ANNUAL COUPLED ENERGYPLUS AND COMPUTATIONAL FLUID DYNAMICS SIMULATION OF NATURAL VENTILATION

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ABSTRACT

Can coupled Computational Fluid Dynamics (CFD) and Building Energy Simulation (BES) be used to conduct annual simulation? This paper tries to investigate the feasibility of annual coupled simulation of CFD and BES. Energy modeling approaches have continued to advance to cater for emerging new design concepts towards "greener" solutions that optimize energy consumption in buildings while maintaining thermal comfort as well as healthy environment. Various efforts have been made to improve the fidelity of the thermal simulation in buildings such as to couple CFD with lumped nodal BES model. Research has shown that the coupled simulation improves simulation accuracy. However, due to the nature of CFD simulation, coupled simulation usually takes much longer computation time. For example, the annual simulation of natural ventilation, which has relatively fewer incidences of CFD simulation runs, would take up to 46 days. In addressing the issue, a coupled lumped heat transfer model (EnergyPlus) and CFD model (Fluent) was implemented, and 8 days of simulation was conducted. Delaunay Triangulation based interpolation model was built from the 8 days' results, which can be used to predict the airflow rates for openings for an annual simulation. It is shown that the interpolation model is able to predict 35% of the natural ventilation deployable time annually, when natural ventilation is appropriate in the Philadelphia climate context. The interpolation model reduces the simulation time by 90%.

INTRODUCTION

Can coupled Computational Fluid Dynamics (CFD) and Building Energy Simulation (BES) be used to conduct annual simulation? This paper tries to investigate the feasibility of annual coupled simulation of CFD and BES. Energy modeling approaches have continued to advance to cater for emerging new design concepts towards "greener" solutions that optimize energy consumption in buildings while maintaining thermal comfort as well as healthy environment. Various efforts have been made to improve the fidelity of the thermal simulation in buildings such as to couple CFD with lumped nodal BES model. Research has shown that the coupled simulation improves simulation accuracy, such as Mora, Gadgil, and Wurtz (2003), Negrao (1998), Wang and Wong (2008), Nagai and Kurabuchi (2009), Hanby et al. (2008) and Hensen, Bartak, and Drkal (2002).

However, due to the nature of CFD simulation, coupled simulation usually takes much longer computation time. For example, in the climate context of Philadelphia, there are about 854 hours that outdoor environment is appropriate for natural ventilation. The computation time for the annual simulation would take up to 46 days.

In addressing the issue, this paper presents an procedure, which uses interpolation method, to reduce the computation time of the coupled simulation for natural ventilation simulation. A coupled lumped heat transfer model (EnergyPlus) and CFD model (Fluent) was implemented, and 8 days of simulation was conducted. Then, Delaunay Triangulation based interpolation model was built from the 8 days' results, which is used to predict the airflow rates for openings for an annual simulation. It is shown that the interpolation model is able to predict 35% of the natural ventilation deployable time annually, when natural ventilation is appropriate in the Philadelphia climate context. The interpolation model reduces the simulation time by 90%.

PREVIOUS WORK

Manual coupling of the CFD model and nodal model has been done for many geometrical complicated buildings. Nagai and Kurabuchi (2009) used CFD to decide the coefficients in the nodal model for a high-apartment building with central void space throughout the height of the building in Japan. Manz and Frank (2005) used a one-way-static coupling to study the thermal performance of double facade buildings. Wong et al. (2005) also coupled CFD and nodal model manually to study the performance of double facade building in a tropical climate in Singapore.

