BIM BASED CFD ALGORITHM FOR A/C PLACEMENT IN OFFICE ENVIRONMENT

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

AHMET BARIŞ ÇELİK

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
CIVIL ENGINEERING

FEBRUARY 2022

Approval of the thesis:

BIM BASED CFD ALGORITHM FOR A/C PLACEMENT IN OFFICE ENVIRONMENT

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ABSTRACT

BIM BASED CFD ALGORITHM FOR A/C PLACEMENT IN OFFICE ENVIRONMENT

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February 2022, 123 pages

Today, cooling systems are one of the main energy-consuming elements in buildings. In the current situation, all cooling systems are designed to minimize the energy consumption of the relevant systems in commercial and residential buildings. Efficiency optimization studies of cooling systems are addressed in studies in the construction sector and the academic field. However, along with the optimization of energy consumption, ensuring the thermal comfort of people, which is the main element of the cooling system, has recently gained importance. Thermal comfort calculations in the construction industry and academic studies are examined with Computational Fluid Dynamics (CFD) software. Related programs examine how the predictive design of the cooling system will have an impact on human comfort. However, since these programs are advanced engineering programs that solve differential equations, they create a disadvantage in terms of time in the design processes. This thesis aims to predict the thermal comfort conditions on people and influence the design with the help of an algorithm that uses numerical approaches for the placement of the air terminals designed for cooling systems, using the geometry and data elements of the building information models, without making detailed CFD analysis. As a result of the study, it is observed that the calculations obtained in long periods with CFD analysis are achieved swiftly and consistently with the help of the developed algorithm. The related process will help pave the way for energy optimization studies aiming to provide thermal comfort conditions efficiently at the same time.

Keywords: BIM, CFD, Thermal Comfort, HVAC, Dynamo

ÖZ

OFİS ORTAMINDA KLİMA YERLEŞİMİ İÇİN YBM TABANLI HAD ALGORİTMASI

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Şubat 2022, 123 sayfa

Günümüzde soğutma sistemleri, binalarda enerji tüketen unsurların başında gelmektedir. Güncel uygulamalarda tüm soğutma sistemlerinin tasarımı binalarda ilgili sistemlerin enerji tüketimini en aza indirecek şekilde kurgulanmaktadır. Soğutma sistemlerinin verimlilik optimizasyonu çalışmaları inşaat sektöründe ve akademik alanda yapılan çalışmalarda ele alınmaktadır. Ancak, enerji tüketiminin optimizasyonu ile beraber, soğutma sisteminin ana unsuru olan insanların ısıl konforunun sağlanması da yakın dönemde önem kazanmıştır. İnşaat sektöründe ve akademik çalışmalarda ısıl konfor hesaplamaları akışkanlar dinamiği yazılımları ile incelenmektedir. İlgili programlar insanların bulunduğu ortamda soğutma sisteminin öngörü tasarımının nasıl bir etki yaratacağını incelemektedir. Ancak bu programlar, diferansiyel denklem çözen ileri düzey mühendislik programları olduğundan tasarım süreçlerinde zaman bakımından dezavantaj yaratmaktadır. Bu tez, detaylı hesaplamalı akışkanlar dinamiği (HAD) analizi yapmadan, yapı bilgi modellemesi olgusunun geometri ve veri unsurlarını kullanarak, soğutma sistemleri için tasarlanan menfezlerin yerleşimlerini nümerik yaklaşımlar kullanan bir algoritma yardımı ile yaparak insanların üzerindeki ısıl konfor koşullarını öngörmeyi ve tasarıma etki etmeyi amaçlamaktadır. Böylelikle konfor odaklı tasarım sürecinin daha efektif bir şekilde yürütülmesinin sağlanması amaçlanmaktadır. Çalışmanın sonucunda, hesaplamaları akışkanlar dinamiği analizleri ile uzun sürelerde elde edilen benzer çalışmaların, geliştirilen algoritma yardımı ile hızlı ve tutarlı bir şekilde elde edildiği gözlemlenmiştir. İlgili süreç, enerji optimizasyonu odaklı yapılan çalışmaların aynı zamanda verimli bir şekilde ısıl konfor koşullarını sağlamasının da önünü açmakta faydalı olacaktır.

Anahtar Kelimeler: BIM, HAD, Isıl Konfor, HVAC, Dynamo

To the greatest two people in my life…

ACKNOWLEDGMENTS

The author wishes to express his deepest gratitude to his supervisor Asst. Prof. Dr. Aslı Akçamete Güngör for her guidance, advice, criticism, encouragements and insight throughout the research.

I would also like to thank the examining committee members.

Lastly, I would also like to express my deepest appreciation to my family.

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LIST OF ABBREVIATIONS

ABBREVIATIONS	
A/C	Air Conditioner
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BIM	Building Information Modelling
BES	Building Energy Simulation
BEPS	Building Energy Performance Simulation
BPS	Building Performance Simulation
CAD	Computer Aided Drawing
CFD	Computational Fluid Dynamics
HVAC	Heating, Ventilation, and Air Conditioning
IDM	Integrated Design and Management
IFC	Industry Foundation Classes
IoT	Internet of Things
MVD	Model View Definitions
MRT	Mean Radiant Temperature
PDE	Partial Differential Equations
PMV	Predicted Mean Vote
PPD	Percent People Dissatisfied
UI	User Interface

CHAPTER 1

INTRODUCTION

1.1 Motivation

Cooling system design and its uses are indispensable in the modern world. It keeps people in comfort in classrooms, offices, workplaces, and shopping malls, and it is vital for mechanical and electrical driven equipment as they have specific operation range using temperature. To keep the comfort of people and the operation of machines stable, the cooling system should be effective and efficient. For each design case, different cooling systems have been introduced regarding geographical and utility factors. To meet the requirements necessary system selection has to be made.

There are many types of cooling systems such as central cooling with diffusers and local cooling with air-conditioners. For each project, a suitable system has to be selected to provide necessary cooling to the control volume.

The cooling system is considered as a part of the HVAC system which consists of Heating, Ventilation, and Air Conditioning. HVAC systems usually consume the most cost and time regarding the design, construction, and further maintenance along with the life of a structure according to [1].

Designing the cooling system brings two major challenges in terms of cost and human comfort. The cost of the design includes equipment price and electricity consumption over the lifespan of the equipment used in the system. On the other hand, ensuring human comfort is another challenge, which can be measured and calculated utilizing the comfort parameters such as Predicted Mean Vote (PMV) and Percent People Dissatisfied (PPD) [2].

In the building services industry, most of HVAC engineers design the cooling system to meet the employer's requirements and standards. This approach leads to inefficient cooling for people and equipment in their controlled volume. Inefficient cooling of equipment led to a great amount of power loss or additional maintenance cost for the operation as they are not in the ideal condition that they should be. On the other hand, in workplaces such as crowded offices, the cooling effectiveness directly influences employee efficiency as in [3] and [4].

To give an example, during the renovation project of an airport, the HVAC design for a press conference room has been made and calculations performed according to the standards and regulations. The press conference room is shown in Figure 1.1.

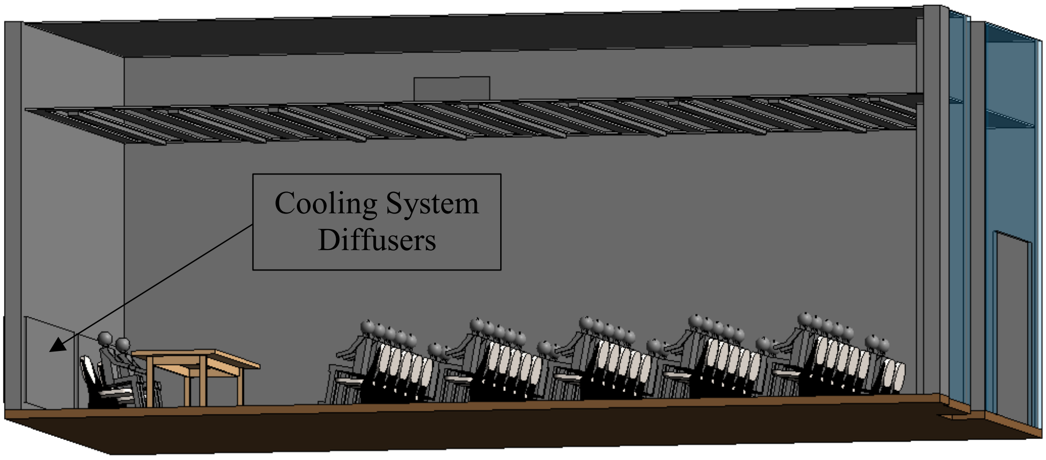


Figure 1.1. Press Conference Room

The cooling system diffusers have been placed right behind the speakers in the room. After finalizing the HVAC design, the employer wanted to conduct a human comfort study to see the effectiveness of the cooling system placement. Following the results of the study, it was seen that the cooling system does not satisfy the needs of the people in the environment although the design complied with the regulations. The velocity and temperature plots of the human comfort study are shown in Figure 1.2 and Figure 1.3, respectively. In the figures, it can be seen that there is a non-homogenous airflow and temperature distribution inside the room, which causes a lack of thermal comfort.

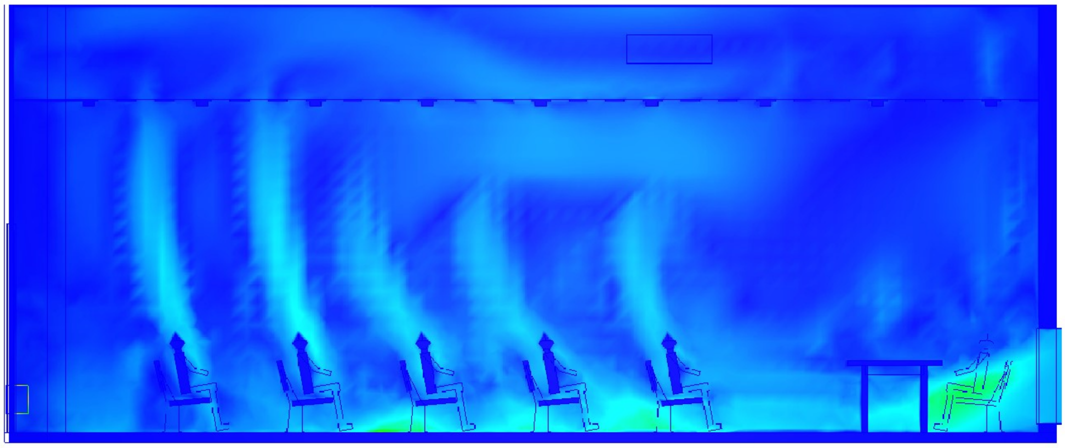


Figure 1.2. Velocity Values (Scaling from Blue = 0 m/s to Green 0.5 m/s)

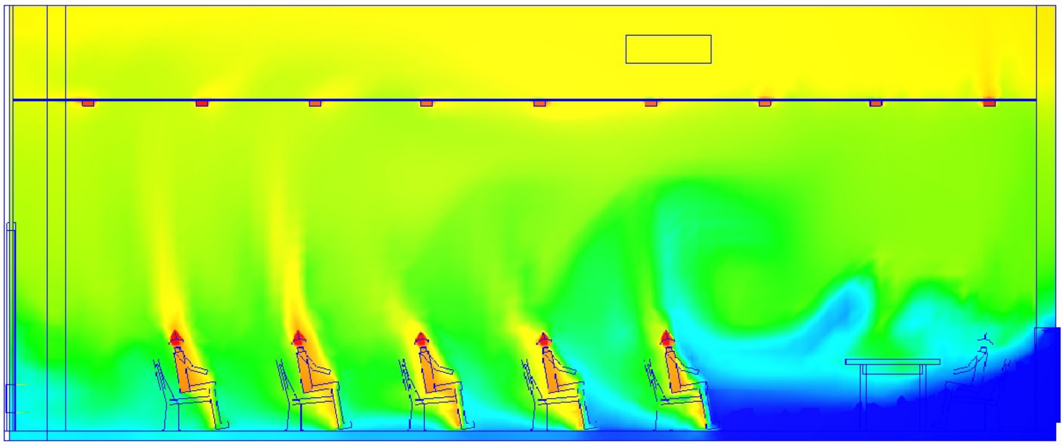


Figure 1.3. Temperature Values (Scaling from Blue = 16 °C to Red = 36 °C)

The results for the PMV, which is one of the human comfort indices required to be near to 0 value, are shown in Figure 1.4, which shows the inefficiency of the cooling system. PMV index of the speakers is very low, which means the speakers will feel cold during the press conference. Moreover, the audience will feel hotter in the room as there is no homogenous cooling air distribution.

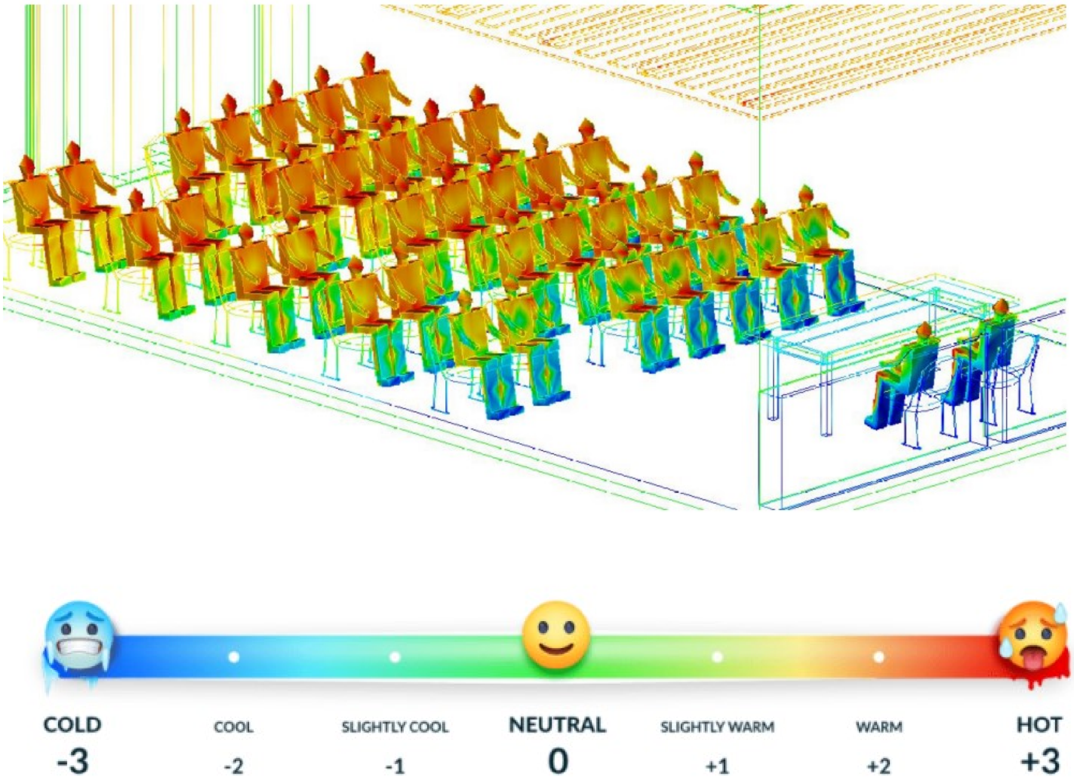


Figure 1.4. PMV Scale for Press Conference Room

In the figures, it can be seen that the diffusers of the cooling system directly blow cold air behind the speakers. Meanwhile, the audience feels hot as the cool air does not penetrate the occupiable area of the audience. This figure shows that the cooling system location is vital for human comfort and the human comfort may not be satisfied even if the system complies with the standards.

As seen in this example, in recent years HVAC engineers have faced such issues and are obliged to design cooling systems according to human comfort [5]. This issue leads engineers to use different calculation and validation methods such as

Computational Fluid Dynamics (CFD). Using CFD software, engineers can determine the human comfort values, which will be later discussed. This helps them to understand the way the cooled air dissipates inside the volume. After they obtain the results of the analysis, they change the location of cooling devices and re-do the CFD analysis. This process, however, is an iterative and long process as CFD software solves various differential equations for every iteration.

Moreover, CFD software requires an input 3D geometry for an engineer to assign the boundary conditions on it. This is a time-consuming process as the designer should model the 3D version of the base architectural and HVAC project. However, in the last decades, 3D intelligent modelling tools have been introduced in the construction industry, i.e. Building Information Modeling (BIM) tools. These tools provide designers to model the base project in a 3D data storing environment. Thus, the modeling issues have been overcome in recent years when BIM is used [6]. Human comfort-focused cooling system design has gained much importance since then. However, these issues are often disregarded by designers to meet the specified deadline of the engineering design project.

1.2 Problem and Objectives

In cooling system design it is vital to meet the human comfort and air-cooled equipment requirements. As it is stated in the previous section, the main focus of the designers is to meet the requirements, which are prescribed in the standards and regulations. To give an example, the main objective of an HVAC engineer should not just be meeting the cooling requirements of a data center that has a great amount of heat dissipation among the data panels. The location of the cold air dissipating units such as air terminals or air conditioners should be determined accordingly to keep the panels cold enough to operate safely. Otherwise, the working range of electrical equipment will be hampered and the life-span of equipment will be lowered.

