IMPLICATIONS OF THE UNCOUPLING OF BUILDING AND HVAC SIMULATION IN THE PRESENCE OF PARAMETER UNCERTAINTIES

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ABSTRACT

Building simulation has made significant advances towards fully integrated building-system simulation. An intriguing question is however, whether a fully coupled "brute force" approach is always relevant and necessary, given the fact that the combined simulation is computationally intensive and, perhaps more important, requires a substantial effort on the part of the energy modeler as the HVAC system model is complicated and requires a high level of expertise and attention to modeling details. In addition there is an increasing focus on the role of modeling uncertainties and modeler's bias in energy simulation outcomes. To analyze the combined effect of uncertainty in building parameters and HVAC system properties, the natural tendency is to model the HVAC system as an integral part of the whole building simulation. In this paper we investigate whether this approach is justified in the light of unavoidable uncertainties which may blur the advantage of the coupled simulation. To do so, we compare an uncoupled sequential approach (using a dynamic building simulation followed by a simplified HVAC calculation platform) with the fully coupled dynamic simulation. We limit the investigation to a case study building with different types of HVAC systems, and focus only on energy consumption outcomes. The results of both a deterministic and uncertainty analysis outcomes are discussed.

INTRODUCTION

Decoupling the HVAC system from the building and running two sequential simulations implies that we ignore the bi-directional dynamic interaction between the demand and supply side. The general expectation is that this leads to unacceptably large errors due to the ignored interaction. This implies an initial rejection of the uncoupled treatment. The counterargument that can be made though is that many industry accepted HVAC design procedures are in fact based on simplified procedures, that operate on approximations of the latent and sensible load profiles of the building (Khazaii, 2012). Moreover, the procedures use empirical relationships for the operation of each component and ignore the deeper dynamic interactions in the system. The typical simplified calculation is based on a (monthly) design day leading to 24 hourly calculations of the energy consumption of the system. The procedure does not claim to be very precise but good enough to compare different system concepts based on predicted total energy consumption. This justifies the hypothesis that the approach may be acceptable in the light of many other sources of uncertainties that could "blur" to some extent the errors resulting from the decoupling. To perform a test on the admissibility of uncoupled sequential building and HVAC simulation we perform the comparison depicted in Figure 1. EnergyPlus is used for the coupled dynamic simulation and EnergyPlus+ROSEC for the uncoupled simulation. ROSEC (Reduced Order System Energy Calculation) was developed as a direct implementation of a simplified HVAC energy consumption procedure in the form of an Excel spreadsheet (Khazaii, 2012). ROSEC follows the standard ASHRAE approach for HAVC sizing closely, and basically contains the same input parameters as encountered in the HVAC component formulations in EnergyPlus. It is obvious that the uncoupling introduces two errors: (1) the effect of dynamic interaction is neglected, and (2) the HVAC simulation is simplified.

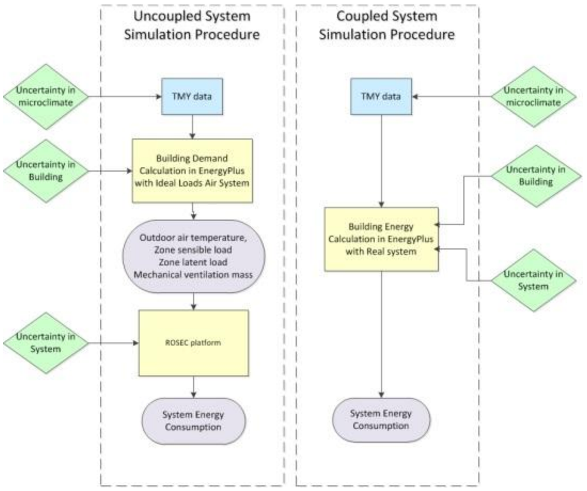


Figure 1 Coupled and uncoupled building simulation procedure

The motivation to attempt the uncoupling is mainly one of convenience. The coupled system simulation approach requires a higher level of expertise of system modeling. In addition, advanced tools like EnergyPlus will require a more detailed

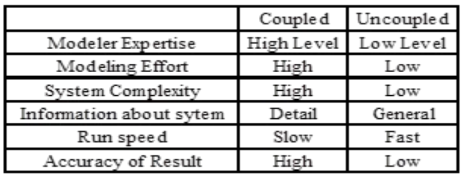
HVAC system model than some modelers would prefer.