Research work on automated coupling of the nodal model and CFD model at run time is dated from

1990s, (Negrao (1995)). Based on the work by Negrao (1995, Negrao (1998), Beausoleil-Morrison (2000, Beausoleil-Morrison et al. (2001, Beausoleil-Morrison and Clarke (1998) continued with the investigation of the coupling between nodal model (ESP-r) and CFD model. An empirical validation of the coupled model by Beausoleil-Morrison (2000) is conducted by Bartak et al. (2002). Djunaedy, Hensen, and Loomans (2003, Djunaedy, Hensen, and Loomans (2004), Chen, Peng, and van Passen (1995), Zhai et al. (2001) discussed both the advantages and disadvantages of internal coupling of the CFD and nodal model. It was concluded that external coupling is more favorable in terms of no stiffness issue, less expensive, nodal and CFD model themselves are independent and can be optimized individually. Djundaedy (2005), Djunaedy, Hensen, and Loomans (2005) also implemented an external coupling of the nodal and the CFD model. Zhai and Chen (Zhai et al. (2002), Zhai and Chen (2003), Zhai, Gao, and Chen (2004), Zhai (2004), Zhai (2005), Zhai (2006)) also investigate the coupling strategy extensively. They implemented a coupling strategy to exchange heat transfer coefficient and surface boundary conditions between nodal model and CFD model through dynamic or static coupling. Hereby, static and dynamic is the strategy used for data exchange instead of thermal process. A sensitivity study was also carried out to investigate the effectiveness of the coupling method in improving the building energy simulations. Their results showed that for rooms with moderated size, without sensible temperature stratification, the coupling approach shows marginal effect. However for rooms with large temperature stratification, the discrepancy between coupled method and nodal model is significant (42%). Wang and Wong (2008) developed a text-based interface for automated coupling program to extract and exchange information between TAS (nodal model) and Fluent (CFD model). However, no method has been introduced to significantly reduce the computation time to conduct coupled simulation for longer time period, such as the annual building energy simulation.

COUPLING MODEL

EnergyPlus is chosen as the nodal model for the coupled simulation platform. EnergyPlus is a program to calculate the energy required for heating and cooling a building using a variety of systems and energy sources over a year's period. It is a sequential simulation program, which starts with zone heat balance and calculates the heating/cooling loads at each time step. This information is fed to the air handling system, and system information is passed to mechanical system simulation. Finally, the yearly energy consumption for the building will be computed.

The Fluent software is chosen as the CFD model for the coupled simulation platform. Fluent uses Finite Volume Method to solve the fluid dynamic problems. Fluent software is one of the most widely used and extensively tested software in the architectural applications domain. It provides multiple modelling capability of flow, turbulence, heat transfer, radiative heat transfer, solar module, and mass transfer, etc.

Progressive-Replacement external coupling was implemented. The nodal model will be used as start-up model and the initial values for exchange variables will be calculated within the nodal model. The time-step to follow will be coupled between nodal and CFD model, and the variables will be exchanged progressively with appropriate time intervals afterwards.

The coupling platform will be based on Building Controls Virtual Test Bed (BCVTB, (Wetter et al. 2011)) , which is a software environment targeted to provide an integration platform for various simulation tools. A c++ program, called *FlowPlus*, was developed to execute the Fluent software to conduct the CFD simulation and extract the results for the coupling variables.

The CFD tool will conduct the steady state natural ventilation simulation. A post processing program will be implemented to extract the temperature profile and velocity fields from CFD tool and then to calculate the values for the exchange variables, which include the following:

- Airflow rates through all the openings.
- Average temperatures of the air flowing through the openings.
- Surface heat transfer coefficients for all of the building envelop surfaces.

More detailed description of the coupling model can be found in another paper published at the same conference of SimBuild 2012, (Zhang et al. 2012).

INTERPOLATION METHOD

Interpolation is a method of constructing new data points within the range of a discrete set of known data points. The known discrete set is usually obtained by sampling or experimentation, which represent the values of a function for a limited number of values of the independent variables. It is often required to interpolate the value of a function for an intermediate value of the independent variables. The interpolation is usually achieved through curve fitting or regression analysis.

CASE STUDY

The live retrofit building 661 on the Philadelphia Navy Yard was chosen for the case study of the coupling platform and methodology developed in the previous section. This historic building features a shared open space at the back with gross area of about $1600m^2$, and a two story space in the front with gross area of about $800m^2$ for each floor. After retrofit, the building will house GPIC personnel, and function as living laboratories for developing tools and methods to transform the building industry's current fragmented serial method into integrated team efforts. The building model is shown in Fig. 1.