Like in the case of the data panels, human comfort is another issue for the HVAC design of an office with a lot of employees. Research says [7] a great number of people are not happy in their office environment because of the quality of air conditioning. Some offices has cooling units placed in a way that cool air blows on top or right across from an employee, which causes health issues for them besides discomfort. If the location of the air conditioner unit is very near to a human, its comfort value will be low as the person feels too cold air which should normally dissipate throughout the volume. On the contrary, if the A/C unit is very far away from the human, the effect of heat dissipation from itself and equipment such as computers will dissatisfy the person as s/he will not feel enough cooling effect. But in both cases, the requirements can be satisfied according to regulations. Figure 1.5 summarizes the statement above for rooms that have the same cooling loads with the same A/C unit as the cooling device. If the A/C is placed very near or far from the occupant, the occupant would feel either cold or hot. The cooling system device should be placed in the most optimum location to provide the best thermal comfort condition for the occupant.

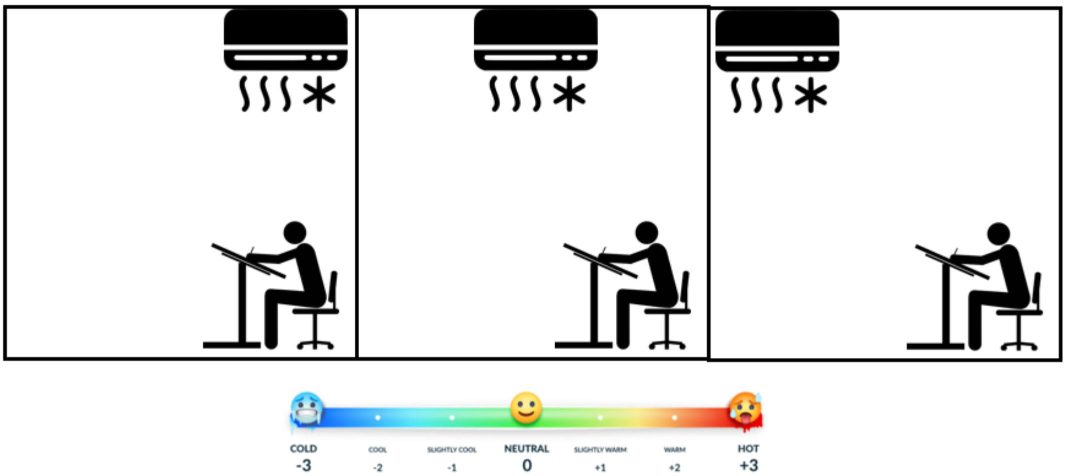


Figure 1.5. Optimal Air Terminal Location Consideration

Thus the HVAC design engineer should not just focus on the design parameters guided by the standards and regulations. The engineer should always design a system that both meet the requirements and human comfort.

The main objective of this research is to provide an algorithm for the design and location optimization of an air conditioner used in the cooling system in terms of human comfort, standards, and requirements. The focus is to achieve this with a split air conditioning system in a single room enclosed with conditioned rooms.

Therefore, in this proposed research, an algorithm is developed to optimize the placement of the cooling device to increase the thermal comfort of humans in the offices whilst meeting the requirements.

1.3 Outline and Organization

In Chapter 2, studies regarding the subject are presented. The motivations and the concepts of these studies are summarized. Then, various effects of cooling systems on human comfort in offices are presented. Reviews of cooling system types and their different uses in the construction industry are presented. Besides, the human comfort parameters such as PMV and PPD and their uses for human well-being are discussed. Moreover, the use of BIM and its features in the literature are discussed in the following sections. CFD studies are covered to give insight into this study's concept. Lastly, the literature gaps and how the findings of this thesis are filling the gap in the literature are presented.

In Chapter 3, detailed information is given regarding the main methodology of the thesis. Detailed schemes are shown to explain the workflow of the algorithm. Concepts such as Autodesk Revit and Dynamo are presented. The scope of the proposed methodology is explained in detail. The human comfort parameters are discussed. In addition to the comfort parameters, energy consumption parameters are shown. Moreover, the geometry and the dimensions of the control volume studied in this thesis are presented. The construction process of the geometry is explained. After, introducing the algorithm and geometry, it is discussed how the parametric data are stored in the geometry. The mesh modeling is shown in detail and its construction process is presented. Moreover, the governing equations of the algorithm are presented. The numerical methods used in the code are shown. Their difference related to complex CFD methods is discussed. After all, boundary conditions of the model are presented. These conditions are stored in the nodes, which exchange parametric information among the control volume. Last, the cooling unit placement procedure is discussed and the optimization results are shown in tables and figures.

In Chapter 4, Implementation and Validation, the outputs of the design parameters are discussed. The method of validation is also presented. The location of the cooling device is analyzed according to the proposed validation method. The comparison of results between validation tools and the generated algorithm is done to verify the developed algorithm.

In Chapter 5, the general outputs of the study are summarized. The benefits of the developed algorithm are explained. Contributions of the proposed study to the literature are presented. Also, the limitations of the study are explained. Possible future works for the algorithm and the methodology are discussed.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

This section gives a preview regarding the vitality and issues about cooling system design and its effects on human comfort in an office environment. This section mainly consists of three sub-sections. The first section is about the cooling system design procedures and their uses in literature and the construction industry. The system selection criteria are reviewed. In addition to those information, human comfort regulations and parameters, defined by Fanger [8] are presented. In the following section, the tools that have been used in the cooling system design are reviewed. Traditional design and calculation methods are discussed. Recent studies regarding the human comfort and cooling system with the introduction of novel technologies are reviewed. BIM and related studies regarding the subject of cooling are presented. The effectiveness and relevant features of BIM are investigated. Moreover, the CFD concept is presented. CFD uses in human-focused cooling design are reviewed. The benefits and disadvantages of novel technologies are presented. Lastly, the gaps in the literature regarding the human-focused cooling system design are discussed.

2.2 Cooling System Design

The cooling system is most simply known as “the system is to decrease the temperature by removing thermal energy from a space”. The vitality of cooling systems cannot be questioned in the modern era where most of people work and study inside closed environment in hot ambient conditions.

This system is a part of the Heating, Ventilation, and Air Conditioning System that regulates the environmental temperature of the space. The principles of cooling system design consist simple theory of operation and the factors that determine the sizing of the device that is used in the system. There are different types of cooling systems regarding location, the use of space, and other specific employer requirements.

Research says people spend 90% of their life in the indoor environment [9]. In commercial buildings, at least 40% of the electricity is used by HVAC systems [10]. The system has evolved in the modern era with the introduction of superstructures and high-rise buildings. Cooling, on the other hand, is more difficult than heating. Rather than utilizing energy to generate heat, cooling devices utilize it to remove heat from a place.

The most significant aspect when installing a new cooling system in a building is precisely estimating the cooling loads that the system should produce. These calculation methods are described in detail in the following paragraphs.

First of all, to design a cooling system, which is a part of a mechanical project, an architect should first design a building, which will be the input of design parameters. The location, number of storeys, climate, space use, properties of partitions, and devices inside the environment, all have great importance. All these factors affecting the control volume should be considered in the design procedure. Figure 2.1 shows the effect of such factors in an office environment.

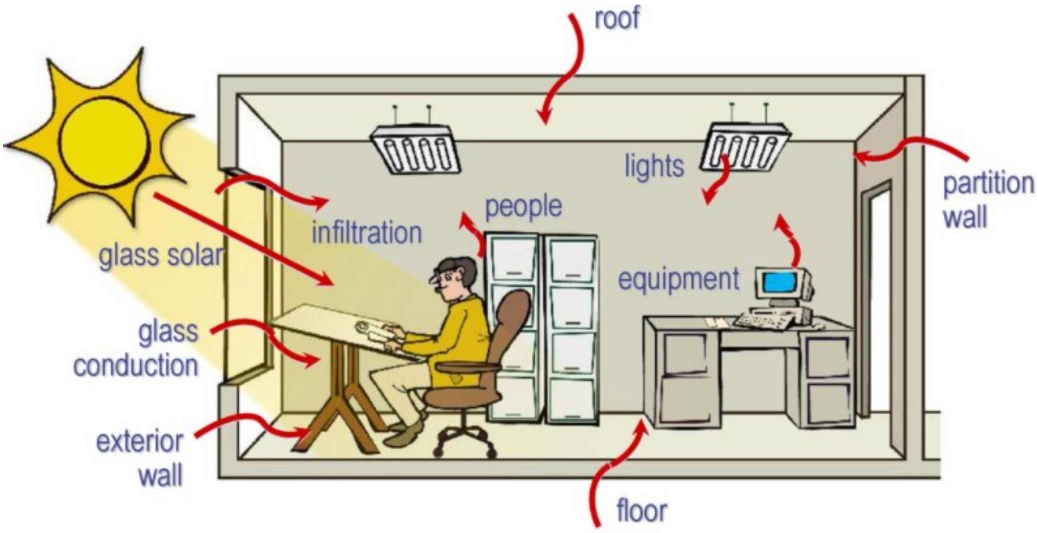


Figure 2.1. Cooling System Boundary Conditions [11]

The heat in the space is created by the numerous sources mentioned above. The entire heat generated inside the space per time should be eliminated to preserve the comfort conditions within the vicinity.

This section is to give an idea for cooling design fundamentals for thermal comfort.

As described above, below factors are the sources of heat generation inside the space affecting cooling system design and calculations;

- Heat Gain by Walls: Conduction transfers heat from the sun to the room's walls. The quantity of heat generated is determined by the wall material and its orientation to the sun. The quantity of heat gained by the walls is reduced if they are insulated [12]. The governing equation for the heat generation by walls is shown in Equation (2.1) below.

$$Q = K * A * (T_o - T_i) \quad (2.1)$$

Where,

Q : Total Heat Gain

K : Heat Transfer Coefficient

A : Area of Wall

T_o: Temperature outside of the Wall, which is affected by sun.

T_i: Temperature inside of the Wall

- Heat Gain by Roofs, Floors, and Partitions: When the roof is directly exposed to the sun, it absorbs the most heat. There is heat gain or loss via roofs, ceilings, floors, and partitions if there is another room above, below, or next to the stated space. There is heat gain from an unconditioned area next to a cooled room, which should be considered throughout the design phase [12]. The governing equation for the heat generation by roofs, floors, and partitions is shown in Equation (2.2) below.

$$Q = K * A * (T_o - T_i) \quad (2.2)$$

Where,

Q : Total Heat Gain

K : Heat Transfer Coefficient

A : Area of Roof, Floor, or Partition

T_o: Temperature outside of the Roof, Floor, or Partition, which can be affected by the sun.

T_i: Temperature inside of the Roof, Floor, or Partition

- Heat Gain by Windows: The room's windows are directly exposed to the outside environment, and heat from the sun is radiated into the space. In the case of the walls, the amount of heat obtained by the rooms through windows is determined by the alignment of the windows. The quantity of heat gained through the windows through radiation is also affected by the kind of glasses on the window [12]. The governing equation for the heat generation by windows is shown in Equation (2.3) below.

$$Q = K * A * (T_o - T_i) + A * \left(\frac{A_R}{A}\right) * q_s \quad (2.3)$$

Where,

Q : Total Heat Gain

K : Heat Transfer Coefficent

A : Area of Window

T_o: Temperature outside of the Window, which is affected by sun

T_i: Temperature inside of the Window

$\frac{A_R}{A}$: Radiation transmission rate of the Window

q_s: Correction and shading factor

- Heat Gain by the People: The individuals in the room produce a large amount of heat. Working folks disperse more heat than persons who are seated [12]. The sensible and latent heat production values of individuals are described in ASHRAE Fundamentals Handbook [13]. Table 2.1 depicts people's heat gain as a function of their activity in the room. The governing equation for the heat generation by people is shown in Equation (2.4) below.

Table 2.1 Sensible and Latent Heat Gains [13]

Degree of Activity	Location	Total Heat, W		Sensible Heat, W	Latent Heat, W	% Sensible Heat that is Radiant[b]	
		Adult Male	Adjusted, M/F[a]			Low V	High V
Seated at theater	Theater, matinee	115	95	65	30		
Seated at theater, night	Theater, night	115	105	70	35	60	27
Seated, very light work	Offices, hotels, apartments	130	115	70	45		
Moderately active office work	Offices, hotels, apartments	140	130	75	55		
Standing, light work; walking	Department store; retail store	160	130	75	55	58	38
Walking, standing	Drug store, bank	160	145	75	70		
Sedentary work	Restaurant[c]	145	160	80	80		
Light bench work	Factory	235	220	80	140		
Moderate dancing	Dance hall	265	250	90	160	49	35
Walking 4.8 km/h; light machine work	Factory	295	295	110	185		
Bowling[d]	Bowling alley	440	425	170	255		
Heavy work	Factory	440	425	170	255	54	19
Heavy machine work; lifting	Factory	470	470	185	285		
Athletics	Gymnasium	585	525	210	315		

$$Q = (n * Q_s + n * Q_l) \quad (2.4)$$

Where,

Q : Total Heat Gain

n : Number of People

Q_s : Sensible Heat per Person

Q_l : Latent Heat per Person

- Heat Gain by the Electrical Appliances: Heat is generated by electrical appliances such as lighting fixtures, coffeemakers, electronic equipment, computers should also be considered for cooling system calculations [12]. In ASHRAE Fundamentals Handbook [13], the heat generation values of appliances are presented. Table 2.2 and Table 2.3, show the heat gain by appliances for their operation in the room. The governing equation for the heat generation by equipment and lighting is shown in Equation (2.5) below.

Table 2.2 Lighting Power Densities per Area [13]

Common Space Types*	LPD, W/m²	Building-Specific Space Types*	LPD, W/m²	Building-Specific Space Types*	LPD, W/m²
Atrium		Automotive		Library	
First 13 m height	0.10 per m	Service/repair	7.2	Card file and cataloging	7.8
	(height)	Bank/office		Reading area	10
Height above 13 m	0.07 per m	Banking activity area	14.9	Stacks	18.4
	(height)	Convention center		Manufacturing	
Audience/seating area—permanent	8.5	Audience seating	8.8	Corridor/transition	4.4
For auditorium	26.2	Exhibit space	15.6	Detailed manufacturing	13.9
For performing arts theater	12.3	Courthouse/police station/penitentiary		Equipment room	10.2
For motion picture theater	13.3	Courtroom	18.5	Extra high bay (>50 ft floor-to-ceiling height)	11.3
		Confinement cells	11.8		
Classroom/lecture/training	13.3	Judges' chambers	12.6	High bay (25 to 50 ft floor-to-ceiling height)	13.2
Conference/meeting/multipurpose	13.2	Penitentiary audience seating	4.6		
Corridor/transition	7.1	Penitentiary classroom	14.4	Low bay (<25 ft floor-to-ceiling height)	12.8
		Penitentiary dining	11.5		
Dining area	7.0	Dormitory		Museum	
For bar lounge/leisure dining	14.1	Living quarters	4.1	General exhibition	11.3
For family dining	9.6	Fire stations		Restoration	11.0
Dressing/fitting room for performing arts theater	4.3	Engine room	6.0	Parking garage	
		Sleeping quarters	2.7	Garage area	2.0
		Gymnasium/fitness center		Post office	
Electrical/mechanical	10.2	Fitness area	7.8	Sorting area	10.1
Food preparation	10.7	Gymnasium audience seating	4.6	Religious buildings	
		Playing area	12.9	Audience seating	16.5
Laboratory	13.8	Hospital		Fellowship hall	6.9
For classrooms	13.8	Corridor/transition	9.6	Worship pulpit, choir	16.5
For medical/industrial/research	19.5	Emergency	24.3	Retail	
		Exam/treatment	17.9	Dressing/fitting room	9.4
Lobby	9.675	Laundry/washing	6.5	Mall concourse	11.8
For elevator	6.88	Lounge/recreation	11.5	Sales area	18.1
For performing arts theater	21.5	Medical supply	13.7	Sports arena	
For motion picture theater	5.6	Nursery	9.5	Audience seating	4.6
		Nurses' station	9.4	Court sports arena—class 4	7.8
Locker room	8.1	Operating room	20.3	Court sports arena—class 3	12.9
Lounge/recreation	7.9	Patient room	6.7	Court sports arena—class 2	32.4
		Pharmacy	12.3	Court sports arena—class 1	28.8
Office		Physical therapy	9.8	Ring sports arena	
Enclosed	10.5	Radiology/imaging	14.2	Transportation	
Open plan	8.1	Recovery	12.4	Air/train/bus—baggage area	3.9
		Hotel/highway lodging		Airport—concourse	5.8
Restrooms	10.5	Hotel dining	8.8	Waiting area	11.6
Sales area	18.1	Hotel guest rooms	11.9	Terminal—ticket counter	
Stairway	7.4	Hotel lobby	11.4	Warehouse	
Storage	6.8	Highway lodging dining	9.5	Fine material storage	6.2
Workshop	17.1	Highway lodging guest rooms	8.1	Medium/bulky material storage	4.6

Table 2.3 Recommended Heat Gain from Typical Computer Equipment [13]

Equipment	Description	Nameplate Power, W	Average Power, W	Radiant Fraction
Desktop computer[a]	Manufacturer A (model A); 2.8 GHz processor, 1 GB RAM	480	73	0.10[a]
	Manufacturer A (model B); 2.6 GHz processor, 2 GB RAM	480	49	0.10[a]
	Manufacturer B (model A); 3.0 GHz processor, 2 GB RAM	690	77	0.10[a]
	Manufacturer B (model B); 3.0 GHz processor, 2 GB RAM	690	48	0.10[a]
	Manufacturer A (model C); 2.3 GHz processor, 3 GB RAM	1200	97	0.10[a]
Laptop computer[b]	Manufacturer 1; 2.0 GHz processor, 2 GB RAM, 430 mm screen	130	36	0.25[b]
	Manufacturer 1; 1.8 GHz processor, 1 GB RAM, 430 mm screen	90	23	0.25[b]
	Manufacturer 1; 2.0 GHz processor, 2 GB RAM, 355 mm screen	90	31	0.25[b]
	Manufacturer 2; 2.13 GHz processor, 1 GB RAM, 355 mm screen, tablet PC	90	29	0.25[b]
	Manufacturer 2; 366 MHz processor, 130 MB RAM (355 mm screen)	70	22	0.25[b]
	Manufacturer 3; 900 MHz processor, 256 MB RAM (265 mm screen)	50	12	0.25[b]
Flat-panel monitor[c]	Manufacturer X (model A); 760 mm screen	383	90	0.40[c]
	Manufacturer X (model B); 560 mm screen	360	36	0.40[c]
	Manufacturer Y (model A); 480 mm screen	288	28	0.40[c]
	Manufacturer Y (model B); 430 mm screen	240	27	0.40[c]
	Manufacturer Z (model A); 430 mm screen	240	29	0.40[c]
	Manufacturer Z (model C); 380 mm screen	240	19	0.40[c]

$$Q = (LPD * A + n * Q_{equipment}) \quad (2.5)$$

Where,

Q : Total Heat Gain

LPD : Ligthing Load per Area

A : Area of Room

n : Number of Elements

$Q_{equipment}$: Equipment Heat Generation

The assessment of cooling loads in the space where the system will be installed is the most essential aspect in the design and selection of a cooling system. The precise selection of the system for the desired construction will be made easier if these loads are accurately assessed.

