through solids are used in the solution procedure. A Gauss iteration scheme is used to solve the relevant equations iteratively. A great deal of input data is needed for a thermal simulation, and a vast amount of data is generated as output. This method is therefore very versatile and should thus be suitable for research work and for the thermal design of non-conventional buildings.

3. PERFORMANCE OF METHODS

The quantitative performance of the three methods will be expressed in non-dimensionalised units, making it to some extent applicable to cases other than the ones that were investigated. It is however realised that the non-dimensionalised performances may vary slightly for different applications.

3.1 *Input data*

Relatively little input data are needed for thermal simulations by the empirical and semi-empirical methods. One of the reasons is that certain data, e.g. natural ventilation flow rates, are already accounted for in these simulation procedures. Further simplifying approximations also reduce the amount of necessary input data.

Much more data are needed as input to the theoretical method, as very little information on the building that is available *a priori* are used in the solution procedure. This of course, makes the method very versatile, but perhaps less efficient for conventional analyses.

Figures 1 and 2 respectively illustrate, for a typical conventional example, the time needed to prepare the input data and the time needed to actually input the data for a first calculation for the three methods [9]. The lengths of the input files for the three methods are shown in Fig. 3 [9, P. H. Meyer, personal communication].

3.2 *Time and cost efficiency*

It takes some time for any inexperienced user of software to become proficient in its use. Typical times [D. Holm, personal communication] for an inexperienced user to use effectively the different methods are shown in Fig. 4.

The estimated computing (CPU) time for a typical problem on a CDC 750 mainframe computer is shown in Fig. 5 [9, P. H. Meyer, D. Holm, personal communications]. The cost of these computations can be calculated from Fig. 5 if the cost of CPU time for the user is known. As expected, the empirical method is the

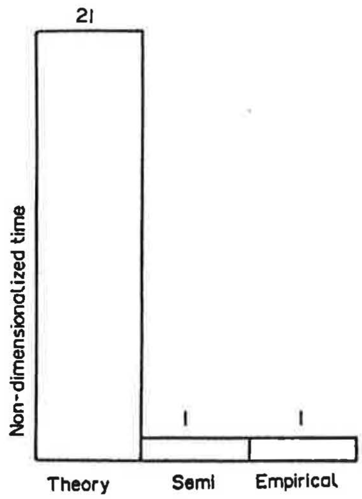

Fig. 1. Time needed to prepare input data (1 unit = typically 1 hr).

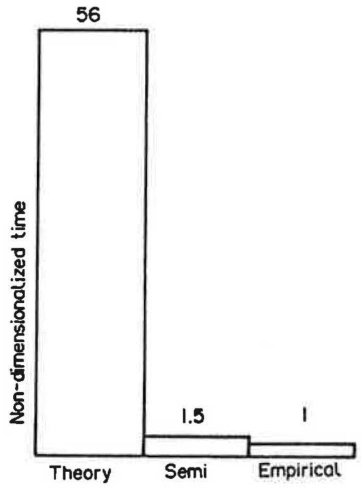

Fig. 2. Time needed to input data (1 unit = typically 8 min).

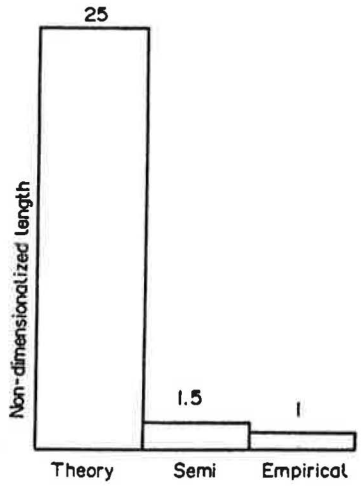

Fig. 3. Length of input files (1 unit = typically 20 lines).

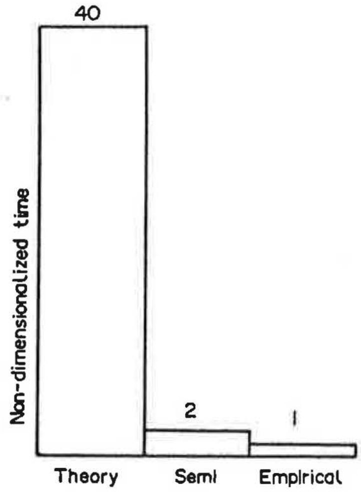

Fig. 4. Time needed for a first time user to become proficient (1 unit = typically 1 day).

