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TOWARDS EXTERNAL COUPLING OF BUILDING ENERGY AND AIR FLOW MODELING PROGRAMS

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ABSTRACT

This paper presents the objectives and results of the initial stage of an going research project on coupling of building energy simulation (BES), air flow network (AFN) and computational fluid dynamics (CFD) programs. The objective of the research underlying this paper is to develop and verify a proto-type co-operative BES, AFN and CFD design environment for optimization of building energy performance and indoor environment.

The initial stage work focuses on developing a Coupling Procedure Decision Methodology (CPDM) which is a decision support methodology to select the appropriate levels of resolution (BES, AFN or CFD) and complexity (e.g. CFD only, BES and CFD uncoupled, BES and CFD thermally coupled, BES and CFD thermal and flow coupled) for airflow simulation in the context of building design. The selection of the appropriate level of resolution results from simulation based sensitivity analysis. The selection of the appropriate level of complexity is an issue to be researched further. A practical case of integrated design of buildings and heating, ventilation and air-conditioning (HVAC) systems is presented to highlight the use of CPDM. The paper finishes with indicating directions for future work.

INTRODUCTION

Building simulation is rapidly becoming the most important engineering tool in integrated design of buildings and HVAC systems. Recent advances in hardware and software make simulation – that required the use of supercomputers in the past – widely available even to a small consulting firm with a single PC.

Also different approaches have become available. In terms of resolution and complexity, currently indoor airflow modeling can be categorized into three approaches:

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. 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.

The practical availability and easy access to different simulation methods and tools poses the question of how to justify the selection of a certain method or tool.

Hensen et al (1996) analyzes the capabilities and applicability of the various approaches in the context of a displacement ventilation system. One of the main conclusions of this work was that a higher resolution approach does not necessarily cover all the design questions that may be answered by a lower resolution approach. Each approach has its own merits and drawbacks. An environmental engineer typically needs each approach but at different moments in the design process. The main conclusion of this study is summarized in Table 1.

BES and CFD each have their own technical shortcomings; some of the more important ones are:

- For CFD the domain boundary is usually the inside surface of a room. However, it is difficult to predict the corresponding boundary conditions (Beusolleil-Morrison, 2000) since these depend on many parameters and variables, e.g. construction details, ambient conditions and HVAC operation.
- In BES, the specification of convective heat transfer is simplified – and its importance often underestimated - by using surface averaged film heat transfer coefficients (h_c). Many studies (e.g.

Spitler et. al. 1991 and Lomas (1996)) however show that the specification of h_c has significant impact on the result (e.g. up to 37% difference in energy consumption prediction).

Integration and/or conflation of CFD and BES has been seen as an opportunity to improve the performance of either method.

Table 1
Summary of prediction potential (--=none, ++=very good) for airflow simulation resolution levels in case of displacement ventilation (Hensen et. al. 1996)

Aspect	BES	AFN	CFD
Cooling electricity	--	++	--
Fan capacity	++	++	--
Whole body thermal comfort	+	++	+
Local discomfort, gradient	--	+	++
Local discomfort, turbulence intensity	--	--	++
Ventilation efficiency	--	0	++
Contaminant distribution	-	-	++
Whole building integration	++	++	--
Integration over time	++	++	--

This paper acknowledges the advantages of integration of different modeling approaches in terms of resolution. The main questions however are how the integration should be realized and, just as important, what selection process should be used to justify the use of a certain integrated approach. The first question will be addressed by summarizing currently available integration techniques as reported in literature. For addressing the second question, a methodology has been developed that guides the process of deciding whether and which coupling procedure should be applied. This methodology is elaborated further by means of a case study.

INTEGRATION OF BUILDING AIRFLOW AND THERMAL DOMAIN

Methods of integration

As described elsewhere in more detail (Djunaedy, 2002), there are two major categories on how to implement the integration of the building airflow and the thermal domain. The first method of integration is to include the dynamics fabric model and (optional) radiation model into CFD to form what is called the conjugate heat transfer method (e. g. Chen et. al. 1995 and Moser et. al. 1995). It is based on including the thermal characteristics and processes in the walls into the model so that the boundary condition of the CFD models can be moved from the inside to the outside of the wall, and thus capturing the dynamics of the external conditions. This will result in a single set of equations to be solved in a single time step. All variables for both the fluid and the solid domains are up-dated simultaneously.

This is the direct answer to the problem of setting up boundary condition for CFD without considering the use of BES. In fact, there is a tendency to avoid the use of BES for at least two reasons (Chen et. al. 1995):

1. If the interior wall temperature is calculated by BES, then it needs the data (at least h_c) from CFD. There would be an iteration process between the two to get an agreement on the values, and this iteration is seen as inconvenient.
2. The conduction heat transfer calculation in most BES packages assumes one–dimensional heat transfer which will introduce errors.

However, the application of the conjugate heat transfer method has several disadvantages:

1. The difference in stiffness of the fluid and the solid side of the model will lead to difficulties in obtaining a converged solution (Chen et. al. 1995).
2. It is computationally expensive (Zhai et. al. 2001). The computing time increases dramatically because of the difference in the time scale between fluid (few seconds) and solid (few hours) so that the calculation must be performed over a long time path to include the dynamics in the solid, but over a very small time step to account for the dynamics in the fluid.
3. Most probably, the code of the solvers must completely be rewritten.

There have been few developments on this method, including a new algorithm to stabilize the computation process. However, Zhai et. al. (2001) conclude that this method is not practical for immediate use in the design context with current computer capabilities.

