SENSITIVITY STUDY OF CALIBRATED DATA CENTER MODELS TO MINIMIZE SITE SURVEY TIME USING CFD

by

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THESIS

Submitted in partial fulfillment of the requirements

for the degree of Master of Science in Mechanical Engineering at

The University of Texas at Arlington

May 2021

Arlington, Texas

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ABSTRACT

Sensitivity Study of Calibrated Data Center Models to Minimize Site Survey Time using CFD

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Data center (DC) consists of components like cooling pipes, data cables, power conduits, etc. To analyze the thermal behavior of DC using computational fluid dynamics, virtual model of DC is required. To build this virtual model, data is required regarding the different components like size, location and defining parameters. Site surveys are required to collect this data. Data collection is important to build an accurate model. There is lack of guidance with respect to which components are crucial to achieve level of accuracy in computational model. Sensitivity study can be used to determine accuracy achieved by introducing simplification in component parameters.

Two calibrated raised floor data center models are used to study sensitivity of DC components. Components were selected based on time and effort required to measure the parameter to define them, quantity of the component and educated prediction about effect of the component on output of interest. A total of 14 DC components are considered for sensitivity study and modifications were made in the individual components and simulations were run for each component. The full range of input parameter values for parameterized component object is considered, and simulations are performed. First, the

effect of the modifications was studied on the data center tiles, further how these changes in tile flow rate affect the IT (severs, switches) parameters was studied. These results are compared with the baseline calibrated model to understand the trade-off between survey effort/cost and model accuracy.

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ACKNOWLEDGEMENTS

I am very thankful to Dr. Dereje Agonafer, my supervising professor for helping me throughout my thesis. His continuous guidance and support throughout my thesis and research at The University of Texas at Arlington helped me to pass every barrier. I am very thankful to him to provide all the resources required for my thesis work.

I would also like to thank Dr. Abdolhossein Haji-Sheikh and Dr. Amir Ameri for taking time out of their busy schedule and evaluating my work as committee members.

I am very thankful to Future Facilities, Dr. Kourosh Nemati and Mark Seymour for providing the calibrated data center models without which this study would not have been possible.

I am forever thankful to Mr. Ashwin Siddarth and Mr. Vibin Simon for sharing their technical expertise throughout my research work. Their mentoring and support have played an important role in finishing this work.

I would like to thank all my friends in the EMNSPC group for being a part of my thesis defense and offering me the moral support to showcase my work.

My special thanks to my Father Mr. Rajkumar Singh and Mother Mrs. Satya Singh and my brothers Shubham Singh and Sushant Singh for always supporting me and for being my strength in difficult times.

May 07, 2021

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CHAPTER 1: INTRODUCTION

1.1. What is a Data center?

A facility that centralizes an organization's shared IT operations and equipment for the purposes of storing, processing, and disseminating data and applications [1]. At simplest, a data center is a physical facility that is used by organizations house their critical applications and data [2]. So, in simple words we can say that DC is a physical facility or room in which organizations house their IT and critical applications.

1.2. Working and Layout of DC

The Computer room air control (CRAC) is the cooling unit also referred to as Air cooling unit (ACU) in this report supplies the cool air. The cool air is blown into the underfloor plenum through fans. The cool air enters the DC room through perforated tiles. The cool air enters the rack also known as cabinet taking the heat from IT due to which air gets heated. This heated air returns to the CRAC through the ceiling plenum. CRAC unit cools the air again and blows it into the under-floor plenum. This cycle is repeated. The figure 1- 1 shows schematic of basic raised floor data center model.

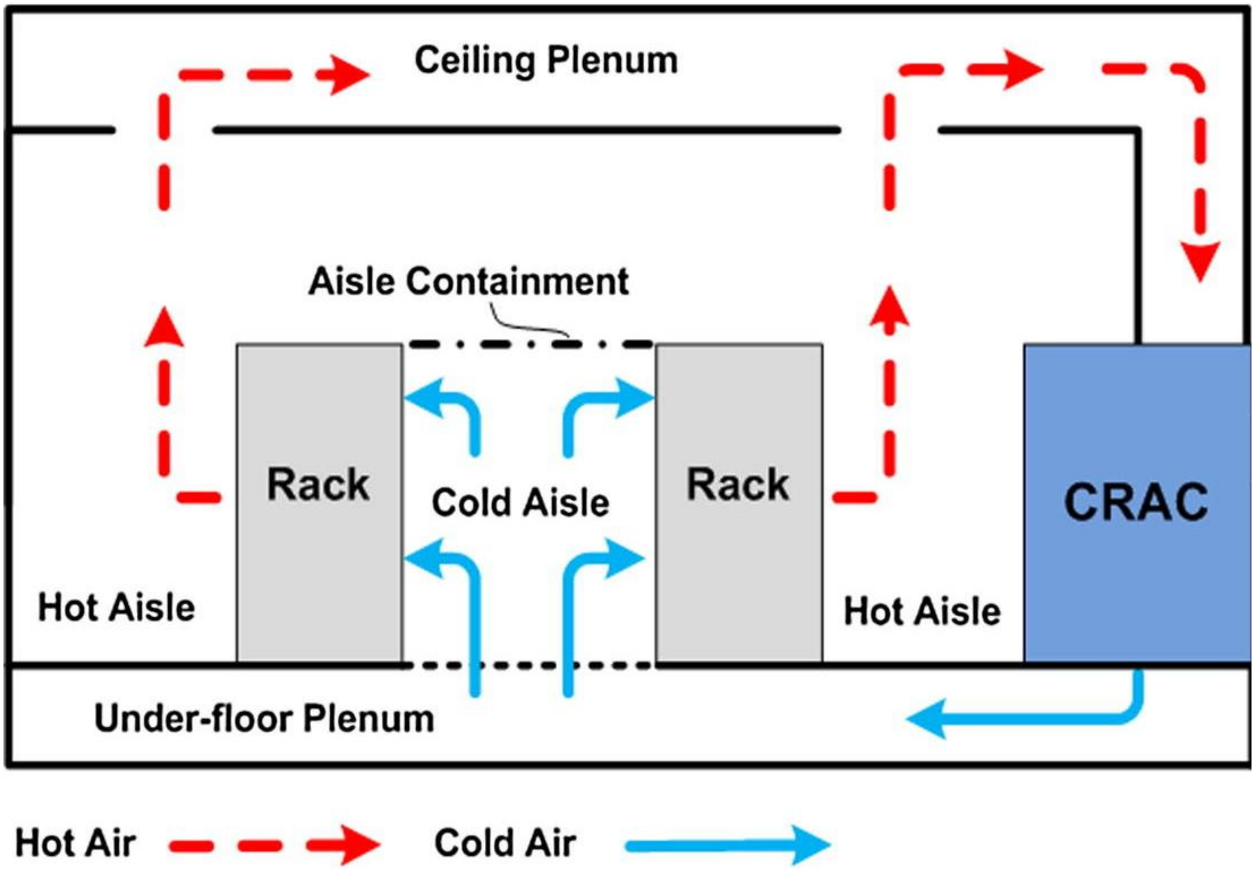

Figure 1- 1. Schematic of basic raised floor data center [3]

1.3. Background

Data center thermal behavior can be reproduced by computer simulations using Computational Fluid Dynamics (CFD). Computer simulations or Digital Twin have become a widely used tool in many engineering applications [3]–[6]. CFD models can be employed to gain new insights into newly designed technology and to predict the thermal performance of DC at any operational changes [7]. To perform this kind of study on DC, 3D virtual models of DC is required.

To produce this 3D model's information is required regarding the components present in DC like their location and parameter which defines those components. Site surveys are done to collect this information. In the computational modeling of DC, the most representative models are achieved through site survey. Site survey allows the modeler access to a far greater amount of information than can conveniently be supplied by other data sources. Alongside gaining model input data, it also allows for the collection of measured performance data with which the model results may be compared.

Data collection is time consuming and tiring process. Firstly, because of the huge size of DC varying from 5000 sq.ft to 50,000 sq.ft and even more. Secondly, due to the difficulty in accessing the components inside DC like cooling pipes, data cables which are placed under the raised floor or overhead and hence are difficult to access. Although, process of data collection is time consuming and tiring, level of detailing of DC model depends on this data and hence cannot be ignored.

Calibration, verification, and validation are three steps of producing an accurate model [8]. A baseline model must be created based on the data collected and calibrated based on the current state of the facility. Here calibration is different from calibration of measuring instruments were measured reading is compared to more accurate tool and error is calculated. In DC, calibration is a process to see if virtual model is accurate representation of actual DC. Calibration is done by monitoring ACU temperature and airflows, tiles air flow rates, IT equipment inlet air temperatures and IT equipment power draw as near to the IT equipment possible [9]. In this study tiles air flow rates are used for calibration.

CHAPTER 2: OBJECTIVE AND MOTIVATION

We believe that sensitivity study can provide scientific judgement in DC modelling and calibration process. In this thesis, we conduct a sensitivity study of a calibrated DC models for factors which we believe can reduce amount of time and effort required for site surveys. The factors in this sensitivity study are the 14 DC components wherein the term ‘factor’ or component, as it will be referred to in this paper, is to be interpreted in a very broad sense. A factor is anything that can be changed in a model prior to its execution. With this study, we aim to reduce the amount of time and effort required in site survey and expediate the calibration process.

This kind of study is important as we see that dependence on DC is increasing with time. Since the dependence on DC is increasing so is the number of the DC and their size. It also recommended to calibrate the DC models quarterly [9].

Simplification of a DC component is achieved through geometry approximation and by the prudent selection of a component object model. Omitting details will always result in a model that is not an exact representation of the real facility, but modeling every nut and bolt is time consuming, unnecessary, and will generate an overly complex and slow model. One must always consider the time a task takes versus the relative benefit it brings. A lot of survey tasks are obvious, but as an example: it is not worth spending an hour detailing the metalwork inside a single rack containing one shelf with a powered-down 56K modem. A better use of that time is to capture the significant details for a rack design that appears many times in the facility.

CHAPTER 3: DC MODELS FOR SENSITIVITY STUDY

Two raised floor DC models were used for sensitivity study provided by Future Facilities. DC models were named as model 1 and model 2. The room size for model 1 is over 15000 sq.ft and model 2 has size of over 7000 sq.ft. The room height for model 1 is over 15 ft and model 2 is over 18ft. The raised floor height for model 1 is little over 3ft and for model 2 is 2.5 ft. The number of ACU in model 1 is 17 out of which 4 are redundant whereas, model 2 has 9 ACU of which one is redundant. The number of cabinets in model 1 is 254 and model 2 has 268 cabinets. The number of IT equipment's in model 1 is over 1300 and in model 2 is around 3000. The number of floor grilles (also referred as tiles in this study) in model 1 is 262 and in model 2 is 280. The power density in model 1 is around 38 W/sq. ft and in model 2 is around 108 W/sq.ft. The power density shows that more cooling air will be required in model 2 as compared to model 1. The total cooling air flow provided in model is over 107 thousand cfm and for model 2 is over 138 thousand cfm. A part 3D image of model 1 and model 2 along with the different components is shown in figure 2-1 and figure 2-2 respectively. The Table 2-1 summarizes all the specifications for model 1 and model 2.

