

Understanding the Impact of Parametric Uncertainty in Validating Building Thermal Behaviour in Computational Fluid Dynamics (CFD).

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ABSTRACT: Understanding the uncertainty in modelling procedures is important to provide confidence in model predictions, but is rarely carried out. Uncertainty in CFD model parameters resulting from empirical investigation and applying accepted standards are assessed to validate model behaviour. The results show that a basic structured approach to uncertainty considerations (i.e. sensitivity analysis) in a steady-state CFD model result in different conclusions of model behaviour than otherwise achieved by a standard deterministic evaluation.

Keywords: validation, uncertainty, sensitivity, CFD

1. INTRODUCTION

Energy modelling and CFD are becoming commonly used tools for assessing a building's energy and thermal performance. As computer simulation is a theoretical account of an expected real situation, validation (by inter-model or empirical data comparison) is a necessary process for giving confidence in model results.

Validation does not infer an exact replication of behaviour but rather commonality in general modelled and observed behaviours. Differences between modelled and monitored values are considered acceptable if insignificant to the intended level of accuracy and if they can be explained by model simplification, for example.

Improving confidence in building energy and thermal modelling tools/processes is a relevant topic of investigation. Confidence results from improved accuracy of a model's description of a physical process combined with analysis of model uncertainties.

Attempts to couple energy modelling tools with CFD have been investigated as a means of improving accuracy by taking an holistic

approach to modelling [1-3]. By doing so internal temperatures and air flow can be more accurately assessed which in turn can improve predictions on building energy performance. Limitations in computer software and hardware have impeded the success and uptake of coupled simulation.

To give confidence to a coupled model an investigation into model uncertainty is still required; as recognised by Zhai and Chen [4]. In [4], sensitivity analysis of a coupled model highlights four main categories influencing model behaviour (summarised in table 1). Zhai and Chen comment on the time costs associated with their sensitivity study that is likely to inhibit the uptake of uncertainty/sensitivity analysis in current modelling practices.

Uncertainty investigations should be applied to all modelling procedures. A review of relevant literature, however, shows a greater focus of uncertainty analysis (structured and unstructured) in building energy modelling studies [5, 6]. Though more common in building energy simulation than in CFD analysis, it is still not widely practised.

Aude et al. study sensitivity analysis in validation of model processes. They conclude

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that greater understanding of a simulation tools capabilities results from this [7].

Pfafferott and Herkel carried out a modelling and monitoring study on the Fraunhofer ISE building in Germany [8]. Their study showed greater correlation between modelled and monitored results was obtained due to uncertainty considerations.

This paper looks at the uncertainty associated with CFD modelling of an existing building and assesses the impact of structured uncertainty analysis (i.e. sensitivity analysis) on the validation of model behaviour.

2. BUILDING MODEL

An office building was put forward for energy and thermal comfort assessment [9]. CFD analysis combined with monitoring was carried out to investigate the influence of Heating Ventilation and Air Conditioning (HVAC) system functionality, building structure, internal casual gains and occupant behaviour on thermal conditions.

The size of the model placed restrictions on the detail applied to model objects. This introduces uncertainty by model abstraction. The abstraction is related to object geometry, where standard model descriptions of thermal behaviour were applied to the representative objects.

The parameters influencing model results as

identified by Zhai and Chen [4] are given in table 1. The parameters for each category are given for an existing building and so differ slightly from those in [4].

When modelling an existing building uncertainty in model parameters can be minimised by investigating building form and monitoring HVAC system functionality. The uncertainty left in the model comes from the accuracy associated with monitoring methods/equipment, standard model values (i.e. standard heat sources given by CIBSE and ASHRAE guides) and model abstraction. The basic considerations of model objects are given in table 2 below.

Table 1: Parameters to which a model is considered sensitive.