The second method of integration is to couple CFD and BES, where two separate simulation tools exchange data in a predefined way (e.g. Zhai et. al. 2001, Srebric et. al (2000), Beausolleil-Morrison et. al. (2001)). This method has some advantages that directly answer the restrictions of the previous approach:

1. There is no internal computational stiffness problem for either tool as the fluid and the solid side of the model are simulated separately.
2. It is computationally less expensive since it does not solve the whole equations at the same time, and thus there are no two different time scales to deal with.
3. The solvers for the separate domains can be optimized individually to account for the characteristics of the respective domains.
4. It is possible to use a separate program without rewriting the code. This is a major advantage as we can immediately use codes that are available from each domain, which have been developed separately over the years, well proven and benchmarked.

From the results of previous research, it appears that coupled simulation is the most promising method of integration for use in building design. context. The remainder of this paper therefore concentrates on his method of integration between CFD and BES.

Coupled simulation

In literature, different terms are used to refer to coupled simulation, e.g. combined simulation, conflated approach, integrated simulation. We define coupled simulation as two (or more) separate simulation tools, each of them solving a separate set of equations, that exchange time-step data between them in a prescribed manner.

A coupled simulation usually involves the following components:

1. Domain solvers.

   It must be clear which code calculates which terms in the overall solution scheme.
2. Geometry modeller and/or grid generator.
3. Master program which coordinates the coupling procedure, e.g.:
   - Frequency and point in the solution procedure where data is exchanged between the codes.
   - Definition of the variables that will be passed between the codes.
   - Method of time step control

Citherlet et. al. (2001) used Figure 1(a) to describe a coupled simulation. They define coupled simulation as simulations where "generally, one application controls the simulation and calls the other application(s) when necessary." With regards to the components of coupled simulation described above, there is one geometry modeller for both domains, and one of the domain applications acts as the master program.

A more generalized view on coupled simulation is shown in Figure 1(b). Each domain can have a separate geometry modeller. A master program coordinates the coupling process, which can be assigned to any of the domain applications, so that one of them acts as the master and the other(s) are the clients, or it can be a separate program.

Based on the interaction between the domain solvers, we further categorize coupled simulation into two categories:

1. *Internal coupling*, where the domain application is tailored to work specifically within a certain environment. Usually the code needs to be rewritten for this.
2. *External coupling*, where the domain application is not changed to cooperate with other domain application.

ESP-r (Clarke, 2001) is a good example to clarify this categorization. It uses internal coupling to couple the energy balance model with the airflow network (Hensen, 1991), and with CFD (Negrao (1995) and Beusolleil-Morrison (2000)). On the other hand it uses external coupling to couple the thermal balance model (and airflow models) with lighting application (Janak et. al., 2001).

In the current work we concentrate on external coupling for two main reasons:

1. Individual domain applications have evolved separately over the years and are well proven. If we know how to make these different domain applications to communicate with each other, then it would be of great advance to the building industry. Rewriting the code can be seen as a set back from these independent advances in the separate domains.
2. Each individual domain can be developed further independently. There is no need to worry about keeping up with the latest development in each domain. Let each domain expand and progress in their respective directions. As it is known how the domains can communicate with each other, it is possible to take advantage of these latest developments.

External coupling has also been adopted in other fields of science and technology, for example in structural aerodynamic (Gluck et. al., 2001), nuclear plant safety (Weaver et. al., 2002), car crash simulation (Schilling et. al. 2002), medicine (Guo et. al., 2002), and earth climate (Joppich et. al., 2002). Future work will include exploring whether some of the findings in the above research can be applied in the current study.

SOME ISSUES ON EXTERNAL COUPLING

The first issue is about the stability of the iteration between CFD and BES in order to obtain a converged value on the data being exchanged, as indicated by Chen, et. al. (1995). This issue has been addressed specifically in a recent study by Zhai et. al. (2003).

Clarke et. al. (1995) indicated that the conflation of the network flow and CFD models can be achieved by maintaining separate solution algorithms for each method based on the sparse matrix theory. The overall system balance is achieved through an iterative procedure. Zhai et. al. (2003) suggested that this conclusion is suitable for CFD - BES coupling since many BES programs use the network model. By using a mathematical analysis, limited by some assumptions, Zhai et. al. (2003) concluded that the solution of CFD-BES coupling does exist and is unique.

The second issue is about the "mechanics" of the external coupling. Three main aspects define the mechanics of the external coupling:

1. The definition of the variables that will be passed between the codes.
   The domain connection between CFD and BES is located on the inside wall of the room. There are several possibilities on which parameters are to be exchanged, e.g. convective heat transfer coefficient (h_c), temperature (T), heat flux (Q), and the airflow rate (V). It must be clear which application program calculates which parameters. Furthermore, it must be clear that all application programs apply the same parameter definition. If they do not have the same definition, then there should be a treatment on the parameter during the exchange of data.
2. The frequency and point in the solution procedure where the data is exchanged between the application programs.
   Should the data be exchanged every time step? Or every hundred time steps? For every exchange of data, should there be an iteration until convergence, or just exchange and march on to the next time step?

3. The method of time step control.
   Should both simulations be dynamic? If both are transient or quasi-steady-state, should they have the same time step?

The third issue is about the use of different geometry modelers. Citherlet et. al. (2001) indicate several disadvantages if we have to create more than one model for a single project. Firstly, it is time consuming. Secondly, any modification in the project has to be translated between models. However, this should be seen as a price for doing a coupled simulation. Furthermore, there are some developments in the area of application interoperability where the issue of data management of computer models is one of the main issues (Karola et. al. 2001). It is expected that this problem will be resolved if these developments mature.

COUPLING PROCEDURE DECISION METHODOLOGY

When various design options have to be assessed, it will be evident that a high resolution (and more complex) approach may require significantly more resources in terms of computing capacity, manpower and time. On the other hand lower resolution (and less complex) approaches may not reliably solve a particular problem. How to select the appropriate approach to solve the design problem at hand remains a challenge.