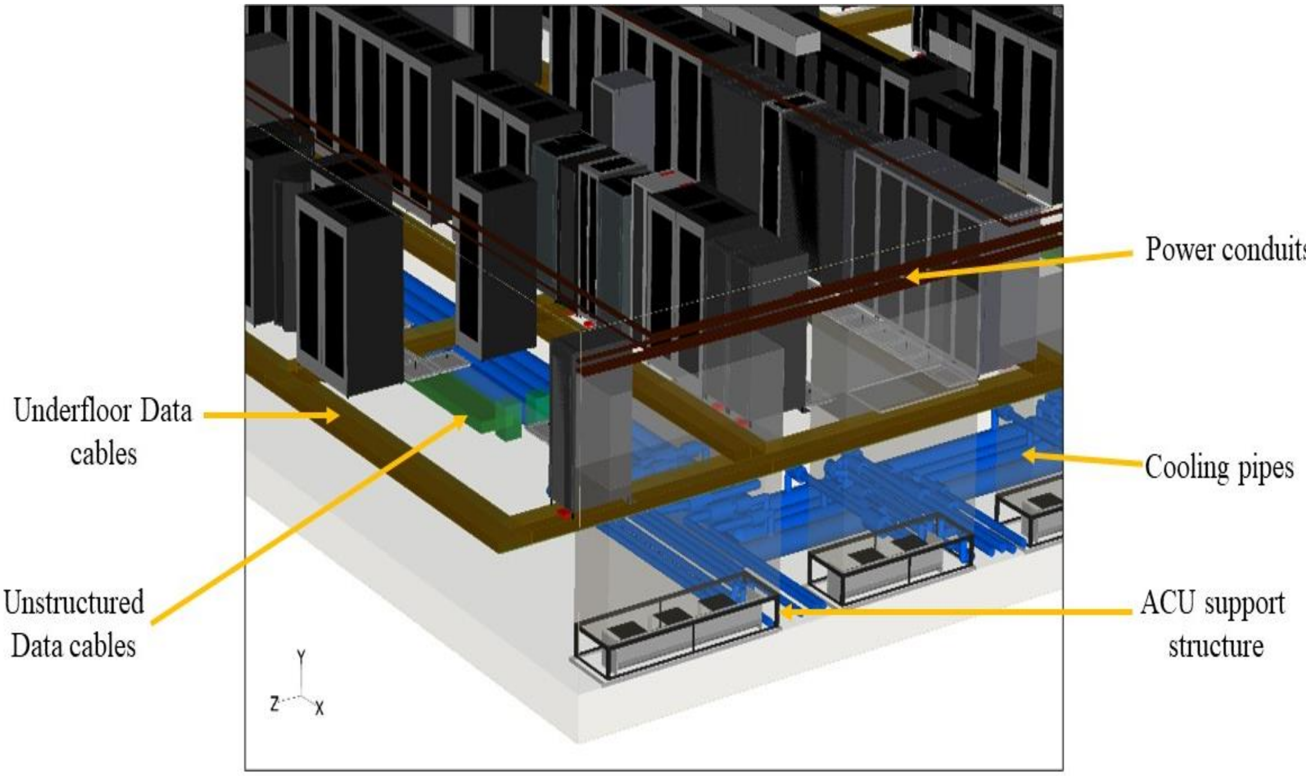

Figure 3- 1. 3D part image of Model 1

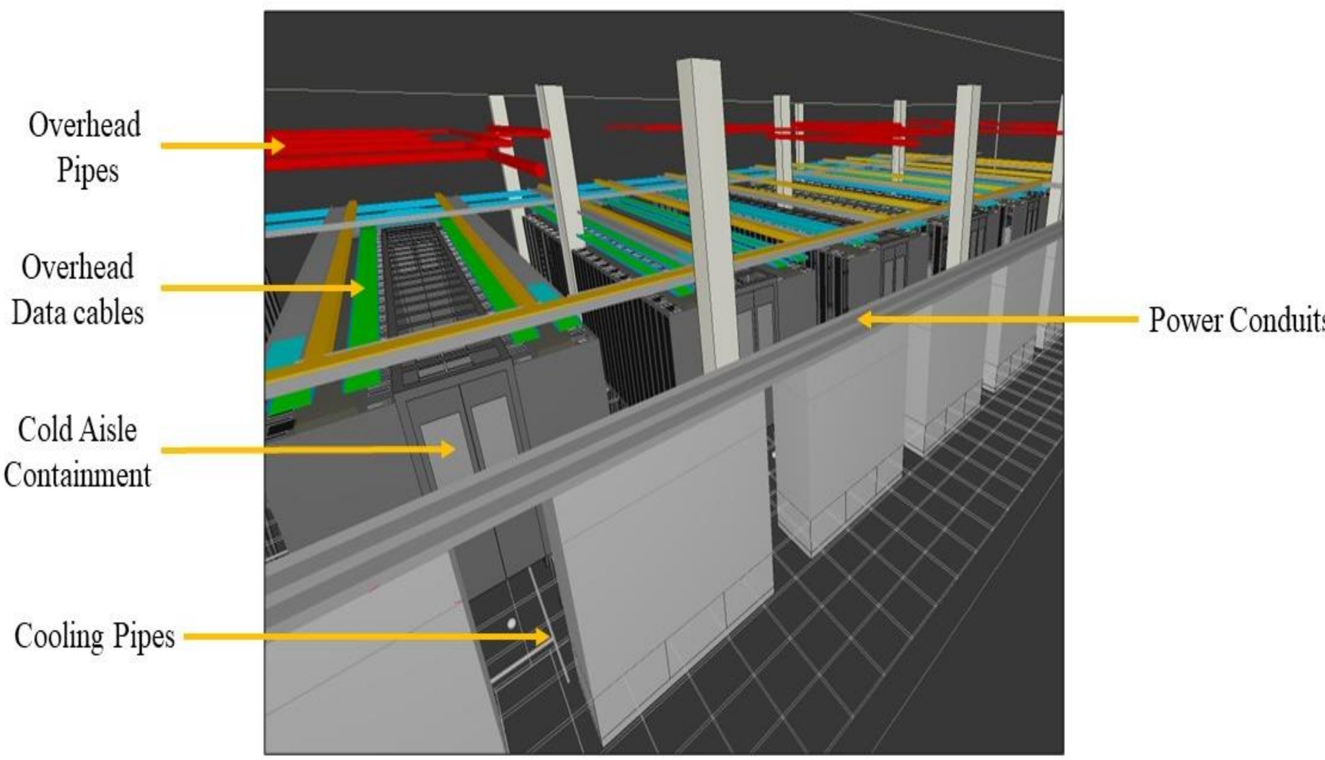

Figure 3- 2. 3D part image of Model 2

	Model 1	Model 2
Room Size	15296 ft^2	7207 ft^2
Room height	>15 ft	> 18 ft
Raised floor height	> 3 ft	2.5 ft
No. of ACU	17	9
No. of Cabinets	254	268
No. of IT Equipment	1372	2939
No. of Floor Grills	262	280
Power density	37.9 W/sq.ft	108.7 W/sq.ft
Total cooling Airflow	107691 cfm	138034 cfm

Table 2- 1. Summary of DC model 1 and model 2

Although, both models are raised floor and contain many similar components they are different in configuration. In model 1 most of the components like cooling pipes, data cables, unstructured data cables, cabinet cable penetration seal are placed under the raised floor whereas in the model 2 most of these components are placed overhead. Thus, the two models have different layout of the components which affects the airflow pattern. The model 2 has cold aisle containment whereas model 1 has no hot or cold aisle containment.

CHAPTER 4: COMPONENTS

4.1 List of components

4.1.1 Cooling pipes

The main chilled-water cooling pipes offer significant obstruction to airflow; however, the smaller cooling pipe branches are often ignored. Ignoring an individual branch is warranted, however, depending on the size, the number of branches clustered together and what is in their vicinity they need to be included. For example, the branches meandering close to the ACUs can significantly affect the path and momentum of the ACU supply cooling jet. In the DC model 1 considered, the main cooling pipes are installed within a trench that extends below the bottom side of the underfloor plenum. The smaller cooling pipe branches traverse across the underfloor plenum either towards the ACUs installed or are routed to a different floor. Capturing the branches in detail involves gaining access to the underfloor plenum and conducting a close inspection of the pipe sizes, bends, valves, and fittings.

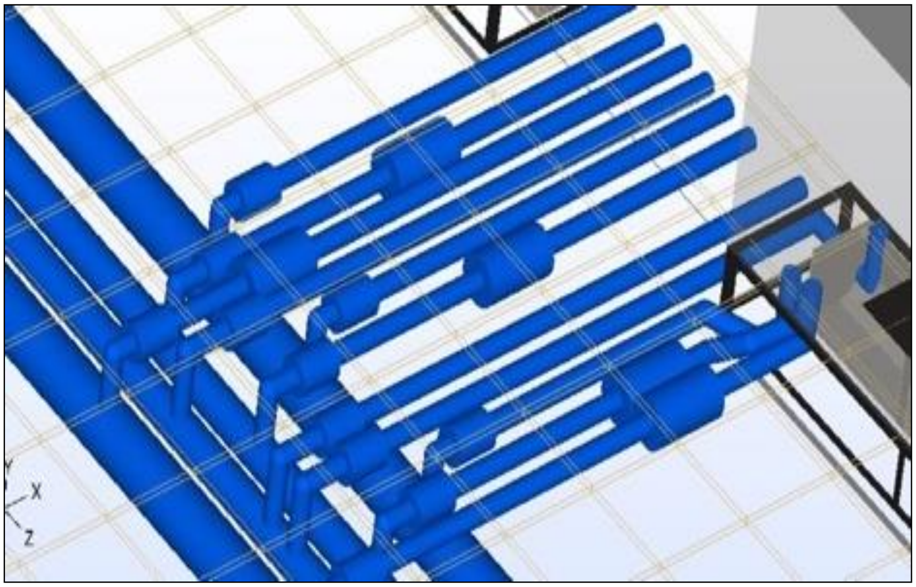

Figure 4- 1. Cooling pipes branches in DC Model 1 with sudden expansions

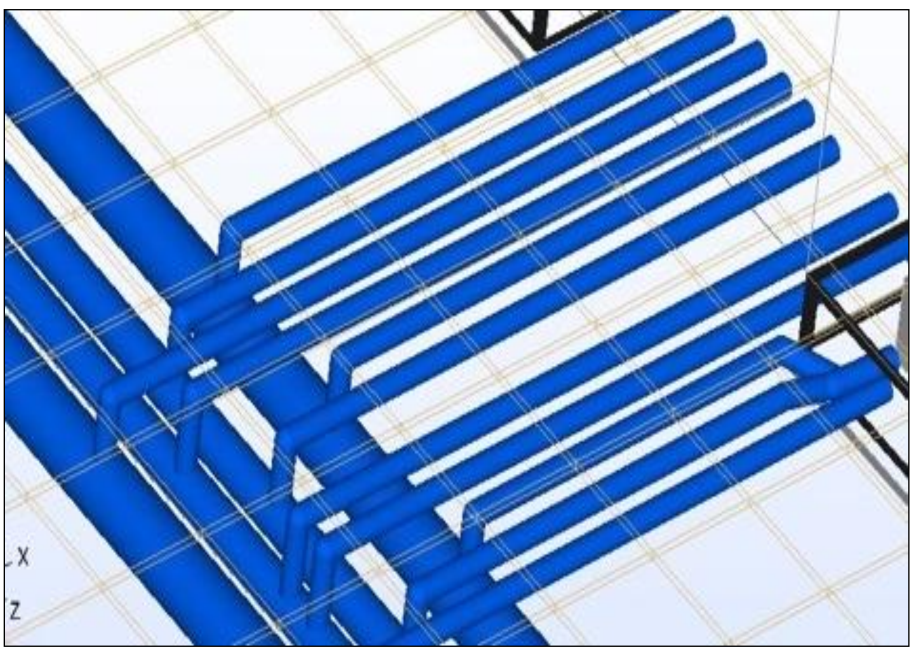

Figure 4- 2. Cooling pipe branches simplified in DC model 1

4.1.2 Data cables

These are data cables which are placed underfloor and are well stacked in cable trays or bundled together. The bottom of the tray can either be a wire-mesh sheet or a solid obstruction. These data cables are present in significant quantity and well distributed in DC hall. These data cables are placed under raised floor for model 1 and overhead in case of model 2. Cable density is the defining parameter for data cables, and this can vary from 0% to 100%. Cable density is the amount by which cable blocks a cross sectional area [10]**.**

Figure 4- 3. Underfloor data cables [11]

4.1.3 Cable penetration seal

The underfloor placed data cables penetrate through the raised floor to be connected to the cabinets or IT. To facilitate this, a hole is punched into the raised floor which needs to be sealed efficiently to prevent air leakage. In case of overhead data cables like in model 2, the cables penetrate the cabinet from the top and hence sealing must be provided to the cabinets. Sealing efficiency is the parameter used to define cable penetration seal. Sealing efficiency is the amount by which hole is obstructed by seals and cables [10]. Sealing efficiency can be varied between 0% to 100% where 0% means no sealing and 100% perfect sealing. The leakage sealing efficiency of cable penetration seal can vary based on the number of cables run through grommets and whether the cables are centered or pulled to a side [12]. The figure 4- 4 shows cable penetrating through raised floor and figure 4- 5 shows holes punched in cabinet to allow cables to penetrate through.

Figure 4- 4. Cabinet cable penetration seal

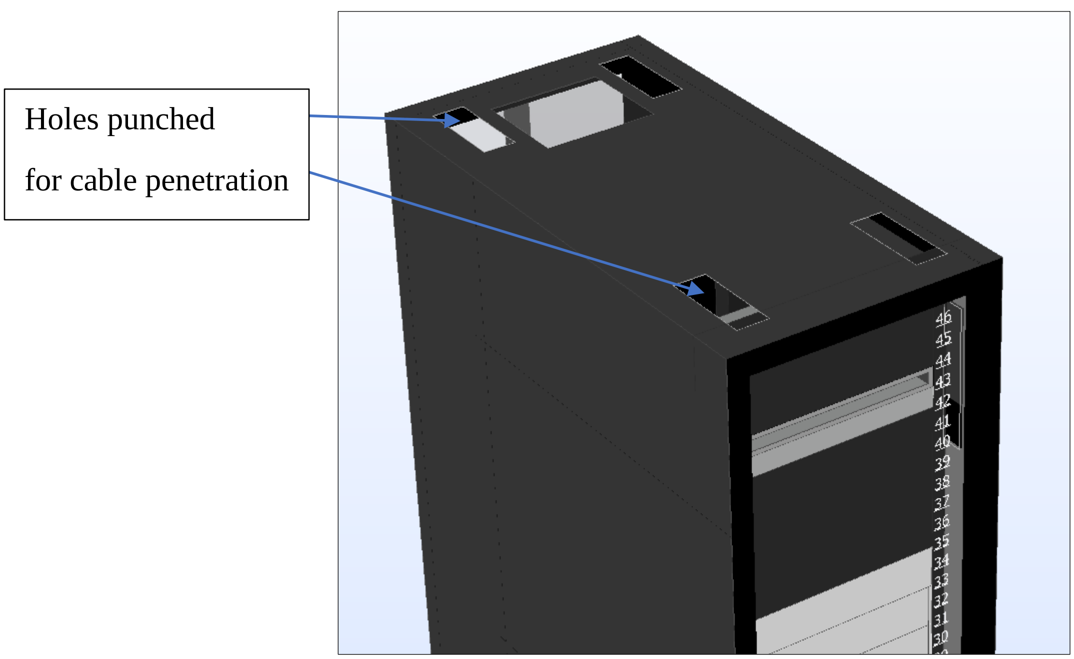

Figure 4- 5. Cable penetration seal in model 2

4.1.4 Unstructured data cable

These data cables are placed underfloor. They are not well ordered and stacked and hence are difficult to model. It is time-consuming to survey and record the details of unstructured cables. The unstructured data cables are also defined by cable density parameter. Moreover, the detailed representation increases the computational time with no viable improvement in prediction accuracy. The figure 4- 6 shows unstructured data cables in an actual data center.