In addition to the elements mentioned above, such as boundary conditions, the following should be considered when evaluating a room's cooling loads in general.

- The quantity of heat dispersed throughout the area is exposed to unheated areas.
- The quantity of chilled air required for the air to cool, enters through crevices near windows and doors, as well as entrances, when humans use them.

The constant average temperature during summer and any continuous supply of cooled air present at all times, which is a steady-state process independent of time, is the basis for computing the cooling loads using the aforementioned governing equations and boundary conditions. The amount of heat accumulated in the space, as well as the energy used by any heating equipment, must be considered.

The following is the standard procedure for determining cooling loads:

First and foremost, determine the current weather conditions outside the structure, including humidity, temperature, and air velocity. The desired internal temperature must be set under the rules and regulations.

The building and its use, including the exposure of the building to wind, the path of the sun, periods of occupancy and portion of the day when the building will be used, and the expected financial impact of the equipment and energy consumption, all influence design calculations and cooling system selection. When calculating a building's cooling demands, all of these aspects should be considered.

2.2.1 System Selection

There are not just one or two cooling system types that one can use to remove the heat inside the space. There are various types of cooling systems as described below.

- Central Air Conditioners

The purpose of central air conditioners is to chill the entire structure. The process is driven by a big compressor unit positioned outside in each system. A refrigerant-filled interior coil cools the air, which is subsequently blown into the room via ventilation ducts. The simple scheme of a central cooling system is presented in Figure 2.2.

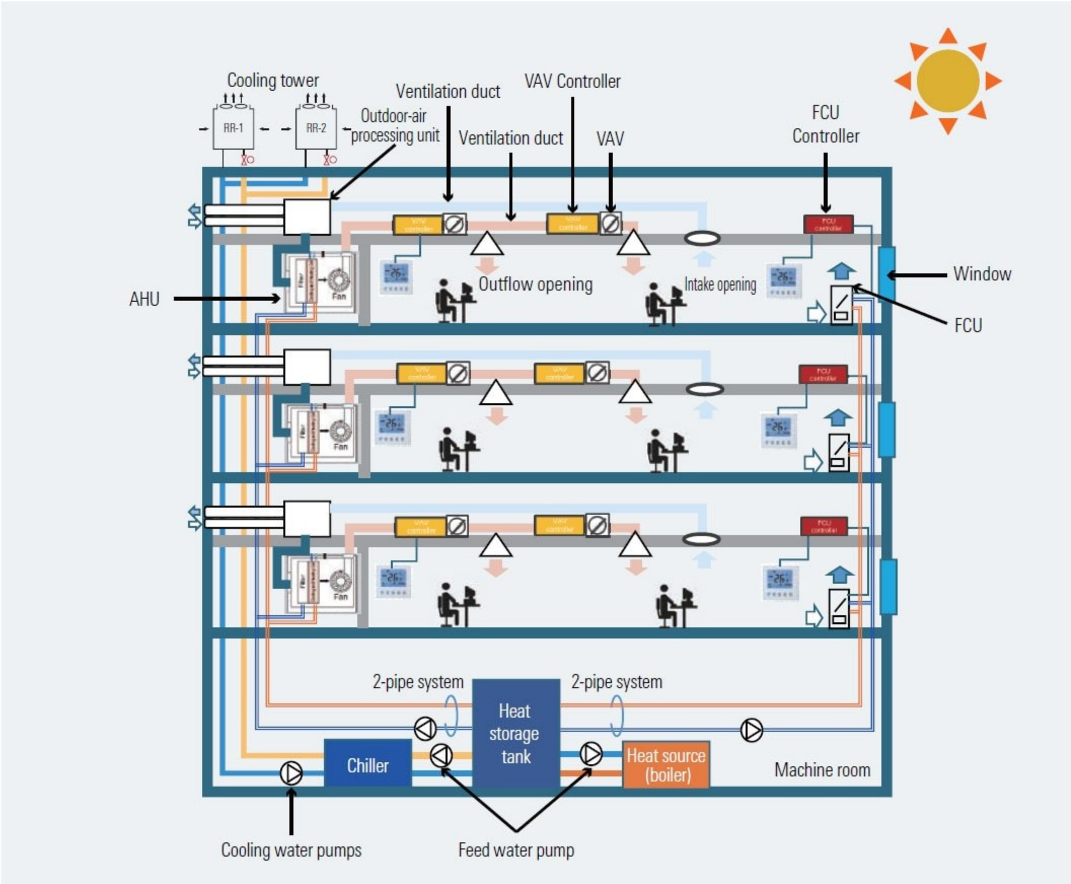


Figure 2.2. Central Air Cooling System [14]

- Water Loop Heat Pumps

The working principle of heat pumps is similar to that of central air conditioners, however, the heat pump system can work in the reverse cycle to heat the room in cooler conditions. A simple scheme of heat pumps is presented in Figure 2.3.

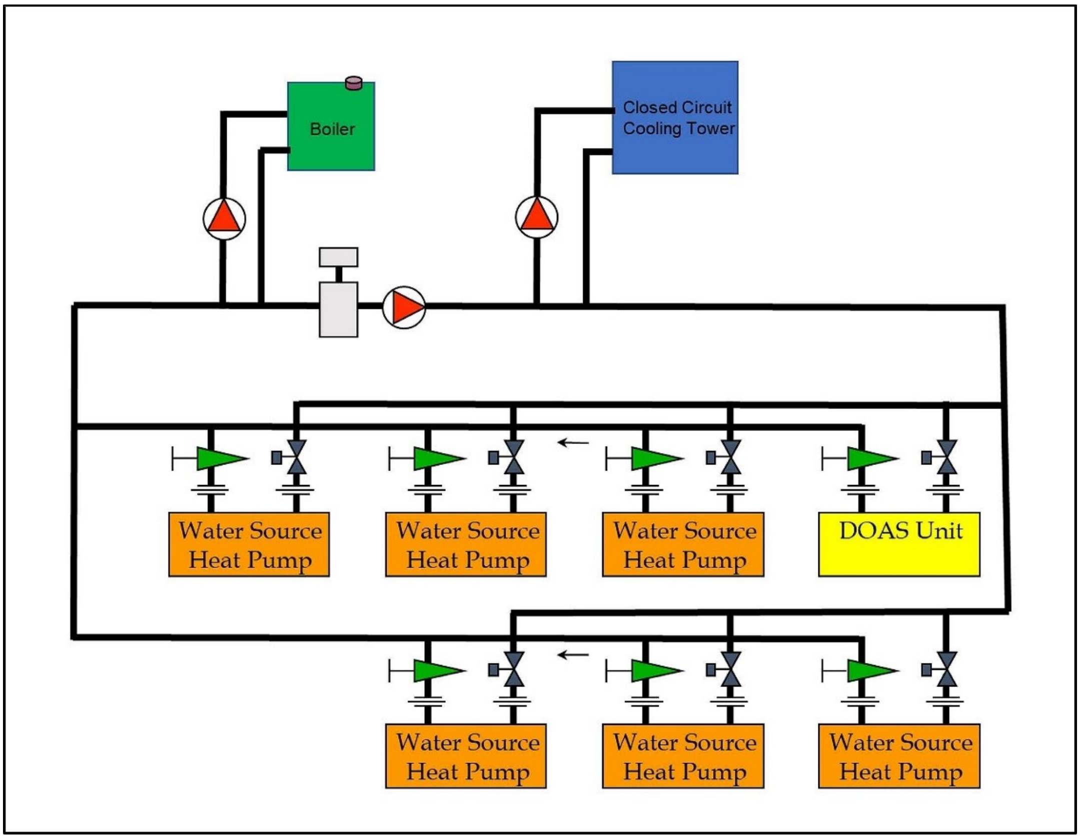


Figure 2.3. Water Loop Heat Pump System [15]

- Variable Refrigerant Flow

Variable Refrigerant Flow devices use a similar technology to the heat pumps. There are indoor cooling devices supplied by an outdoor device that has a compressor outside. The end-user can control the level of temperature inside the room with the help of variable flow technology. They are more efficient than heat pump systems for 5-6 room or multiple storey buildings. A simple scheme of variable refrigerant flow systems is presented in Figure 2.4.

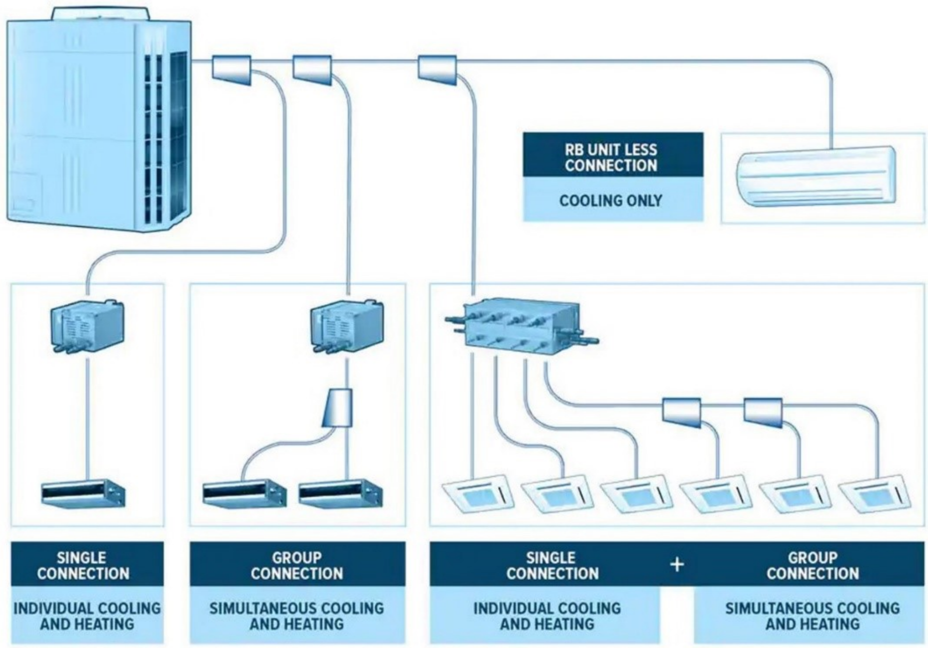


Figure 2.4. Variable Refrigerant Flow Systems [16]

- Split Air Conditioning

Split-type air conditioners may be installed on windows, walls, and ceilings. They do, however, have external units with a compressor outdoors. Split-type air conditioners are just large enough to cool one room. Individual units are less expensive to purchase than central systems. A simple scheme of split air conditioning system is presented in Figure 2.5.

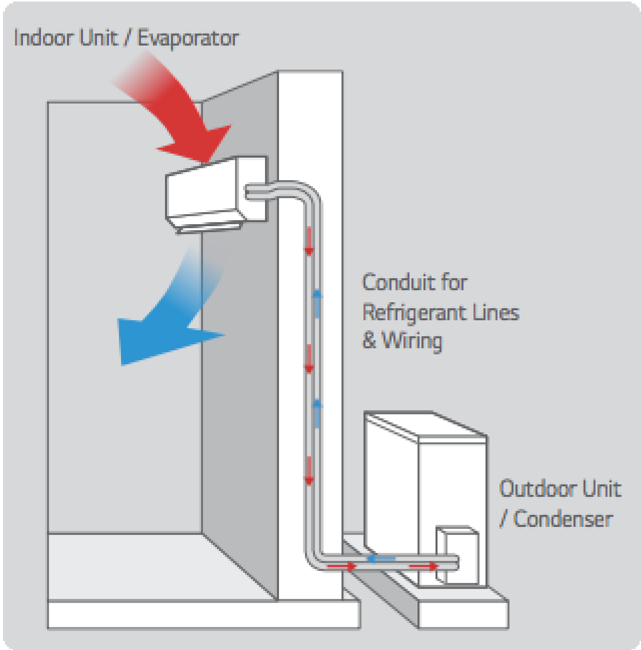


Figure 2.5. Split Air Conditioning Systems [17]

In the scope of this study, the cooling device location optimization is conducted in a single room with single A/C equipment. In single rooms, split air conditioning systems are the most economic and simple solutions to ensure human comfort inside the environment. Thus, a split air conditioning system is used as the cooling device in this thesis. For further and future studies, the study can be expanded for a central cooling system with multiple A/C units or cooling system diffusers to obtain the optimal human comfort level.

2.2.2 Human Comfort

Thermal comfort boundaries are limits that assist building physicists in determining how much heat or cold should be applied to a structure. The term "thermal comfort" refers to a condition that indicates happiness with one's thermal surroundings [18]. It's hard to forecast the temperature range for this degree of comfort because it's affected by environmental and personal factors, as well as cultural influences. A historical overview of current thermal comfort information reveals two distinct approaches: climatic chamber experiments and outdoor surveys. The earlier, which is based on the skin's heat transfer systems, has resulted in steady-state experimental thermo-physiological models and standards such as ASHRAE 55 [19]. In the subject of thermal comfort, these guidelines are increasingly being employed in both study and practice.

According to ASHRAE, “Human comfort is condition of mind, which expresses satisfaction with the thermal environment”.

The subjective impression of temperature, humidity, and velocity in a place is referred to as thermal comfort. Maximum productivity is aided by optimal levels of thermal comfort. Temperature, humidity, air purity, and air movement are all key elements that impact human comfort. A cooling system is a system that successfully manages these circumstances to create the intended effects on the inhabitants of space. Air is brought to a specified temperature and humidity for public health, comfort, and efficiency in comfort air conditioning [20].

With the development of intelligent analysis tools such as CFD, thermal comfort analysis can be held once the design of the cooling system has been finished.

Comfort Requirements

Thermal comfort is achieved when body temperature is maintained within certain limits, skin moisture is low, and the physiological effort required for regulation is reduced [13]. Air temperature, mean radiant temperature, relative air velocity, and relative humidity are environmental variables in the thermal comfort indexes [21]. The temperature of the air around the occupiable area is referred to as air temperature. Heat transmission between human and the environment continues until the temperature of the human and the temperature of the environment is equal. The thermal radiation for the human body from all directions is described by the mean radiant temperature, which is measured with a black globe thermometer [13]. Heat loss from a body can be accelerated by a change in relative air velocity that impacts evaporation from the skin. Personal parameters that affect thermal comfort, activity level, and clothing insulation are known as individual variables. Human performance is influenced by activity level [13]. If inadequate heat is produced, skin temperature drops, making the occupier feel cold and uneasy [22]. The metabolic rate, which will be mentioned in the comfort characteristics, is closely related to activity level. Furthermore, garment insulation is a significant factor in determining thermal comfort. A thermal manikin [13] can be used to test clothing insulation.

Both ASHRAE 55 and ISO 7730 have developed guidelines for acceptable thermal conditions in terms of rules and regulations as stated in [23]. If the environment is thermally homogeneous, ASHRAE defines the comfort zone as the area where 90% of occupants or moderately active people find the environment thermally acceptable [13]. The ISO 7730 standard, on the other hand, aims to define comfort evaluation in moderate conditions [18]. For a satisfactory degree of thermal comfort, ISO 7730 recommends that PMV be kept between +-0.5 ranges, as specified in the section below.

Comfort Parameters

When it comes to thermal comfort, it's a mix of environmental and human elements. As a consequence of "Fanger's comfort equation," the PMV reveals how the inhabitants evaluate the climate. The percentage of people dissatisfied (PPD) may be predicted using PMV [8]. Fanger provided the criteria for comfort that were established via clinical, experimental, and statistical investigations [24]. Considering all parameters affecting human comfort, it can be categorized as input parameters and output parameters. The input parameters are the ones that directly affect the human comfort conditions described in the above section. On the other hand, output parameters are the results of these input effects.

Input parameters consist of;

- Room/Space

The area or volume of a room or space in which the humans are present. The area and height of the room are directly effecting the selection of the cooling system and human positioning inside the room.

- Cooling System

As an input parameter cooling system is a factor. Regarding the region of the control volume, which is to be cooled, the cooling system type may differ as described in the Cooling System section. This system type is directly effecting the temperature and air distribution inside the control volume.