BACKGROUND

Building energy models are based on heat and mass balance equations, temperature set point schedules, operational schedules and psychometric equations to calculate total sensible and total latent loads for all zones and the building as a whole, for each hour of the year. Back in the early 80's, major building performance simulation tools, such as BLAST and DOE-2, used the energy balance method to conduct a sequential simulation of building annual energy consumption. In these early building simulation programs, the building model was divided into three parts: building, systems, and plant. These were then simulated sequentially in feed forward mode, without feedback from one to the other while in the current integrated simulation approach, these three parts are solved simultaneously. The sequential approach starts with solving the energy balance equations at the building zone level, then feeds the zone conditions and heating/cooling loads to the HVAC system model. The HVAC system model will then calculate the energy required to remove the calculated zonal loads. (DOE-2 Basics, 1991; BLAST 3.0 User's Manual, 1980). This separated system and building modeling approach can provide accurate results when the system response is smooth and fairly independent of the dynamics of the building. In the case the system's behavior is highly dependent on the interaction of building-system behavior, e.g. in the light of varying loads in different zones, dynamic responses to varying outside conditions and inertia in the way that zones respond to supplied heating and cooling, large errors are potentially introduced through the uncoupling. One could therefore expect that in an air-based VAV or CAV system the interactions, hence errors are minor, whereas for a water-based systems such as radiant floor heating, the uncoupled approach could lose its applicability (Witte, et al., 1989). The question how large the error from ignoring the dynamic interaction is in different systems and building combinations has not been answered conclusively in literature. Our research poses this question against the background of unavoidable uncertainties, even in the fully coupled integrated simulation. The answer therefore requires the quantification of the uncoupling errors whilst also quantifying uncertainties introduced in the modeling processes. A comparison of the two should provide a more meaningful answer to the question. Before we do so let's explore the advantages and usefulness of different modeling approaches suggested in the literature.

Both coupled and decoupled method of modeling a whole building have been advocated in various situations as both have their advantages and disadvantages. The energy modeler needs to find a trade-off between the effort and time to put in the coupled simulation method, and the level of accuracy of the final outcome. Table 1 gives a feature comparison between the coupled and uncoupled simulation.

Table 1 Feature comparison



	Coupled	Uncoupled
Modeler Expertise	High Level	Low Level
Modeling Effort	High	Low
System Complexity	High	Low
Information about sytem	Detail	General
Run speed	Slow	Fast
Accuracy of Result	High	Low

There are obviously different levels of HVAC modeling fidelity and each level poses different requirements on modeling expertise. For certain types of applications, such as the development of a building energy management system, comparing HVAC system alternatives and evaluating different control strategies, one will need an integrated model with sufficient level of detail in the HVAC system model to meet the above goals. However, for earlier stages of building design analysis, mostly dominated by the need to estimate annual energy consumption, it is more likely that a simplified approach that greatly reduces the modeling work load and improves the calculation efficiency (Trcka, M, and JLM Hensen, 2010) is acceptable. Indeed, when one is focused mostly on energy use, simplified models can save time and provide a fast way to explore different HVAC systems and their impact on energy cost. In fact, there is some evidence that most design analyses do not require detailed system modeling since the overall energy consumption can be estimated with simple reduced order calculation. Korolija (2011) studied the response of different types of HVAC systems and fitted regression models to predict HVAC cooling/heating energy requirements with building cooling/heating demand and proved that simple regression models can also guarantee a sufficient level of accuracy and be used in selecting a suitable HVAC system for office building in the design phase. This raises the expectation that uncoupled simulation is acceptable in many cases.

METHODOLOGY

As indicated above, our objective is to compare the outcomes of coupled and uncoupled simulations, while quantifying the effect of uncertainties in both. In the last decades, there has seen an increasing trend to focus on the uncertainty in the building simulation outcomes. This has called for a type of uncertainty analysis that quantifies the impact of physical parameter uncertainty, modeler assumptions and model simplifications on the outcomes. Such analysis is typically carried out using a Monte Carlo approach with an appropriate sampling technique in order to increase computational efficiency Saltelli, Ratto et al. (2008), MacDonald (2002) and De Wit and Augenbroe (2002) introduced a general procedure for uncertainty analysis of thermal building performance. Hu (2009) conducted uncertainty analysis in a power reliability study for the design of an off-grid solar energy house. Sun and Heo (2011) conducted a study on uncertainty of microclimate variables. Khazaii (2012) studied different sources of HVAC system uncertainty such as equipment manufacture tolerance, system degradation, and duct leakage. Rasouli (2013) studied the impact of the uncertainty in building and system parameter on the energy saving potential and economics of ERVs. These efforts represent only a small slice of a growing body of work that studies the effect of uncertainties encountered at different model levels (e.g. micro-climate, building level, system level) on building performance. This paper uses the parameter uncertainty quantifications and techniques developed in the mentioned sources. Our special focus is on the parameterization and implementation of HVAC system uncertainties as they have received less attention in the literature thus far.