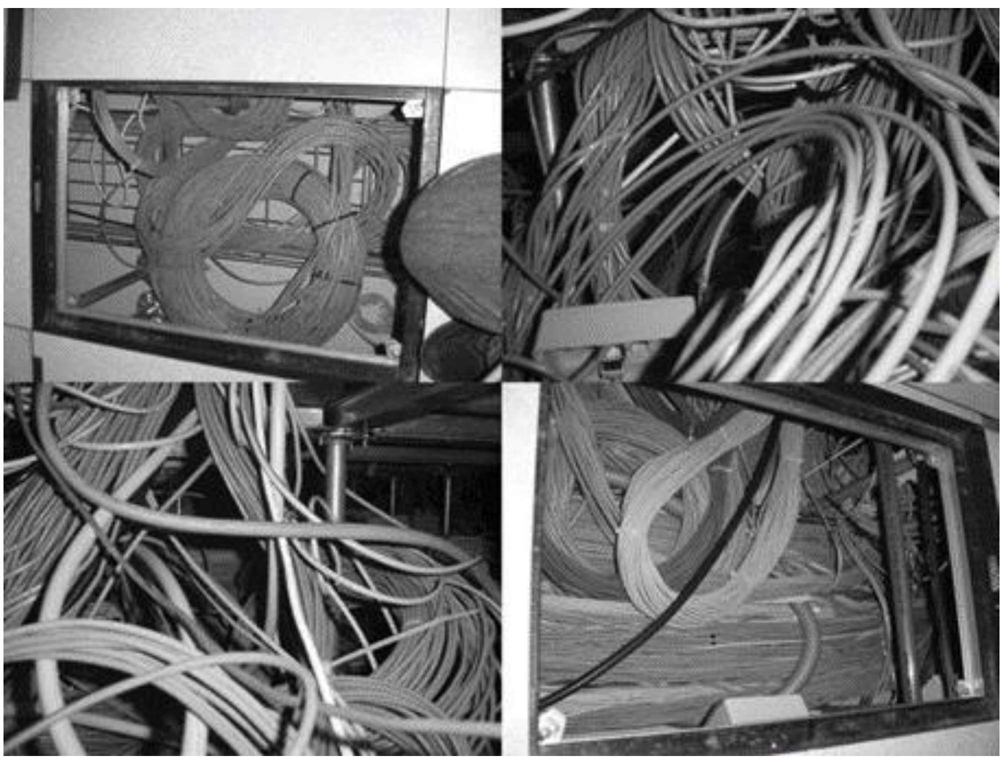

Figure 4- 6. Unstructured data cables [10]

4.1.5 Cables inside cabinets

Cabinets contain several IT equipment like server, switches etc. Cables are used to connect these IT which takes a form of a bundle inside the cabinet unit. These are also defined by the cable density parameter like data cables and unstructured data cables. A typical cabinet connected with cabling is shown in figure 4-7.

Figure 4- 7. Cables inside cabinet [13]

4.1.6 Power conduits

These are cables which supply power to the cabinets from power distribution unit. These are in the form of conduits circular in shape and are run usually across the ceiling. They are similar to cooling pipes in modeling and defined by diameter and length.

Figure 4- 8. Power conduits [14]

4.1.7 Power strips

Power strips are the sockets to which the IT equipment are connected to supply power. These power strips are mounted to the cabinets.

4.1.8 **ACU support structure**

ACU placement requires a support structure to bear its load. This support structure is part of what is commonly referred to as a floor stand. This is often accompanied with other components for seismic restraint and/or vibration isolation. An optional turning vane can be included to meet the airflow and acoustical requirements and are not to be ignored in the ACU model. The close proximity of fans, the height-adjustable frame and the survey effort involved due to poor access makes this a good candidate to study how it affects the air flow in the DC. The figure 4-9 shows a ACU support structure with scoop.

Figure 4- 9. ACU Support structure [15]

4.1.9 Cabinet Frame

Cabinet frames form the outer structure of the cabinet. The cabinet panels are attached to this frame. These frames are present in significant quantity in model 2 and hence were considered for sensitivity study. The figure 4-10 shows a typical cabinet frame and figure 4-11 shows image of cabinet frame in model 2.

Figure 4- 10. Cabinet frame [16]

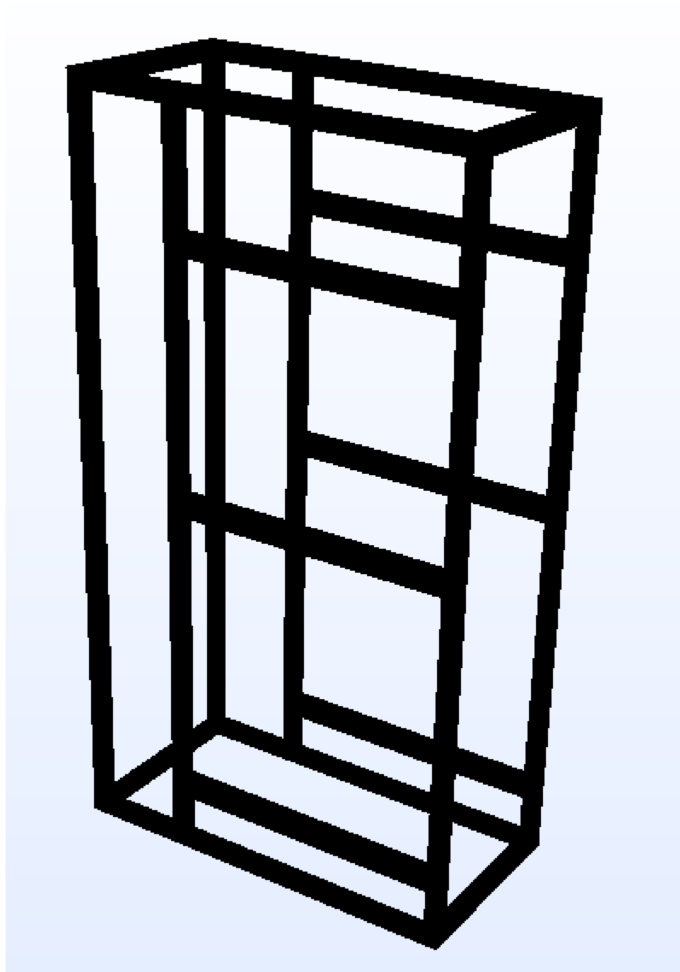

Figure 4- 11. Cabinet frame representation in model 2

4.1.10 Containment Leakage

Containment leakage is usually present when there is hot or cold aisle containment present in DC. The figure 4-12 shows cold aisle containment. Door and containment panels are used to contain in a certain region. Leakage usually occurs due to the loose fitting of these door and containment panel. Leakage is defined by the percentage open area. The highlighted part in the figure 4-13 represents the containment leakage.

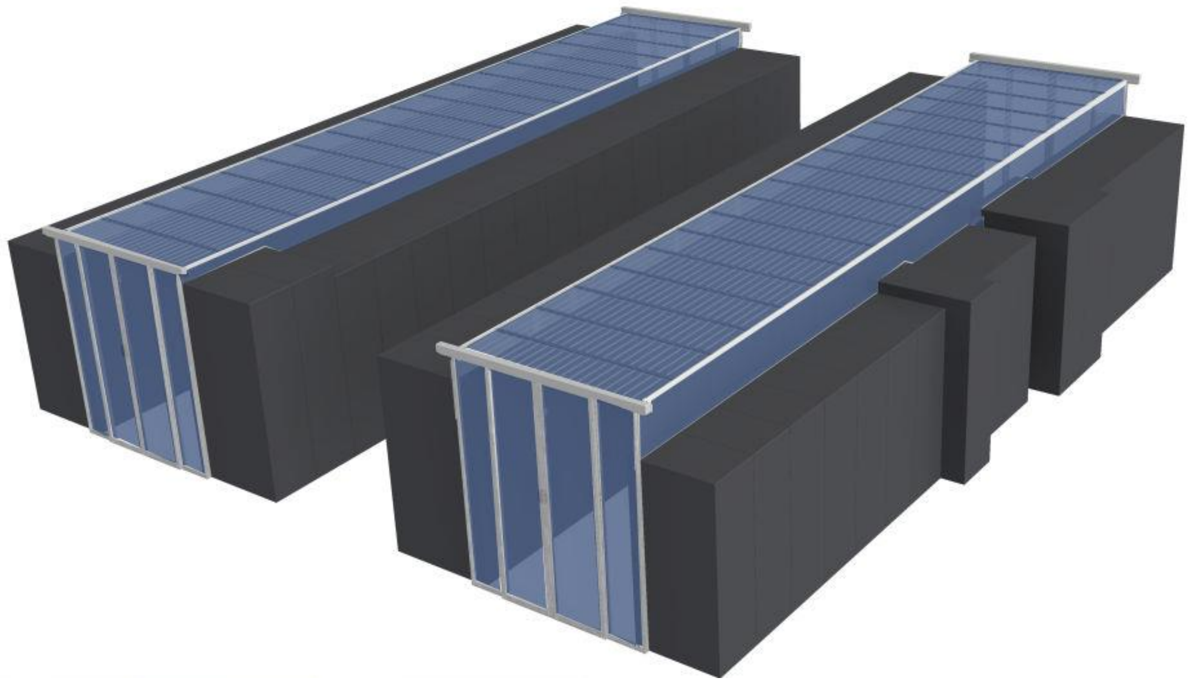

Figure 4- 12. Cold Aisle containment [17]

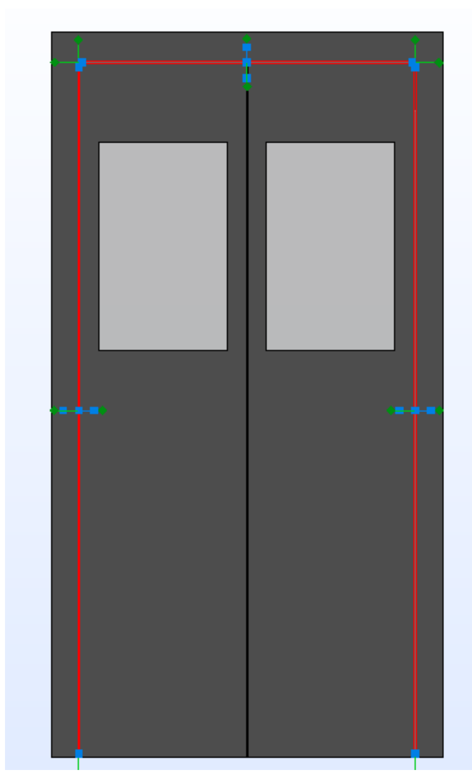

Figure 4- 13. Highlighted region representing containment leakage in model 2

4.1.11 IT depth offset

The IT depth offset is a value by which IT equipment is offset from the mounting rail [10]. In actual DC, the IT depth offset can be different for all the IT. This offset has to be measured for all IT and will be certainly very time consuming. The figure 4-14 shows the IT equipment different IT depth offset and figure 4-15 shows all IT equipment depth offset set to zero.