- Cooling Loads

Cooling Loads, or the heat gain from the vicinities, walls, leakages, humans, electrical appliances are directly affecting the air temperature and air distribution inside the room.

- Human Position

For an office, human positioning is very important for thermal comfort. People located at nearer places to cooling devices tend to feel much cooler. On the other hand, if people are far away from the cooling devices, they tend to feel the heat gain much more from other means.

- Activity Type / Metabolic Rate

Activity type is a factor that defines the activity or work being done by the human. For different uses of different locations, activity types may differ greatly. A silent office and a dancing hall will have different activities and the metabolic rates of people in them differ accordingly. As defined in ASHRAE Fundamentals Handbook [13], the sensible heat gain and latent heat gain values are presented for different uses in Table 2.1.

Metabolic rate production values are selected from tables [25]. This table is shown in Table 2.4.

Table 2.4 Metabolic Rates for Typical Tasks [25]

Activity	Metabolic Rate		
	Met Units	W/m^2	($Btu/h{\cdot}ft^2$)
Resting			
Sleeping	0.7	40	(13)
Reclining	0.8	45	(15)
Seated, quiet	1.0	60	(18)
Standing, relaxed	1.2	70	(22)
Office Activities			
Reading, seated	1.0	55	(18)
Writing	1.0	60	(18)
Typing	1.1	65	(20)
Filing, seated	1.2	70	(22)
Filing, standing	1.4	80	(26)
Walking about	1.7	100	(31)
Lifting/packing	2.1	120	(39)

- Clothing Type

Clothing type is the factor that affects human comfort by means of wearable clothes. For instance, it is different when a person wears a t-shirt compared to a coat and a jacket as they have different textile materials, coating, thickness, and insulation [26]. Their effects are tabulated in Table 2.5.

Table 2.5 Clo Value for Thermal Insulation [26]

NO	Thermal zone	CLO
1	Lobby	0.6
2	Office	0.6
3	Praying room	0.7
4	Kindergarten	0.6
5	Catering area	0.6

- Gender

Human comfort, of course, differs from male to female as they both have different metabolic rates in nominal conditions generally [27].

Moreover, output parameters, which is the scope of interest of this study and the base of the analysis can be defined as;

- Air Temperature

Air temperature in the case of thermal comfort study can be considered as mean radiant temperature (MRT). The temperature of an imaginary enclosure in which the heat transfer from the human body equals the heat transfer in the actual enclosure is known as MRT. Cooling systems try to set MRT to a specific value.

Air Temperature is a function of the cooling system, activity type, and human position as well as other heat gains.

- Air Relative Humidity

The moisture content of the environment is stated as a percentage of the quantity of moisture that can be kept by the environment without consideration at a certain temperature and pressure.

The relative humidity is a function of the cooling system, activity type, and human position as well as other heat gains.

- Air Velocity

Air velocity inside space is simply the rate of air displacement. This is greatly affected by the cooling system and its location. The system defines the relative speed of the air inside the room or space.

Air velocity is a function of the cooling system, activity type, and human position as well as other heat gains, as the heat gains affect the movement of air regardless of the air supply system.

- Predicted Mean Vote

The PMV Equation is a thermal comfort index with a function of activity, clothing, air temperature, mean radiant temperature, air velocity, and relative air humidity. PMV equation is shown in Equation (2.6).

$$PMV = [0{,}303 \cdot \exp(-0{,}036 \cdot M) + 0{,}028] * \left\{ \begin{array}{c} (M-W) - 3{,}05 \cdot 10^{-3} \cdot [5733 - 6{,}99 \cdot (M-W) - p_{\mathrm{a}}] \\ -0{,}42 \cdot [(M-W) - 58{,}15] \\ -1{,}7 \cdot 10^{-5} \cdot M \cdot (5867 - p_{\mathrm{a}}) - 0{,}0014 \cdot M \cdot (34 - t_{\mathrm{a}}) \\ -3{,}96 \cdot 10^{-8} \cdot f_{\mathrm{cl}} \cdot [(t_{\mathrm{cl}} + 273)^4 - (\bar{t}_{\mathrm{r}} + 273)^4] - f_{\mathrm{cl}} \cdot h_{\mathrm{c}} \cdot (t_{\mathrm{cl}} - t_{\mathrm{a}}) \end{array} \right\}$$

$$t_{\mathrm{cl}} = 35{,}7 - 0{,}028 \cdot (M-W) - I_{\mathrm{cl}} \cdot \left\{ \begin{array}{c} 3{,}96 \cdot 10^{-8} \cdot f_{\mathrm{cl}} \cdot \\ [(t_{\mathrm{cl}} + 273)^4 - (\bar{t}_{\mathrm{r}} + 273)^4] + \\ f_{\mathrm{cl}} - h_{\mathrm{c}} - (t_{\mathrm{cl}} - t_{\mathrm{a}}) \end{array} \right\} \quad (2.6)$$

$$h_c = \begin{cases} 2{,}38 \cdot |t_{cl} - t_a|^{0{,}25} & \text{for} \quad 2{,}38 \cdot |t_{cl} - t_a|^{0{,}25} > 12{,}1 \cdot \sqrt{v_{ar}} \\ 12{,}1 \cdot \sqrt{v_{ar}} & \text{for} \quad 2{,}38 \cdot |t_{cl} - t_a|^{0{,}25} < 12{,}1 \cdot \sqrt{v_{ar}} \end{cases}$$

$$f_{\mathrm{cl}} = \begin{cases} 1{,}00 + 1{,}290 I_{\mathrm{cl}} & \text{for } I_{\mathrm{cl}} < 0{,}078 \mathrm{m}^2 \cdot \mathrm{K/W} \\ 1{,}05 + 0{,}645 I_{\mathrm{cl}} & \text{for } I_{\mathrm{cl}} > 0{,}078 \mathrm{m}^2 \cdot \mathrm{K/W} \end{cases}$$

Where,

PMV : Predicted Mean Vote

M : the metabolic rate, in watts per square meter (W/m²)

W : the effective mechanical power, in watts per square meter (W/m²)

I_{cl} : the clothing insulation, in square meters kelvin per watt (m²K/W)

f_{cl} : the clothing surface area factor

t_a : the air temperature, in degrees Celcius (°C)

$\bar{t}_r$: the mean radiant temperature, in degrees Celcius (°C)

v_{ar}: the relative air velocity, in meters per second (m/s)

p_a : the water vapor partial pressure, in pascals (Pa)

h_c : the convective heat transfer coef., in watts per square meter kelvin [W/(m²*K)]

t_{cl} : the clothing surface temperature, in degrees Celcius (°C)

The Thermal Sensation Scale explains the score provided by the PMV equation. The scale is shown in Figure 2.6.

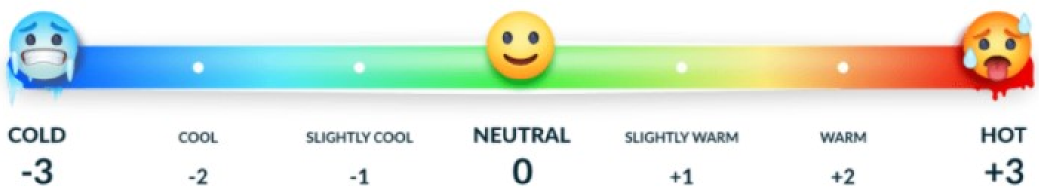


Figure 2.6. Thermal Sensation Scale [24]

If the value from the PMV equation converges to zero, the occupants' contentment with thermal surroundings is at its optimum [24]. PMV is a function of metabolic rate, clothing type, gender, temperature, air velocity.

- Percent People Dissatisfied

PPD equation can be seen in Equation (2.7).

$$PPD = 100 - 95 * \exp(-0{,}03353 * PMV^4 - 0{,}2179 * PMV^2) \qquad (2.7)$$

Where,

PPD : Predicted Percentage Dissatisfied

PMV : Predicted Mean Vote

PPD Estimates the proportion of persons who are likely to be dissatisfied with their surroundings. The approximate relationship between PPD and PMV is shown in Figure 2.7.

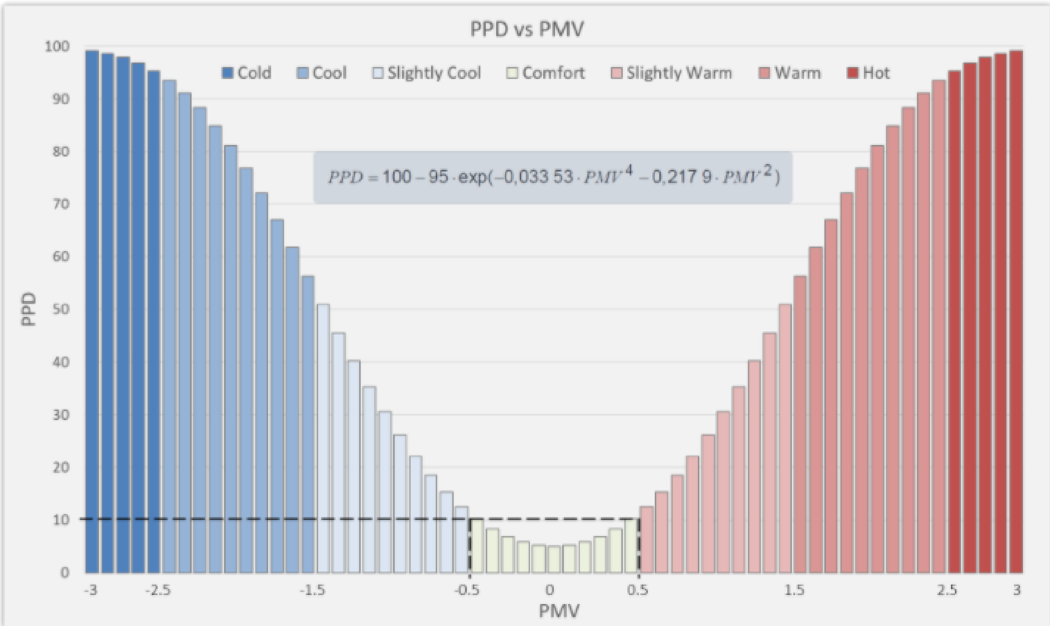


Figure 2.7. PMV-PPD Relation [23]

Even under the most pleasant settings, 5% of the occupants would be dissatisfied., at PMV=0 [23].

2.3 Cooling System Design Tools

Cooling system design and calculation principles rely on the equations and parameters stated in the previous sections. These parameters were calculated by hand before the innovation of computer software. After the introduction of high-rise buildings, various complexes such as shopping malls, airports, stadiums into the construction industry, the cooling system design tools have been developed to support design for complex geometries. These tools have helped engineers to calculate the needs of a structure much more rapidly and the software are reducing human error while calculating the needs. Since the innovation of computer aided drawing (CAD) tools, the data on the CAD drawings have been used as an input for these calculations.

2.3.1 Traditional Methods

At the times when tracing papers were used in the construction industry, the calculation of design cooling loads is a long procedure as all loads of premises in a huge complex should be calculated one by one. An example of a designer with tracing paper is given in Figure 2.8.

Figure 2.8. Designer with Tracing Paper [28]

Engineers used to measure walls, windows, doors, and height of the premises manually with a ruler on a scaled drawing and use these data in calculation equations given in the previous section.

After the introduction of CAD method, these data can be obtained in a computer environment. However, this procedure was still manual as the designer still measures the input parameters with manual methods on a computer such as measuring the wall with drawing a line. Moreover, designers still used to calculate the output parameters manually.

Increasing the technological developments in computer science, scientists and engineers develop software that calculates the design loads automatically according to the equations embedded into the software.

Nowadays, in the cooling design industry, software such as Carrier H.A.P., Elite CHVAC, UI as shown in Figure 2.9, and Linear Building GMBH are widely used by engineers.

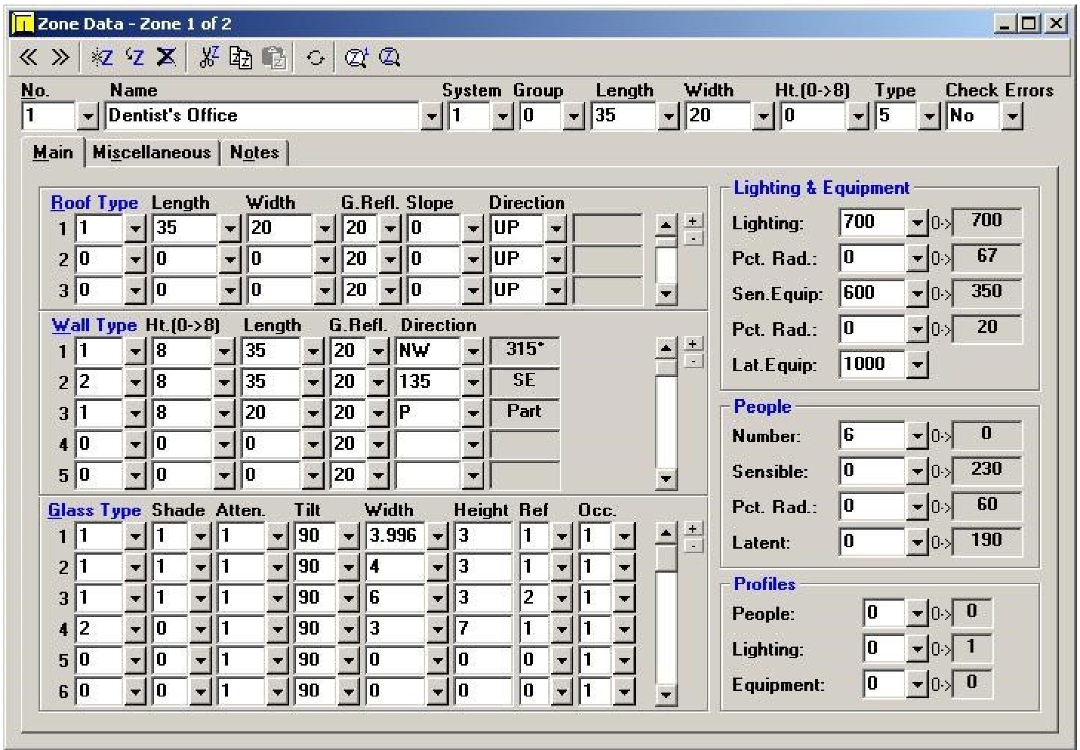


Figure 2.9. User Interface of HVAC Design Software [29]

However, increasing technological capability of software, this process is still considered manual process as the input data is given to the software with the help of an engineer, and the design is made by hand in software such as AutoCAD. The main workflow of cooling system calculation and design with software is given in Figure 2.10.

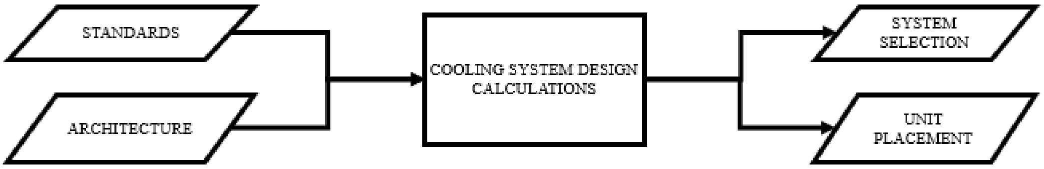


Figure 2.10. Traditional Design Scheme of Cooling System Project

Engineers are translating the information in the architectural project into a cooling design load with the help of software. But as described, all other parameters are given to the software by hand. In this case, the architectural projects have been drawn in AutoCAD, which is the most used software for building design by construction industry people. In the architectural project, the design engineer takes input data such as room area, volume, wall surfaces, etc. to integrate them into the calculation software. Thus, the only automated process is the calculation of cooling loads. After calculation, parameters such as the location, orientation, and cooling temperature are selected by the engineer manually. After the calculation process is finished, the design and the placement of indoor units for the selected system are manually inserted into plans in design software such as AutoCAD.

If the designer wants to check the effects on thermal comfort for the designed system, s/he should make a CFD analysis which is a great time-consuming procedure that solves various differential equations as described in Section 2.3.3. The flow of the design verification looks as in Figure 2.11.

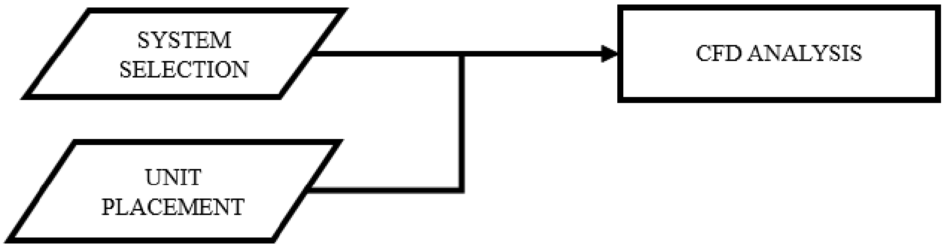


Figure 2.11. Traditional Methodology for Cooling System Design Check

2.3.2 Building Information Modelling

The notion of green construction was initially proposed by Chuck Eastman of Carnegie Mellon University in 1975. To define BIM, Autodesk formally applied to the AIA (American Institute of Architects) in 2002. BIM is defined by the National Building Information Model Standard (NBIMS) as "a digital representation of a facility's physical and functional attributes." It serves as a data storage mechanism for information regarding a facility, giving a strong foundation for choices made during its lifetime. Computer science has advanced significantly in the twenty-first century, providing a firm foundation for the use of BIM technology, as well as significant growth in relevant BIM research.