In practice – especially with inexperienced users – one may observe the tendency to use the most sophisticated and highest resolution method to simulate a design option. Obviously, the perceived sophistication of a high resolution approach would not fail to impress any client. However, the additional cost of using a higher resolution method should always be justified. Failing to do so will only risk that a client will hesitate to use the method – or simulation in general - in the future.

A prototype Coupling Procedure Decision Methodology (CPDM) has been developed to help the decision making on what approach should be used for a particular problem. The main ideas behind the CPDM as schematically shown in Figure 2 are:

1. A simulation should be consistent with its objective, i.e. the designer should not be tool-led (the use of tools – usually the most sophisticated – without considering the apropriateness of the tools for the problem at hand).

2. There should be a problem-led (not tool-led) rationale to progress from one level of resolution and complexity to the next.

3. The selection of a better design option (among many design options) should be made at the lowest resolution possible, so that less design options need to be simulated at a higher resolution level.

The vertical axis of the chart in Figure 2 represents layers of different resolution of building simulation. Increasing levels of resolution are, e.g. energy simulation, airflow network simulation, and 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 the building simulation.

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

- If energy consumption is of interest, then BES would probably be sufficient.
- If a temperature gradient should be predicted, then at least an AFN is required.
- If local mean age of air is in question, then CFD is necessary.

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

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

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 very much depend on the skills and experience of a design engineer. Instead, e.g. sensitivity analysis is proposed as a decision making tool.

Starting from the top of the chart, there should be an assessment whether a certain case should be simulated at the simplest level of complexity at a certain level of resolution. If the problem cannot be solved at the simplest level of complexity - whatever the resolution is - then a certain form of coupled simulation is required.

Performance Indicators

The decisions in building design are based on performance indicators. Table 2 presents some typical performance indicators (PI) that are of interest to a building engineer. With regard to the CPDM, these indicators can be used to select the appropriate approach to simulate the problem at hand. However, not every indicator needs to be calculated by simulation. On every level, simpler calculation methods may be employed to calculate some of the indicators. For example, at BES level, the gas consumption can be simulated through explicit HVAC system simulation. However, this is complicated. A much simpler "paper-and-pencil" method could just as well be employed with acceptable accuracy.

Table 2 also gives an indication of the minimum resolution that would be required to evaluate the performance indicator. As can be seen, only a few indicators require an immediate jump to the higher resolution AFN or CFD-approach.

Table 2
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

Energy demand and maximum load, both for heating and cooling, may well be calculated from BES. Fan electricity, gas consumption and primary energy, normally, are more difficult to simulate, as the simulation must include explicit system simulation. Instead fan electricity consumption, gas consumption and primary energy can be calculated manually using a BES simulation result as the base.

PPD (Percentage People Dissatisfied) is used as an indicator for the general thermal comfort of occupants in the space. The maximum and minimum zone temperature and the overheating period are relevant as comfort indicators for naturally ventilated building. For air-conditioned buildings these indicators determine the capacity of the installations.

Performance Assessment

The performance assessment is a two-step procedure. In the first step of the assessment it should be clear that the performance indicators have been derived at the correct level of resolution. The second step then deals with the judgment of the actually derived value and the required performance.

To assess the validity of the applied resolution level, sensitivity analysis is used as the decision tool. Sensitivity analysis is the systemic investigation of the simulation response to either extreme values of the model's quantitative factors or to drastic changes in the model's qualitative factors (Kleijnen 1997). This analysis is used in many fields of engineering as a what-if analysis, and one example of the use of this method in building simulation is given by Lomas and Eppel (1992).

The main use of sensitivity analysis is to investigate the impact of a certain change in one (or more) input parameter on 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.

For the CPDM, the sensitivity analysis is used for a slightly different purpose. The sensitivity analysis is not use to identify which input parameter is important, but rather to identify the effect of changes in one input parameter to a number of outputs. Which input parameter is used in this study is selected from the result of previous research in this area.

From previous studies, e.g. Hensen (1991), Negrao (1995), and Beusolleil-Morrison (2001), it is known that there are two main inputs that should be tested through a sensitivity analysis in order to decide if progress to a higher resolution level is necessary:

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

For the "normal" use of sensitivity analysis where there are many input parameters and a single output, the effect of each input parameter can be quantified relative easy. However, with the use of sensitivity analysis as described for the CPDM, it is not intended to compare the effect of changes in one input parameter (e.g. airflow parameter) on different outputs (e.g. heating demand and heating load). Different outputs have different significance in different building designs. Therefore within the CPDM the performance indicators are not weighted. Instead, to quantify the effect of changes in input to the performance indicators, the difference in the performance indicator value when the input is changed from a minimum to a maximum value is used.

Figures 3 shows two possible scenarios for the sensitivity analysis. Here two examples are shown of results for two performance indicators with different target values. In Figure 3(a), a sensitivity analysis at the lower (BES-) resolution level indicates that the performance may not be met as a result of the large sensitivity for the convective heat transfer coefficient. The next level of resolution therefore is applied to calculate the specific performance. The sensitivity analysis for the (AFN-) resolution level indicates that the investigated design meets the required performance, also when including the sensitivity, and higher resolution simulation is not required for this performance indicator. The second example, Figure 3(b), shows that in another situation a further resolution increment may well be possible.

CASE STUDY

To indicate the applicability of the Coupling Procedure Decision Method a case study has been prepared in which the method is followed step by step. After a short description of the investigated case, some results and the related rationale are given that is used to proceed through the CPDM.

