Djunaedy, E., Hensen, J. L. M., Loomans, M. G. L. C. (2004). Selecting an appropriate tool for airflow simulation in buildings. Building Services Engineering Research and Technology, 25(3), pp. 289 - 298.

AUTHORS

E Djunaedy BEng, MSc, **JLM Hensen** Prof, ir, dr, **MGLC Loomans** ir, dr

Center for Building & Systems TNO - TU/e

Technische Universiteit Eindhoven

P.O. Box 513, 5600 MB EINDHOVEN, Netherlands

http://www.kcbs.nl

CORRESPONDING AUTHOR

E. Djunaedy
Technische Universiteit Eindhoven

P.O. Box 513, 5600 MB EINDHOVEN, Netherlands

Phone : +31 40 247 5790
Fax : +31 40 243 8595
Email : e.djunaedy@bwk.tue.nl

TITLE

Selecting an appropriate tool for airflow simulation in buildings

ABSTRACT

With the advancement of technology, and with the widespread availability of simulation tools, we are forced to consider which simulation tool would be appropriate for a particular problem. The seemingly trivial decision is in reality not very easy to make. Very often this leads to the practice of using the most sophisticated tool available for every problem.

The levels of resolution and complexity of simulations are directly related to the accuracy of the simulation and to the total cost of the simulation process. A simple tool may be cheaper, but there is a high risk of inaccuracy. An advanced tool could be more accurate, but it needs a huge amount of resource in terms of computing power, labour, and the advanced knowledge to perform the simulation and interpret the results.

This paper proposes a guideline for selecting a simulation tool for airflow prediction. Sensitivity analysis is selected as the tool for decision making. A case study is used to highlight the proposed method.

1 INTRODUCTION

The traditional method to design HVAC systems is the paper-and-pencil method using various engineering guidelines. This method has survived over the years, since the early days of engineering guidelines, as the trusted method.

However, there is a move towards simulation, which is rapidly becoming the most important engineering tool in integrated design of buildings and HVAC systems. There are at least three reasons for this[1]:

1. Newer and cost-effective construction techniques mean that the building form is departing more frequently from the stacked rectangular box. The data provided by the guidelines is less applicable to these new building forms.
2. There is a constant push for efficiency and refinement and to promote new design. The simplified equations in the guides are usually applied very generally. This means they have been formulated to be conservative to ensure that the designs that result from their use do not fail. Trying to refine this fail-safe design (to get more efficiency), without reducing the unknowns, is a direct path to failure. Simulation is seen as a way to reduce the unknowns.
3. The definition of successful HVAC is changing. The traditional "never over 24 °C" rule is often broken without complaints. The more advance rule with statistical measure – "temperature should not rise above 25 °C for more than 5% of the occupied hours" – means that the guides need additional tools as a supplement.

Recent advances in hardware and software make simulation approaches – that required the use of supercomputers only a decade ago – widely available. The flood of simulation tools poses the question of how to justify the selection of a certain approach or tool.

2 PROBLEM STATEMENT

In airflow simulation, there are at least three approaches representing different resolution level:

1. Building energy balance models (BES) that basically rely on guessed or estimated values of airflow.
2. Zonal airflow network (AFN) models that are based on (macroscopic) zone mass balance and inter-zone flow-pressure relationships; typically for a whole building.

3. Computational fluid dynamics (CFD) that is based on energy, mass and momentum conservation in all (minuscule) cells that make up the flow domain; typically a single building zone.

Hensen et. al.[2] analyze the capability and applicability of these approaches in the context of a displacement ventilation system. The main conclusions from this study are:

1. Each approach has its own merits and drawbacks. An environmental engineer typically needs each approach but at different times during the design process.
2. A higher resolution (and more complex) approach does not necessarily provide answers to all the design questions that may be answered by a lower resolution (less complex) approach.

These are important findings in the middle of the abundance of simulation tools. When the various tools become available, it should be realized that a high resolution (and more complex) approach requires an enormous amount of resources in terms of computing capacity, manpower and time. On the other hand, lower resolution (and less complex) approaches might not reliably solve a particular problem. How to select the appropriate approach to solve the problem at hand remains the challenge.