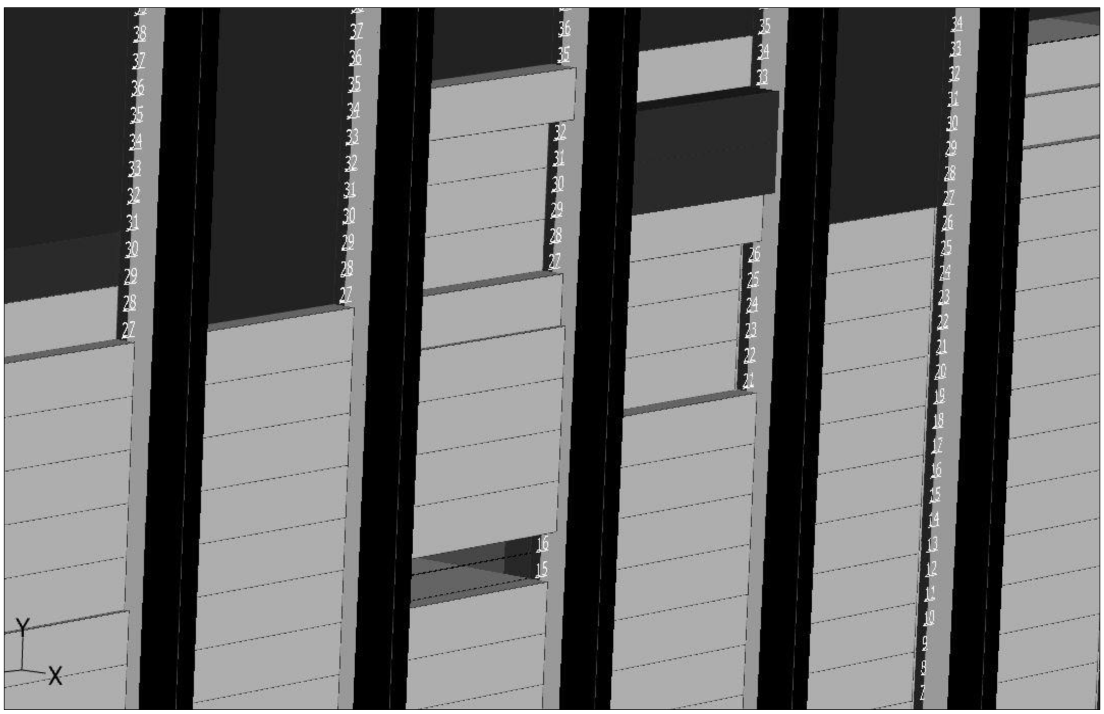

Figure 4- 14. IT depth offset for IT Equipment

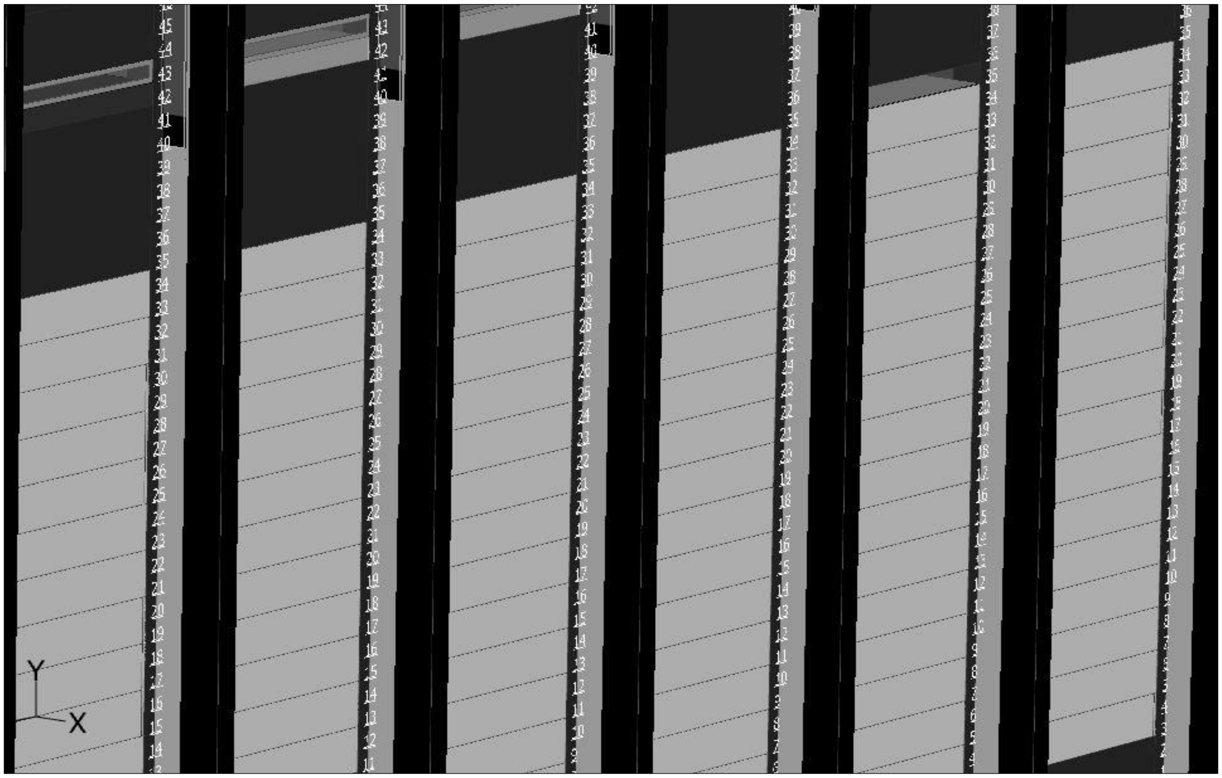

Figure 4- 15. IT depth offset set to zero

4.2 Modifications in individual components

Sr. No	Components	Present	Modifications
1	Cooling Pipes	Model 1 and 2	Cooling pipes were deleted in both models. In model 1 sudden expansions were deleted.
2	Data cables	Model 1 and 2	Data cables were deleted in both models, Cable density model 1: 0%, 25%, 50%,75% and 100%. Cable density model 2: 0%,25%, 40%,60%,75% and 100%.
3	Power conduit	Model 1 and 2	Power conduit were deleted
4	Cable penetration seal	Model 1 and 2	Sealing efficiency model 1: 0%, 25%, 50%, 80%, and 100% Sealing efficiency model 2: 0%, 25%,50%,75% and 100%.
5	Unstructured cable	Model 1 and 2	Deleted
6	IT depth offset	Model 2	IT Depth offset set to 0
7	Cable inside cabinet	Model 1 and 2	Deleted
8	Internal cabinet frame	Model 2	Deleted
9	Power strips	Model 1 and 2	Added
10	Support structure ACU/Cabinets	Model 1 and 2	Deleted
11	Containment leakage	Model 2	Deleted
12	Ducts	Model 2	Deleted
13	Obstructions	Model 2	Deleted

Table 4- 1. List of components with modifications made

The level of detail necessary to model a component can either be the geometry or the parameters that constitute the component object model. In Table 3-1., the changes made to the component geometry or the model parameters are shown. As evident from Table 3-1, components pertaining to geometry definition are simplified either by ignoring or sacrificing details such as the sudden expansions found in cooling pipe branches as shown in Fig. 3-1. Fig. 3-2 shows the simplified geometry of the cooling pipe branches.

The components pertaining to cabling range from an individual loose cable to a bundle of data cables. The volume obstruction effect of such cables can be accounted for by resistance coefficients or by model parameters that require visual inspection during survey **[7]**. To study the effect of data cables, changes were made in cable density parameter of data cables. For structured cables, the presence of a cable tray and the cable density allow for a simplified representation using a solid obstruction. To study the sensitivity of the data cables, they were first removed from the model completely and compared with the baseline case. Subsequently, simulations were run for different cable density values for both models as shown in Table 3-1. In the case of unstructured cabling, the degree of volume obstruction is difficult to estimate. Unstructured data cables are similar to the underfloor data cables in definition. To study its effect on tile flowrate and IT, data cables were deleted. Cables within cabinet and connecting IT are modeled using the cable density percentage. Again, the cables were deleted from the model to study how it affects the tile flow rates and IT.

Cable penetration seal is defined using the sealing efficiency. To observe the effect of cable penetration seal, the sealing percentage is set to zero for the comparison with the baseline model. Furthermore, simulations were run for different sealing efficiency values as shown in Table 3-1. To study the effect of the power cables on tile flowrate, power conduits were removed from the model for the simulations, similar action was taken for ACU and Cabinet support structure, and other components like obstructions, containment leakage and internal cabinet frame. Whereas to study the effect of power strips, they were added to the model.

CHAPTER 5: METHODOLOGY

The detailed DC model built in 6Sigma Room has been provided by Future Facilities **[10]**. The detailed model is calibrated with on-site measurements not limited to tile flow rates. Figure 5-1 and figure 5-2 provides the minimum (min), maximum (max), mean and the standard deviation of tile flow rates for the baseline model and on-site measurements made with an airflow capture hood for every single tile for model 1 and model 2 respectively.

The detailed model forms the baseline for comparison and is referred to as the baseline model in this paper. Simulations are run with a modification made for each component listed in Table …. to obtain tile flow rate predictions for each simulation case.

The percentage change in the tile flow rate is calculated as shown by the equation 1 below:

$$\%\ \text{Change} = \frac{(\text{Tile flow rate}_{B} - \text{Tile flow rate}_{S})}{(\text{Tile flow rate}_{B\ max} - \text{Tile flow rate}_{B\ min})} * 100$$

B – Baseline model

S – Simulated model

B_{max} – Maximum value of tile flow rate in baseline model

B_{min} – Minimum value of tile flow rate in baseline model

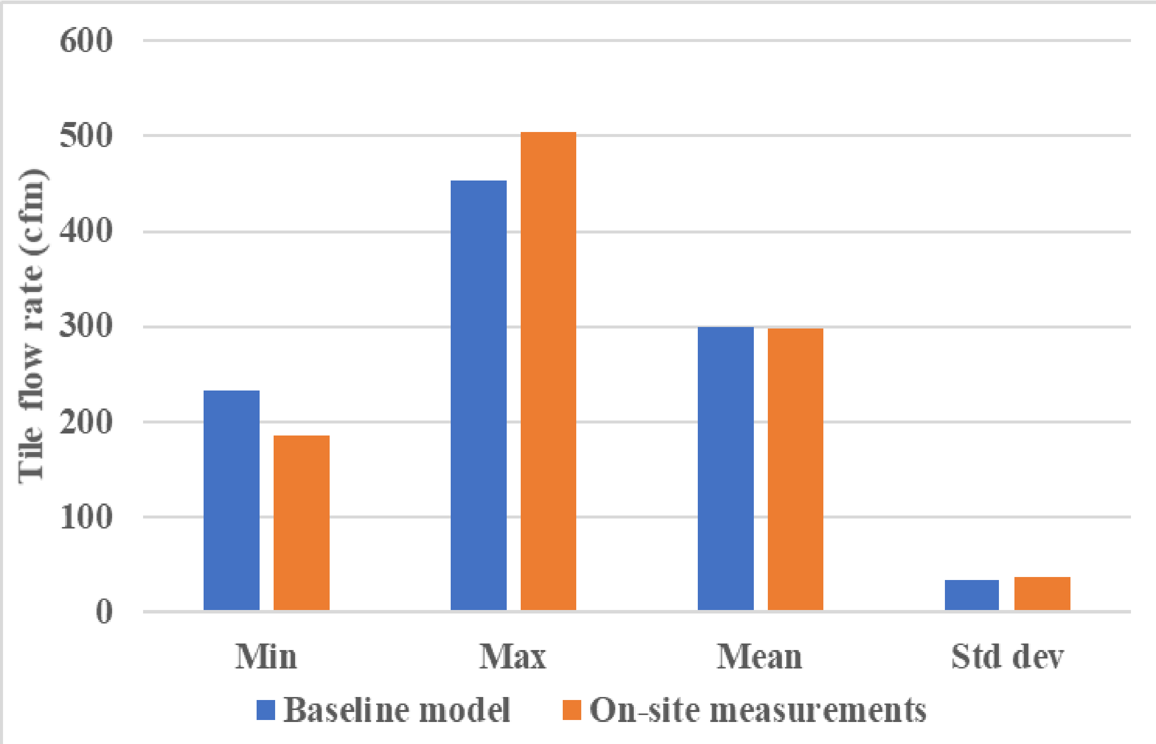

Figure 5- 1. Comparison of baseline model and measured tile flow rates in model 1

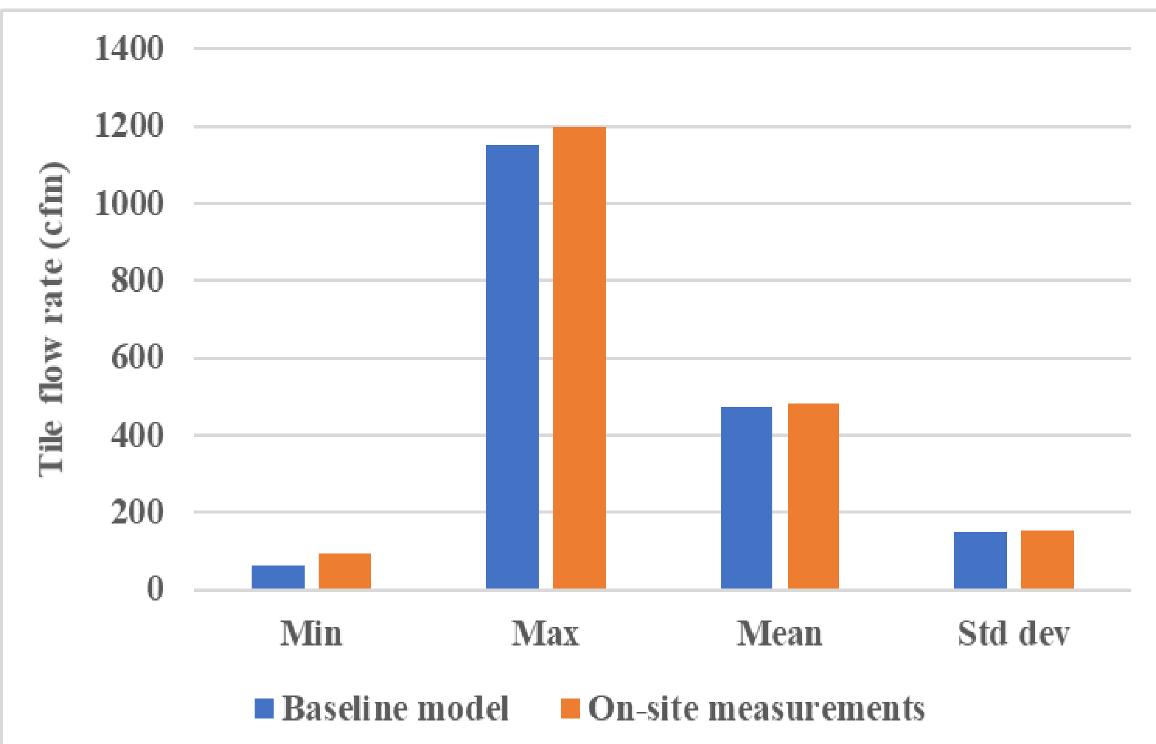

Figure 5- 2. Comparison of baseline model and measured tile flow rates in model

CHAPTER 6: RESULTS

Once the simulations performed for all the components in both model 1 and model 2. The tile flow results, and IT results are collected from the simulations.

6.1 Model 1 Tile flow results

The % change in tile flow rate is calculated using the formula in equation 1. After calculating % change, % change in tile flow rate is distributed in bins like 0% to 2%, 2% to 4% and so on and then number of tiles or percentage of tiles in particular bins were calculated. After that, these numbers were plotted to able compare the relative sensitivity of the components. Ideally, components which have low sensitivity to tiles will have maximum number of tiles close to zero percentage and components which have high sensitivity to tiles will have least number of tiles close to zero.

Figure 6- 1 shows the number of tiles in particular % change bin for all the components. We can see that cabinet cable penetration seal has maximum number of tiles is range of 20% to 26%. For underfloor data cables, we see that number of tiles are evenly distributed across -7% to 14%. For cooling pipes, 40% of tiles are in range of -1% to 2% change. Cable inside cabinet, power strips, power conduits and unstructured data cables components have 98% to 95% of tile in range of -1% to 2% change. Cooling pipe branches model have 71% of tiles in range of -1% to 2% change.

From figure 6-1, we can say that cabinet cable penetration seal, cooling pipes, and underfloor data cables show relatively higher sensitivity to tile flow and cable inside cabinet, power strips, ACU support structure, and unstructured data cables show relatively less sensitivity to tile flow. The Table 6- 1 shows percentage of tiles for all the components in particular % change.