To perform a whole building simulation under uncertainty is equipping building energy models with uncertainty ranges of all relevant parameters in the model. They are related to building physical behavior, occupant behavior, workmanship, scheduling and control uncertainty, as well as uncertainty in the HVAC system parameters. If the simulation tool is able to handle the whole building including the dynamic interaction between the building and the systems, a full uncertainty analysis can be performed with the whole building simulation model but as alluded to earlier, the question posed in this paper is whether such a "brute force" approach to the combined demand and supply uncertainty is indeed necessary in the light of uncertainties..

To answer the question, we need to identify all sources of uncertainty in both the building and HVAC model. On the HVAC side we limit our treatment to the tolerances of the equipment performance curves. We assume these tolerances to be within the range that current industrial compliance tests allow in reference to the nameplate information that identifies the performance of the equipment. This is described in detail by Khazaii (2012) who performed an uncertainty analysis based on equipment tolerances, duct leakage, sensor drift and performance deterioration. In the current study we limit the treatment to the equipment tolerances, that we express in the part load performance curves, as indicated for an example equipment below. Fig 2 shows the performance curve tolerance parameterized by a tolerance factor that ranges from 0 (red curve) to 5 (black curve) percent underperformance. The tolerance uncertainty parameter can take on any value between 0 and 5 indicating curves between the two extremes shown in the figure.

These and the other mentioned parameterized uncertainties can easily be integrated in ROSEC, which has special macro parameters to indicate system performance decrease factors or loss factors. In the coupled simulation however, the HVAC system models that are used in this study only contain the performance curve tolerances from Fig 2. The reason for this limitation is that in the detailed component based description in for example EnergyPlus, there is no easy implementation of macro loss factors such as caused by duct leakage. Whereas a generic loss factor that accounts for duct leakage can be introduced quite easily in the simple calculation procedure, it has to be explicitly modeled in EnergyPlus as a physical parameter of the HVAC model, e.g. through a plenum that can accept the lost air. In order to remain objective and generic in our attempt to prove the hypothesis, these workmanship and deterioration effects are not regarded.

In the building model used in our study, all sources of uncertainty, traditionally used in whole building uncertainty analysis are considered (De Wit and Augenbroe 2002, Macdonald 2002, Cóstola, Blocken et al. 2010, Domínguez-Muñoz, Anderson et al. 2010, Hopfe and Hensen 2011). In addition the recent work based on rigorous UQ of different model formulations (Sun et al, 2013) is considered as well in our analysis.

Figure 1 above introduced the procedure of the analysis. In first instance a deterministic comparison of the results of coupled and uncoupled simulation is performed. This is followed by a comparison of the results if both approaches are performed under consideration of uncertainties in the models, both on the building and HVAC side. In the uncoupled simulation the EnergyPlus model is equipped with an abstract HVAC system that generates hourly heating and cooling loads (either deterministic or as probability distributions), which are then used as input to the ROSEC tool which calculates the HVAC energy consumption in each hour based on its simplified calculation, which we will now introduce in more detail.