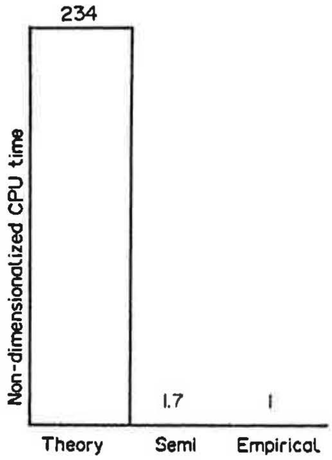

Fig. 5. Computing time (1 unit = typically 5 CPU s).

most cost- and time-efficient, followed by the semi-empirical and theoretical methods.

3.3 *Output data*

There is often a tendency for users of sophisticated procedures to produce redundant output information, as an enormous amount of information is generated by the procedure and is therefore available for output. Although such information is useful for research purposes, it is often less useful in design. Typical lengths of output files for the three methods are compared in Fig. 6.

3.4 *Acuracy of predictions*

The accuracy of predictions by the three methods was investigated for a small conventional experimental building [9]. Dimensions and other detail of the building are given in Fig. 7.

As the empirical method primarily predicts minimum and maximum indoor air temperatures, it was decided to compare the three methods' abilities to predict the maximum and minimum indoor air temperatures in the experimental building. Predicted and measured tem-

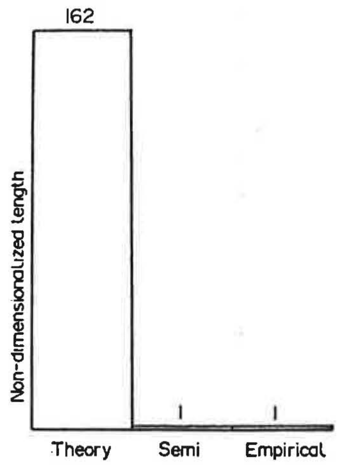

Fig. 6. Length of output files (1 unit = typically 50 lines).

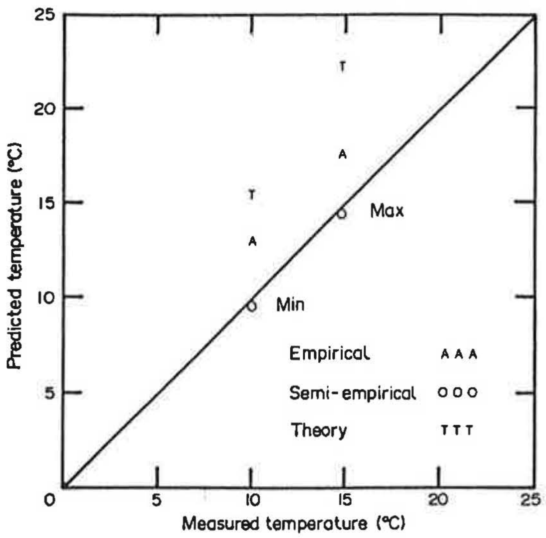

Fig. 8. Measured and predicted minimum and maximum temperatures.

peratures are given in Fig. 8. From Fig. 8 it is seen that the semi-empirical method performed better than the empirical or theoretical methods. The empirical method's predictions were also more accurate than the predictions by the theoretical method.

One of the reasons for the difference between measured temperatures and DEROB predictions, is that the ground contact of the house is not reliably modelled in the modelling procedure (see [10]). The influence of ground contact is significant for lightweight structures where the floor is not insulated from the indoor environment. It should therefore be modelled as reliably as possible.

The empirical and semi-empirical approaches use certain empirical data to establish the effect of ground contact and are successful in modelling low and high mass buildings [3, 6]. Although a general conclusion cannot be drawn from only the one discussed example, it seems that the use of *a priori* empirical data as part of the solution method could in some cases enhance the accuracy of predictions.