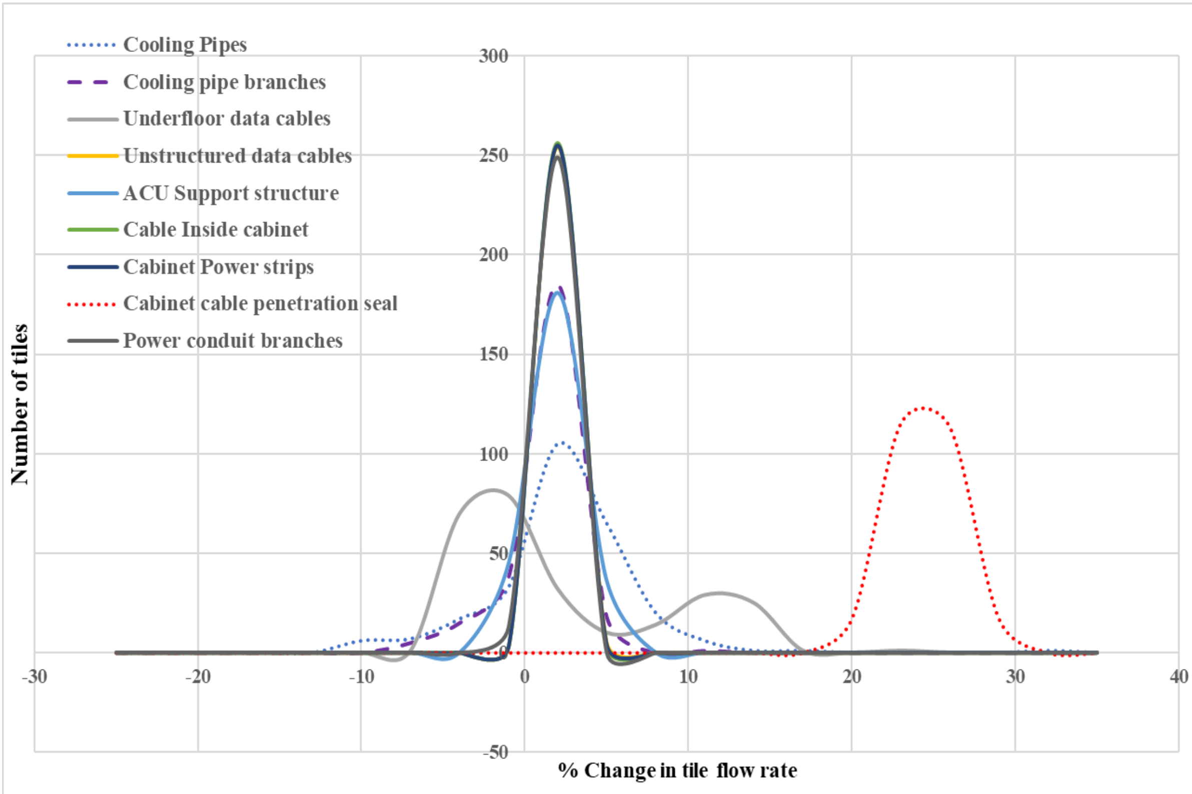

Figure 6- 1. Comparing the % change in tile flow rate for all components

% Change	Percentage of Tiles								
	Cooling pipe branches	Underfloor data cables	Unstructured data cables	ACU support structure	Cable inside cabinet	Power strips	Cabinet cable penetration seal	Power conduit branches	Cooling Pipes
>= -13	0	0	0	0	0	0	0	0	0
-10	0	0	0	0	0	0	0	0	2
-7	2	0	0	0	0	0	0	0	3
-4	6	27	0	0	0	0	0	0	6
-1	15	30	1	17	1	1	0	5	13
2	71	12	97	69	98	97	0	95	40
5	7	4	2	14	1	2	0	0	25
8	0	5	0	0	0	0	0	0	8
11	0	11	0	0	0	0	0	0	2
14	0	10	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	6	0	0
23	0	0	0	0	0	0	44	0	0
26	0	0	0	0	0	0	43	0	0
29	0	0	0	0	0	0	6	0	0
32	0	0	0	0	0	0	0	0	0

Table 6- 1. Percentage of tiles in particular % change range for all components

Figure 6- 2 shows plot for underfloor data cables, for model without data cables, and cable density values of 0%, 25%, 50%, 75%, and 100%. The plot shows not much of a difference in tile flow values as maximum tiles lie in range of -2% to 2%. The Table 6- 2 gives a clear idea about the effect cable density on tile flow. For cable density value of 0% we see that around 86% of tiles are in range of -2% to 2%. For cable density values of 75% and 100%, 95% and 93% of tiles are in range of -2% to 2% respectively. Although, these values look high, we observe that for cable density values of 25% and 50%, 99% and 98% of tiles are in range of -2% to 2%.

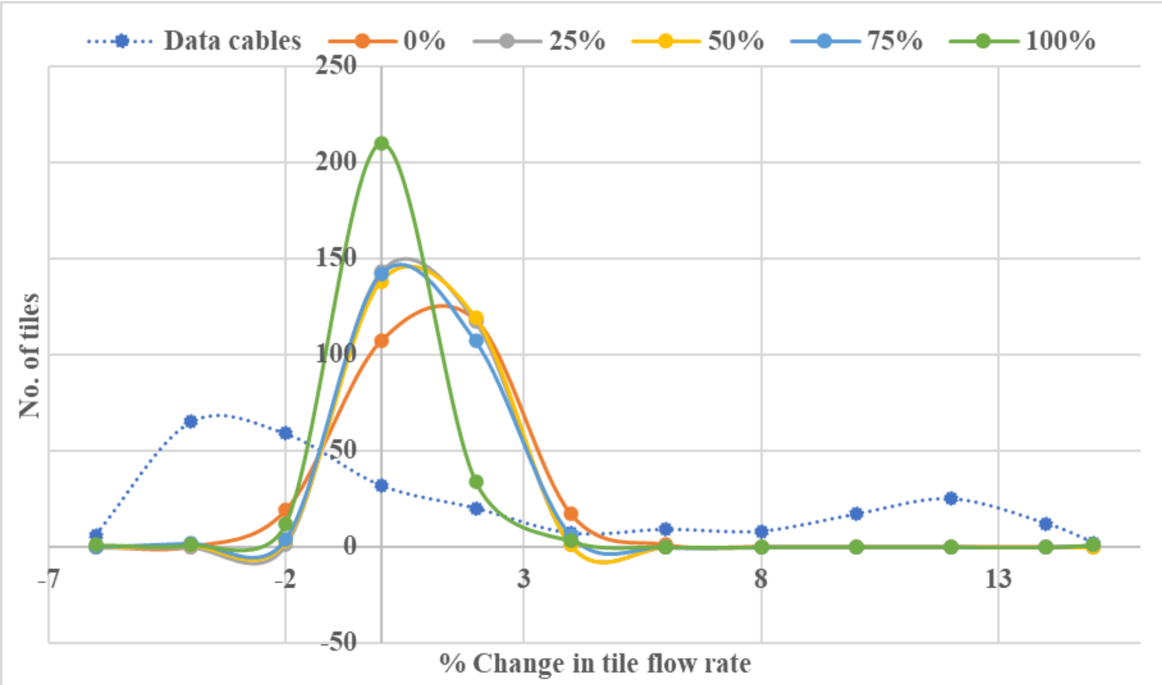

Figure 6- 2. Comparison of % change in tile flow rate for different cable density

% Change	Data cables	0%	25%	50%	75%	100%
-6	2.3	0.0	0.0	0.0	0.0	0.4
-4	24.8	0.0	0.0	0.4	0.8	0.4
-2	22.5	7.3	0.4	1.1	1.5	4.6
0	12.2	40.8	54.6	52.7	54.2	80.2
2	7.6	45.0	44.7	45.4	40.8	13.0
4	2.7	6.5	0.4	0.4	2.3	1.1
6	3.4	0.4	0.0	0.0	0.0	0.0
8	3.1	0.0	0.0	0.0	0.0	0.0
10	6.5	0.0	0.0	0.0	0.0	0.0
12	9.5	0.0	0.0	0.0	0.0	0.0
14	4.6	0.0	0.0	0.0	0.0	0.0
15	0.8	0.0	0.0	0.0	0.4	0.4

Table 6- 2. Percentage of tiles in particular % change range for different cable density values

For cabinet cable penetration seal, sealing efficiency parameter was varied to 0%, 25%, 50%, 80%, and 100%. From figure 6-3 we see that for sealing efficiency of 0%, 85% of tiles are in range of 21% to 27%. For 25% sealing efficiency, 92% of tile are in range of 15% to 21%. For 50% sealing efficiency, 100% of tiles are in range of 6% to 12%. For 80% sealing efficiency, 99% of tiles are in range of -6% to 0%. For 100% sealing efficiency ,99% of tiles are in range of -15% to -9%. From this, we can say that cabinet cable penetration seal has significant effect on tile flow rate.

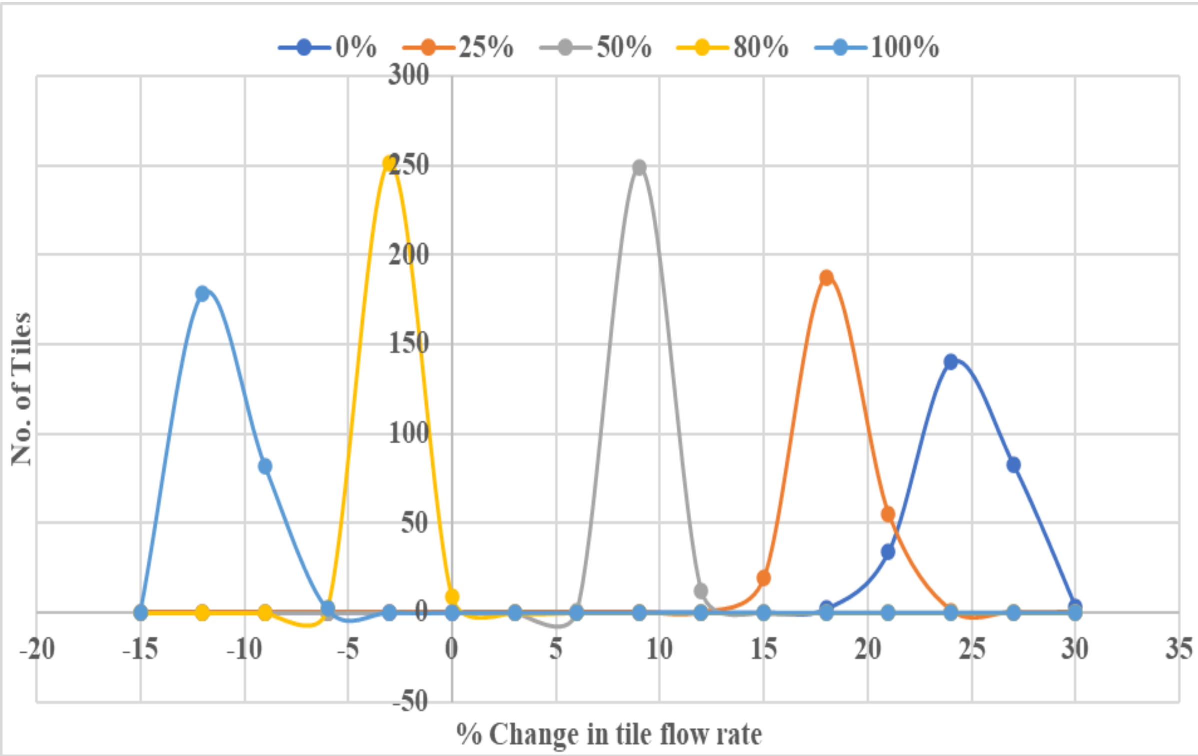

Figure 6- 3. Comparison of % change in tile flow rate for different sealing efficiency

6.2 Model 1 IT results

6.2.1 IT Compliance

It is the number of IT which are under the ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning) allowable inlet temperature value, set to 32°C in this case. The % change in IT compliance is calculated from the formula below.

$$\%\,Change\ =\ \frac{(No.of\ IT)_B-\ (No.of\ IT)_S}{(No.of\ IT)_B}*100$$

B – Baseline model

S – Simulated model

From the Table 6- 3 we see that % change in IT for all the components is less than 1% i.e., almost 10 IT. We can say that IT compliance is not affected much by the changes in the tile flow rate. Figure 6- 4 shows the plot for IT compliance where x-axis is the models created from modifications in the components. The serial number in the table represents the model number for the figure 6- 4.

Sr. No	Models	No of IT	% Change
1	Cable penetartion seal	1142	-0.88
2	Power strips	1134	-0.18
3	Unstructured cable	1135	-0.27
4	Cable inside cabinet	1134	-0.18
5	ACU Support	1134	-0.18
6	Power conduits	1131	0.09
7	Data cables	1133	-0.09
8	Cooling pipe branches	1130	0.18
9	Cooling pipes	1126	0.53
10	Baseline	1132	0.00

Table 6- 3. Comparing number of IT in compliance and % change in IT compliance for model 1

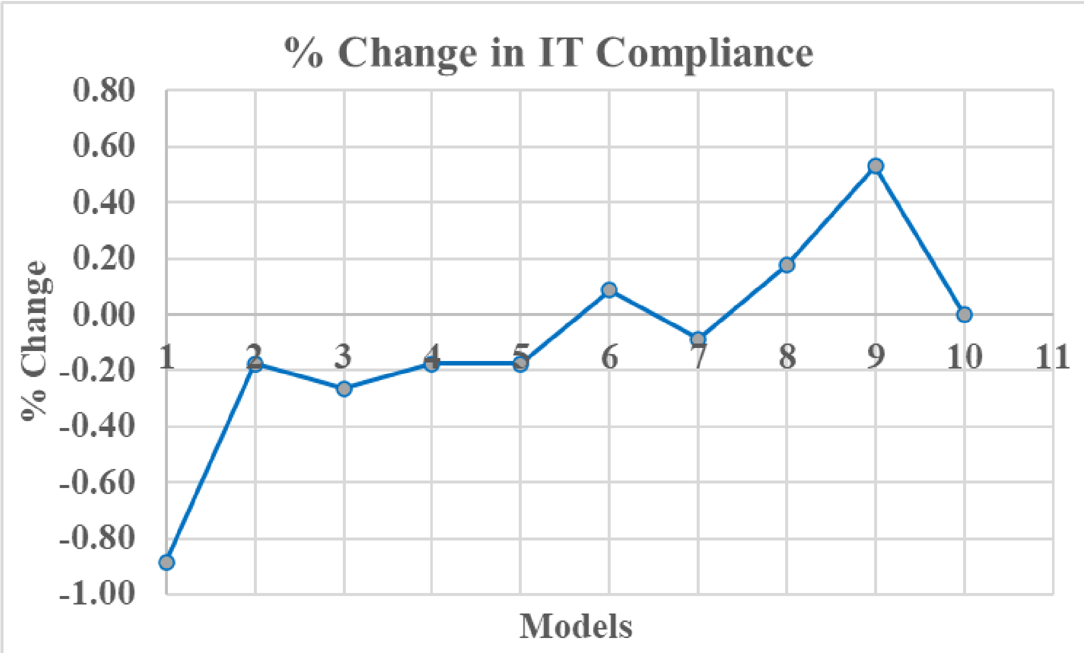

Figure 6- 4. Comparing % change in IT compliance for different components for model 1

6.2.2 Net flow across IT:

The % change in the net flow across IT is calculated from the formula below.

$$\%\ \text{Change} = \frac{(\text{Net flow across IT})_B - (\text{Net flow across IT})_S}{(\text{Net flow across IT}_{B\ max} - \text{Net flow across IT}_{B\ min})} * 100$$

B – Baseline model

S – Simulated model

B_{max} – Maximum value of net flow across IT in baseline model

B_{min} – Minimum value of net flow across IT in baseline model

From the figure 6- 5 we see that maximum number of IT are in the range of -0.5% to 0.5% change in net flow across IT. The 1% change here accounts for 0.83 cfm change in net flow. The Table 6-4 shows the percentage of IT in particular percentage range of net flow across IT. From both figure

6- 5 and Table 6- 4 we can say that change in the tile flow rate has negligible effect on net flow across the IT.