Available commercial simulation programs are not capable of directly analyzing the effects of equipment test tolerance uncertainty in their algorithms. ROSEC uses a spreadsheet based calculation procedure that is capable of hourly simulation of HVAC energy consumption with inclusion of uncertainty stemming from equipment test tolerances and other sources of HVAC installation, operation and component performance. The procedure's inputs are the building heating and cooling demands which include room sensible cooling load, room latent cooling load, quantity of outside air and the outdoor temperatures (dry and wet bulb) on an hourly basis. If there is no dynamic simulation that generates these inputs, ROSEC calculates them for a design day based on building location, size, application, facade data, lighting, occupancy and equipment schedule. The hourly demand is used in conjunction with the room conditions and entering air conditions (dry and wet bulb temperatures, enthalpy and humidity ratio) to calculate the total air flow capacity and total cooling required for satisfying the cooling or heating demand. ROSEC is implemented for six predefined heating and cooling systems defined by their components, such as chiller, cooling tower, supply fan, etc. A performance (part load fraction) curve is designated to each of these equipment components (Fig 2). The curves show the variation of energy consumption of the equipment (kWh) versus variations of either total flow capacity (cfm) or total cooling (tons) generated by the equipment within the full range of the its capacity. ROSEC can be used in deterministic or uncertainty analysis mode. The deterministic calculations use the minimum acceptable efficiency curve for each equipment as specified in energy codes and standards (ASHRAE 90.1). The outcomes of the calculations are hourly energy consumption which are aggregated to derive total energy efficiency of the HVAC system for a typical design day. The results are in the form of a single value, such as 3000 kWh overall energy consumption or 1.4 kW/ton overall efficiency for a full day. In the probabilistic procedure, each component efficiency curve is sampled from a distribution as indicated above and used in the Monte Carlo simulation. We used the equipment library of the Trane Trace 700 program for the performance curves of different equipment. Each curve was translated into a formula with embedded parameters that parameterize tolerance uncertainty. The range of the tolerances was derived from testing agency (e.g. ARI) specifications. ROSEC automatically performs the Monte Carlo simulation in Excel based calculations via integration with the ModelCenter software and its embedded Latin Hypercube Sampling method. The calculations treat the building as one zone that represents the aggregated loads, schedules and air supply needs of all zones combined. Obviously this is in some cases a radical simplification of the spatial and temporal variability of real buildings.

ROSEC is used in the second step of the uncoupled approach. It receives the loads and mechanical air volumes generated by EnergyPlus without regard of an actual system. To achieve this, we use the "purchased air" option to represent an ideal operating HVAC system that at any moment provides sufficient air to meet the zone cooling or heating requirements.

The hourly results of the ROSEC calculations represent the equipment electricity and natural gas consumption (kWh). In EnergyPlus, the ideal air system load is composed of zone heating/cooling loads (sensible and latent), and mechanical ventilation volume. The zone heating/cooling loads can be decomposed in occupancy load, lighting load, equipment/plug load, and infiltration/ventilation load. All simulations are carried out for a full year. We thus run an annual load calculation and use the calculated hourly zone heating/cooling loads and mechanical ventilation volumes as input to ROSEC in order to calculate the hourly HVAC energy consumption. This means that we do not use ROSEC for a design day but for the actual full year with the real weather.

For the fully integrated coupled simulation method, we use the integrated building and HVAC model in EnergyPlus to get the deterministic simulation result. For the uncertainty analysis of the same model, we use the Georgia Tech Uncertainty and Risk Analysis Workbench (GURA-W). The workbench is a software environment that can be used to flexibly automate the processes of uncertainty quantification and analysis. The user must only supply a valid input EnergyPlus model file (IDF) of a building under consideration as well as the corresponding weather file for the location. Then, the user is directed to a UQ repository containing probability distributions of all considered uncertainty parameters. These pre-defined distributions are based upon previous work in characterizing the uncertainty in building simulation related to various parameters and model structures (Sun et al, 2013). Latin Hypercube sampling is used to propagate these uncertainty distributions through an EnergyPlus simulation for each sample). For a more complete discussion of the functionality of the GURA-W, the reader is directed to (Lee et.al. 2013).

CASE STUDY RESULT AND DISCUSSION

We use a campus building (Fig. 3) as case study building. The primary system is chilled water and hot water loop. The secondary system is variable air volume (VAV) system with a terminal reheat unit located in each conditioned zone. The VAV system with terminal reheat is equipped with a central air handling unit (AHU) which conditions the mixing air to 12.8 ℃ and distributes certain amount of mixing air into each terminal unit. When the system is in cooling mode, the supply air temperature is constant at the terminal unit, which will adjust the opening of the damper in order to vary the flow of the supply air to meet the zone cooling demand. When the system is in heating mode, the supply air at the terminal damper is fixed at minimum flow volume and the supply air temperature will be varied in order to meet the zone heating demand. Only when the maximum supply air temperature at minimum flow cannot meet the zone demand, the terminal unit will increase the opening of the damper to meet the load.