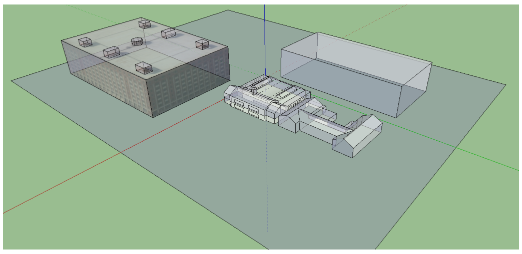


Figure 1: The SketchUp model of the Building 661 and the surrounding buildings for the coupling study.

The thermal properties and internal gains of the building are listed in Table. 1

Table 1: The thermal properties and internal gains of the Building 661.

Parameters	Value	Reference
External Walls	Steel Framed R13 Insulation Ext Walls (U-value = 0.703 W/m^2K)	ASHRAE 90.1 2004
Windows	U-value: 3.24 W/m^2K (operable and fixed windows); SHGC: 0.39; Visible Transmittance: 0.622	ASHRAE 90.1 2004
Roofs	Metal Deck Roof Insulation Entirely Above Deck (IEAD), R15 Insulation (U-value = 0.358 W/m^2K), Roof Albedo: Roof Surface Reflectivity = 0.30	ASHRAE 90.1 2004
Occupancy	18.58 $m^2/person$	DOE reference model
Lighting	10.76 W/m^2	DOE reference model
Equipment	10.76 W/m^2	DOE reference model

The nodal model will provide to the CFD tool all the interior and exterior surface temperatures of the envelope components of the building and outdoor weather conditions. The CFD tool will take temperatures of various building surfaces as settings of the thermal boundary conditions, including both interior surfaces and exterior surfaces. For natural ventilation, wind is the driving force of the flow through the openings in the building. The wind conditions, in terms of speed and direction, provided by the nodal tool from weather data will be used to determine the boundary type of the four boundary surfaces of the simulation domain. For example, if the wind is coming from south, with a speed of $2m/s$, the surface of the south bound will be set as velocity inlet, with incoming wind velocity of $2m/s$. The north bounding surface of the domain will be set as outflow. The east and west boundaries will be set as symmetry assuming there is no shear strain on the surface.

Simulation Scenarios Selection

The simulation of natural ventilation conditions was chosen as the case study of the coupling between the nodal model and the CFD model. Natural ventilation is considered to be one of the most complicated building thermal simulations, and it is a very important passive strategy of energy efficient buildings. The accurate simulation of natural ventilation will provide architects and engineers with more insight during the design process of the energy efficient buildings.

The weather condition in Philadelphia is first analysed. It is believed that natural ventilation should be used to provide ventilation air and remove internal heat gains, when outdoor conditions are appropriate. However, the actual control strategy of natural ventilation is beyond the focus of this paper. Our future research work will include the integration of control strategies with the coupled CFD simulation of natural ventilation conditions. The main focus of this paper is to investigate the feasibility of conducting annual coupled CFD simulations. Therefore, in this paper, we define natural ventilation conditions as the hours, when windows could be open, that outdoor weather conditions satisfy the criteria of ASHRAE Fundamentals Comfort Model. Analysis shows that the month of June has the highest number of hours that outdoor conditions are comfortable, and potentially natural ventilation can be deployed (windows could be open). Thus the month of June is chosen as the simulation period for the study of coupling between nodal model and the coupled CFD model.

CORRELATION STUDY

It is natural to assume that there is a strong correlation between the airflow rates of the openings and the environmental variables under natural ventilation conditions, since the airflow is a result of the wind and internal layout of the building. For a given building internal design, the airflow rates under natural ventilation conditions will be the result of outdoor wind condition, i.e., wind speed, direction and temperature. In this section we will quantitatively measure the correlation between the environmental variables. After the correlation has been proved, the airflow rates of the openings is highly correlated with the external wind condition. Therefore, an interpolation model can be built to derive the behaviour of the airflow rates under various wind conditions, while being computational much less expensive to evaluate.