The case study concerns an open-plan office space in a new faculty building of the Eindhoven University of Technology (Figure 4). The 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 equipment this leads to 35 W/m2 internal gains. There is an all-air heating and cooling system serving the area.

Given the large glazing area, the building designer would like to predict the energy consumption, heating and cooling loads, and most importantly the likelihood of thermal comfort complaints, that 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. The designer considers several design options for comparison. Table 3 shows the different design options for this case study. An extended description of the case is described in Djunaedy (2002).

Methodology for the case study

Referring to the first layer of Figure 2, BES, typical office conditions are used as simulation parameters for the "base condition". The performance assessment of a case is based on two sensitivity analyses:

1. Airflow parameters.
   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, and these two values are assumed as minimum and maximum value for the sensitivity analysis.

2. Convective heat transfer coefficient.
   In the base condition, the simulation will apply the Alamdari-Hammond empirical relation (Alamdari and Hammond 1983) as a specification of the convective heat transfer coefficient. This relation applies for natural convection flows. However, the flow in the room may be of another flow type. Therefore, it is assumed that the heat transfer coefficient may range from 1 - 6 W/m^{2}K. These two values are taken as the minimum and maximum value for the sensitivity analysis.

Table 3
Considered design options

Isometric view	Glazing	Remarks
[FigureTable3a]	Double Glazing, no blinds	Conf. 1 = Base case
[FigureTable3b]	Double Glazing, no blinds	Conf. 2 is the same as the Conf. 1, but the glazing area is reduced to 2mX4m.
[FigureTable3a]	Double Glazing, internal blinds	Conf. 3 is the same as Conf. 1, with additional blinds in the internal part of the room
[FigureTable3a]	Double Glazing, blinds in the middle	Conf. 4 is the same as Conf. 1, with additional blinds in the middle between the two glazing.
[FigureTable3c]	Double Glazing, no blind	Conf. 5 is the same as Conf. 1, with additional curtain 0.5m from the wall, down to 2m above the floor.

ESP-r has been applied for the simulations in this layer. The air conditioning strategy for all simulations is to maintain a PPD level that is lower 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 simulations show the energy consequences of maintaining a high comfort level for the space. The results of the sensitivity analyses are used to determine whether the simulation on a higher resolution level is needed or not, and, if this is required, which configurations are tested.

On the second layer, AFN, the airflow network model is used to represent some significant airflows in the buildings. Figure 5 and 6 present the airflow network configurations that have been used for the AFN-coupled simulation. The fans supply fresh air for 10 person (i.e. 10 lps per person or 0.1 m^3/s). The infiltration through the exposed wall is now calculated by the network model and not assumed as in the BES-only simulation. This is represented by the line between "south" and "zone" nodes. For Configuration 5, as in Figure 6, there is one additional node in the gap between the glazed wall and the curtain. The air in the gap exhausts at 0.01 m^3/s when the temperature reaches 27 °C.

The coupled BES-AFN simulation is indicated as the "base condition" on this level. All selected configurations were subject to a sensitivity analysis for the convective heat transfer coefficient. In the base condition again the Alamdari-Hammond method for the specification of convective heat transfer coefficient is applied.Again, the result of the sensitivity analysis is used to determine whether a simulation on a higher resolution level is needed or not, and if it is required, which configurations should be tested.

On the third layer, CFD, the simulation is focused on the distribution of the airflow parameters in the room. Zhai et. al. (2001) proposed several methods of coupling. In this study, the simple two way coupling is used. The result from a previous simulation (i.e. wall temperature and heat extraction rate) is supplied as boundary condition for the CFD calculation. The energy calculation is repeated using the convective heat transfer coefficient value supplied from the CFD calculation result.

Table 2 indicates the minimum required resolution for each performance indicator. It is obvious that the simulations on higher resolution level should have less configuration (or cases) to be tested. The decision on which configurations are to be simulated at higher resolution cannot be made in advance, this is the result of the performance assessment.

Results of BES-only simulations

In Table 4 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, “min” and “max” refer to the value of the performance indicators when airflow or convective heat transfer coefficient is set to the minimum and maximum value respectively. The result of sensitivity analysis can also be presented in terms of maximum deviation from the base condition. This deviation is expressed as a percentage deviation.

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 weigthing 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 is the criteria for the simulation.

It should be noted that the PPD values presented in the results are not in the same location as the controlled location. The control strategy in the simulation is to set the operative temperature in the center of the zone so that the PPD value is 10% in this location.

However, in the result, the PPD values considered for decision making (in CPDM) are from other location, i.e. in occupied zone (1m from the floor, three location along long axis of the room). The PPD presented in the paper 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 is indicated.

The use of the CPDM to determine the correct resolution level - The above presented sensitivity analysis is used in the CPDM to select the appropriate level of resolution for each case. 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 5. Here the sensitivity higher than 20% is shaded, indicating the need for that specific case to be simulated at a higher resolution level.

The use of CPDM to select a better design option - Before the next higher resolution level is addressed a selection procedure should be performed. The results in Table 4 and Table 5 support this selection procedure. 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 therefore are 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 (see Table 4) and therefore is not preferred. If architectural consideration is not important, and hence the construction can be changed, Configuration 2 is the best design option. However, if the architectural consideration is the main restriction and cannot be changed, then Configuration 4 and Configuration 5 should be selected for simulation at a higher resolution level. The results of this investigation will be discussed in the next paragraph.

Results of BES-AFN coupled simulation

As in BES-only simulations, again the PPD is used as the target parameter that is to be maintained throughout the simulations. The target PPD value is 10%. In Table 6 results for the coupled simulation, including the sensitivity study are shown, similar to results presented in Table 4. The sensitivity in this case is restricted to the convective heat transfer coefficient, as the airflow parameter is dealt with in the AFN.