Category	Parameter
Environmental	Outside Air temp
	Solar Radiation
HVAC System	Conditioned Air Temp
	Air Flow Rate
	Vent Geometry
Internal Load - level and spatial distribution	People (met. rate, activity, occupancy levels)
	Equipment (computers, printers, on/off)
Building Envelope	Wall
	Window (glass properties)
	Ceiling
	Floor

Table 2: Summary of CFD model objects and associated properties

Category	Model Object / Setting	Associated Values
Environmental Conditions	Ambient Air Temperature	Used to set the ambient air temperature in the model (°C). Taken from weather station data.
	Wind Speed and Direction	Used to define the air flow associated with openings on the model boundary. Not considered as model size too big for accurate representation.
	Cloud Cover	Used to set the solar fraction incident on the building.
HVAC System	Supply Vents	Individually set air temperatures and static pressure (representing air flow). Based on monitored data.
Internal Loads	Person	Based on standard metabolic rates and power output for given activity levels. (CIBSE and ASHRAE Guides).
	Computer	Set at 80% of nameplate rating due to type of work carried out by office occupants. Uncertainty resulting from level of computer use during validation points.
	Printer	15% - 20% power of nameplate rating.
	Light	Recessed Lighting Units, 62% downward distribution of light power.
Building Structure	External Wall	0.411m thickness, constant thermal Conductivity (k) = 0.112 W.K-1.m-1.
	Internal Wall	0.15m thick concrete and plaster.
	Window	Double glazed unit represented as single object.
	Desk/Partitions	Given an effective thickness to represent thermal behaviour of real object thickness.
	Internal Blinds	Not considered.
Building Geometry	Open Plan Office Size	25m x 25m x 2.74m (w x d x h)

2.1 Solar Loading Analysis

Models of the building were developed in Ecotect and used for daylighting analysis and basic solar load distributions. The grid based solar loading calculations in Ecotect provided a method for identifying solar loads to be applied within the CFD model. Solar flux incident on the internal surfaces in the Ecotect model were applied as heat sources on the equivalent surface regions within the CFD model.

Clear sky conditions were used to determine maximum loads for the initial differential sensitivity analysis. It was assumed that no internal shading (other than from the basic office partitions and equipment) existed. This provided a maximum solar load potential that could be applied during uncertainty testing.

2.2 Mesh and Convergence Considerations

Investigations of mesh-influenced performance were carried out in order to optimise mesh size and quality for simulation

runs. Initial runs of base case models were performed to determine the convergence criteria to be set for the residuals of the measured physical values. This was done in order to reduce simulation time without significantly compromising accuracy, provided residuals were demonstrating convergence.

3. MONITORING EQUIPMENT AND ACCURACY

The building underwent a series of monitoring procedures to observe thermal behaviour. Long term monitoring of randomly chosen conditioned air-supply vents was used to demonstrate the response of the HVAC system to internal and external thermal loads.

T-type thermocouples were used to monitor air supply temperature to occupied spaces as well as record air temperature within the office space. The thermocouples are accurate to

$\pm 0.5^{\circ}\text{C}$. Attempts to calibrate the thermocouples showed inconsistent temperature readings within the accuracy range. All long-term monitored thermal data was, therefore, considered with an error range of 1°C .

Air flow within the air supply vents to the office space was averaged from a grid measurement of static pressure using a handheld pitot tube attached to a digital anemometer. The model assumes the room pressure is equal to the boundary condition atmospheric pressure, allowing supply vents to be set to the grid averaged static pressures measured during monitoring. For sensitivity analysis the standard deviation in the grid measurements is applied to the CFD model.

4. RESULTS - SENSITIVITY ANALYSIS AND VALIDATION

The monitoring within the study was designed to investigate thermal behaviour in the building, provide input values to a CFD representation and to validate model results. The CFD model was used to identify thermal distribution and air flow patterns within the office spaces with greater detail than achieved by monitoring.

The temperature and air speed out of the vents are identified as uncertain, due to equipment accuracy and potential error within monitoring procedures. Variations in the base case values are made to individual components for differential sensitivity analysis of each unsure component. The base case results and variations due to uncertainty are used in comparison to monitored data for validating model behaviour.

4.1 Base Case Model Results

Three different days were used to assess the accuracy of the steady-state CFD model used for thermal comfort prediction. The conditions for each validation period varied in time of day (within a range of 3 hours) and external conditions (air temperature in a range of 1°C , relative humidity within a range of 10% and

similar levels of cloud cover).

A register of building occupancy and electrical equipment (in use) was taken for each validation period. The occupant positioning and equipment were replicated in the CFD model.