Application

BIM is a notion that originated in the United States and is now extensively utilized in Europe and Asia. The United States is ahead of other countries in the globe in terms of BIM research and development since it was the first to adopt it. In 2006, the USACE convened a meeting with academics and law firms to examine BIM problems. According to a survey conducted by McGraw-Hill as cited in [30], the percentage of BIM-based projects in North America increased from 17% in 2007 to 49% in 2009 and 71% in 2012.

According to the National BIM Report 2018, 78 percent of them agree that BIM is the future of construction projects, 31 percent are using BIM in their projects, 75 percent believe they will use BIM technology in some projects, and nearly 95 percent plan to use BIM within the next five years.

Characteristics

BIM has several advantages over 2D CAD drawings. That is why BIM may well be accepted and supported by a wide range of countries. BIM now has the following main features, thanks to the constant updating of BIM tools.

- 3D Visualization

The intended structure is in three dimensions (3D), allowing the architectural design to be viewed and the model to be turned into some highly realistic views. 2D drawings may show how basic ducts and water pipelines function in plumbing and electrical engineering. However, if one continues to cut through the pipeline to verify them for increasingly difficult projects, it will put a lot of effort on engineers' shoulders, resulting in faults that cannot be checked. BIM's 3D visualization capacity can help with this kind of issues. When the pipeline has to be fixed later in the operating and maintenance stage, the 3D model will make it extremely easy to locate the problematic pipeline, which will save time hunting for it in the bulky 2D drawings.

- Collaboration

Architectural and structural design are generally the first steps in the conventional engineering design process. Electrical, heating, piping, and plumbing engineers complete their conceptual designs independently and separately based on the basic design. Architectural engineers alter design drawings in response to issues raised by other engineers. The amended designs are sent out to a new set of engineers. During the design phase, separate engineers would communicate with one another in pairs to make adjustments to their designs. It is vital to verify the complicated overlapping sections to determine if there are any difficulties in the pipeline for engineering designs that take up a lot of areas, such as HVAC design. If deficiencies in the inspection procedure are not found, higher expenditures and a longer building duration will ensue. BIM, on the other hand, is not the same as conventional design. The basic model is kept on the main server when it has been finalized with the help of architectural and structural engineers. Other engineers can connect their design models to the main model directly. Others will be able to see if any component of the plan is updated. The communication between various engineers is decreased, and design time is saved, thanks to collaborative design. It will be simple to check for overlapping regions using 3D views. The upshot of collaborative design is that the need for a redesign is avoided, saving money and cutting the construction time.

- Simulation

The model created in the BIM environment may be utilized for solar analysis, outdoor airflow simulation, and heat conduction simulation at the preliminary stages of design, in addition to design, construction, and operation. Construction simulation can be used to direct the building process throughout the construction stage. Evacuation can also be mimicked during the operating stage. The above-mentioned simulations may be carried out using a variety of tools, but they are all based on the original BIM model, which eliminates the need for re-modeling in other applications and thereby reduces effort.

- Parameterization

It is among the most essential features of BIM. Designers utilize parameterized components to develop their models during the design and modeling process. The flow in air ducts and water pipelines, as well as the material composition and material features of walls and buildings, are all digitized in the model.

- Software Development

The BIM function is quite strong, but no software can manage and distribute information from the whole BIM life cycle independently. An application programming interface (API) or scripting tools such as Dynamo for Autodesk Revit are included in the BIM tool. Modeling work may be transmitted automatically thanks to API development, which enhances modeling productivity. Other software functions can also be consolidated within a BIM tool.

After the introduction of BIM, geometric and functional data can still be obtained in the computer environment. However, this procedure now is automated as the BIM model contains all the information the designer needs. The BIM software such as Autodesk Revit has also the capability of doing heat gain, heat loss calculations which prevent the designers do extra work using external calculation software.

Now, increasing technological capability of BIM software, this process is considered as an automated process as the input data is given to the software with the help of the model itself. In this case, the architectural projects have been modeled in Autodesk Revit, which is the most used software for building design by construction industry people in the BIM platform.

After the calculation process is finished, the design and the placement of indoor units for the selected system are manually inserted into plans in design software such as Autodesk Revit.

Still, if the designer wants to check the effects on thermal comfort for the designed system, s/he should make a CFD analysis which is a great time-consuming procedure that solves various differential equations as described in Section 2.3.3.

2.3.3 Computational Fluid Dynamics

CFD is based on fluid dynamics' governing equations. They are mathematical expressions of physics' conservation rules. This chapter's goal is to present the explanation of these concepts, where the physical laws listed below are applied;

- Conservation of Mass.
- Conservation of Momentum
- Conservation of Energy

It is critical for anybody working with CFD to have a basic grasp of the physical processes of fluid motion, as CFD examines and predicts these phenomena. CFD is based entirely on these equations. As a result, one must start with the most fundamental definition of fluid flow processes, as well as the meaning and relevance of each word within them. Following the discovery of these equations, CFD solutions are defined. Because the proper numerical form of a boundary condition is largely reliant on the mathematical form of the governing equations and numerical algorithm utilized, the physical characteristics of the boundary conditions and their corresponding mathematical formulations will also be created.

CFD was founded during the 1940s by J. von Neumann, a mathematician who is considered as the founder of CFD [31]. His approach quickly put the world's first programmable electronic computers to the test. Throughout the years, CFD has earned a legitimate place among the established areas of theoretical and experimental fluid mechanics. It's a discipline of research that appeals to mathematicians, physicists, and engineers equally. CFD technique developers build a virtual world that users can fill with anything that flows at any scale. CFD approaches allow users to perform virtual experiments that would be "expensive, difficult, dangerous, or impossible" in the actual world, according to P.L Roe. The fluid may be thought of as a continuum for most purposes, and its dynamics are characterized by conservation rules expressed as partial differential equations (PDEs) or integral equations when constructed for a tiny but finite volume of fluid.

CFD discretizes these modeling equations on a computer grid, resulting in finite-difference, finite-volume, or finite-element approximations. If the fluid does not collide enough within the desired spatial and time scales, it is no longer considered a continuum; pseudo-particles are then created, traveling across a backdrop grid and transporting/exchanging the fluid's attributes. Although CFD methods are frequently used outside of the range of flow parameters and experiment space-time scales, the dependability of calculated flows can only be evaluated under settings when experimental and/or theoretical data are available for comparison. The standard procedure is to run the same calculation on a series of meshes with increasing resolution; this "convergence research" reveals how close the precise answer is to the PDEs that explain the flow physics. However, modeling mistakes persist, while the experiments utilized for comparison have their own set-up circumstances and measurement uncertainties. With so much depending on flow simulations, methods for monitoring and forecasting the trustworthiness of computed solutions and computational methods are in high demand.

Since massively parallel computing has been accessible to every research organization in the first decade of the twenty-first century, CFD has become more powerful than ever. There is a wide range of difficult applications that need the study of progressively sophisticated physics in the face of increasingly complex geometry. Given this rise in complexity, it's easy to see why grid optimization, design optimization, and uncertainty quantification are still hot topics in the study.

In summary, CFD analysis has the following steps;

- Importing of Geometry or Model

A two-dimensional (2D) or three-dimensional (3D) drawing geometry is the starting point for solving a CFD issue. In CFD, it's common for the geometry system to incorporate features that aren't wanted. Because intricate geometry might degrade mesh quality and influence outcomes as more or less conservative, the specifics of the geometry should be disregarded or reduced according to the simulation aim. It should be assured that CAD designs allow flow simulation throughout the simplification of geometry. Another difficulty with this stage is that the CAD model for the researched environment must be generated. Because the computational domain covers this environment, it cuts off the surroundings, which are represented by approximate boundary conditions. The computational domain refers to the region that is visualized through simulation. The domain should be broad enough to prevent fluid streams from reflecting and causing anomalous pressure fields around the model.

- Defining Materials

For CFD analysis, materials, which are actual objects in each type of analysis, are divided into two categories: fluids and solids. The basic physical substance in CFD modeling for AEC applications is air as a fluid. As a result, fluid parameters such as viscosity, density, temperature, and pressure should be specified. Furthermore, heat movement through a building material layer is influenced by its thermal qualities and composition. These physical qualities are stored in CFD software databases, and CFD applications also allow for physical property modifications.

- Defining Boundary and Initial Conditions

The importance of indicating boundary conditions is that it allows the physical issue to be solved using CFD, which is represented by the specification of boundary conditions. In particular, when modeling CFD in interior situations, it is critical to have properly stated boundary conditions. Furthermore, the beginning conditions are required for the iterative procedure used to solve the problem. Almost all flow parameters must be determined as starting circumstances before solution. Even if the beginning circumstances are arbitrary, they must be well-defined to reap the benefits of the iterative process.

- Meshing

The use of grids for partitioning of the computational domain has a significant impact on the computational output. If the cell counts are higher while creating the mesh, the CFD result will be better and more accurate. However, as the number of cells in a computer grows, so does the amount of time it takes to calculate and store data. The details are presented in Section 3.4.

- Solving

By defining the materials, boundary conditions, the solving procedure is started by solving the differential equations which are the governing equations of CFD analysis are presented in Section 3.5.

- Postprocessing

After the analysis is complete, the plots of different parameters such as Temperature and Velocity can be shown as planes, streamlines.

CFD Principles

Because CFD is concerned with the numerical approximation of partial differential equations, it must adhere to a set of basic numerical analytic principles. These ideas and some related analytical methods are presented in this section.

- Discretization

Since a computer could only store and process a fixed amount of data, PDE solutions must be represented using restricted data. A computational net or grid is typically used to partition the space-time continuum into tiny domains (meshes or cells) for this purpose. For finite-difference methods (FDMs), the data can be specified as point samples in the nodal points of the net, or as averages across the interior of the meshes, for finite-volume techniques (FVMs). In these circumstances, interpolation must be used to approximate the detailed behavior of the solution within a mesh. Discretization refers to the method of describing a solution with a smaller amount of variables, as well as an approximation of a PDE using these data.

- Consistency

A numerical approach to a PDE must be compatible with the PDE, which means that the discretization error must disappear when the grid mesh size is made infinitesimally tiny.

- Stability

If a little perturbation to the starting values leads to a tiny fluctuation in the solution at any later time, the initial-value issue for a PDE is properly posed. A finite-difference approach is considered to be stable when used to such a problem if a minor perturbation of the starting values causes a tiny perturbation in the numerical solution at any fixed later time, regardless of the mesh size. This "later time" is moved to infinity for steady-flow situations, needing stronger absolute stability.

- Convergence

When calculating a sequence of discrete solutions on grids with increasing spatial and temporal resolution with a single difference technique, one wants to be confident that the sequence converges to the precise solution of the problem. For convergence of the numerical solution, the difference scheme's consistency and stability are both required and sufficient. Although this theorem is frequently employed outside of its limitations, particularly in nonlinear situations, consistency and stability are still required for convergence.

- Monotonicity

PDEs like the advection-diffusion equation provides a solution that is monotone at all times, starting from a monotone initial-value distribution. A discretization should have this quality in common with the PDE; such schemes are known as monotonicity-preserving or non-oscillatory. Monotonicity-preserving techniques, on the other hand, ensure the positivity of a numerical solution derived from positive data.

- Conservation

The equations of fluid dynamics represent mass, momentum, and energy conservation.

- Irreversibility

To be able to describe flows, a discretization of a nonlinear PDE must be conservative and irreversible. Irreversibility is required to explain the irreversible processes that occur (friction and heat conduction).

The use of CFD in thermal comfort research and design is becoming increasingly common. CFD software can now handle larger and more complicated issues thanks to the rising capability of the processors on that they are run. Even as coding and uses get increasingly complex, a core of ideas and methodologies for designing and analyzing CFD codes remains essential.

A screenshot of CFD software is shown in Figure 2.12.

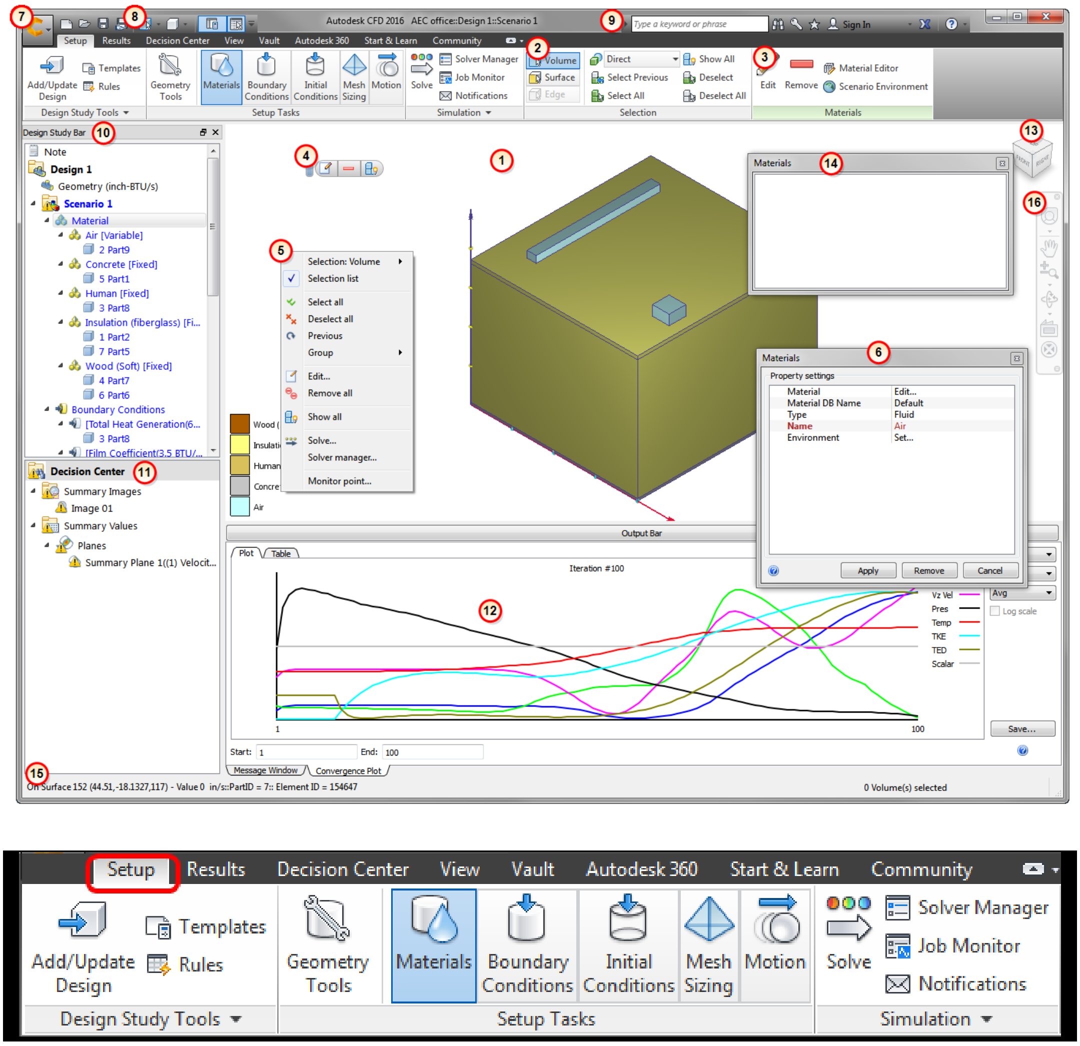


Figure 2.12. CFD Software User Interface – Autodesk CFD

2.4 Literature on Cooling System Design and Optimization

There are many studies combining the concepts of HVAC system optimization and BIM. These studies have been integrated into CFD software to have a result and verify the data obtained in the studies.

In this chapter, to clarify the literature gaps, first, the studies in the field of this thesis are described.

2.4.1 Studies on Human Comfort

First of all, for the thermal comfort concept, some studies have been conducted recently. The importance of the thermal comfort concept has been presented in several studies [32]. The importance of implementing PMV and PPD is presented. The studies have reviewed the development of the idea of human comfort [8]. In these studies as the main result, international thermal comfort standards such as ASHRAE 55 and EN15251 were created. In those studies, case studies have been conducted to show the implementation and correctness of thermal comfort parameters.

To understand and verify the thermal comfort indices, surveys have been conducted. In [33], 30 subjects each participated in six 3 hours sessions and completed a questionnaire every half an hour. They have collected 1080 data points and got significant results. They have found that the mean thermal sensation vote was closer to neutral in both homes and offices if the system is designed regarding human comfort.

In [3], the paper presents results of over 34000 survey responses regarding air quality and thermal comfort. International standards generally recommend acceptable conditions in which 90% of people are satisfied within their environment. The survey has resulted that much higher rates of dissatisfaction occurring in buildings. It has been found that only 11% of buildings had 80% of thermal comfort satisfaction. The mean satisfaction rate has been found as 59% only which is a much lower rate than the standards recommend. This study's findings revealed the condition of indoor environmental quality in office buildings and highlighted the significance of post-occupancy review. This knowledge has significant consequences on how buildings are designed, constructed, and operated to improve occupant comfort and productivity. Moreover, in another thermal comfort survey study [4] which has been conducted for old houses and offices, it has been found that %18,5 of people are in dissatisfaction with their environment. These studies have shown the importance of thermal comfort as it is directly affecting human happiness and productivity.