Again, at this point in the design process, there are two decisions that should be made, whether a CFD-coupled simulation is needed, and if yes, which configuration(s) should be selected for further simulation. Therefore in Table 7 the results of the sensitivity analysis with the AFN-coupled simulations are compared to the results for the BES-only simulations. The results are shown for Configurations 1, 4 and 5 respectively.

Table 4a
Results of sensitivity analysis for different configurations (BES-only) (continued)

	Configurations	Base Condition	af		hc		S_{af}	S_{hc}
			min	max	min	max		
Heating energy demand	Configuration 1	4891	3057	6383	4510	5866	38%	20%
	Configuration 2	3570	1415	5346	3462	3920	60%	10%
	Configuration 3	6883	4586	8664	6443	8012	33%	16%
	Configuration 4	4798	2638	6529	4641	5336	45%	11%
	Configuration 5	4207	2212	5833	4008	4791	47%	14%
Cooling energy demand	Configuration 1	3734	4803	3148	3583	3612	29%	4%
	Configuration 2	1462	2572	971	1476	1361	76%	7%
	Configuration 3	719	1134	529	676	737	58%	6%
	Configuration 4	1448	2251	1053	1388	1455	55%	4%
	Configuration 5	2168	3209	1628	2175	2016	48%	7%
Max heating load	Configuration 1	17	14	19	12	28	17%	66%
	Configuration 2	14	11	17	11	23	25%	61%
	Configuration 3	18	15	20	13	29	16%	64%
	Configuration 4	16	13	18	12	26	20%	62%
	Configuration 5	15	12	18	11	24	21%	57%
Max cooling load	Configuration 1	14	14	13	10	15	5%	25%
	Configuration 2	6	6	5	5	6	13%	11%
	Configuration 3	7	7	6	5	8	7%	25%
	Configuration 4	7	8	7	6	8	7%	21%
	Configuration 5	8	8	7	7	8	10%	13%
Gas consumption	Configuration 1	611	382	798	564	733	38%	20%
	Configuration 2	446	177	668	433	490	60%	10%
	Configuration 3	860	573	1083	805	1002	33%	16%
	Configuration 4	600	330	816	580	667	45%	11%
	Configuration 5	526	276	729	501	599	47%	14%
Fan energy consumption	Configuration 1	3714	3714	3714	3714	3714	0%	0%
	Configuration 2	3714	3714	3714	3714	3714	0%	0%
	Configuration 3	3714	3714	3714	3714	3714	0%	0%
	Configuration 4	3714	3714	3714	3714	3714	0%	0%
	Configuration 5	3714	3714	3714	3714	3714	0%	0%

In Table 7 significant differences can be found between the calculated individual performance indicators for the two approaches. Differences up to a factor of five and higher are calculated, especially for the energy related performances.

Some differences are expected as in this case an explicit definition of the infiltration rate through the glazed wall is applied. However, the large difference with the values of the performance indicators for the base condition suggests that there is a large difference in the infiltration value between the two simulation approaches. Table 8 therefore shows the typical infiltration rates through the glazed wall that is calculated with the BES-AFN coupled simulation. When the fan is on (during office hours), the infiltration value is negative, indicating an outflow from the zone. The infiltration rate remains relatively constant. When the fan is off, the values fluctuate and the flow direction alternates. The table indicates the average values of this fluctuating flow. The values are much lower than the 0.3 ACH that was assumed in the BES-only simulation. The values are even less than the minimum value for sensitivity analysis, which was set at 0.05 ACH.

Table 4b
Results of sensitivity analysis for different configurations (BES-only) (continued)

	Configurations	Base Condition	Af		hc		S_{af}	S_{hc}
			min	max	min	max		
Primary energy	Configuration 1	12339	11573	13245	11806	13193	7%	7%
	Configuration 2	8745	7701	10031	8651	8995	15%	3%
	Configuration 3	11316	9434	12907	10834	12463	17%	10%
	Configuration 4	9959	8603	11295	9743	10506	14%	5%
	Configuration 5	10089	9135	11175	9897	10521	11%	4%
PPD winter	Configuration 1	8	8	8	8	8	0%	6%
	Configuration 2	8	8	8	8	7	1%	4%
	Configuration 3	8	8	8	8	8	0%	6%
	Configuration 4	8	8	8	8	7	0%	5%
	Configuration 5	7	7	7	7	7	1%	4%
PPD summer	Configuration 1	6	6	6	6	6	1%	8%
	Configuration 2	6	6	6	6	6	0%	3%
	Configuration 3	7	7	6	7	6	2%	3%
	Configuration 4	7	7	7	7	7	0%	5%
	Configuration 5	6	6	6	6	6	0%	2%
Max zone temperature	Configuration 1	36	39	36	37	35	9%	4%
	Configuration 2	33	31	34	35	30	6%	8%
	Configuration 3	36	34	36	37	31	4%	11%
	Configuration 4	34	33	35	37	31	3%	9%
	Configuration 5	33	33	34	35	31	3%	7%
Min zone temperature	Configuration 1	9	11	8	9	10	22%	9%
	Configuration 2	11	14	10	11	13	24%	13%
	Configuration 3	9	11	8	8	10	22%	10%
	Configuration 4	10	12	9	10	11	23%	12%
	Configuration 5	11	13	9	10	12	21%	11%
Overheating	Configuration 1	522	1061	359	1162	296	103%	123%
	Configuration 2	80	621	56	238	36	681%	199%
	Configuration 3	169	155	207	495	25	22%	193%
	Configuration 4	150	384	157	338	64	157%	126%
	Configuration 5	262	983	150	599	118	275%	129%

This (large) difference between the results of BES-only and AFN-coupled simulation should be seen as an example on the extreme limitation of both simulations. In one hand, BES-only simulation needs assumption on airflow parameters, on the other hand AFN-coupled simulation needs additional information on the airflow network components (e.g. crack model of the façade, fan model, etc). In this case, for the AFN-coupled simulation additional information is needed on the airtightness of the façade. Moreover, from the airtightness data, the crack characteristic of the façade should be derived. In the applied model the crack is assumed to be represented by a width and a length (assumed 1 mm and 6 m respectively). At this point, however, there is not enough information to support this assumption.