The base level model applied a sensible heat source of 90W (latent heat source of 50W) to each person object in the model. Air flow rate from vents and air temperature from the vents was set to the monitored values. All lights were on in the modelled building areas.

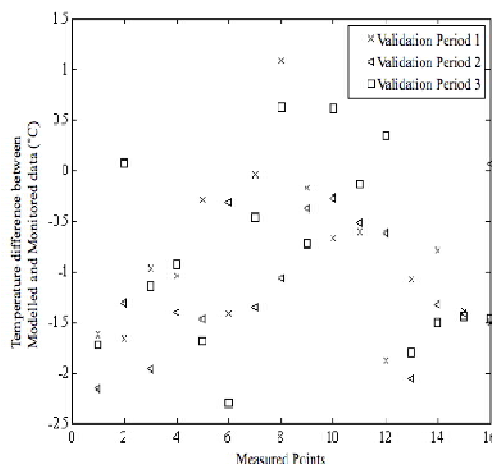
Solar load was set as a fraction of the clear sky loads calculated using Ecotect. The fraction was determined by the level of cloud cover obtained from a nearby weather station.

The validating points remained constant for all three validation dates.

A general trend in the accuracy associated with the validating points is seen in figure 1, with greater accuracy associated with points 8 to 11. Between each validation period, however, the difference between monitored and modelled values varies for each point. The relationship between points also varies for each simulation. This suggests an inconsistent representation of thermal and fluid behaviour in the CFD model.

The model generally provided an under estimation of monitored values.

Figure 1: Base Level CFD Model validation from monitored data for three distinct points in time.



4.2 Consideration of Differential Sensitivity

A structured approach to analysing the model uncertainty was taken using differential sensitivity analysis. Besides the uncertainty associated with monitoring equipment accuracy, occupant heat loads, solar loading, lighting heat loads and computer (and associated equipment) heat loads are also recognised as sources of model uncertainty.

Figures 2 to 4 show a plot of modelled versus monitored temperature values. Each plot contains the differential variation due to identified uncertainty in occupant heat source, variation in applied vent air speed and vent air temperature. Solar load was omitted for these simulation runs.

The solid line in each graph represents the ideal correlation between monitored and modelled results. The dashed lines provide a region of acceptable model behaviour, accounting for accuracy in the monitoring equipment used for validation.

Figure 2: Varying Occupant Heat Load - Base Case 90/50W, Lower Limit 74/41W, Upper Limit 104/56W (sensible/latent loads)

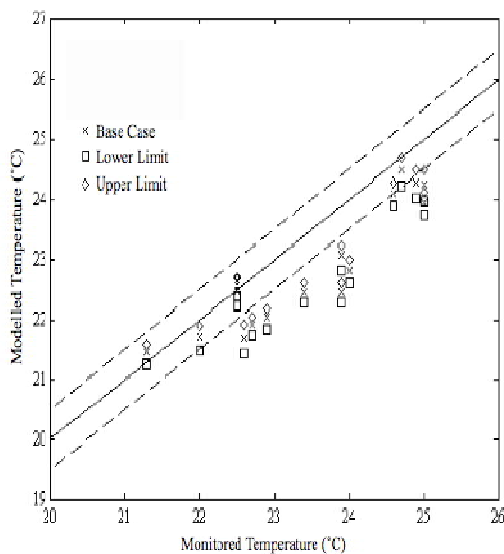


Figure 3: Varying air inlet vent pressures, according to grid measured values

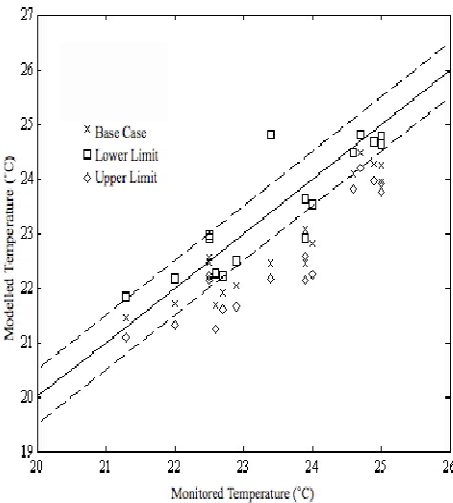


Figure 5 shows all the differential sensitivity analysis results carried out with maximum solar load (i.e. clear sky and no internal obstruction) applied. This shows that the range in solar load is the most sensitive factor in the given study.