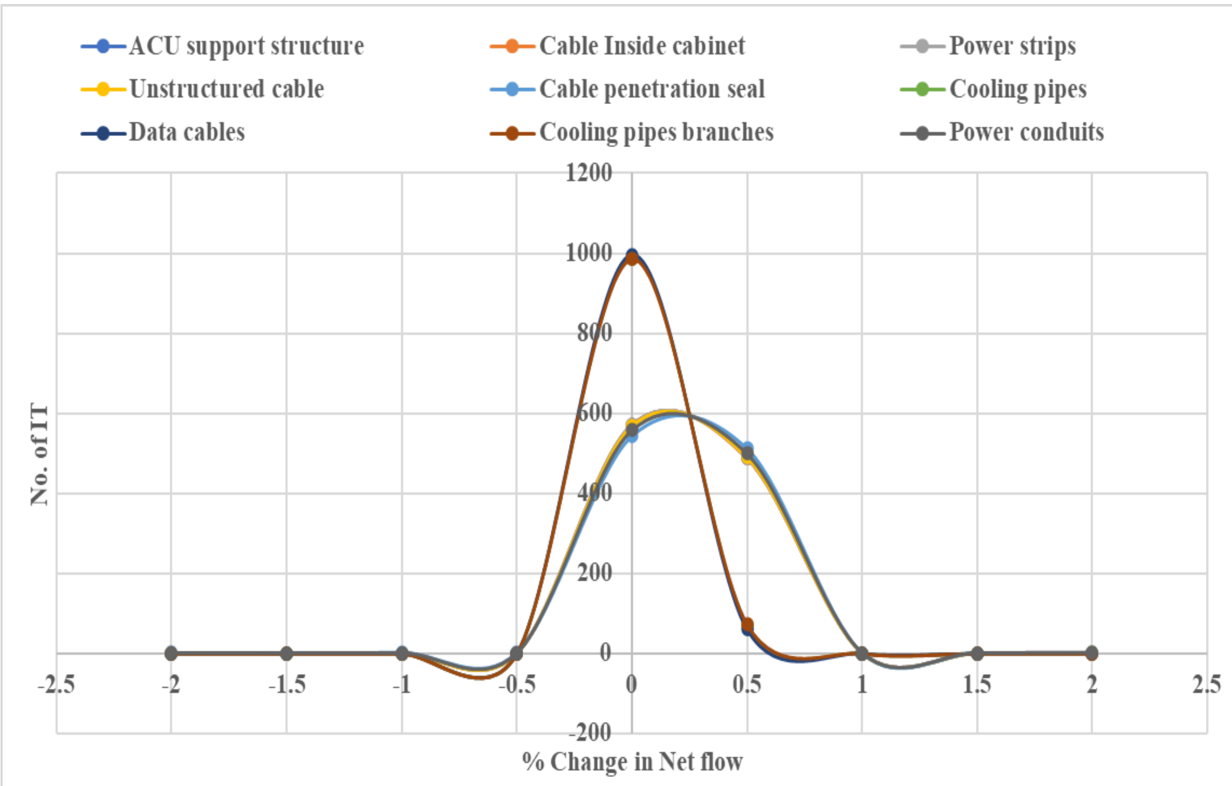

Figure 6- 5. Comparing the % change in net flow rate for all components

% Change	Percentage of IT								
	ACU support structure	Cable Inside cabinet	Power strips	Unstructured cable	Cable penetration seal	Cooling pipes	Data cables	Cooling pipes branches	Power conduits
-2	0	0	0	0	0	0	0	0	0
-1.5	0	0	0	0	0	0	0	0	0
-1	0	0	0	0	0	0	0	0	0
-0.5	0	0	0	0	0	0	0	0	0
0	54	54	54	54	51	93	94	93	53
0.5	46	46	46	46	48	7	6	7	47
1	0	0	0	0	0	0	0	0	0
1.5	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0

Table 6- 4. Percentage of IT in particular % change range for all components

6.2.3 Temperature at Inlet of IT:

To see the effect on inlet temperatures of IT, difference in inlet temperature of IT is calculated between the baseline model and simulated model i.e.

$$\text{Inlet Temperature difference} = (\text{Inlet Temperature})_B - (\text{Inlet Temperature})_S$$

Where B – Baseline model

S – Simulated model

For simplification in observation of results the components were divided in to two parts, one the components which showed relatively less sensitivity to tile flow rate and second, components which showed relatively substantial sensitivity to tile flow rate. The figure 6- 6 shows number of IT in for range in inlet temperature difference. We see that cable inside cabinet, power strips, unstructured data cables, power conduits have maximum number of IT in range of -1°C to 1°C. From figure 6- 7 we see that cable penetration seal, cooling pipes and underfloor data cables have relatively a smaller number of IT in range of -1°C to 1°C. Thus, we can say that change in the tile flow rate has substantial effect on IT for cable penetration seal, cooling pipes, and underfloor data cables.

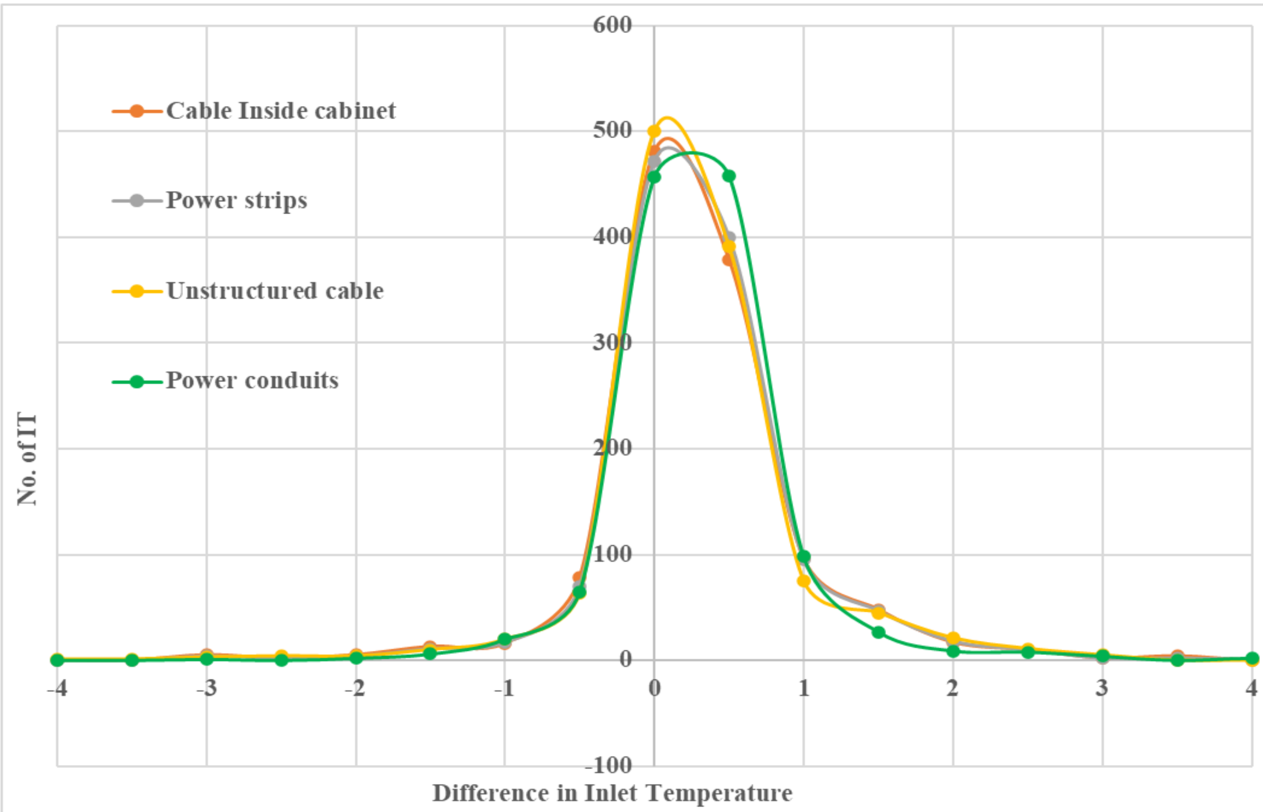

Figure 6- 6. Comparison of difference in inlet IT temperature for all components which showed less sensitivity to tile flow rate

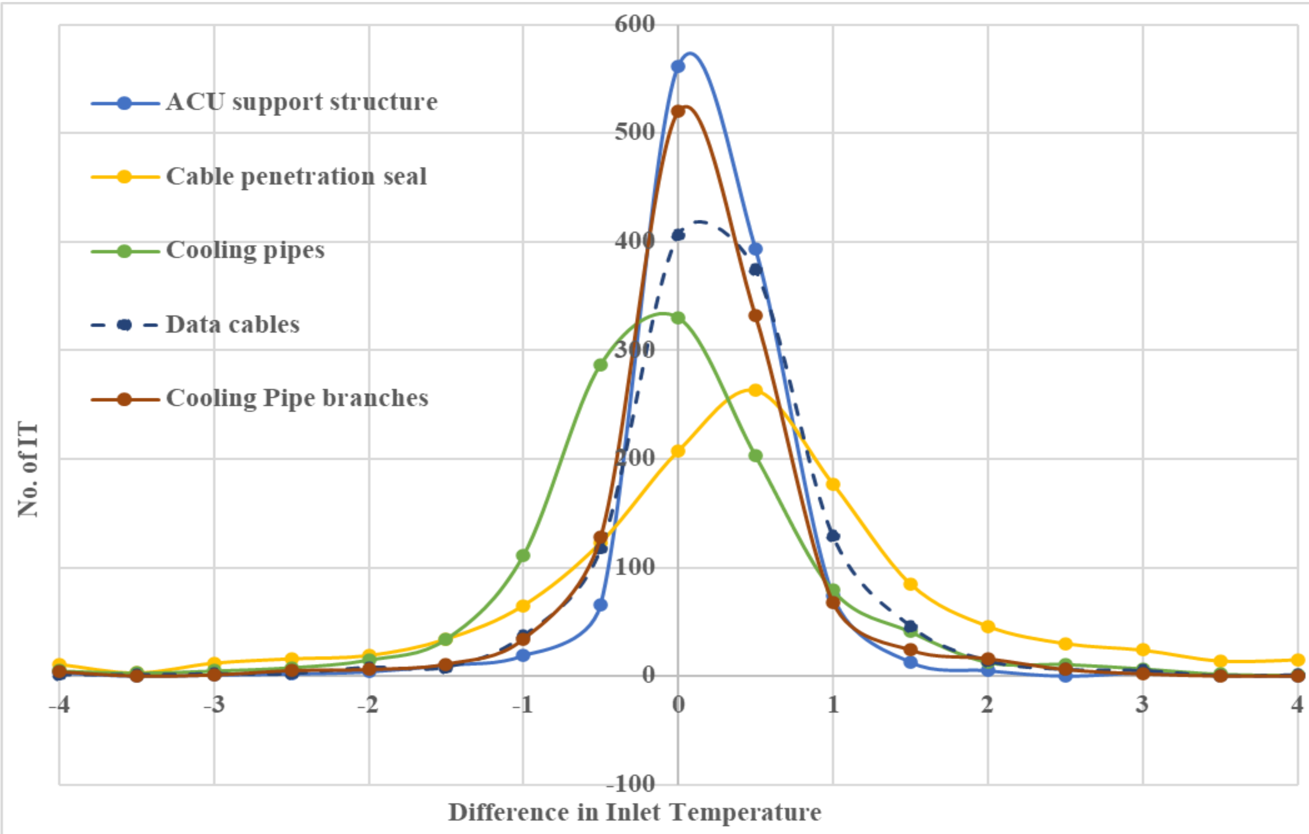

Figure 6- 7. Comparison of difference in inlet IT temperature for all components which showed substantial sensitivity to tile flow rate

6.3 Model 2 Tile flow results

To observe the results clearly the components in model 2 are divided in to two parts, one which show relatively less sensitivity to tile flow rate and second which showed relatively substantial sensitivity to tile flow rate. From figure 6- 8 we see that cable inside cabinet, containment leakage, power strips, cable penetration seal, ducts, unstructured data cables have maximum tiles in range of -1% to 1% change in tile flow rate. From figure 6- 9 we see that obstructions, overhead pipes, cabinet frame, cabinet support, data cables, cooling pipes models relatively have smaller number of tiles in range of -1% to 1% change in tile flow rate.