To design the HVAC system by focusing on thermal comfort and indoor environment quality some algorithms have been developed in previous studies. In [1] an air distribution network design optimization study has been presented to calculate the optimal air distribution system configuration. It has been found that the generated algorithm has a great influence on the air system cost. This optimization study has been resulted in minimizing the material and equipment cost while increasing the air quality inside the environment.

In [34], a neural network algorithm has been generated that combines CFD simulations to perform an inexpensive simulation. The case was handled for natural ventilation design and louver design of a building. Conducting the algorithm, the flow patterns have been well predicted without conducting a comprehensive CFD analysis. The project's approximately 300 CFD simulations produced 250 terabytes of data, with each simulation taking roughly 45 minutes to complete. The neural network uses less than 1 megabyte of data and can calculate airflow in seconds for various wind and louver circumstances. This demonstrates how, using this approach, a yearly simulation with optimization is conceivable, which would not be possible with only CFD simulations. This project was used to demonstrate the feasibility of this simulation method. Changes in the simulation settings might be used to fine-tune it. As samples for the neural network, around 300 simulations were run. It is feasible that fewer simulations might be employed, or that more possibilities for wind direction should be available rather than wind speed, which appeared to have a linear relationship with the air exchange rate and hence would be picked up by the neural network with fewer alternatives. Finally, this research effectively incorporated components of computing, architectural design, and building science in a process that is practical and accessible, employing software that is widely used in the architecture business.

2.4.2 Studies on BIM and Energy Consumption

In addition to the studies regarding the thermal comfort and air quality presented above, there are frameworks constructed in the literature. These frameworks are intended to lower the energy consumption indices by optimizing the HVAC system design using algorithms. In [35], the algorithm evaluates the energy implications of occupancy diversity at a building level, where the BIM concept is integrated to provide building geometries. Iteratively reducing occupancy diversity is accomplished using an agglomerate hierarchical clustering-based iterative evaluation technique. This study adds to an understanding of the influence of occupancy variety on HVAC system energy efficiency, potentially resulting in energy savings and facilitating better-informed decision making for energy-efficient HVAC system control techniques. However, the research described here was not intended to suggest a precise method to remove diversity for a certain building, HVAC system, or environment.

After the introduction of BIM, the number of studies regarding building energy consumption have increased. In [36], building energy management systems and BIM have been combined to conduct a comprehensive energy consumption analysis. Autodesk Revit was used to create BIM data for the proposed building in the research. The suggested building's energy performance simulation was implemented. In the study, it was found that BIM implementation in energy simulations gives more accurate and followable results compared to traditional methods. This result was used to apply the generated algorithm to the updated HVAC simulation model. The supply air system's HVAC schedule was needed. In [37], the paper focuses on the examination of the possible performance of integrated systems and explores the prospective use of data integration methods for an office setting. The benefits of such BIM and building performance simulation tools are stronger, according to the study, especially when monitoring and improving environmental conditions. The outcomes of this study revealed that BIM and building performance simulation (BPS) tools had clear linkages. Even though BIM and BPS technologies were created from separate viewpoints, they can become compatible to help with energy-efficient building retrofits and design. As a result, developing techniques to incorporate them for building performance analysis during design, construction, and refurbishment is critical. Moreover, sustainability studies have been conducted as in [38]. The study focused on energy consumption and the environmental comfort of a traditional retail market. A green BIM model of the market area was constructed in Autodesk Revit. Using the BIM model, integrated environmental solutions virtual environments were used. Based on the results, heat radiation was found as the major energy consumption source. The study also presents the inefficiency of the operating HVAC system in terms of environmental comfort.

2.4.3 Studies on Generating Algorithms to Optimize Energy Consumption

Several research studies aimed to develop algorithms to overcome the issues regarding energy consumption. In [39], a solver was developed to increase the energy efficiency of a building in the design phase which is a multi-objective optimization engine using an algorithm. The algorithm works with Autodesk Revit and its software development tool Dynamo. When employing Building Information Models, the tool may help designers enhance their design optimization. The study contributes by developing and demonstrating multi-objective optimization for architectural design in a parametric BIM system.

Considering the thermal comfort and energy consumption in buildings, an intelligent control system was designed to automate the decisions taken to provide thermal comfort in real-time depending on the number and location of the occupants in [40].

CFD modeling is used to evaluate the system's decisions in terms of thermal comfort based on wind velocity and airflow distribution. In terms of location and quantity of residents, one typical and two severe scenarios are investigated. Under severe conditions and with thermal comfort factors within acceptable levels, the results show up to 50% energy savings. These data, together with the LEED criteria, are included in a BIM model that may be evaluated automatically using rules. This will enable the management or owner to estimate and diagnose energy usage and achieve energy efficiency, as well as analyze alternative scenarios and do spatial analysis during design to prevent rework and enhance green grade.

To overcome the time-consuming tasks and to design cost-effective buildings, an airflow simulation tool for exterior airflow has been generated in [41]. A case study was conducted and it was shown that the algorithm can provide airflow simulation results of simple estate building geometries with a short turnaround time. Moreover in the concept to reduce energy indices and cost of a building, a holistic approach has been presented in [42]. The fundamental goal of building performance optimization should be to provide better places for residents in terms of interior environment quality, thermal comfort, and energy efficiency. On the other hand, to accomplish the exact construction performance of various alternative designs in the context of the complexity of the construction processes as well as the incorporation of newly developed technologies, detailed assessments and visualizations are required and a holistic approach is evaluated. In addition to the algorithms described above, in [30], a decision-making system for HVAC design for low-rise green buildings was conducted. The factors for evaluating HVAC performance are described as follows: environmental, economic, technical performance, and green building rating system. The decision-making process is then provided as a combined Analytic Hierarchy Process for HVAC systems. Finally, BIM tool interoperability is being created to provide a link between BIM and HVAC decision-making systems across the life cycle of a building. The complete model is written in C# in Visual Studio. Last, the developed decision-making system ranks the alternatives for HVAC selection.

2.4.4 Studies on Human Comfort Analysis

Furthermore, regarding the thermal comfort-focused studies, [43] seeks to enhance the information interchange process by providing data and information required for thermal comfort simulation in a consistent manner to provide a Model View Definition for thermal comfort. This method shows the information that building designers and operators will need to offer an acceptable degree of thermal comfort in a typical modest, single-occupant workplace. This study provides a standardized interchange of data from BIM to Building Energy Performance Simulation (BEPS) tools, such as EnergyPlus, utilizing the Industry Foundation Classes (IFC) standard, based on an investigation of the suggested approach's performance. It claims that present systems prioritize data entry by hand, which is a waste of time, money, and effort, with the possibility of errors. Furthermore, a flaw in BIM-based traditional software for thermal comfort assessments has been discovered. As a result, this article outlines a technique for developing BIM-based BEPS tools utilizing the Integrated Design and Management and Model View Definitions (IDM/MVD) methodology, as well as the data interchange needs for thermal comfort study using IFC. A case study has been given to verify the suggested technique by identifying the available and missing elements in the current edition of the IFC schema that are significant for thermal comfort assessments.

In [44], thanks to the Internet of Things (IoT) technology, a platform is created by creating and testing it using the prototyping approach. The prototype's algorithm combines real-time interior thermal data and real-time meteorological data with the user's body temperature. Furthermore, the platform combines the thermal values with material data from an existing BIM file. The comfort conditions have been evaluated by measuring the data regarding human positioning.

In [45], to improve the presentation and accuracy of building energy analysis, the study uses IoT technology to collect data from sensors and show it through BIM, making it easier to investigate the specifics of the building's energy situation. The PMV method is extensively used to determine the level of thermal comfort. Four environmental indicators and two physiological parameters can be used to calculate the PMV. A C#.NET programming environment was utilized to create a PMV Evaluation System in this study. It incorporated information transfer for the Internet of Things, as well as a 3D model visual display, using Autodesk Revit API extensions. It was offered to the construction industry users with an analysis and display system that was more energy-efficient, along with an index specification for thermal comfort.

Furthermore, there are data exchange studies regarding thermal comfort indices inside a building. In the study [46] thermal simulation tools are integrated into the BIM model to visualize and analyze the comfort conditions inside the BIM model.

There are not many studies regarding the integration of BIM using its software development tools such as Dynamo. Moreover, CFD algorithms are still being used as the verification and/or validation of generated proposals.

2.4.5 Studies on Generating Algorithms to Optimize Human Comfort

In the following studies, some algorithms are developed to obtain a human comfort-focused HVAC design.

In [47], a neural network has been constructed to obtain energy-efficient and thermally comfortable interior space. The system automatically calculates the energy indices and thermal comfort values such as PMV and PPD inside the BIM model with Dynamo for Autodesk Revit scripts.. The study is conducted by changing the indoor furniture and human positioning without altering the HVAC system to find the optimal location for the human being to be in comfort. The algorithm has been developed in C#. Then the algorithm is integrated into Dynamo for Autodesk Revit to lay more friendly use to the end-user.

Regarding indoor air quality, which is another index of thermal comfort, [48] proves that BIM models can be implemented by a workflow that utilizes the model as an input and analyzes to give appropriate results for thermal comfort.

In [49], an algorithm has been developed to optimize the location of thermostat placement in a typical office room. The validation of the study was followed by a CFD analysis. To determine the ideal thermostat positions, three scenarios were considered: achieving the best PMV of the occupant zone, achieving the least energy consumption, and achieving an overall optimal of combined PMV and energy consumption. The results have been investigated with a case study that verifies the results for the specified office environment.

Moreover, [50] provides a logical and systematic way for designing and optimizing the HVAC air distribution system in terms of ductwork layouts, sizes, and kinds of ducts to standardize building processes in the off-site environment and save time and money. BIM is used in the suggested technique to coordinate the air distribution system utilizing a 3D database. Furthermore, the data is processed by a trained genetic algorithm, which finds alternate solutions. The algorithm develops the ideal air distribution system in the BIM 3D environment for visual inspection and detailing as the last stage. The findings are backed up by case studies from a Canadian prefabricated, panelized building firm. The possible advantages include a 23 percent reduction in duct material consumption and a 32 percent reduction in daily disputes when compared to standard design approaches, which may save $10,119.5 and 175 man-hours each week. Dynamo for Autodesk Revit was used to create the algorithm. The relationships between the blocks are shown in Figure 2.13. As seen in this figure, there are user and BIM-based inputs. The parametric analysis script manages and calculates the optimal diffuser location.

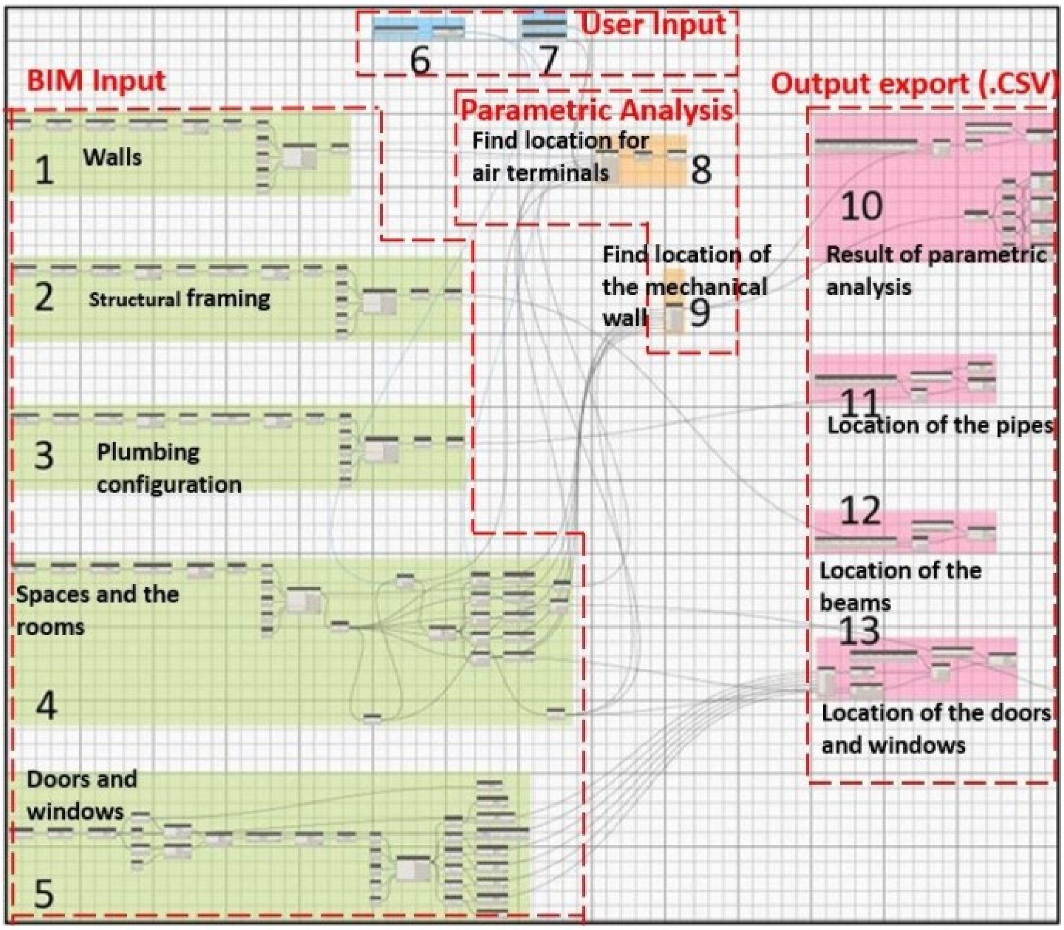


Figure 2.13. Flowchart of Algorithm [50]

Last, in [51] a modern open-plan office environment, the impact of a flexible space layout design on thermal comfort and energy demand is explored. The usability of three distinct HVAC systems (mechanical ventilation, radiant ceiling, and a thermally active building system) paired with four control zoning schemes is evaluated using dynamic thermal modeling. During the design planning or interior remodeling phase, finding a solid solution for each configuration and control approach may help with design selections. The key goal is to allow for variable room arrangement design across the whole building life cycle while maintaining thermal comfort and energy efficiency. The findings suggest that radiant ceilings and thermally active building systems are viable options for flexible office spaces in Stuttgart, but mechanical ventilation systems need a more complicated management strategy to maintain thermal comfort. Connecting the fields of building controls and parametric building modeling allows for the evaluation of flexible space layout solutions with various HVAC systems. This study however conducted for radiant ceiling equipment with heating and cooling modes without using BIM.

2.4.6 Literature Gaps

In summary, in the literature, studies including the below subjects were found;

- Surveys and Studies on Thermal Comfort
- HVAC Design Optimization Algorithms regarding Thermal Comfort without using BIM
- HVAC Design Analyses regarding Energy Consumption and Sustainability using BIM
- HVAC Design Optimization Algorithms regarding Energy Consumption and Sustainability using BIM
- HVAC Design Analyses regarding Thermal Comfort using BIM
- Ventilation Design Optimization Algorithm regarding Thermal Comfort using BIM

Thus, regarding the findings in the literature, there is an absence of studies considering BIM-based numerical node method algorithm, for optimizing air conditioner location for a cooling system in offices.

In order to increase thermal comfort conditions of offices, air conditioner location is vital for people. There are studies integrating algorithms to BIM models to locate the air system devices to increase the air quality of rooms. However, considering thermal comfort efficiency, locating air distribution system only provides air quality in an office. Cooling system devices are important as they manage the thermal conditions inside the room. To see the effectiveness of cooling systems during the design phase of cooling system projects, designers are still using CFD-based solutions to determine the comfort conditions.

To decrease the computational time for increasing thermal comfort efficiency in offices, there is a need for swift calculation tools instead of traditional CFD solutions. Although there are some studies considering this issue, they are still using CFD fundamentals which takes time to complete the design configuration, even if they use BIM-based algorithms. Integrating numerical node method algorithm into BIM model and locating the A/C inside the room by design optimization tool fills the gap of this computational time consideration in the literature.

CHAPTER 3

METHODOLOGY

The objective of this research is to propose an optimization algorithm regarding human comfort for cooling systems. The algorithm as described in the objectives chapter is to determine the optimal location of the air conditioning unit for better PMV and PPD values specified in the previous chapter. The results of this research save time and man-hour for designers who tend to design the cooling system considering human comfort without preparing a comprehensive CFD analysis. In this thesis BIM data is used for the generation of the algorithm. Autodesk Revit software is used as the BIM tool for the modeling and data storing processes. Moreover, Dynamo, which is an add-in in Autodesk Revit, is used to manipulate the coding and optimization itself.

3.1 General Algorithm

The proposed algorithm consists of input and output variables similar to other cooling load calculation software. The input values are the parameters defined in the previous sections such as human position, cooling load, design temperature, and model geometry, which are needed to calculate the cooling load and temperature distribution inside the space. The main objective of the algorithm is the optimization of A/C location concerning human positioning inside an office. Thus, the temperature distribution of the area is needed to get human comfort parameters.

The study is conducted in an office environment. In the office, the cooling system consists of split air conditioning units. Analyses are conducted in the office are to investigate the effectiveness of cooling system design and human comfort. The study is conducted in the summer time as it is investigating the location of a cooling unit.

The general workflow algorithm is presented in Figure 3.1. The standards and architectural model are the base inputs for the design case. After the necessary cooling load calculations, the cooling load of the room is found. Then, the system selection is made by the designer. In this study, the system is selected as an air conditioner. Lastly, the equations in the nodal network analysis are integrated into the A/C placement algorithm to get the optimal A/C location which gives the unit location as the output of the algorithm.