Covariance Analysis

First, the correlation between the airflow rates and individual environmental variables, i.e., wind speed, wind direction and temperature, are studied. Fig. 2 shows the scatter plot of the environmental variables and the airflow rates for one window on the south facade. Table. 2 shows the covariance between environmental variables and airflow rates for the same window as shown in Fig. 2. As is shown that there is no simple linear correlation exists between individual environmental variables and the resulting airflow rates.

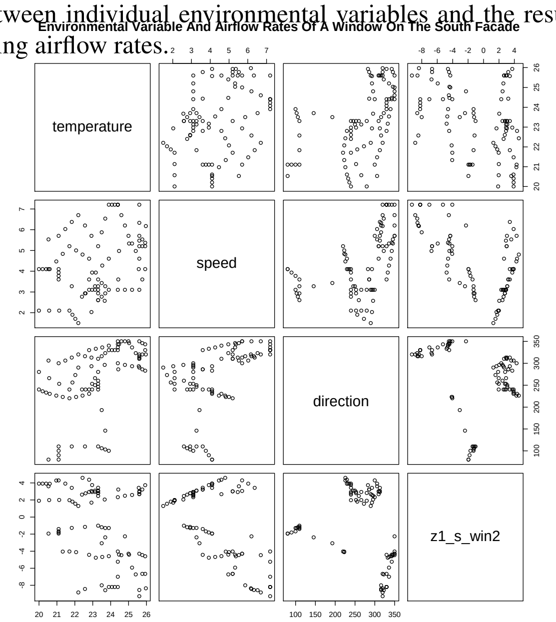


Figure 2: The scatter plot of environmental variables, and airflow rates of one window on the south faade.

Table 2: The covariance between environmental variables and airflow rates of one window on the south facade.

Covariance	Temperature	Speed	Direction	Airflow rates
Temperature	1.00	0.34	0.51	-0.33
Speed	0.34	1.00	0.51	-0.61
Direction	0.51	0.51	1.00	-0.20
Airflow rates	-0.33	-0.61	-0.20	1.00

Information Gain Analysis

In order to quantitatively analyse the combined correlation between multiple input variables, i.e., environmental variables, and the output i.e., airflow rates, the information theory-based ((Shannon (1948), Anderson (2007)) correlation analysis is carried out. The Relative Information Gain (RIG) is taken as the measure of correlations. Higher RIG indicates higher correlation between the outdoor conditions and airflow rates. The RIGs of the three outdoor features are evaluated individually, and RIGs for any combinations of the three features are also evaluated. Data mining and machine learning tool Accelerated Statistical Learning (ASL) is used to conduct the computation (Moore and Lee (1998), Mitchell (1997) and B. and Moore (1998)).

An underlying concept in information theory is that of entropy, which characterizes the amount of uncertainty associated with a random variable. High entropy corresponds to high uncertainty (e.g., in the case of a uniformly distributed random variable), and low entropy corresponds to low uncertainty (e.g., in the case of a variable that always takes the same value). Mathematically speaking, entropy is defined as the (negative) expected value of the log of the probability distribution:

$$H(y) = \sum_{i=0}^{n} -P(y_i)log_2 P(y_i). \quad (1)$$

where:

$H(y)$	entropy
y	a random variable
y_i	the i^{th} instance or possible outcome of random variable y
n	the size of the sample space associated with y
$P(y_i)$	the probability of $y = y_i$

As demonstrated in the example plot of Fig. 3, entropy will be 0 if the probability of an outcome is zero or 1; there is no uncertainty in the random variable.((Brona and Damato 2007))

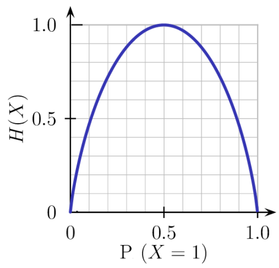


Figure 3: Information entropy of a Bernoulli trial X. X is the random variable with two possible outcomes. If X can assume values 0 and 1, entropy of X is defined as H(X) = -P(X=0) log2 P(X=0) - P(X=1) log2 P(X=1). It has value 0 if P(X=0)=1 or P(X=1)=1. The entropy reaches maximum when P(X=0)=P(X=1)=1/2 (the value of entropy is then 1).