4. DISCUSSION AND CONCLUSIONS

It is in the interest of the building designer or researcher to choose an optimum thermal analysis method for the specific application. Such a decision will *inter alia* be based on what output is needed and what input data are available as well as what the cost of obtaining unavailable input data is. (Unavailable data could be natural ventilation flow rates or environmental data for a specific location.)

Different amounts of input data are needed for different methods. A very versatile method like DEROB will need more input data than empirical or semi-empirical,

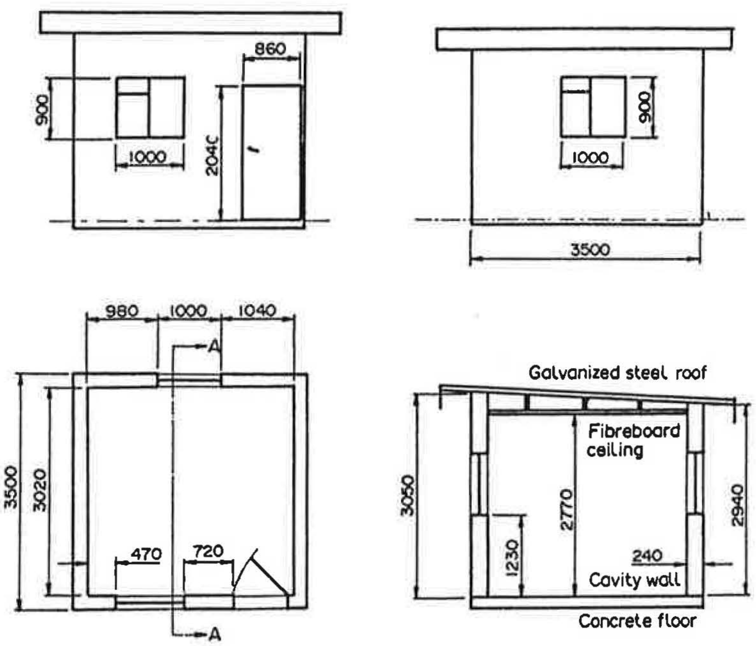

Fig. 7. Experimental building.

but less versatile methods. The versatile method is therefore more suitable for research purposes or for the design of non-conventional buildings as more physical detail of the problem is needed to describe non-standard buildings. However, if some of the necessary input data are unavailable, simulations with the more versatile method can be problematic. It was, for example, found that input data needed to simulate natural ventilation in DEROB were not always available. It was further found that a small change in these 'guessed' input data could introduce a significant change in the predicted indoor thermal environment [9].

Empirical and semi-empirical methods need much less input data, as certain data are known beforehand for most conventional buildings and these data are already included in the method. Empirical methods, however, have the disadvantage that they are only applicable to buildings similar to ones on which the methods are based [5]. Semi-empirical methods have the advantage over empirical methods that they can usually be extended to include more input data to give more detailed analysis of even non-conventional buildings.

The output information that is required is also an important factor to take into account in the choice of a thermal prediction method. If only the indoor air temperature is needed as output, most of the information contained in a typical output of DEROB will be redundant. Much more information than necessary is generated in this case. The empirical and semi-empirical methods generate less data, making these methods more suited to design but less ideal for research purposes.

In choosing an optimum method for a given purpose, the designer or researcher should also investigate the efficiency and accuracy of the method. For design purposes, a method should be cost- and time-efficient. The quantitative difference in efficiency between methods with different levels of empiricism was demonstrated in this study. Theoretical methods are often inefficient for design purposes.

A method should not only be efficient, but also sufficiently accurate for its intended purpose. (It should be kept in mind that no method can produce more accurate results than the accuracy of the input data to the method). Predictions of sufficient accuracy can only be generated if the physical thermal system is described in an appropriate way. At least the important characteristics of the system should be reliably identified [1]. This study shows that even an empirical and a semi-empirical method can reliably identify the important characteristics of a physical thermal system.

The quantitative investigation of the three thermal analysis methods with different degrees of empiricism leads the author to make a similar conclusion as Lord and Wilson [1], namely that the optimum predictive method for design purposes is often a semi-empirical method, which consists of a subtle interplay between theory and experiment.

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