There is always a temptation to use the most sophisticated method to simulate every design option. The sophistication would hardly fail to impress any client. However, the cost of such sophistication should always be justified, otherwise the client will hesitate to use the same method in the future. This could affect the positive growth in the widespread use of simulation in building design. In this perspective, there is a need for a guideline to decide which simulation tool/ approach is appropriate for a certain problem.

Slater and Cartmell[1] developed what they called “early assessment design strategies” (Figure 1). From the early design brief, the required complexity of the modelling can be assessed. Starting from the design standard, a building design can be assessed whether it falls safely within the Building Regulations criteria, or in the borderline area where compliance might fail, or whether it is a new innovative design altogether. Based on this initial assessment, and with the proposed HVAC strategy, several decision points in Figure 1 would help the engineer to decide which level of complexity should be used for simulation.

3 THE GUIDELINE

The proposed guideline is developed based on the findings of the previous research described above. Early assessment design strategies as proposed by Slater and Cartmell[1] can be used for initial assessment. However, we indentified the need to go further because of the following reasons:

1. As Hensen et. al.[2] pointed out, we need to use different levels of complexity and resolution at different stages of a building design.
2. Coupled simulation (between energy simulation and CFD) is now a viable option, which is not addressed in Figure 1.

Figure 2 shows the proposed performance-based airflow modeling selection strategy (AMS). It initially was developed as part of a research in coupled simulation between CFD and BES[3]. Because of the high cost of coupled simulation, AMS was proposed to identify the need for such simulation. However, the AMS can be applied more generally to assess the need for a certain level of complexity and resolution for simulation.

The main ideas behind the AMS are:

1. a simulation should be consistent with its objective, i.e. the designer should not be tool-led,
2. there should be a problem-led rationale to progress from one level of resolution and complexity to the next,
3. the selection of good design option (among many design options) should be made at the lowest possible resolution and complexity, so that there would be less design option to be simulated at higher resolution level.

In the vertical axis (Figure 2) there are layers of different resolution of building simulation. There are four layers representing the increased level of resolution, i.e. energy simulation, airflow network simulation, and two levels of CFD simulation. Each of the resolution layers is separated by one or more decision layers. The horizontal axis shows the different levels of complexity of building simulation.

The first step is to select the minimum resolution based on the design question at hand. For example:

- If energy consumption is needed, than BES would be sufficient.

- If the temperature gradient is needed, than at least an AFN is required.
- If local mean age of air is in question, than CFD is necessary.

A second step is to check whether the above minimum resolution is sufficiently accurate for the design question at hand. For example:

- A load analysis based on BES may be over-sensitive to the convective heat transfer coefficient (h_c) values, thus requiring CFD to predict more accurate h_c values.
- A load analysis may be over-sensitive to the 'guestimated' values of infiltration or inter-zonal ventilation, thus requiring AFN to predict more accurate airflow rates.

How to actually make these decisions is to a large extend still vague as denoted by the question marks in Figure 2. In practice the decisions are often made implicitly and depend very much on the skills and experience of a design engineer. With AMS this implicit process is made explicit and structured. Performance indicators and sensitivity analysis are used for this purpose.

3.1 Performance Indicators

AMS uses performance indicators as the base to make decisions on which simulation tool/approach is the appropriate tool for the design question at hand. This is a step further from what was proposed by from Slater and Cartmell[1] who used the early design brief as the base for the decision making. Table 1 shows a typical list of performance indicators (PI) that are of interest for an environmental engineer. The indicators basically fall into three categories, i.e. energy related, load related and comfort related performance indicators. Each of these categories will be used for different kinds of decisions in the building design process.

In every category, there is more than one indicator. Some indicators can be obtained directly from simulation results. Others need additional treatments, either manual "paper-and-pencil" calculation or additional simulation. There is no attempt to put a weight on the indicators to highlight their significance, as each building design could have different weight for the same performance indicators.

With regard to the AMS, these indicators are used as the basis for the selection of the most appropriate approach to simulate the problem at hand. Table 1 also shows the minimum resolution required to calculate a performance indicator. As we can see, only a few indicators require an immediate jump to the AFN or CFD approach. It should be noted that this list is case dependent. In case of naturally ventilated double skin façades, for example, load and energy calculations will require an airflow network approach.