The conditional entropy is defined as :

$$H(y|x) = \sum_{j=1}^{A_X} P(x = x_j)H(y|x = x_j), \quad (2)$$

Where the entropy of y given $x = x_j$ is defined as:

$$H(y|x = x_j) = \sum_{i=0}^{n} P(y = y_i|x = x_j)log_2 \frac{1}{P(y = y_i|x = x_j)}. \quad (3)$$

where:

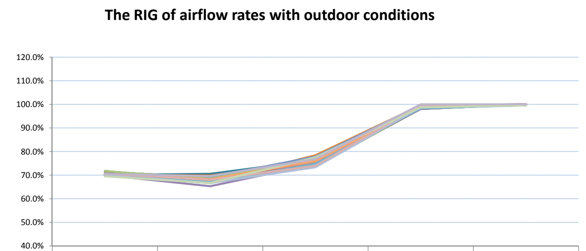
$H(y\|x)$	conditional entropy of y given x
$H(y\|x = x_j)$	conditional entropy of y given $x = x_j$
x, y	random variable
x_j	the j^{th} possible outcome of x
A_x	the sample space of random variable x
$P(x = x_j)$	the probability of $x = x_j$
$P(y = y_i\|x = x_j)$	the conditional probability of y given x

The mutual information (referred to here as Information Gain, IG) between y and x is:

$$IG(x,y) = H(y) - H(y|x). \tag{4}$$

Relative Information Gain (RIG) is:

$$RIG(x,y) = \frac{IG(y,x)}{H(y)} \cdot 100\%. \tag{5}$$



	temp	speed	dir	speed & dir	speed & dir & temp
z2_cc1_win1	70.4%	68.7%	74.4%	98.1%	100.0%
z2_cc2_win2	70.3%	67.6%	76.3%	99.2%	100.0%
z2_cc3_win3	71.8%	67.4%	75.2%	99.2%	100.0%
z2_cc4_win4	71.4%	69.1%	75.6%	99.2%	100.0%
z1_s_win1	70.1%	70.6%	76.4%	99.6%	100.0%
z1_s_win2	70.2%	69.9%	75.3%	99.3%	100.0%
z1_s_win3	70.2%	67.6%	73.6%	98.5%	100.0%
z1_s_win4	70.2%	67.0%	76.8%	99.2%	100.0%
z1_s_win5	70.6%	67.4%	74.0%	98.1%	100.0%
z3_n_win1	69.6%	67.5%	75.4%	98.9%	100.0%
z3_n_win2	70.2%	66.6%	75.9%	98.7%	99.6%
z3_n_win3	70.0%	67.2%	78.4%	99.6%	100.0%
z3_n_win4	69.8%	69.1%	77.9%	99.6%	100.0%
z3_n_win5	70.4%	67.3%	75.4%	99.2%	100.0%
z5_e2_win1	71.7%	68.5%	76.5%	99.6%	100.0%
z5_e2_win2	70.0%	65.3%	74.7%	98.1%	100.0%
z4_e2_win1	70.2%	67.1%	74.8%	98.3%	99.6%
z4_e2_win2	70.5%	68.3%	76.0%	99.2%	100.0%
z1_z2_d	69.9%	66.7%	73.3%	98.9%	100.0%
z2_z5_d	70.7%	68.0%	74.0%	99.6%	100.0%
z2_z3_d	69.5%	66.7%	77.6%	98.7%	99.6%
z2_z4_d	70.5%	69.6%	76.8%	100.0%	100.0%

Figure 4: The RIG of flow rates for the openings with outdoor conditions of dry bulb temperature, wind speed and wind directions, and combinations of them.