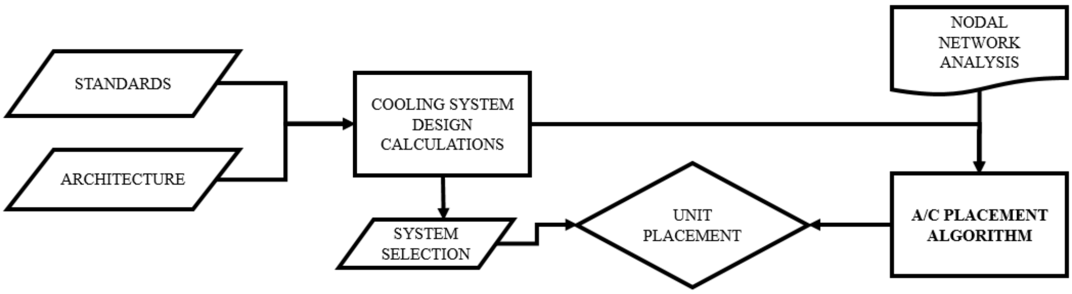


Figure 3.1. General Workflow of Algorithm

As it is stated in the previous sections, thermal comfort analyses are held by CFD software even if the process is automated with the help of BIM. The developed dynamo script helps the designer to oversee the effect of location of the A/C units without proceeding with a time-consuming CFD analysis.

The input data required for design, analysis, and optimization of the location of the air conditioning unit consists of;

- The architectural 3D model in Autodesk Revit, including space requirements, walls, floors, and ceiling,
- Available A/C unit library with different cooling capacity and supply temperature.

There are several design criteria to be satisfied to develop the required air conditioning system, including;

- The locations of the A/C unit must satisfy ASHRAE and TS 825 guidelines,

- The cooling unit shall satisfy the necessary heat removal as the capacity should be higher than the cooling design need.

Based on the input and criteria, the proposed methodology to design the A/C system involves three procedures;

1. Parametric analysis of the BIM model is constructed to determine the alternative locations for the installation of air conditioning units, permissible boundaries for installation of the units within the ceiling.
2. Based on the design constraints defined by parametric analysis and input parameters, an algorithm is used the generate the optimal location of a single A/C unit, which provides the best solution in terms of human comfort and cooling system design.
3. After all, the A/C unit is created in the 3D environment based on the result of the previous optimization model and the input defined by the user.

The output of the proposed methodology includes;

- The location of the air conditioning unit to increase the human's comfort.
- Location of the A/C unit to reduce the energy consumption based on the unit supply temperature.

This methodology is aiming to help the designer with the design of the air conditioning unit. Implementing this framework can automatically generate an A/C layout for any given project with optimized system performance parameters in terms of human comfort and energy consumption. This research aims to provide a tool and process for increasing the efficiency of the human comfort-focused cooling system design and elimination of time-consuming tasks such as conducting CFD analysis to improve human comfort during the design phase of the A/C systems in the office environment.

3.2 Parameters

This proposed methodology involves a parametric study, in which the primary inputs and secondary inputs are manipulated to obtain the optimal output parameters.

Parameters considered in this study are classified as primary inputs, secondary inputs, and outputs. Table 3.1, Table 3.2, and Table 3.3 show the parameter classifications among the study.

Primary inputs are defined as the inputs related to architectural spatial and informational data, and user inputs such as human position in the office and cooling system type. These inputs are not a function of other parameters and are directly used inside the algorithm.

Table 3.1 Primary Inputs

Primary Inputs	Format/Explanation
Architectural BIM Data	Spatial BIM data in Autodesk Revit
Cooling System	User input, Selection of the System
Human Position	User input, as designed in the office environment
Activity Type	User input
Clothing Type	User input

- Architectural BIM Data

The spatial data of a room or space in which the humans are present. The area and height of the room are directly effecting the selection of the cooling system and human positioning inside the room. The data will be the base input for the study. The other parameters are defined in Section 2.2.2, and are listed below;

- Cooling System
- Human Position
- Activity Type / Metabolic Rate

- Clothing Type

Moreover, based on primary inputs, the cooling loads are calculated for the algorithm as a secondary input;

Table 3.2 Secondary Input

Secondary Input	Format/Explanation	Function Of
Cooling Loads	Watt	Architectural and Environment Data

Lastly, output parameters, which are the scope of interest of this study and the base of the analysis can be defined as;

Table 3.3 Outputs

Outputs	Format/ Explanation	Function Of
Air Temperature	Celcius	Architectural and Environment Data
Relative Humidity	%	Temperature
Air Velocity	m/s	System Selection
Predicted Mean Vote	-	
Percent People Dissatisfied	-	

These parameters are used to compare the results for different A/C locations. The proposed algorithm changes the location of the cooling unit and finds the most effective location in terms of human comfort comparing the values obtained in different locations.

3.3 Geometry

The geometry of the office environment was designed in Autodesk Revit software. The geometry was used to define spatial information and boundary conditions to be explained in the proceeding sections.

To verify the results of the implementation, an architectural model is used. While constructing the 3D model, the following objects have been modeled.

- Obstructions : Heat conducting elements such as walls, floors, ceilings, and air distribution obstructions such as furniture.
- Heat Dissipating Elements : Lighting appliances, computers.
- Air Openings : The air conditioning unit for this study
- Humans : The objects that dissipate heat and the comfort parameters to be investigated.

The geometry, which is the office space, has dimensions of 6 m, 3 m, and 3 m for length, width, and height respectively. The office room has a rectangular-shaped geometry in an x-y plane.

There will be one air conditioning unit for the case of this study. The A/C unit is on the suspended ceiling. Moreover, there is an office desk in the model which is in front of an employee working in the office.

Plan view, section view, and 3D view of the base model are shown in Figure 3.2, Figure 3.3, and Figure 3.4, respectively.

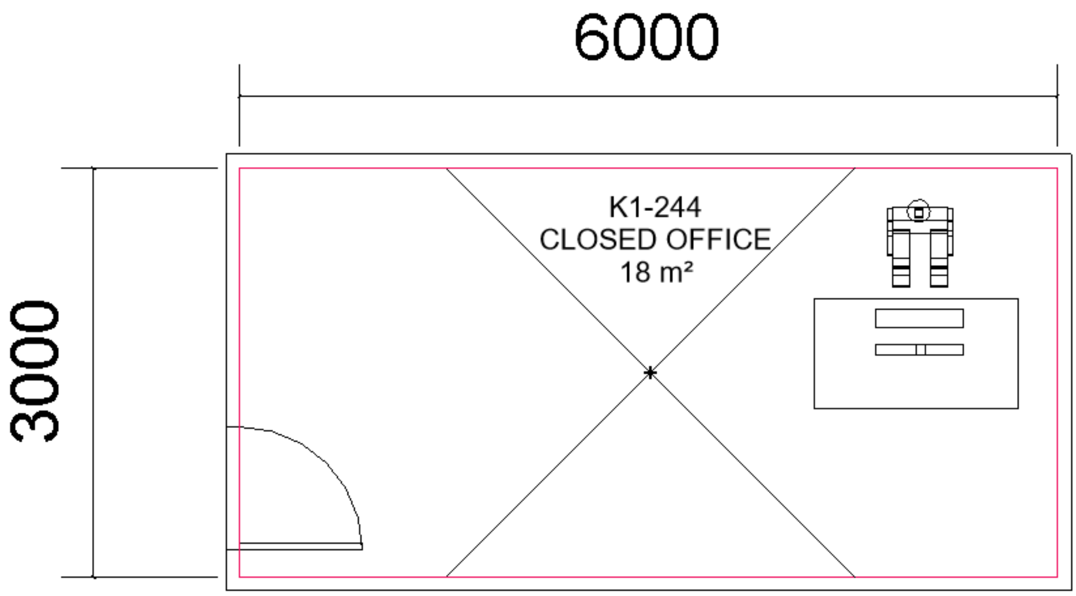


Figure 3.2. Plan View of the Base Model

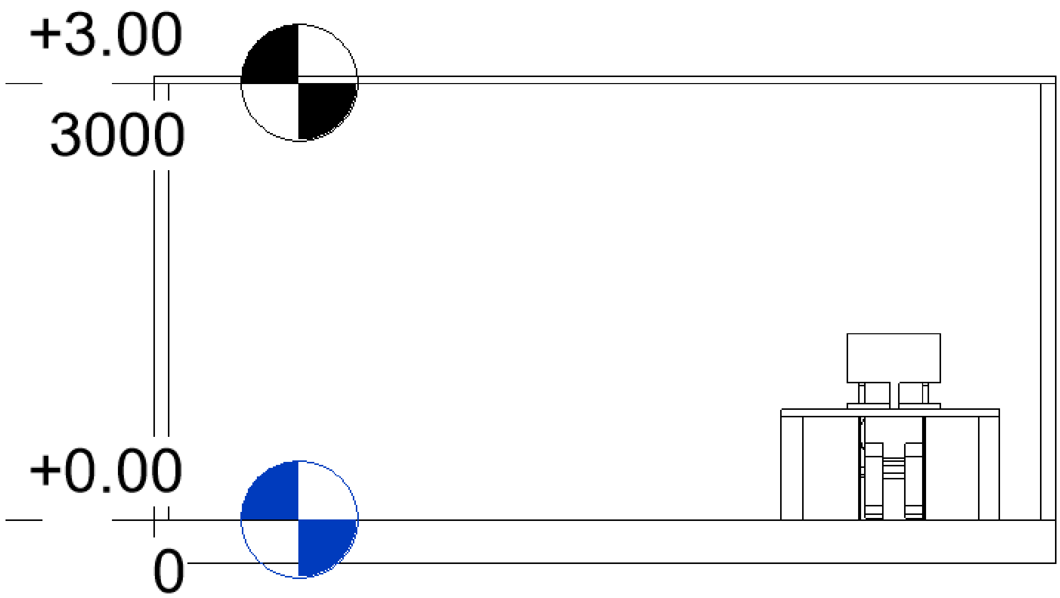


Figure 3.3. Section View of the Base Model

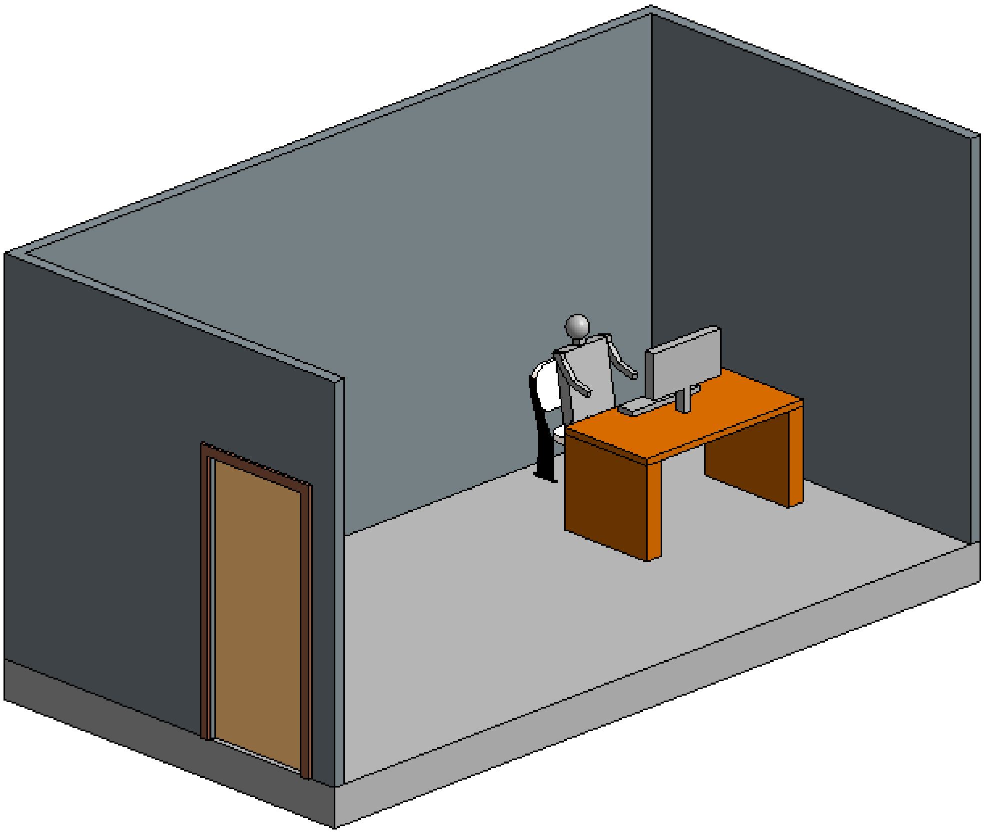


Figure 3.4. 3D View of the Base Model

This model is considered as the base model for the verification. Further analyses are conducted for different geometries, heat loads, and the number of people. The main geometry has been simplified in the further analysis to conduct a meshing study which is the subject of the next section.

3.4 Mesh Modelling

Meshing is the act of breaking down an object's continuous geometric space into thousands or more forms to adequately define the object's physical shape. The more intricate a mesh, the more precise the 3D model, enabling high-fidelity simulations. Mesh generation, also known as meshing, is the act of separating complicated geometries into pieces that may be used to divide a domain into a two-dimensional or three-dimensional grid. Advanced automated meshing techniques can deliver quicker and more effective solutions since meshing takes up a substantial amount of time while obtaining simulation results.

When it comes to engineering simulation, meshing plays an important role. One of the most important elements to consider when ensuring simulation accuracy is the creation of a high-quality model. Because the mesh affects the simulation's accuracy, convergence, and speed, it is essential to create the best mesh possible for engineering simulations. Because the governing equations cannot be fitted to an arbitrary shape, machines cannot solve scenarios on the model's real geometric shape. Mesh features allow governing equations to be resolved on volumes that are mathematically specified and have a predictable form. The equations that are solved on these meshes are usually partial differential equations. Because solving these equations by hand is impractical due to the repetitive nature of the computations, computer methods such as CFD are used. Types of meshes are shown in Figure 3.5.

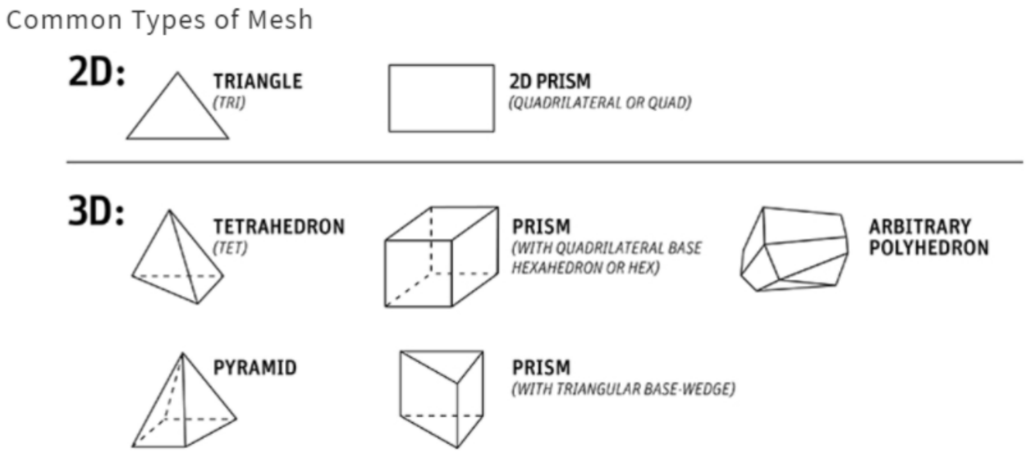


Figure 3.5. Mesh Types [52]

For a long time, the idea of partitioning a model into many meshed bodies to make use of the benefits of different meshing algorithms has been around.

In the model of this thesis, 60x60x60 cm cubic meshes have been constructed for analysis. The cubic meshes are generic model families in Autodesk Revit and they have family instance parameters such as temperature, PMV, and PPD. Every mesh has a node at the center of the cube which stores temperature and velocity data. The mesh model of the geometry is shown in Figure 3.6 and Figure 3.7.