3.2 Sensitivity analysis

Sensitivity analysis is the systemic investigation of the reaction of the simulation response to either extreme values of the model's quantitative factors or to drastic changes in the model's qualitative factors[4]. This analysis has been used in many fields of engineering as a what-if analysis, and one example of the use of this method in building simulation is described by Lomas and Eppel[5].

The main use of sensitivity analysis is to investigate the impact of a certain change in one (or more) input parameters to the output. Depending on the particular problem, the end result is usually to identify which input parameter has the most important impact on the output. It is an unavoidable step in model verification and/or validation. However, Fuhrbringer and Roulet[6] suggested that sensitivity should also be used in performing simulations.

In the AMS, the sensitivity analysis is used for a slightly different purpose, as we are not trying to identify which input is important, but we rather try to identify the effect of changes in one input to a number of outputs. Which input is used in this study is selected from the result of previous research in this area.

From previous studies, e.g. Hensen[7], Negrao[8], and Beausolleil-Morrison[9], there are two main inputs that should be tested for sensitivity analysis for the decision to progress to higher resolution level:

1. Airflow parameters assumption, especially the infiltration rate, for the decision to use AFN-coupled simulation. (Further sensitivity analysis on airflow parameters is denoted as SA_{af})
2. Convective heat transfer coefficient, for the decision to use CFD. (Further sensitivity analysis on airflow parameters is denoted as SA_{hc})

In the usual use of sensitivity analysis where there are many inputs and one single output, the effect of each input can be easily compared and there is a single term (or parameter) to quantify the effect of each input parameter on the output. However, with the use of sensitivity analysis for the AMS, it is not possible to compare the effect of changes on one input (say, airflow parameter) on different (many) outputs (say, heating demand and heating load). Different outputs would have different significance in different building design. This is the reason why we do not attempt to put a certain weight to the performance indicators.

Figure 3 shows two scenarios on how to use the AMS. Each of the performance indicators would have a “target value” that can be found from building codes, standards, or guidelines, or even from “good-practices” experience. The target value can be a maximum value, minimum value, or a range of acceptable values. The result of the SA would be presented as a bar chart with three output conditions of the performance indicators, each of them corresponding to the minimum value, maximum value and base condition value of the input. In Figure 3(a), the output value could be more than the maximum target value, based on the result of BES-only simulation, and the SA_{af} result indicates that an AFN-coupled simulation is necessary. However, in the AFN-level, the SA_{hc} result indicates that all predicted values are below the maximum target value, thus no subsequent CFD calculation is required.

In Figure 3(b), the output value could be less than the minimum target value, based on the result of BES-only simulation, and the SA_{af} result indicates that an AFN-coupled simulation is necessary. In the AFN-level, the SA_{hc} result indicates that there is a possibility that the output value is below the minimum target value, thus in this case a CFD calculation is required.

4 CASE STUDY

4.1 Model description

The following case study is presented to highlight the application of the AMS. This case study concerns an open-plan office space in a new faculty building (Figure 4) at the Eindhoven University of Technology. The computer model comprises a 6 m wide and 12.5 m deep section of a 5.4 m high office space. The one external wall is a double-glazed structure, facing south. All other walls are assumed to be adiabatic. The section is assumed to have 10 occupants during office hours, with lights and equipments this leads to 35 W/m^2 internal gains. There is an all-air heating and cooling system serving the area.

Given the large glazing area, the environmental designer would like to predict the energy consumption, heating and cooling loads, and the most important is the likelihood of thermal comfort complaints, which may arise both in summer and winter conditions. Thermal comfort complaints might result from thermal radiation asymmetry and/ or from a cold down draft due to the large glazed area. Several design options are considered for comparison. Table 2 shows the different design options for this case study.

4.2 Case study methodology

On the first layer in Figure 2, BES-only simulation, typical office conditions are used as simulation parameters for the "base condition". After that, the cases are subjected to two sensitivity analyses:

1. Airflow parameter.
   In the base condition, the infiltration rate is assumed to be 0.3 ACH. In reality, it could be somewhere between 0.05 - 0.5 ACH. These two values would be the minimum and maximum value for the sensitivity analysis.
2. Convective heat transfer coefficient.
   In the base condition, the simulation uses the Alamdari-Hammond method for the specification of the convective heat transfer coefficient. However, the flow in the room could be another type of flow, which has coefficients ranging from 1 – 6. These two values are taken as the minimum and maximum value for the sensitivity analysis.