Note that x and y are perfectly associated if $H(y|x) = H(x|y) = 0$, $IG(y,x) = H(y)$, $IG(x,y) = H(x)$. Knowing x reveals everything about y and vice versa.

On the other hand, x and y are perfectly disassociated if $H(y|x) = H(y)$, $H(x|y) = H(x)$, and $IG(y,x) = IG(x,y) = 0$. Knowing x, does not reveal any information about y and vice versa.

In this research work, information gain is used to study the correlation between combination of environment variables and airflow rates of the openings. The random variable y corresponds to the airflow rates of the openings. The input variable x corresponds to the vector of environmental variables.

The RIGs of the three outdoor conditions of dry bulb temperature, wind speed and wind direction for each of the openings are summarized in Fig. 4. As shown, the correlation is strongest with the combinations of all 3 factors together, with RIG of 100 for most of the openings except three openings with RIG of 99.6%. The combination of wind speed and wind direction shows strongest correlation with flow rates.

INTERPOLATION MODEL DEVELOPMENT

Weather analysis for natural ventilation shows that there are 854 hours, in the climate context of Philadelphia, fall in the ASHRAE thermal comfort zone. The computation time for one set of CFD simulation on average is 27 minutes. Therefore, to perform a yearly coupled simulation for Philadelphia, the computation time will be: $27 \times \#timeStep/Hour \times 854 = 27 \times 3 \times 854 = 69174 minutes \approx 46 days$. The computation time becomes more expensive for milder climate where number of hours outdoor condition satisfies natural ventilation requirements is much higher. Based on the coupled simulation results during the period of June 1_{st} to 8_{th}, the interpolation method will be able to predict the airflow rates for other weather conditions over the year. the interpolation method will reduce the computation time for annual coupled simulation significantly. This section will study such correlations and develop interpolation method to predict the airflow rates of openings given outdoor weather condition. The computation time saving on conducting a yearly couple simulation with interpolation method will be estimated, the error introduced by interpolation will also be provided.

Interpolation Method

A scattered data set defined by locations X and corresponding values V can be interpolated using a Delaunay triangulation of X. This produces a surface of the form $V = F(X)$. The surface can be evaluated at any query location QX, using $QV = F(QX)$, where QX lies within the convex hull of X. The interpolant F always goes through the data points specified by the sample. (MathWork (2007))

Interpolant F was created for each of the openings with 99 data points obtained from the simulation period between June 1_{st} and June 8_{th}. An incremental interpolant creation method was developed to find the trade-off between number of simulation runs and expected prediction error. The procedure is described as follows:

By incrementally creating the interpolant data set, data points that are very close to each other will not all be added to the interpolant data set. Since, in the coupled simulation each data point is a set of CFD simulation, which requires on average 27 minutes of computation time, it is very important to limit the total number of CFD simulations. The following section will compare the interpolation accuracy of interpolant with different sizes of data set.

Algorithm 1 The algorithm to incrementally create the interpolant data set

```
Load TrX {The starting (training) data set}
Load TsX {The testing data set}
for i = 1 → numDataInTesting do
   Delaunay Triangulate TrX
   Generate TriScatteredInterp Function for Interpolation
   Inquiry with a data point in the testing data set
   if Can not find value for the query point then
      add the query point to the training data set TrX
   else
      record the relative prediction accuracy
   end if
end for
```