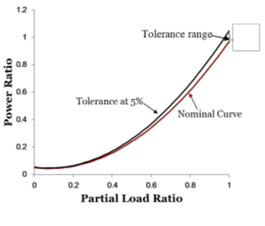


Figure 2 Tolerance range of Performance curve

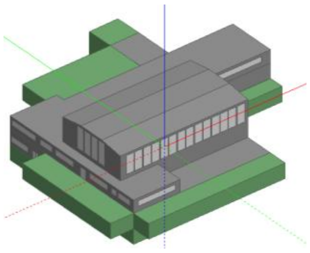


Figure 3 Schematic view of case building

As shown in Figure 4, the equipment in the primary loop includes an electric-input ratio (EIR) chiller with variable flow, water-cooled cooling tower with variable speed, and electric boiler with variable flow, hot water supply pump with variable speed, chilled water supply pump with variable speed, and condense water supply pump with variable speed. The equipment in the secondary loop include the air loop supply fan with variable speed, pre-heating coil, cooling coil, and terminal unit with reheat coil.

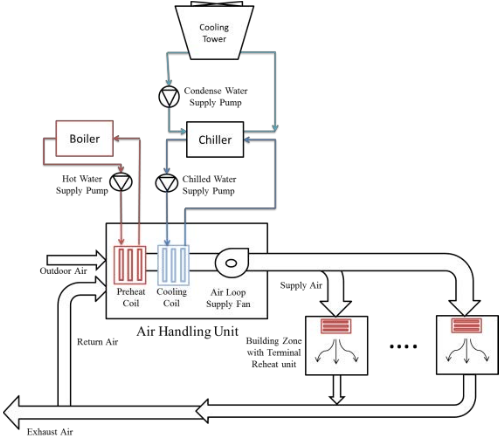


Figure 4 VAV system

It should be noted that the case study is performed on an average low-efficient building. Other more efficient building types may show different results than presented below. It should also be noted that the system in the case building can be treated in ROSEC as well as in EnergyPlus in a straightforward way, using an identical set of parameters to describe the systems in both approaches.

Case study 1: Campus building with VAV in Atlanta

Figure 5 shows the result of the difference in daily energy use in the deterministic simulation result of the coupled and uncoupled system. Figure 6 is the histogram of the daily difference (%) based on:

$$\text{Diff}\ (\%) = \frac{(E_{coupled} - E_{uncoupled})}{E_{coupled}} \times 100\%$$

Although hourly differences can be larger, the difference (measured as fraction of the daily mean) in daily energy use seem to fall in the range between -0.15 and +0.25.

The major dynamic interaction between the HVAC system and building is how the system responds to the temporal variation in the demand of the building and how the system distributes the air into zones with different loads due to spatially varying conditions and loads in different building zones. Neither of these two is well captured in the uncoupled simulation. In the uncoupled method, we treat the building as one combined zone, lumping the individual zone cooling/heating loads calculated by running EnergyPlus with the purchased air option. In the coupled method, the VAV system mixes the return air with a fresh air amount that is calculated by the summing all zone requirements and distributing the conditioned air to each terminal unit. The way that fresh and conditioned amounts of air is simulated is rather convoluted and depends on a balancing act of zonal fresh air need and heating/cooling needs. It is obvious that these air distribution issues caused by zonal variability are ignored in the uncoupled simulation.

To isolate the effect of the zonal supply variability we next conduct another case study for a simplified two-zone VAV building.

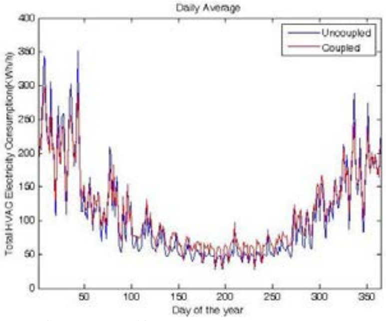


Figure 5 Daily average system energy

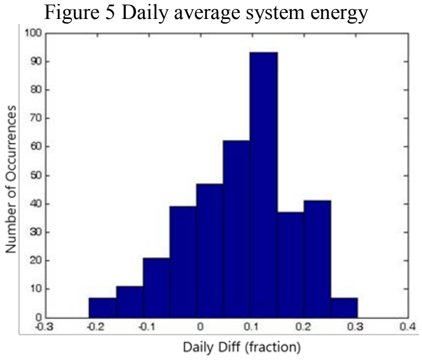


Figure 6 Daily diff between coupled and uncoupled simulation

Case study 2: Simplified two-zone VAV in Atlanta

One zone is facing west and the other one facing east. The two zones have the same area, same material and same operation schedule. Apart from the difference in solar gain distribution over the course of a day, both zones have a relatively equal zone cooling/heating demand.