ESP-r is used as the software for the simulation. The air conditioning strategy for all simulations is to maintain the PPD level to be less than 10% during office hours. This is achieved by setting the operative temperature at 23 °C and 26 °C for winter and summer respectively, i.e. the temperature in the middle of the zone. By maintaining the PPD level, the whole simulations want to show the energy consequences of maintaining a high level of comfort standard to the space. It should be noted however, that the PPD "controller" as used in this simulation is not a normal parameter, but it is an idealized scenario that is interesting to be studied due to the presence of a large window area.
A further description of the case study (and also the result) is not presented in this paper, as the intention is not to report the whole case study but to highlight the use of AMS.

4.3 Results

In Table 3 the results are presented for the investigated performance indicators. Here "af" indicates the sensitivity for the airflow parameter and "hc" for the convective heat transfer coefficient. The results of the sensitivity analysis are presented in terms of the maximum deviation from the base condition. This deviation is expressed in a percentage value (S_{af}. and S_{hc}).

All cases in this example have been weighted similarly. However, a 20% deviation in the maximum zone temperature will have a less important meaning than a 15% deviation in primary energy. Therefore, in reality a design team will apply weighting factors to the individual cases and make their decision based on these weighing factors and the sensitivity results.

The PPD level in the room during office hours in a typical week in winter and summer is shown. As can be seen, the PPD values are well below 10% as expected, as this was the criteria for the simulation. The PPD presented in the paper is only from one location, i.e. near the glazed wall, as this is the most critical location where discomfort complaints are expected. The value of PPD in this location should of course be different from the center of the zone where the operative temperature is controlled.

For heating energy demand, Configuration 3 shows the highest energy demand, while Configuration 2 is the lowest. Nevertheless, all configurations show a high sensitivity to the airflow parameters. The sensitivity to the convective heat transfer coefficient is lower.
A similar discussion can be made for the cooling energy demand, the maximum heating load, and the maximum cooling load. The gas consumption, fan electricity consumption and the primary energy consumption can be derived from the above results and by applying some assumptions on, e.g. the boiler and fan efficiency. Finally, the maximum and minimum zone temperature and the overheating period are indicated.

4.4 Discussion

4.4.1 The use of the AMS to determine the correct resolution level –

The above presented sensitivity analysis is used in the AMS to select the appropriate level of resolution. The maximum deviation from the base condition indicates the level of sensitivity of each performance indicator to the airflow parameter and the convection coefficient. In this example an arbitrary value of 20% is selected as the limit of sensitivity below which the performance indicator is not considered sensitive to the airflow parameter (S_{af}) or the convective heat transfer coefficient (S_{hc}). This is shown in Table 3. Here the sensitivity higher than 20% is shaded, indicating the need for that specific case to be simulated at a higher resolution level.

4.5 The use of AMS to select a better design option

Before the next higher resolution level is addressed a selection procedure should be performed. The selection will normally be made in consultation with the design team. In the example, the simulation principle is based on maintaining the PPD level. The important parameters for the selection process are therefore the energy related performance indicators, most importantly the primary energy.

From the primary energy point of view, Configuration 1 has the highest primary energy value and therefore is not preferred. If architectural considerations are less important, and hence the construction can be changed, Configuration 2 is the best design option. However, if architectural considerations are the main restriction and cannot be changed, then Configuration 4 and Configuration 5 should be selected for simulation at a higher resolution level. Although it is not presented in this paper, the same decision procedure can be made on the other decision points (the question marks in Figure 2).

5 CONCLUSIONS

This paper proposes a method for the selection of a simulation tool for airflow simulation. This guideline however does not intend to fully automate the decision process. Sensitivity analysis is used as a tool, but the decision whether to use higher resolution (and more complex) simulation still considers other factors. The main contribution of this work is that it tries to make a logical scheme to what is usually an abstract and subjective endeavour.

AMS suggests a rationale for selecting appropriate energy and airflow modeling levels for practical design simulations, which:

- reduces the number of design alternatives to be considered at higher levels of resolution,
- focusses in terms of simulation periods at higher levels of resolution (for example, CFD is only necessary for winter condition),
- indicates whether (de-)coupled BES / CFD simulation will be needed.