Interpolation Accuracy Analysis

We define the accuracy of the interpolant as the accuracy compared with the coupled CFD simulation, instead of that compared with any field measurements. The more data points used in the interpolant, the more accurate the interpolant will be compared with the coupled CFD simulation. However, the more data points used, the more computation time will be needed to build the interpolant. Therefore, is it important to study the accuracy of the interpolant with different number of data points. Based on the incremental method used to construct the interpolant, the number of data points will increase as the size of the starting data set increases. To investigate the relative accuracy between interpolants with different sizes of data sets, four sizes of the starting dataset, i.e., 20, 40, 60 and 80, were tested. The error of the interpolant is defined as the average percentage difference between the interpolant predicted value and the coupled CFD simulation value for the data points remain in the testing data set. The total number of data points used in the interpolant and prediction error are summarised in Fig 5. As shown, there is a decrease in prediction error with larger initial data set, yet, the number of data points in the interpolant also increases. The computation time needed to generate each data point is on average 27 minutes. Therefore, it is important to compare the trade-off between increase of prediction accuracy and the increase of computation time. The increase of averaged accuracy, for 22 openings, and computation time is plotted in Fig. 6. As shown, a starting data set size of 40 provides good accuracy with prediction error of 24% and moderate computation time of 36.9 hours.

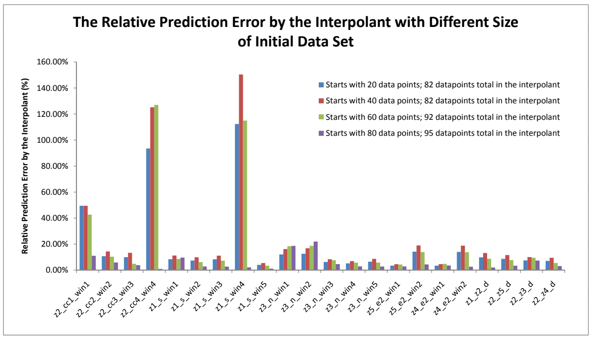


Figure 5: The relative prediction error for interpolant with different size of initial data set.

Predicted Interpolation Accuracy for Simulation of the Whole Year

The interpolant F, which is built with the data set obtained from the simulations during period between June 1_{st} and June 8_{th} with initial size of 40 data points, was used to predict the airflow rates through openings over the whole year. The interpolant was able to predict 296 hours out of 854 hours of simulation time. Therefore, the interpolant reduced simulation time by $1-(82\times 27/60)/(296\times 3\times 27/60) = 1-36.9hr/399.6hr = 91\%$ and with expected prediction error of 24%. Therefore, the computation time for the coupled CFD simulation over the simulation period of the whole year is expected to be $36.9hr/(296/854) = 114.25hr \sim 4.8Days$ instead of $854\times 3\times 27/60 = 1152.9hr \sim 46Days$. The computation time saving is significant with the interpolation method.

CONCLUSION

The paper presented a method to reduce the computation time for the annual simulation of the coupled Building Energy Simulation (BES) and Computational Fluid Dynamics (CFD) under natural ventilation conditions. A coupled simulation platform between BES and CFD tool has been implemented. Eight days of natural ventilation simulation in the live retrofitting project of Building 661 at the Philadelphia Navy yard was conducted. It is found that the interpolation model, which is built from the 82 coupled simulation incidences, is able to predict airflow rates for all the openings in the building for 296 hours out of 854 hours (35%), with expected error of 24%. The computation time is reduced to 114 hours from 1152 hours for an annual simulation of natural ventilation conditions in the Philadelphia climate condition.

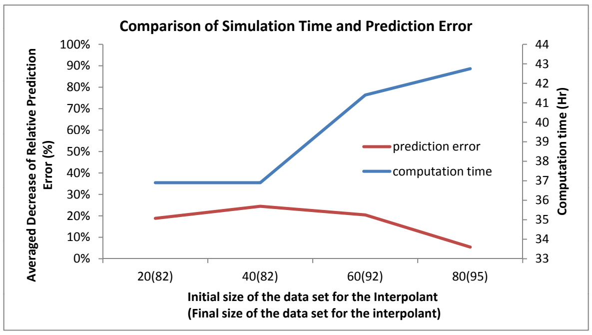


Figure 6: The comparison between simulation time and relative prediction accuracy with different sizes of data sets for the inerpolants.

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