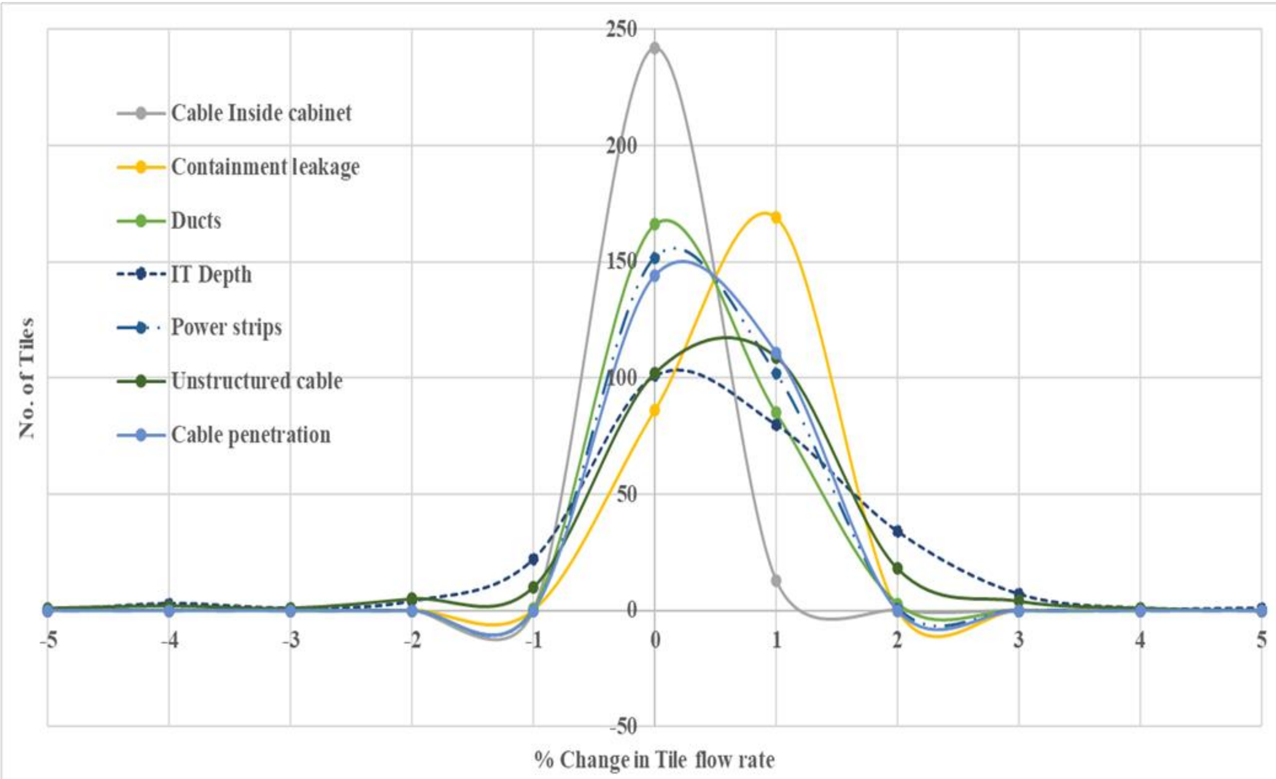

Figure 6- 8. Comparison of % change in tile flow rate for components which showed less sensitivity to tile flow rate

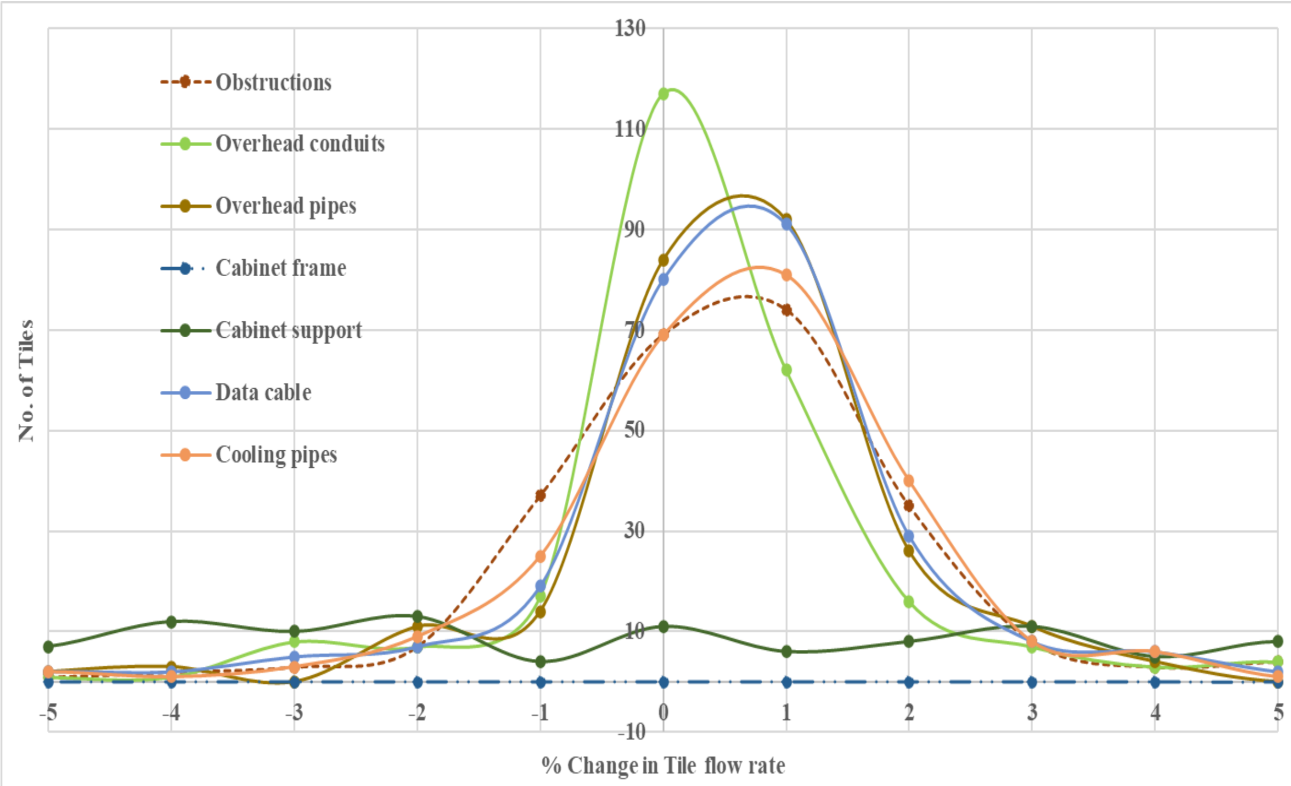

Figure 6- 9. Comparison of % change in tile flow rate for components which showed substantial sensitivity to tile flow rate

Table 6- 5 shows the number of tiles in particular percentage change for model without data cables, and cable density values of 0%, 25%, 40%, 60% 75%, and 100%. It shows not much of a difference in tile flow values as maximum tiles lie in range of -0.5% to 1.5%, which accounts for 2 cfm to 6 cfm change in tile flow values. Hence, we can say that cable density parameter has negligible effect on tile flow rate.

% Change	Data cables	0%	25%	40%	60%	75%	100%
-3	10	0	0	0	0	0	0
-2.5	2	0	0	0	0	0	0
-2	5	0	0	0	0	0	0
-1.5	5	0	0	0	0	0	0
-1	14	0	0	0	0	0	0
-0.5	30	1	0	1	0	0	1
0	50	174	3	174	3	3	173
0.5	45	76	98	76	98	98	77
1	46	2	151	2	151	151	2
1.5	21	2	2	2	2	2	2
2	8	0	0	0	0	0	0
2.5	5	0	1	0	1	1	0
3	3	0	0	0	0	0	0
4	11	0	0	0	0	0	0

Table 6- 5. Percentage of tiles in particular % change range for different cable density values for model 2

For cabinet cable penetration seal, sealing efficiency parameter was varied to 0%, 25%, 50%, 80%, and 100%. From Table 6- 6 we see that for sealing efficiency of 25%, 50%, and 75%, all tiles are in range of -0.5% to 0.5%. For 0% sealing efficiency some of the tiles are in range -1% to 1%, while for 100% sealing efficiency there are considerable number of tiles in range from -2% to 2%. Hence, we can say that between 0% to 75% range of sealing efficiency, cable penetration seal component has negligible effect on tile flow rate.

% Change	Sealing Efficiency percentage				
	0%	25%	50%	75%	100%
-2	0	0	0	0	3
-1.5	0	0	0	0	1
-1	0	0	0	0	2
-0.5	5	0	0	0	7
0	139	155	168	228	152
0.5	105	100	87	27	76
1	6	0	0	0	9
1.5	0	0	0	0	2
2	0	0	0	0	2

Table 6- 6. Percentage of tiles in particular % change range for different sealing efficiency values for model 2

6.4 Model 2 IT results

6.4.1 IT Compliance

From the Table 6- 7 we see that % change in IT compliance for all the components is almost zero, except for cabinet frame and cabinet support components. For cabinet frame, number of IT in compliance with AHSRAE allowable range decrease by 1.74% i.e., decrease of 51 IT units, while for cabinet support component number of IT in compliance increases by 1 IT unit. Hence, we can say that IT compliance is not affected much by the changes in the tile flow rate, except for cabinet frame component. Figure 6- 10 shows the plot for IT compliance where x-axis is the models created from modifications in the components. The serial number in the table represents the model number for the figure 6- 10.

Sr. No	Models	No. of IT	% Change
1	Cooling Pipes	2938	0.00
2	IT depth offset	2938	0.00
3	Cabinet frame	2887	1.74
4	Cable inside cabinet	2938	0.00
5	Containment Leakage	2938	0.00
6	Ducts	2938	0.00
7	Obstructions	2938	0.00
8	Overhead conduits	2938	0.00
9	Overhead Pipes	2938	0.00
10	Cabinet support	2939	-0.03
11	Unstructured cable	2938	0.00
12	Power strips	2938	0.00
13	Cable penetration seal	2938	0.00
14	Data cables	2938	0.00
15	Baseline	2938	0.00

Table 6- 7. Comparing number of IT in compliance and % change in IT compliance for model 2

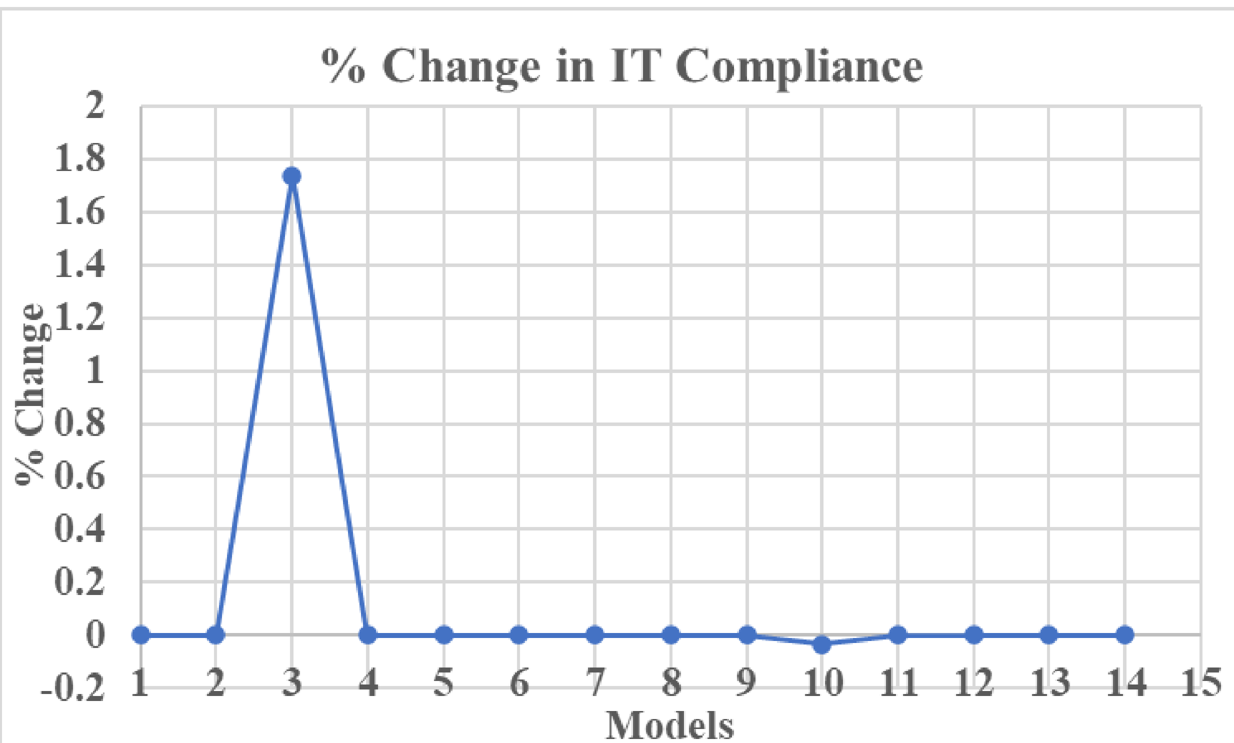

Figure 6- 10. Comparing % change in IT compliance for different components for model 2

6.4.2 Net flow across IT

Similar to tile flow results for model 2, net flow result for IT is also divided into two parts, one, components which showed negligible effect on tile flow rate and second, components which showed substantial effect on the tile flow rate. Figure 6 -11 and figure 6 -12 shows number of IT that are in particular range in % change in net flow across IT. We see that in figure 6- 11 all the components except the cable penetration seal have maximum IT in range of -0.5% to 0.5% change in net flow rate across IT. We see from figure 6- 12 all the components except cabinet frame and cabinet support have maximum IT in range of -0.5% to 0.5% change in net flow rate across IT.

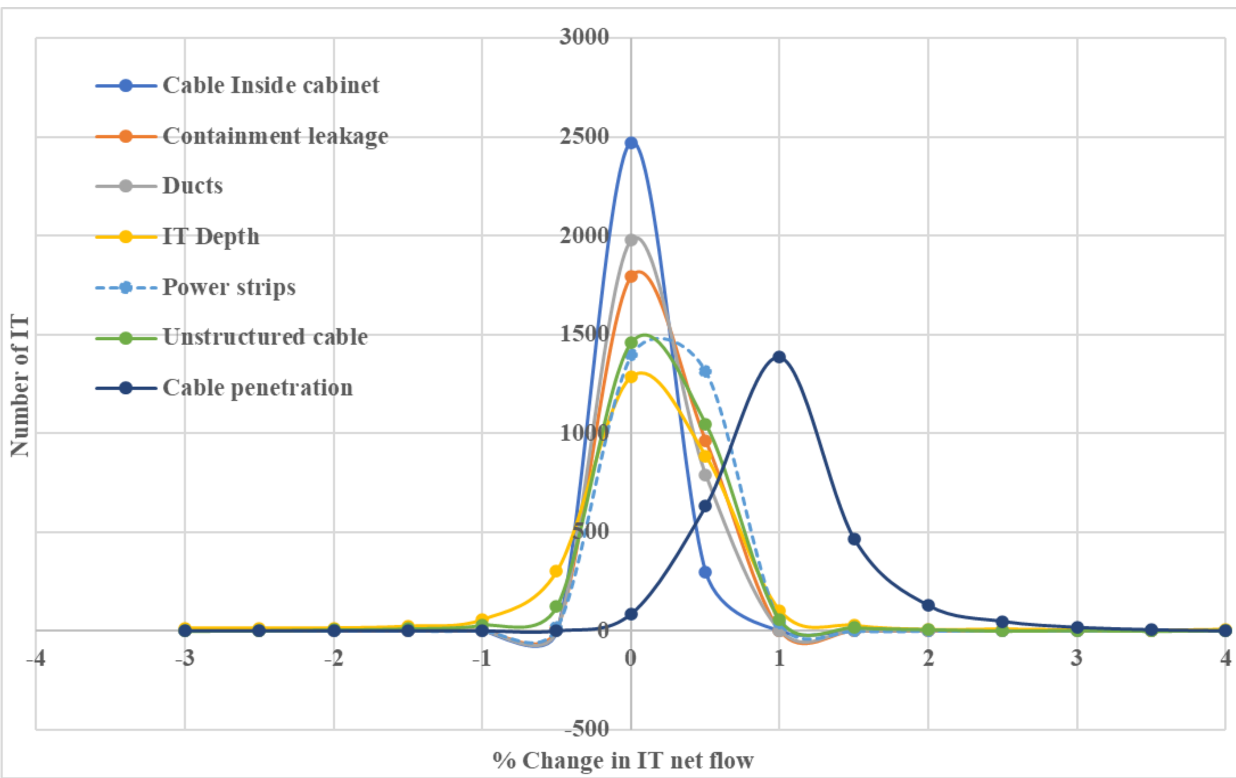

Figure 6- 11. Comparison of % change in net flow rate across IT for components which showed less sensitivity to tile flow rate