Although initially developed for coupled simulation in building airflow, AMS can be applied generally to all simulation, coupled or otherwise, and with a slight modification, it could also be applied to domains other than airflow. Figure 2 could be made in 3 dimensions (or more) to include other domains, e.g. lighting or control system, or plant system.

REFERENCES

1. Slater S, Cartmell B. Hard working software. Building Services Journal 2003; February: 37 – 40.
2. Hensen JLM, Hamelinck MJH, Loomans, MGLC. Modelling approaches for displacement ventilation in offices: Roomvent '96 Proceedings of the 5th International Conference on Air Distribution in Rooms, Yokohama, 1996.
3. Djunaedy E, Hensen JLM, Loomans MGLC. Towards external coupling of building energy and airflow modeling programs. ASHRAE Transactions 2003; 109(2).
4. Kleijnen JPC. Sensitivity analysis and related analyses: A review of some statistical techniques, Journal of Statistical Computation and Simulation 1997; 57: 111 – 142.
5. Lomas K J, Eppel H. Sensitivity Analysis Techniques for Building Thermal Simulation Programs, Energy and Buildings 1992; 19:21 – 44.
6. Fuhrbringer JM, Roulet CA. Confidence of simulation results: put a sensitivity analysis module in your MODEL – The IEA – ECBCS Annex 23 experience of model evaluation. Energy and Buildings 1999; 30: 61 – 71.
7. Hensen JLM. On thermal interaction of building structure and heating and ventilating system, PhD thesis. Eindhoven: Technische Universiteit Eindhoven, 1991.
8. Negrao COR. Conflation of Computational Fluid Dynamics and Building Thermal Simulation, PhD Thesis. Glasgow: University of Strathclyde, 1995.
9. Beausoleil-Morrison I. The adaptive coupling of heat and air flow modeling within dynamic whole-building simulation. PhD thesis. Glasgow: University of Strathclyde, 2001.

TABLES

Table 1

Performance indicators and minimum required modeling resolution in terms of simulation approach

Performance Indicators	Approach
Energy Related	
a. Heating energy demand	BES
b. Cooling energy demand	BES
c. Fan electricity	BES
d. Gas consumption	BES
e. Primary energy	BES
Load Related	
f. Max heating load	BES
g. Max cooling load	BES
Comfort Related	
h. PPD	BES
i. Max temperature in the zone	BES
j. Min temperature in the zone	BES
k. Over heating period	BES
l. Local discomfort, temp gradient	AFN
m. Local discomfort, turbulence intensity	CFD
n. Contaminant distribution	AFN
o. Ventilation efficiency	AFN
p. Local mean age of air	CFD

Table 2

Design options for case study

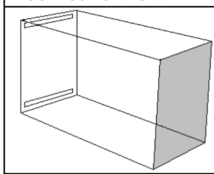
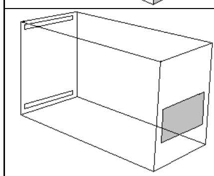
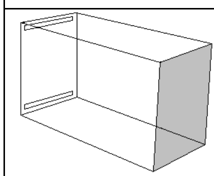
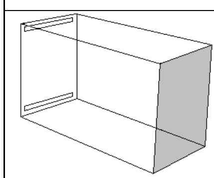
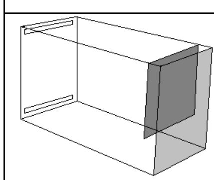
Isometric view	Glazing	Remarks
	Double glazing, no blinds	Configuration 1 = Base case
	Double glazing, no blinds	Configuration 2 is the same as the Configuration 1, but the glazing area is reduced to 2mX4m
	Double glazing, internal blinds	Configuration 3 is the same as Configuration 1, with additional blinds in the internal part of the room
	Double glazing, blinds in the middle	Configuration 4 is the same as Configuration 1, with additional blinds in the middle between the two glazings.
	Double glazing, no blinds	Configuration 5 is the same as Configuration 1, with additional curtain 0.5m from the wall, down to 2m above the floor

Table 3

Results of sensitivity analysis for different configurations (BES-Only)