Turning back to the results, in Table 7 a sensitivity of more than 20% is shaded. Applying this information, all of Configurations 1, 4 and 5 have several cases that would require a CFD-coupled simulation. Nevertheless, this information is not enough to decide on which configuration requires further investigation.

Table 5
Results of sensitivity analysis with BES-only simulation for all configurations

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)

Additional information from the results for the different configurations must be used to select which design option has the best overall performance. Table 6 shows that Configuration 1 is outperformed by Configurations 4 and 5. There is no significant difference in comfort performance between Configuration 4 and 5. However, Configuration 4 has a higher heating and a lower cooling demand, while for Configuration 5 this is the other way around. They both have a similar value for the primary energy. Configuration 4 has a maximum heating load that is around 40% higher than Configuration 5. This may result in higher design specifications for the heating equipment for Configuration 4. This is not desirable. From the above discussion, it therefore is concluded that Configuration 5 has the best overall performance.

BES-AFN-CFD coupled simulation and more

From the evaluation of the results thus far Configuration 5 shows the best performance. Is it necessary that Configuration 5 be simulated with a CFD-coupled simulation? If we use the 20% limit of the maximum deviation, there are several cases that need to be simulated with a CFD-coupled simulation. However, further consideration should be used in addition to the 20% limit value.

Most of the sensitive cases are energy related. If energy is the main consideration then the decision should be based on the primary energy, which represents the total amount of energy. The tables indicate that the primary energy is not sensitive to the convection coefficient. So, even if a CFD-coupled simulation is performed, theoretically this will not influence the primary energy value that is predicted by the AFN-coupled simulation, ±1% which is the maximum deviation from the base condition of the AFN-coupled simulation. With this argument, one therefore can conclude that the results from AFN-coupled simulation are sufficient to answer the design questions for this building. There is no need to do the CFD-coupled simulation.

Table 6
Results of sensitivity analysis for different configurations (AFN-coupled)

Configuration	**Heating energy demand**		**Cooling energy demand**		**Fan energy consumption**	
	BaseValue	**S_{hc}**	**BaseValue**	**S_{hc}**	**BaseValue**	**S_{hc}**
Configuration 1	1029	83%	7055	3%	3714	0%
Configuration 4	3128	14%	2539	3%	3714	0%
Configuration 5	573	64%	5369	4%	3714	0%
	(a)		(b)		(c)	

Configuration	**Gas consumption**		**Primary energy**		**Max heating load**	
	BaseValue	**S_{hc}**	**BaseValue**	**S_{hc}**	**BaseValue**	**S_{hc}**
Configuration 1	129	83%	11798	7%	12	89%
Configuration 4	391	14%	9381	5%	14	60%
Configuration 5	72	64%	9656	2%	11	82%
	(d)		(e)		(f)	

Configuration	**Max cooling load**		**PPD winter**		**PPD summer**	
	BaseValue	**S_{hc}**	**BaseValue**	**S_{hc}**	**BaseValue**	**S_{hc}**
Configuration 1	14	30%	6	6%	6	10%
Configuration 4	8	21%	6	3%	7	4%
Configuration 5	8	18%	8	4%	6	1%
	(g)		(h)		(i)	

Configuration	**Max zone temperature**		**Min zone temperature**		**Overheating**	
	BaseValue	**S_{hc}**	**BaseValue**	**S_{hc}**	**BaseValue**	**S_{hc}**
Configuration 1	40	7%	12	6%	1966	65%
Configuration 4	35	11%	13	9%	841	97%
Configuration 5	34	7%	14	9%	1707	68%
	(j)		(k)		(l)	

Table 7
Results of sensitivity analysis with AFN-coupled simulation for all configurations

	Performance Indicators	**BaseValue**		**S_{hc}**	
		BES-only	**AFN-coupled**	**BES-only**	**AFN-coupled**
Configuration 1	Heating energy demand	4891	1029	20%	83%
	Cooling energy demand	3734	7055	4%	3%
	Max heating load	17	12	66%	89%
	Max cooling load	14	14	25%	30%
	Gas consumption	611	129	20%	83%
	Fan energy consumption	3714	3714	0%	0%
	Primary energy	12339	11798	7%	7%
	PPD winter	8	6	6%	6%
	PPD summer	6	6	8%	10%
	Average zone temp - winter	25	27	5%	5%
	Average zone temp - summer	23	22	9%	12%
	Max zone temperature	36	40	4%	7%
	Min zone temperature	9	12	9%	6%
	Overheating	522	1966	123%	65%
Configuration 4	Heating energy demand	4798	3128	11%	14%
	Cooling energy demand	1448	2539	4%	3%
	Max heating load	16	14	62%	60%
	Max cooling load	7	8	21%	21%
	Gas consumption	600	391	11%	14%
	Fan energy consumption	3714	3714	0%	0%
	Primary energy	9959	9381	5%	5%
	PPD winter	8	6	5%	3%
	PPD summer	7	7	5%	4%
	Average zone temp - winter	25	26	5%	4%
	Average zone temp - summer	24	24	4%	5%
	Max zone temperature	34	35	9%	11%
	Min zone temperature	10	13	12%	9%
	Overheating	150	841	126%	97%
Configuration 5	Heating energy demand	4207	573	14%	64%
	Cooling energy demand	2168	5369	7%	4%
	Max heating load	15	11	57%	82%
	Max cooling load	8	8	13%	18%
	Gas consumption	526	72	14%	64%
	Fan energy consumption	3714	3714	0%	0%
	Primary energy	10089	9656	4%	2%
	PPD winter	7	8	4%	4%
	PPD summer	6	6	2%	1%
	Average zone temp – winter	25	27	4%	4%
	Average zone temp – summer	24	23	6%	7%
	Max zone temperature	33	34	7%	7%
	Min zone temperature	11	14	11%	9%
	Overheating	262	1707	129%	68%

However if local discomfort is suspected and if comfort considerations are given a higher priority, then another conclusion may be drawn. In that case a CFD-coupled simulation may be necessary.