Figure 7 is the histogram of the daily diff (fraction of mean). Comparing Figures 6 and 7 confirms our intuition that daily difference range becomes significantly smaller when zonal variations are small. To further confirm this idea and limit the temporal variability as well we conduct a third case study for the simplified building with constant air volume system (CAV) with a terminal reheat unit.

Case study 3: Simplified two zone CAV in Atlanta

The major difference between the CAV and VAV system is that with CAV the air flow volume in the central AHU is constant. This system with the simplified two-zone building will therefore have less dynamic interaction with the HVAC system. Figure 8 is the histogram of the daily diff (fraction). From Figure 7 & Figure 8, we could see that the daily diff is slightly smaller in case study 3.

Case study 4: FCU in campus building, in Atlanta

We use the building from case study 1 with a fan coil unit (FCU). The primary system is a chilled water and a hot water loop. The secondary system is a fan coil unit system located inside each zone. The central system will supply the hot water and chilled water into each terminal FCU and the air will be recirculated in the conditioned zone. FCU is operated as a zone-based control system.

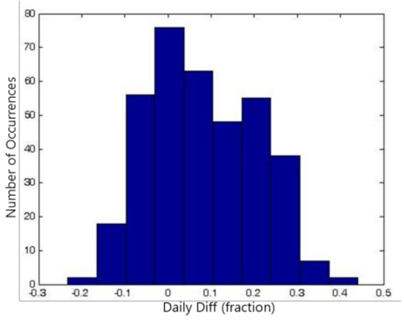


Figure 7 Daily diff between coupled and uncoupled simulation

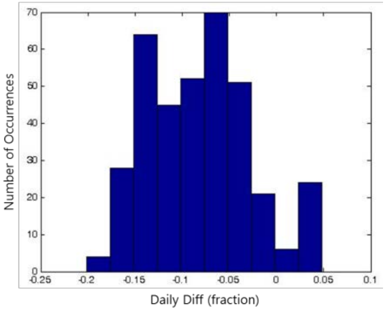


Figure 8 Daily diff between coupled and uncoupled simulation

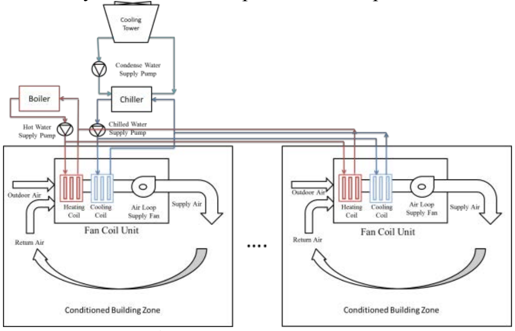


Figure 9 FCU system

As shown in Figure 9, the equipment in the primary loop includes an electric-input ratio (EIR) chiller with variable flow, water-cooled cooling tower with variable speed, and electric boiler with variable flow, hot water supply pump with variable speed, chilled water supply pump with variable speed, and condense water supply pump with variable speed. The equipment in the secondary loop include the air loop supply fan with variable speed, heating coil, cooling coil as parts of the FCU box located in each zone.

Figure 10 shows that the average diff is about 10%, but due to the ignorance of the zone level demand-respond relationship, the diff can also be as large as 30-40%.

Case study 5: VAV system in Chicago

As buildings located in different climate zones have different load profiles, it is worthwhile looking at the results in a climate like the Chicago one. We use the same building as in case study 1, but move it from a cooling dominated to a heating dominated location (Chicago). This leads to different equipment sizing and the results should tell us how this impacts the comparison between coupled and uncoupled outcomes. Figure 11 shows the distribution of daily diff (fraction of mean). Comparing Fig. 6 with Fig. 11 leads to the conclusion that there seems to be no large influence but obviously more case studies are needed.