Performance Indicators	Configuration 1			Configuration 2			Configuration 3		
	Base Value	S_{af}	S_{hc}	Base Value	S_{af}	S_{hc}	Base Value	S_{af}	S_{hc}
Heating energy demand	4891	38%	20%	3570	60%	10%	6883	33%	16%
Cooling energy demand	3734	29%	4%	1462	76%	7%	719	58%	6%
Max heating load	17	17%	66%	14	25%	61%	18	16%	64%
Max cooling load	14	5%	25%	6	13%	11%	7	7%	25%
Gas consumption	611	38%	20%	446	60%	10%	860	33%	16%
Fan energy consumption	3714	0%	0%	3714	0%	0%	3714	0%	0%
Primary energy	12339	7%	7%	8745	15%	3%	11316	17%	10%
PPD winter	8	0%	6%	8	1%	4%	8	0%	6%
PPD summer	6	1%	8%	6	0%	3%	7	2%	3%
Max zone temperature	36	9%	4%	33	6%	8%	36	4%	11%
Min zone temperature	9	22%	9%	11	24%	13%	9	22%	10%
Overheating	522	103%	123%	80	681%	199%	169	22%	193%
	(a)			(b)			(c)		

Performance Indicators	Configuration 4			Configuration 5		
	Base Value	S_{af}	S_{hc}	Base Value	S_{af}	S_{hc}
Heating energy demand	4798	45%	11%	4207	47%	14%
Cooling energy demand	1448	55%	4%	2168	48%	7%
Max heating load	16	20%	62%	15	21%	57%
Max cooling load	7	7%	21%	8	10%	13%
Gas consumption	600	45%	11%	526	47%	14%
Fan energy consumption	3714	0%	0%	3714	0%	0%
Primary energy	9959	14%	5%	10089	11%	4%
PPD winter	8	0%	5%	7	1%	4%
PPD summer	7	0%	5%	6	0%	2%
Max zone temperature	34	3%	9%	33	3%	7%
Min zone temperature	10	23%	12%	11	21%	11%
Overheating	150	157%	126%	262	275%	129%
	(d)			(e)		

FIGURE CAPTIONS

Figure 1

Early assessment design strategies[1]