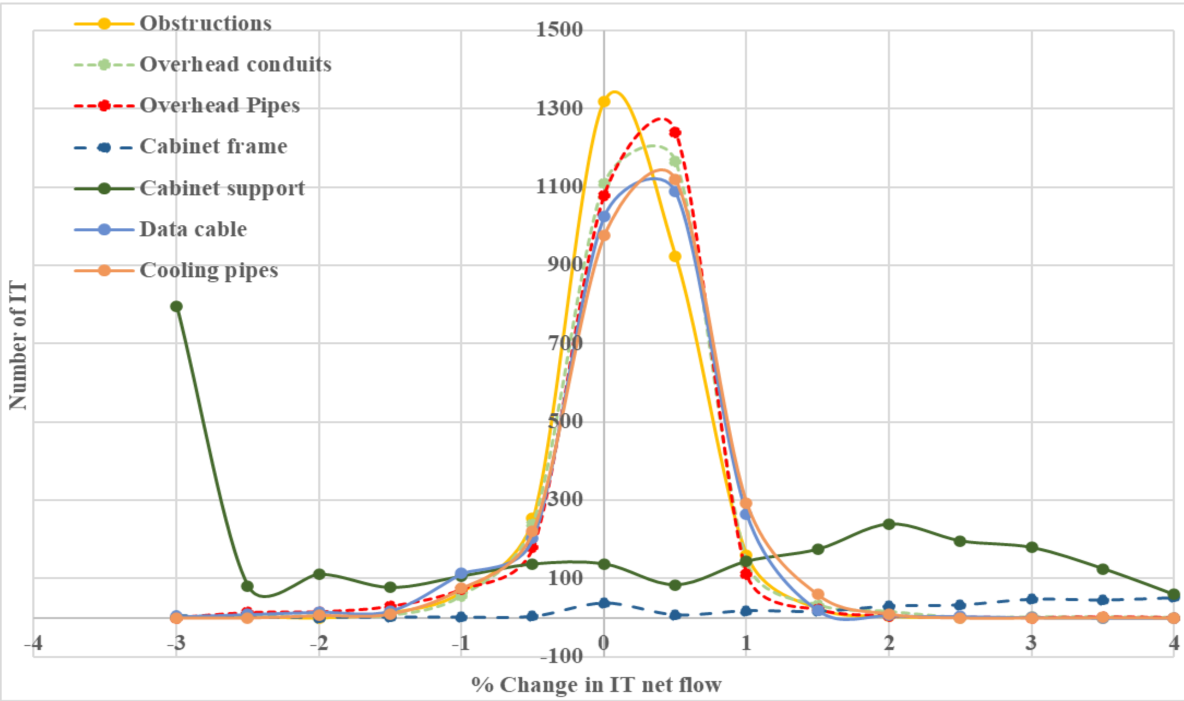

Figure 6- 12. Comparison of % change in net flow rate across IT for components which showed substantial sensitivity to tile flow rate

6.4.3 Temperature at Inlet of IT

The figure 6- 13 shows number of IT in for range in inlet temperature difference for components which showed negligible sensitivity to tile flow rate and figure 6- 14 for components which showed substantial sensitivity to tile flow rate. We see from figure 6- 13 all the components have all the IT in range of -0.5°C to 0.5°C. From figure 6-14, we see that all the components except cabinet frame have maximum IT in range of -0.5°C to 0.5°C.

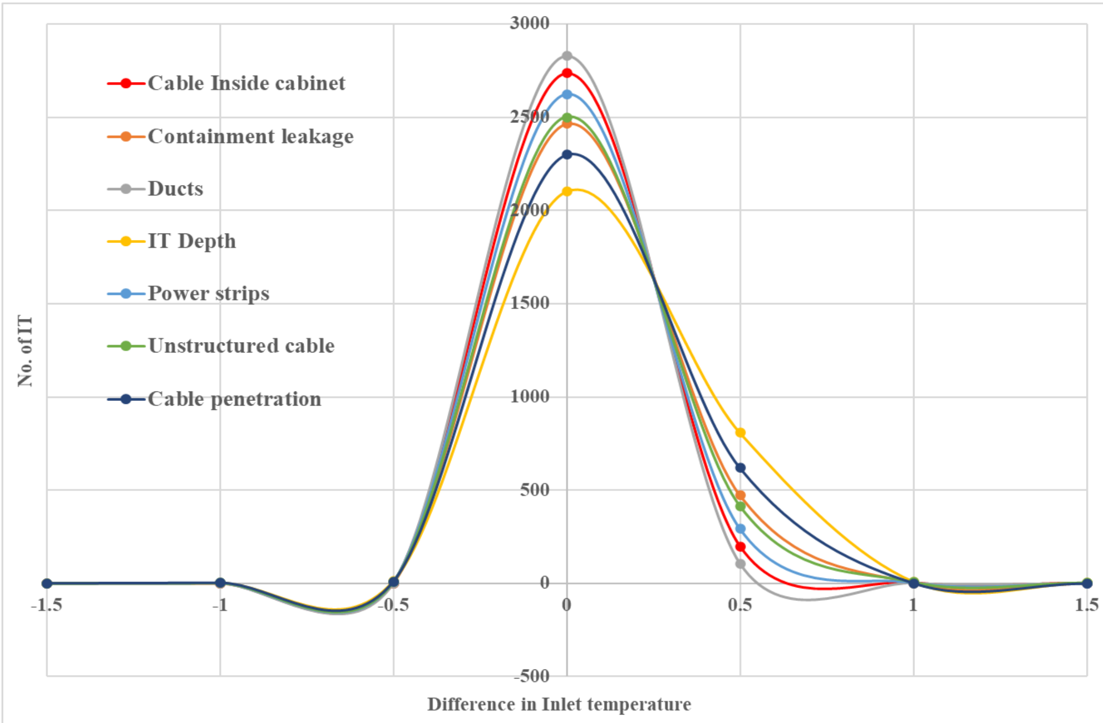

Figure 6- 13. Comparison of difference in inlet IT temperature for all components which showed less sensitivity to tile flow rate

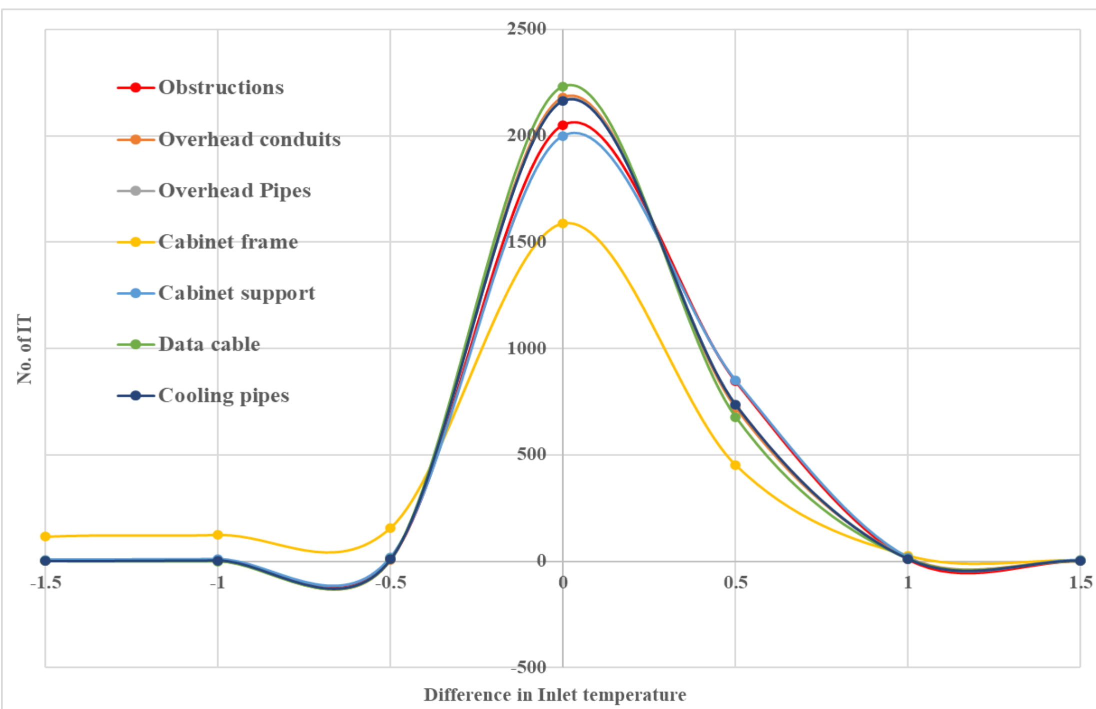

Figure 6- 14. Comparison of difference in inlet IT temperature for all components which showed substantial sensitivity to tile flow rate

6.5 Observations from results in Model 1 and Model 2

6.5.1 Model 1

a) From the tile flow results, we saw that cable penetration seal, cooling pipes, and underfloor data cable components have significant effect on tile flow rate.

b) For underfloor data cable component, it was observed that cable density had negligible effect on tile flow in range of 25% to 50% cable density. Hence, certain amount of inaccuracy in cable density parameter is acceptable.

c) For cable penetration seal component, it was observed that sealing efficiency had significant effect on tile flow rate. Hence, it is necessary to accurately model the cable penetration component.

d) Effect on IT compliance was negligible.

e) Effect on net flow across IT was negligible.

f) Cable penetration seal, cooling pipes and underfloor data cable components showed higher difference in inlet IT temperature.

6.5.2 Model 2

a) From tile flow results, we saw that cabinet frame, cabinet support, obstructions, cooling pipe models have significant effect on tile flow rate.

b) For underfloor data cable model, it was observed that cable density had negligible effect on tile flow. Hence, certain amount of inaccuracy in cable density parameter is acceptable.

c) For cable penetration seal model, it was observed that sealing efficiency had negligible effect on tile flow, except in case of 100% sealing efficiency.

d) No effect was observed on IT compliance except for cabinet frame model.

e) Cabinet frame, cabinet support, cable penetration seal models show significant effect on net flow across IT.

f) Cabinet frame model has higher difference in inlet IT temperature.

6.6 Ranking the components

Rank	Model 1		Model 2	
	Tiles	IT (Inlet Temp.)	Tiles	IT (Net flow)
1	Cable inside cabinet	ACU support structure	Cable inside cabinet	Cable inside cabinet
2	Power strips	Power conduits	Containment leakage	Containment leakage
3	Unstructured data cables	Cooling pipe branches	Cabinet cable penetration seal	Ducts
4	Power conduits	Unstructured data cables	Power strips	Power strips
5	ACU support structure	Cable inside cabinet	Ducts	Unstructured data cables
6	Cooling pipe branches	Power strips	Unstructured data cables	IT depth offset
7	Cooling pipes	Underfloor data cables	IT depth offset	Overhead pipes
8	Underfloor data cables	Cooling pipes	Power conduits	Power conduits
9	Cabinet cable penetration seal	Cabinet cable penetration seal	Overhead pipes	Obstructions
10			Data cables	Cooling pipes
11			Cooling pipes	Data cables
12			Obstructions	Cabinet cable penetration seal
13			Cabinet support	Cabinet support
14			Cabinet frame	Cabinet frame

Table 6- 8. Components arranged in ascending order of their sensitivity to tile flow rate and IT

The components are ranked on two ways first based on their effect on tile flow rate and second based on their effect on IT. For model 1, to rank the components on basis IT, IT inlet air temperature parameter is considered as we saw components showed sensitivity to inlet air temperature. For model 2, to rank the components on basis IT, net flow across IT parameter is considered as we saw components showed sensitivity to net flow across IT.

CHAPTER 7: CONCLUSION

1. We saw in model 1 that cooling pipe branches have sudden expansion in pipes may be to fit in pressure sensors or control valves. We saw that when these sudden expansions are ignored from the model, 71% of tiles are in range of -1% to 2% which maximum change of 4cfm in tile flow rate and have negligible effect on IT. If this inaccuracy in the results is acceptable great amount time in modelling this sudden expansion can be saved, as we have to measure diameter and length of these sudden expansion, but also their location and to do these tiles have to be removed in order to have access to this pipes.

2. Components like cable inside cabinet, unstructured data cables, which are defined by cable density parameter have negligible effect on tile flow rate and IT. To model cable density parameter significant amount of time is required since cabinets and data cables both are present in significant quantity in DC room. Hence, a significant amount of time spent in measuring cable density parameter can saved. This will save a large amount of time in site survey and expediate the calibration process.

3. The underfloor and overhead data cable components are also defined by cable density parameter. We observed from the results that both in case model 1 and model 2, cable density parameter has negligible effect on tile flow rate. Hence, certain amount of inaccuracy like within 10% to 15% of cable density can provide sufficiently accurate results. This will save enormous amount of time spend on site surveys as these data cables are widespread in the DC hall.

4. Thousands of IT equipment (1100 in model 1 and 3000 in model 2) are present DC hall. IT depth offset parameter was studied in model 2 from which we found that inaccuracy

introduced due to ignoring IT depth offset parameter are in acceptable range. Thus we can save a significant amount of time required in measuring offset value for each IT.

CHAPTER 8: FUTURE STUDY

- In this study simulations were performed for two different types of DC models. DC could have different configurations like one were ACU are placed in row with cabinets. So, to have more confidence with the results more models similar to two models in this study should be solved.
- Once more models are solved and confidence is developed with results. We should try to come up with a metric by which we can categorize components into low sensitivity and high sensitivity for DC in terms of tile flow rate and IT.

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