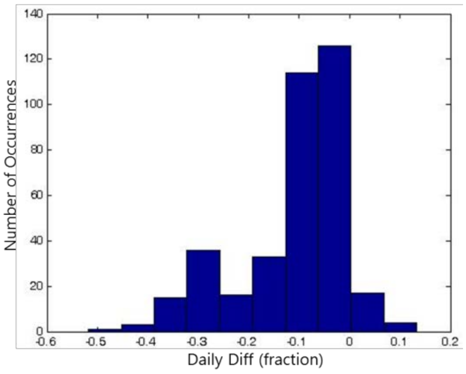


Figure 10 Daily diff between coupled and uncoupled simulation

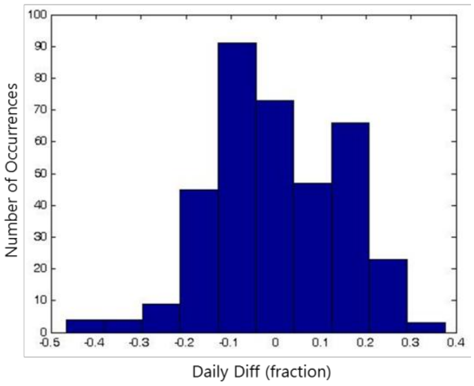


Figure 11 Daily diff between coupled and uncoupled simulation

All results shown above deal with the daily total energy consumption. It can be expected that monthly total energy amounts show a closer match as certain day to day dynamic effects will smooth out when monthly totals are compared.

Figure 12 shows an example of the outcome for the monthly result comparison for case study 2. Figure 13 summarizes the information in a box plot of monthly differences (%) for the five case studies. Figure 13 tells us that the mean of the difference in monthly energy consumption is around 10% for all cases. The variance decreases slightly for the CAV system (as expected) and for a heating dominated climate (less expected).

Uncertainty propagation

From the deterministic treatment of the case studies, we conclude that the daily and monthly percentage difference lies within 30% and 20% respectively. We will now compare these discrepancies to the influence of uncertainties in all typical parameters in both building and HVAC system. Figure 14 shows the distributions of monthly energy consumption for all 12 months generated by an UA analyses of both coupled and uncoupled approaches. For all months we show the HVAC energy consumption density for (1) the uncoupled approach, in red, (2) the coupled approach, in black.

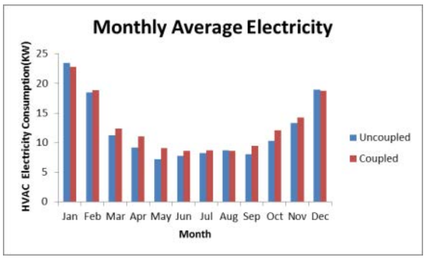


Figure 12 Case study 2: simplified two zone VAV in Atlanta

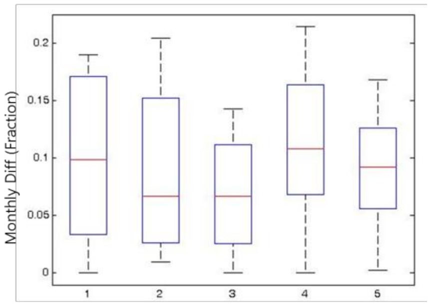


Figure 13 Box plot of monthly diff (fraction)
1-VAV Atlanta 2-Simplified VAV 3-Simplified CAV
4-FCU 5-Chicago

Table 1 Monthly mean and standard deviation

	Monthly Mean		Standard Deviation	
	Coupled	Uncoupled	Coupled	Uncoupled
January	91342	82924	15664	15961
February	69894	61569	11171	11308
March	52229	43818	6297.9	5950.6
April	41386	34875	3702.3	3330.9
May	35650	29065	2200.4	1637.8
June	31086	26114	1817	9128
July	31917	28207	1883.8	711.8
August	32243	28246	1879.1	544.2
September	36097	30909	1897.4	1037.5
October	49470	41843	4598.6	4089
November	57279	48794	7285.8	7001.3
December	78332	70272	12110	11997

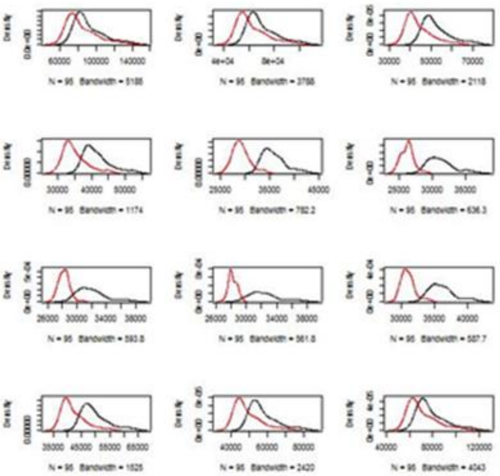


Figure 14 Monthly HVAC energy density

We find that the band of uncertainty generated by both simulations is quite similar and large for all months. In some months the two distributions overlap (which would confirm our original hypothesis) but in other months they are too far apart.