Figure 2

Coupling Procedure Decision Methodology

Figure 3

Different scenarios in sensitivity analysis in the AMS

Figure 4

The building and the model

FIGURES

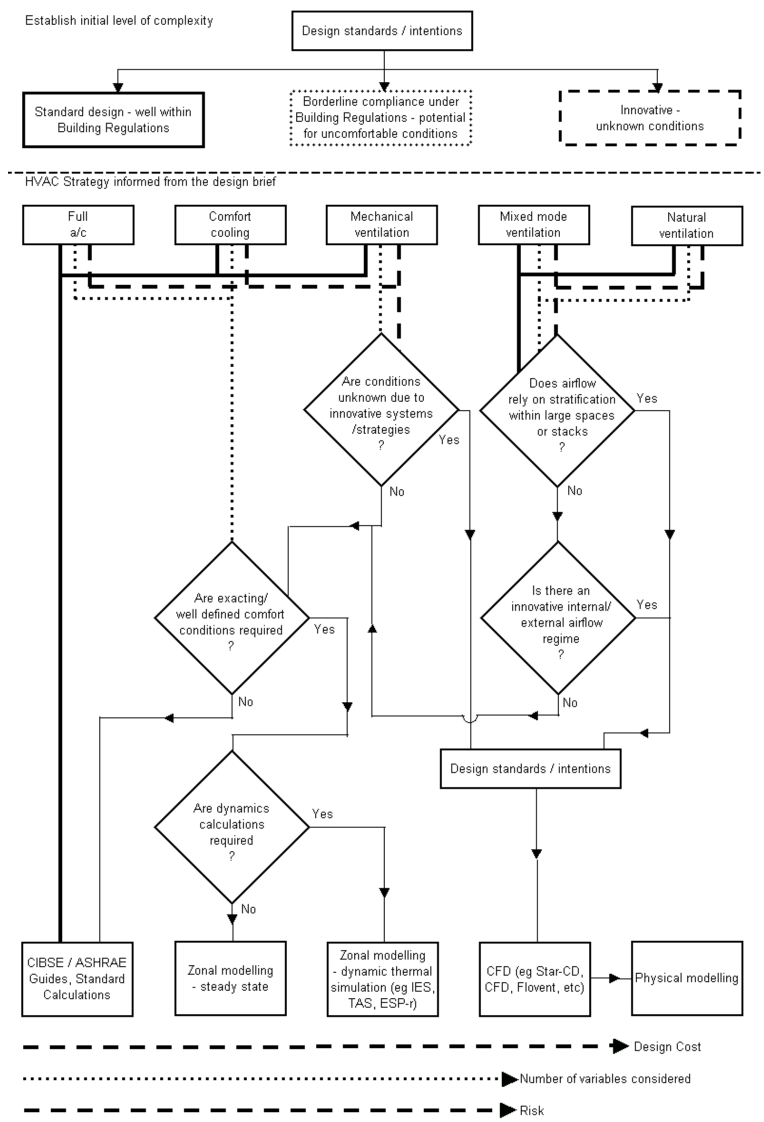


Figure 1

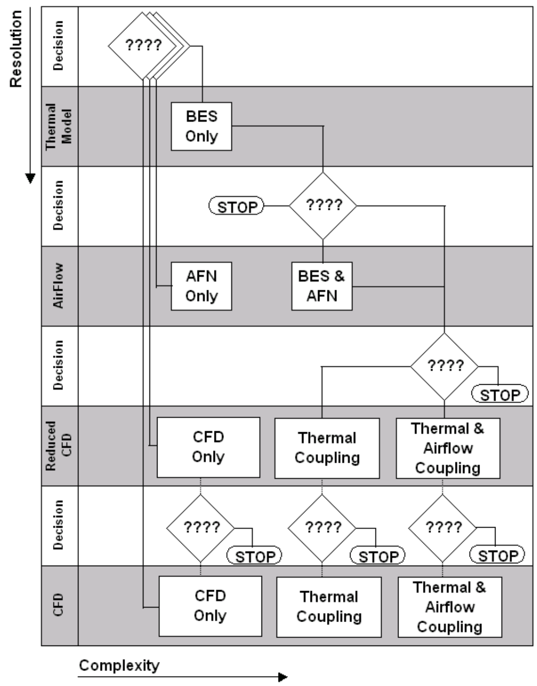


Figure 2

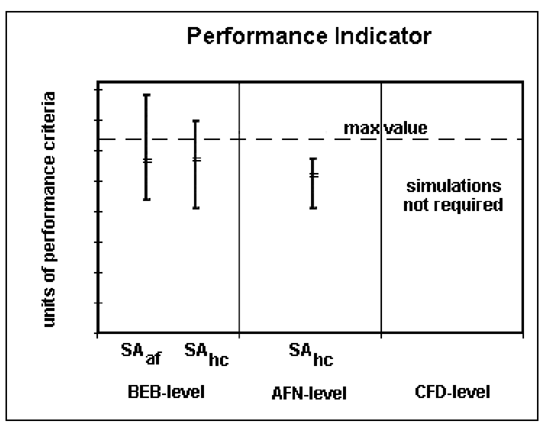


Figure 3(a)

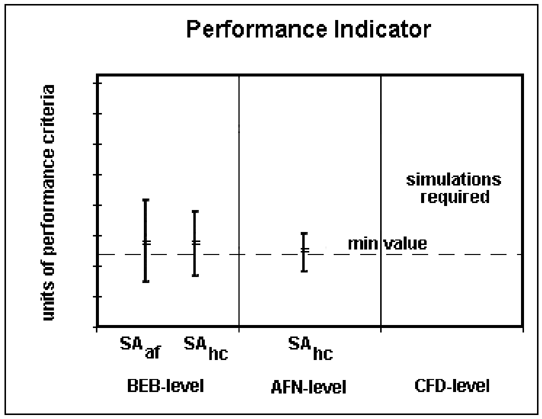


Figure 3(b)

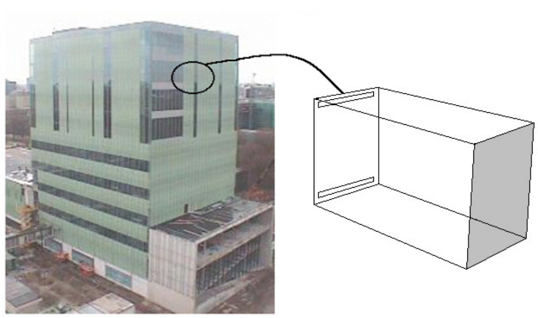


Figure 4