In the above described example in principle the gas consumption should be simulated at a higher resolution level, considering the high sensitivity to the airflow parameter. However, even with the airflow network model included in the simulation, the result will not give any indication as to how many hours the boiler will work. A higher resolution level should be used to calculate the gas consumption, i.e. by applying explicit plant simulation. This level of resolution, however, is not on the same axis as the airflow.

Table 8
Infiltration rate through the facade

	ACH	
	Fan OFF	Fan ON
Configuration 1	0.0016	-0.0053
Configuration 4	0.0004	-0.0202
Configuration 5	3.75E-11	-0.0935

CONCLUSION AND FUTURE DIRECTIONS

This paper elaborated and demonstrated the objectives and initial results of an ongoing research project aimed at external coupling of building energy simulation programs with air flow network simulation tools and CFD software. This research is part of a larger project of which the objective is a co-operative distributed integrated building simulation environment for optimization of building energy performance and indoor environment as schematically shown in Figure 7.

As elaborated in this paper, the objective of the initial stages of the current project on coupling of building energy and air flow domain software is to develop the Coupling Procedure Decision Methodology (CPDM). Its task is to systematically guide the selection process of resolution level and complexity of the simulation. In our opinion, this is an essential step because it will clarify for which purpose the coupling is needed at a particular point in the design process. On the basis of this knowledge it can then be decided which parameters and variables need to be exchanged between the coupled tools, and at which time-steps this should take place.

The novelty of this work is the CPDM which covers the whole range of simulation tools and uses the tools according to the need at a specified time. Simulation analysis is proposed as the tool for decision making, however other mechanisms might also be possible and more work is needed to refine the decision criteria.

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LIST OF CAPTIONS FOR FIGURES