Figure 14 shows the densities of the UA results for both methods. Table 2 shows the mean and standard deviation for all months produced by both methods. We conclude that the difference in monthly means is within the 20% range, with a SD significantly smaller than the mean difference. A few months show anomalies in the value of SD however, probably caused by the occurrence of "extreme" samples in the Monte Carlo simulation.

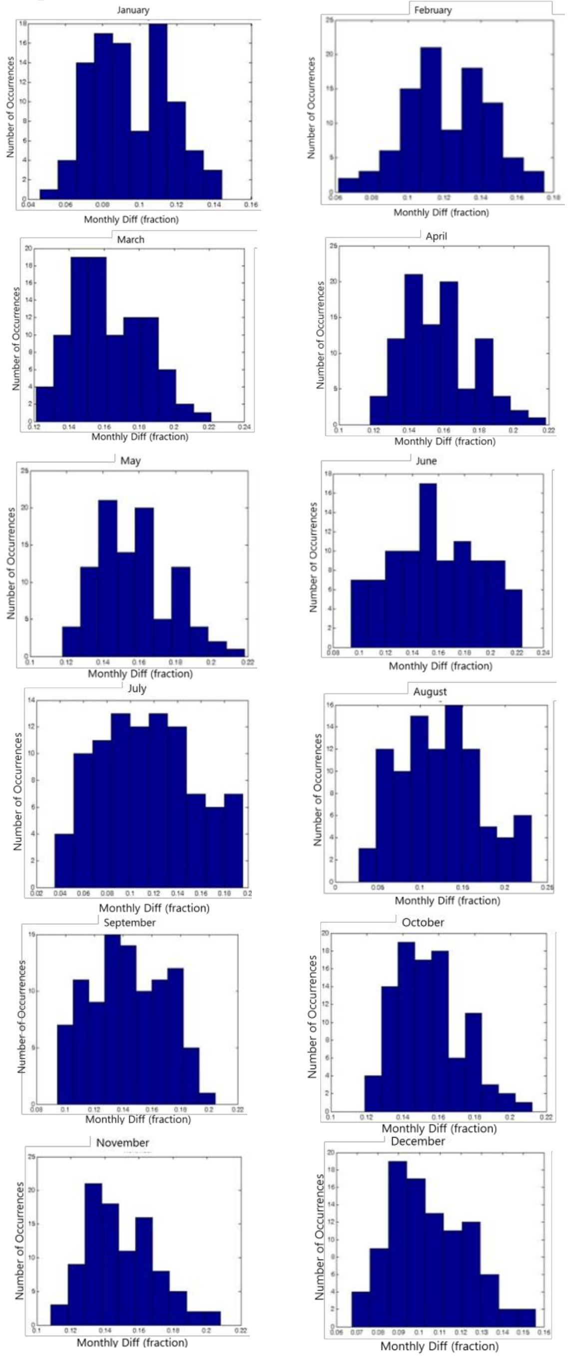


Figure 15 Monthly diff between coupled and uncouple under uncertainty using matching samples

For all 12 months, the two densities do not overlap in large regions. There is a shift in the mean and the variances sometimes are different as well. Figure 15 shows the difference between coupled and uncoupled prediction for each possible realization of the case building, i.e. only considered for matching sample values. The maximum differences are all within the 20% range and the anomalies disappear when we take the differences between both approaches, as can be expected.

CONCLUSION AND FUTURE WORK

The paper has raised the question whether uncoupled sequential simulation of building and HVAC system is acceptable when one is interested in (monthly) energy consumption. If so, one could save time and effort by not having to define the HVAC system in the fully coupled integrated simulation model. To study the proposition, the difference between coupled and uncoupled simulation results is investigated on five case studies. The comparison of the deterministic results gives some reason to be optimistic as the difference falls within an acceptable band. The discrepency of monthly result falls within 20% and will decrease to 10% if zonal control variability is less. When uncertainty is added to both simulations, the resulting distributions are in some months overlapping but in other months too far apart. It is found however that for a given building the difference in monthly total energy is seldom more than 20%. This is for many purposes within the range of acceptable accuracy which seems to confirm our hypothesis.

Our study has been limited to an office building that reflects building practice of the last decades. As buildings are becoming lower energy consumers, the relative difference between coupled and uncoupled approach may change drastically, and the motivation for this study may become more pronounced. This is a topic that should be studied as a follow up of this study. It will also be intetesting to study the prediction of peak loads. It is expected that the uncoupled approach performs worse in those cases.

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