Figure 4: Varying air inlet temperature according to reported thermocouple accuracy ($\pm 0.5^{\circ}\text{C}$)

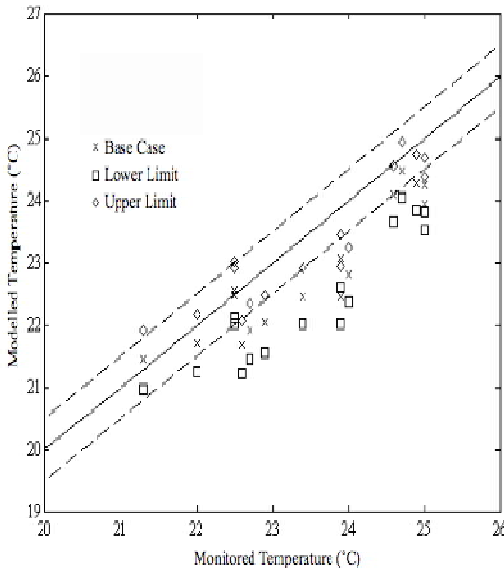
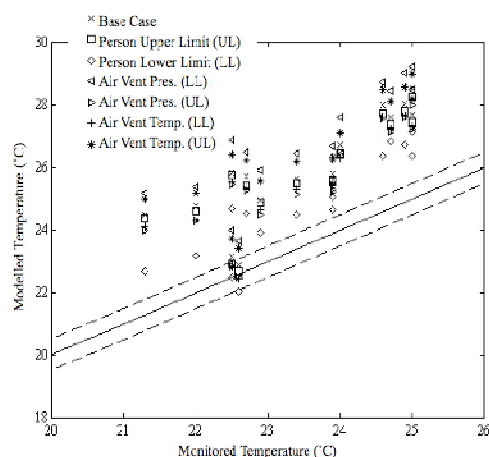


Figure 5: Sensitivity Results with full solar loading potential

Increased solar load demonstrates an affect on the sensitivity of the other uncertain parameters. This raises issues of interdependencies of model parameters that would encourage factorial sensitivity testing or an unstructured approach such as Monte Carlo analysis.

Lack of integrated sensitivity and uncertainty analysis techniques within CFD tools makes this process too time consuming for detailed building thermal assessment.

5. DISCUSSION

The base level results from figure 1 show a maximum variation of 2°C between temperature predictions, at any given validation point over the three validating dates. All model values are within 2.5°C of monitored values.

Sensitivity of the model to uncertainty in input parameters provides confidence to model behaviour.

With only basic solar loading consideration the resulting uncertainty in the model validation points is in the region of 4°C to 5°C. The error in base case model results is evidently within the model uncertainty range. This gives confidence in the model behaviour, suggesting inconsistencies between validation runs and discrepancies between modelled and monitored behaviour is subject to unavoidable

and considered uncertainty.

Comparison of results in figures 2 to 4 and figure 5 show the model is most sensitive to solar load, under steady-state consideration and within the identified ranges of parametric uncertainty.

6. CONCLUSION

Model abstraction is often unavoidable due to limited knowledge of real building behaviour and limited computer capability. Issues of accuracy result from model simplifications that must be investigated to give a true reflection of model behaviour.

Using a deterministic approach (represented by the results in figure 1) suggested a poor level of model accuracy and inconsistent model behaviour with varying model conditions.

The sensitivity study (within the uncertainty ranges of the model parameters) provided a better understanding of the model behaviour and discrepancies between empirical and modelled data. Applying a structured method of uncertainty analysis resulted in greater confidence in the model behaviour. The inconsistent model behaviour in the deterministic representation of the model is accounted for when considering parametric uncertainties.

The sensitivity analysis carried out was not exhaustive. The values associated with equipment power output and lighting as a heat source consideration, supply vent geometry and other object geometry also contain model uncertainty that has not been presented here.

Investigating parametric uncertainty in building thermal analysis by CFD provides a more robust method for validating model performance than simply following a deterministic approach.

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