Figure 1
Coupled simulation; a. Citherlet et. al. (2001), b. generalized

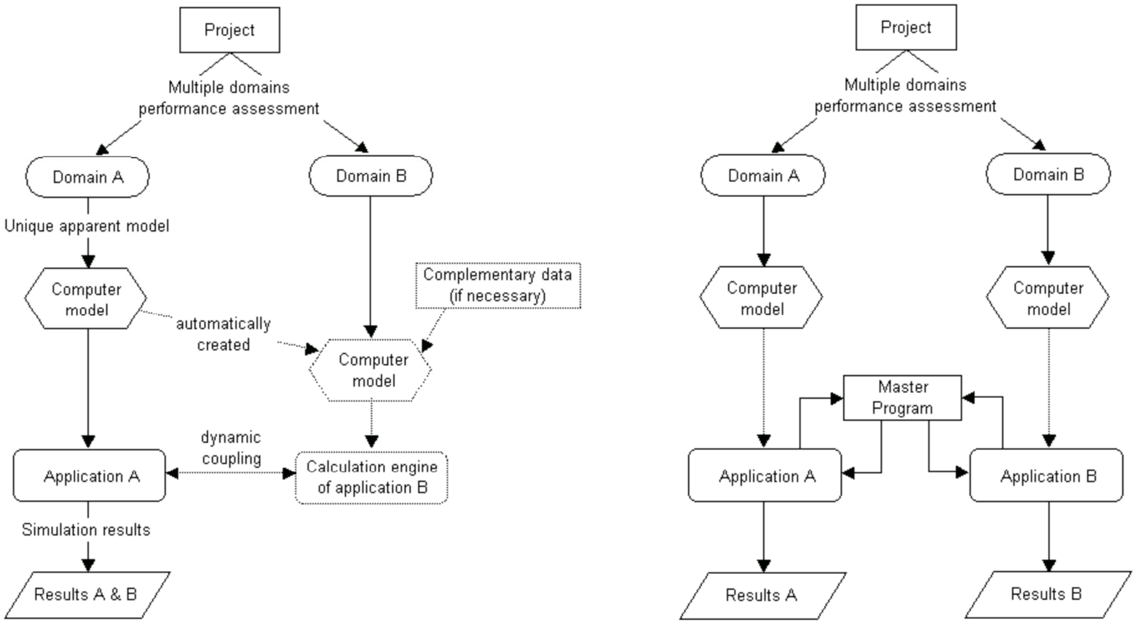


Figure 2
Prototype airflow based performance assessment methodology

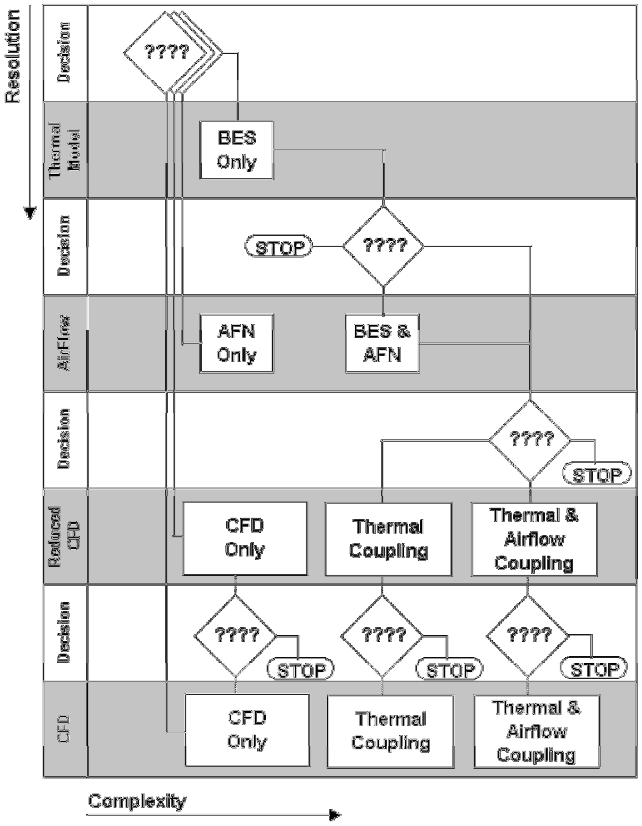
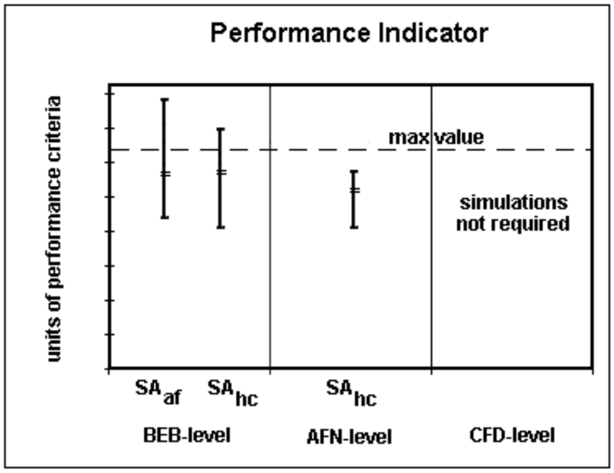


Figure 3
Assessment of the validity of the level of resolution through sensitivity analysis.
(a) Scenario 1



(b) Scenario 2

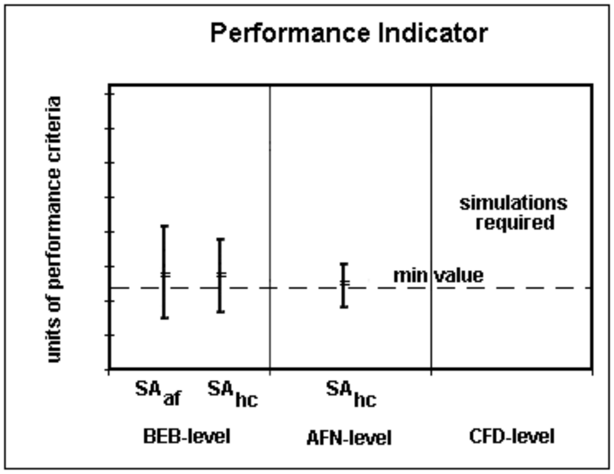


Figure 4
The building and the model

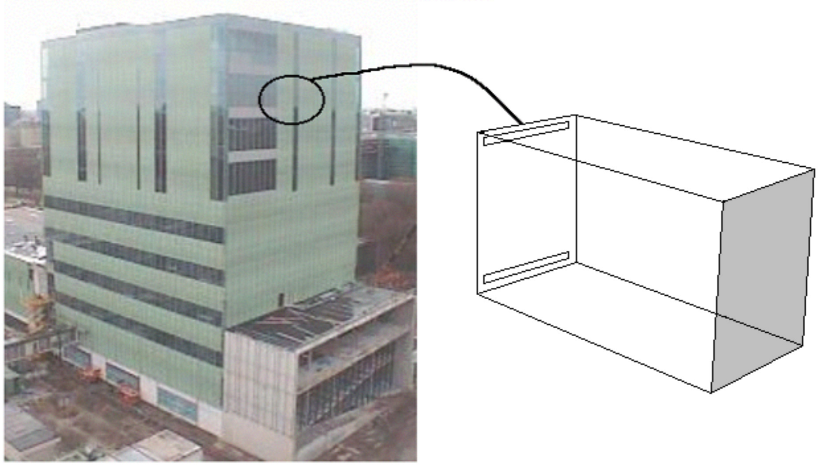


Figure 5
Airflow network model for Configuration 1 and 4

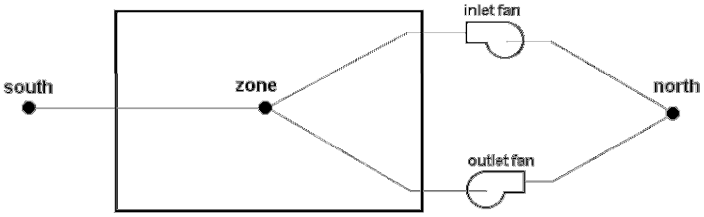


Figure 6
Airflow network model for Configuration 5

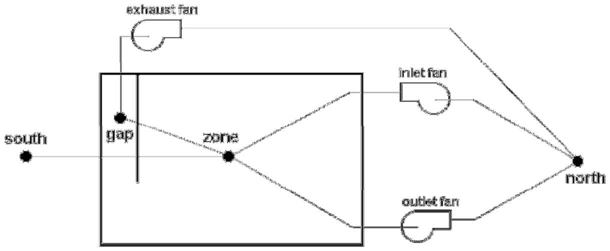


Figure 7
A distributed integrated building simulation environment based on an advanced multi-zone building simulation software run-time linked to external software packages