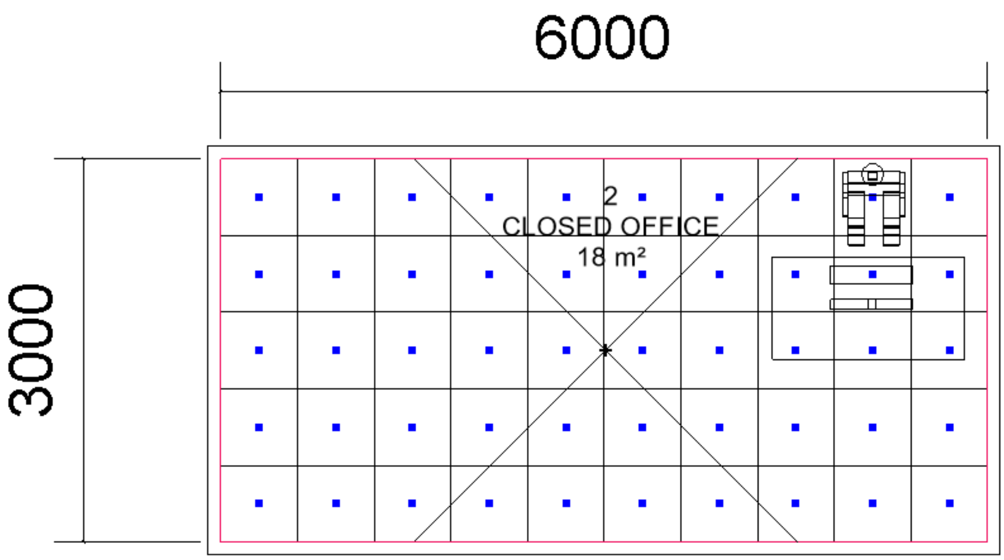


Figure 3.6. Plan View of the Mesh Model

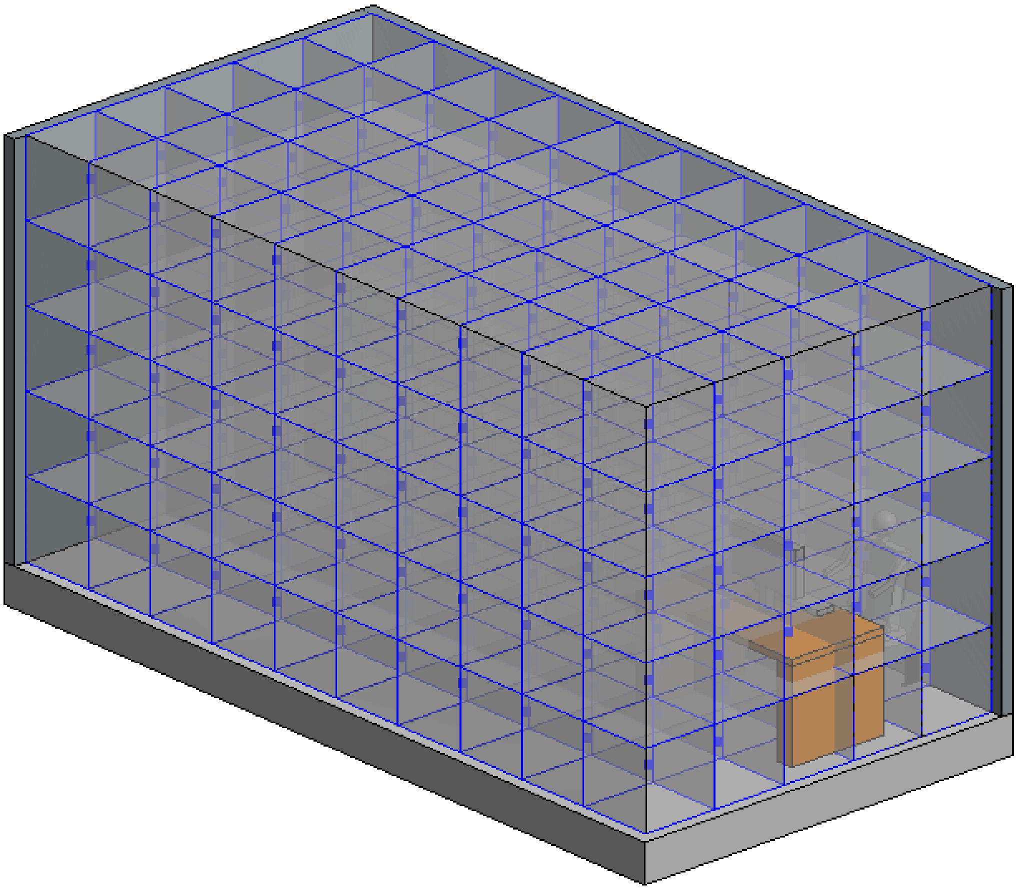


Figure 3.7. 3D View of the Mesh Model

3.5 Governing Equations

In this section, the governing equations for fluid dynamics are presented.

- The Continuity Equation

Matter cannot be generated or destroyed, according to one conservation law that applies to fluid movement. The fluid flows over the control surface as it passes through the predetermined control volume. The rate of change of mass within the control volume must be equal to the mass flow across the surface of a volume, according to mass conservation. In integral form, Equation (3.1) is the mass conservation. In the Cartesian coordinate system, it can be expressed as,

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0 \qquad (3.1)$$

where the local velocity components u, v, and w are functions of location (x, y, z) and time (t), and the fluid velocity V at every point in the flow field is characterized by the local velocity components u, v, and w.

- The Momentum Equation

The significant derivative of ϕ concerning time, abbreviated as Dϕ/Dt, is the general variable property per unit mass defined in Equation (3.2),

$$\frac{D\phi}{Dt} = \frac{\partial \phi}{\partial t} + u\frac{\partial \phi}{\partial x} + v\frac{\partial \phi}{\partial y} + w\frac{\partial \phi}{\partial z} \qquad (3.2)$$

The rate of change of the variable property per unit mass is defined by the equation above.

The momentum equations with the stress-strain relationships may be simplified by using the continuity equation defined in Equation (3.3) and (3.4),

$$\underbrace{\frac{\partial u}{\partial t}}_{\text{local acceleration}} + \underbrace{u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}}_{\text{advection}} = - \underbrace{\frac{1}{\rho}\frac{\partial p}{\partial x}\frac{\partial p}{\partial x}}_{\text{pressure gradient}} + \underbrace{v\frac{\partial^2 u}{\partial x^2} + v\frac{\partial^2 u}{\partial y^2}}_{\text{diffusion}} \qquad (3.3)$$

$$\underbrace{\frac{\partial v}{\partial t}}_{\text{local acceleration}} + \underbrace{u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}}_{\text{advection}} = -\underbrace{\frac{1}{\rho}\frac{\partial p}{\partial y}}_{\text{pressure gradient}} + \underbrace{v\frac{\partial^2 v}{\partial x^2} + v\frac{\partial^2 v}{\partial y^2}}_{\text{diffusion}} \quad (3.4)$$

The Navier-Stokes equations (3.3) and (3.4), which are derived from Newton's second law and where v is the kinematic viscosity (v = 1/p), explain the conservation of momentum in fluid flow.

- The Energy Equation

The equation for energy conservation is derived from the first rule of thermodynamics in Equation (3.5), which states,

$$\begin{matrix}\text{Time rate of} \\ \text{change of energy}\end{matrix} = \begin{matrix}\text{Net rate of} \\ \text{heat added}\end{matrix}\left(\Sigma\dot{Q}\right) + \begin{matrix}\text{Net rate of} \\ \text{work done}\end{matrix}\left(\Sigma\dot{W}\right) \quad (3.5)$$

The product of the density and the significant derivative of any arbitrary variable attribute is defined as the time rate of change. The flowing fluid element's energy rate of change over time is simply in Equation (3.6),

$$\rho\frac{DE}{Dt}\Delta x\Delta y\Delta z \quad (3.6)$$

The two quantities zQ and zW indicate the net rate of heat addition to the fluid inside the control volume as well as the net rate of work done on the fluid by surface forces. The study of the x-direction automatically results in the rate of work done and heat added in the y and z directions. The product of the surface forces with the velocity component u equals the rate of work done on the control volume in the x-direction.

Fourier's law of heat conduction is given in Equation (3.7), which connects the heat flux to the local temperature gradient, may be used to define the energy fluxes,

$$q_x = -k\frac{\partial T}{\partial x}q_y = -k\frac{\partial T}{\partial y}q_z = -k\frac{\partial T}{\partial z} \quad (3.7)$$

where k is the thermal conductivity. Thus, the energy equation becomes Equation (3.8),

$$\rho\frac{DE}{Dt}=\frac{\partial}{\partial x}\left[k\frac{\partial T}{\partial x}\right]+\frac{\partial}{\partial y}\left[k\frac{\partial T}{\partial y}\right]+\frac{\partial}{\partial z}\left[k\frac{\partial T}{\partial z}\right] -\frac{\partial(up)}{\partial x}-\frac{\partial(vp)}{\partial y}-\frac{\partial(wp)}{\partial z}+\Phi. \tag{3.8}$$

The dissipation function, which can be proven to be, describes the effects of viscous stresses in the energy equation is Equation (3.9),

$$\Phi=\frac{\partial(u\tau_{xx})}{\partial x}+\frac{\partial(u\tau_{yx})}{\partial y}+\frac{\partial(u\tau_{zx})}{\partial z} +\frac{\partial(v\tau_{xy})}{\partial x}+\frac{\partial(v\tau_{yy})}{\partial y}+\frac{\partial(v\tau_{zy})}{\partial z}+\frac{\partial(w\tau_{zz})}{\partial x}+\frac{\partial(w\tau_{yz})}{\partial y}+\frac{\partial(w\tau_{zz})}{\partial z} \tag{3.9}$$

The dissipation function is a source of energy resulting from fluid deformation effort. The mechanical energy that generates fluid movement is turned into heat, and this work is taken from it. Internal energy, kinetic energy, and gravitational potential energy are frequently used to define a fluid's energy. The energy equation is frequently adjusted for compressible flows to obtain an expression for the enthalpy. The enthalpy h may be simplified to CpT by ignoring the kinetic energy, where Cp is the specific heat and is considered to be constant. Equation (3.9) may be written as follows in Equation (3.10),

$$\rho C_p\frac{DT}{Dt}=\frac{\partial}{\partial x}\left[k\frac{\partial T}{\partial x}\right]+\frac{\partial}{\partial y}\left[k\frac{\partial T}{\partial y}\right]+\frac{\partial}{\partial z}\left[k\frac{\partial T}{\partial z}\right]+\frac{\partial p}{\partial t}+\Phi \tag{3.10}$$

A two-dimensional version of Eq. (3.10) will be generated to make the equation easier to grasp. The equation for energy conservation in two dimensions may be stated as in Equation (3.11), assuming that the temperature is invariant in the z-direction and that the thermal conductivity k is constant,

$$\underbrace{\frac{\partial T}{\partial t}}_{\text{local acceleration}}+\underbrace{u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}}_{\text{advection}}=\underbrace{\frac{k}{\rho C_p}\frac{\partial^2 T}{\partial x^2}+\frac{k}{\rho C_p}\frac{\partial^2 T}{\partial y^2}}_{\text{diffusion}} \tag{3.11}$$

The governing equations are differential equations that takes time to solve even for computational software. The differential equations are simplified into many basic equations in CFD software. To increase the solving speed, mathematicians and physicians have developed a concept called the nodal network. Although it is a basis of CFD software and gives coarser results, the computational speed of such procedure is shorter compared to a regular CFD analysis and can be integrated into BIM design software via API or programming software such as Dynamo Studio. Regular CFD software are hard-coded and it is difficult to integrate the input-output sequence into design software. As it was stated before, regular CFD software takes just the input data from design tools.

The Nodal Network Principle

The nodal network principle, which is a numerical method enables the determination of the temperature at discrete points.

As a result, the identification of these places must be the first step in any numerical analysis. This may be performed by breaking down the medium of interest into smaller portions and assigning each one a central reference point. A nodal point serves as a reference point, while a nodal network, grid, or mesh is a collection of points. The x and y coordinates are designated by the indices m and n, respectively.

Each node represents a distinct location, and its temperature reflects the average temperature of that region. The average temperature of the shaded region around node m, n, for example, can be understood as the temperature of node m, n. Nodal points are seldom chosen at random, and they are typically affected by considerations such as geometric convenience and desired precision. The numerical validity of the computations is influenced by the number of detected nodal points. If this number is large enough, precise answers can be derived.

The construction of an adequate conservation equation for each of the unknown temperature nodal points is required for the numerical calculation of the temperature distribution. Using the resultant set of equations, the temperature at each node may be solved concurrently. For each interior node of a two-dimensional system with no generation and uniform thermal conductivity, the heat equation yields the exact form of the energy conservation requirement. However, if the system is characterized as a nodal network, an approximate, or finite-difference, version of this equation must be utilized. It is feasible to deduce a finite-difference equation for the inner nodes of a two-dimensional system directly. The temperature gradients may be used to express the nodal temperatures.

For the m, n node, the heat equation, which is an exact differential equation, is reduced to an approximation algebraic equation, which is the main advantage of the implementation of this thesis study. This approximate finite-difference variation of the heat equation may be used to solve any inner node that is equidistant from its four bordering nodes. It just requires that the temperature of an inner node be equal to the average of its four neighbors' temperatures.

As previously indicated, in many cases it is desirable to construct the finite-difference equations using an alternate approach known as the energy balancing method. This approach may be used to study a variety of concerns, such as problems with multiple materials, embedded heat sources, and exposed surfaces that do not line with a coordinate system axis. The energy balance technique is used to get the finite-difference equation for a node by applying the conservation of energy to a control volume surrounding the nodal area.

Because the true direction of heat flow is usually unknown, it is easier to compute the energy balance if all heat flow is directed into the node. Of course, such a condition is impossible to achieve, but if the rate equations are expressed in a fashion that is consistent with this assumption, the right form of the finite-difference equation may be determined. For steady-state circumstances with the generation, the appropriate form of the equation is then applied to a control volume around the inner node m, n. In two-dimensional scenarios, the energy exchange is influenced by conduction between m, n, and its four neighboring nodes, as well as generation. Figure 3.8 depicts the relationship between neighboring nodes.

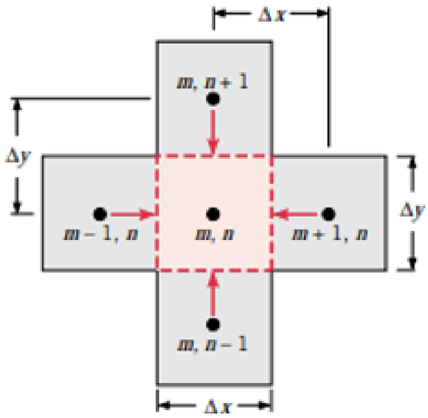


Figure 3.8. Conduction to an interior node from its adjoining nodes [53]

To calculate the conduction rate terms, it is assumed that conduction transfer happens solely in lanes that are oriented in either the x or y-direction.

As a result, simpler versions of Fourier's law are possible to apply. The rate at which energy is moved by conduction from node m1, n to node m, n, for example, may be expressed as the term represents the finite-difference approximation to the temperature gradient at the border between the two nodes, while the quantity indicates the heat transfer area. When computing each conduction rate, the temperature of the m, n node is deducted from the temperature of its neighboring node. This convention is required by the assumption of heat flow into m, n, which is also compatible with the direction. By inserting equations into the energy balance and noting that x and y, the finite-difference equation for an inner node with generation is produced.

However, it is not always possible to classify all of these locations as internal, necessitating the use of equations. It's possible that the temperature of an insulated surface or one exposed to convective conditions, for example, is unknown. To find the finite difference equation for points on such surfaces, the energy balancing technique must be utilized. This technique is more detailed for nodes that correspond to the internal corner. Through convection, this node symbolizes the three-quarter darker region and transfers energy with a neighboring fluid at T, as shown in Figure 3.9.

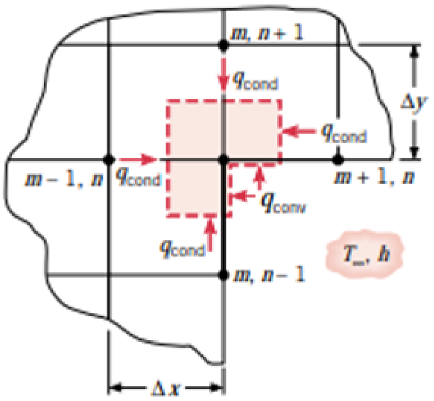
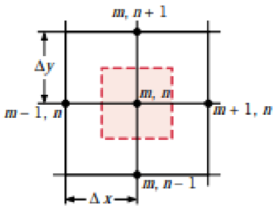
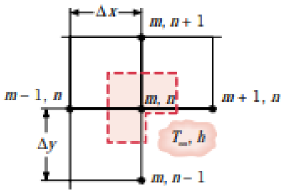
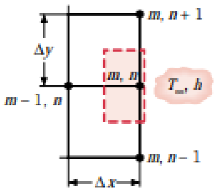
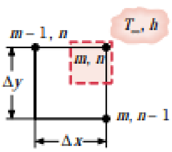
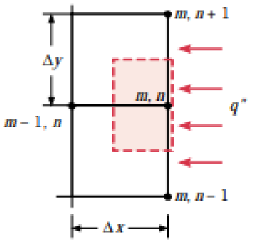


Figure 3.9. Formulation of the finite-difference equation for an internal corner of a solid with surface convection [53]

Conduction to the nodal region occurs along four separate channels from neighboring nodes in the solid. Conduction from nodal areas occurs along y/2 and x/2 lanes, respectively, whereas conduction from and occurs along y/2 and x/2 lanes, respectively. Conditions in the nodal region m, n are influenced by convective exchange with the fluid, which may be visualized as happening along half-lanes in the x and y axes. This calculation implicitly assumes that the exposed surfaces of the corner are at a uniform temperature that matches the nodal temperature. This assumption is consistent with the notion that the whole nodal area is characterized by a single temperature that is the average of the region's actual temperature dispersion.

For different conditions of internal or vicinity nodes, such as above, different equations are formed in nodal network analysis as shown in Figure 3.10. These equations are integrated into the Dynamo script to utilize the temperature data inside the office environment.

Configuration	Finite-Difference Equation for $\Delta x = \Delta y$	
	$T_{m,n+1} + T_{m,n-1} + T_{m+1,n} + T_{m-1,n} - 4T_{m,n} = 0$ **Case 1.** Interior node	(4.29)
	$2(T_{m-1,n} + T_{m,n+1}) + (T_{m+1,n} + T_{m,n-1}) + 2\frac{h\Delta x}{k}T_\infty - 2\left(3 + \frac{h\Delta x}{k}\right)T_{m,n} = 0$ **Case 2.** Node at an internal corner with convection	(4.41)
	$(2T_{m-1,n} + T_{m,n+1} + T_{m,n-1}) + \frac{2h\Delta x}{k}T_\infty - 2\left(\frac{h\Delta x}{k} + 2\right)T_{m,n} = 0$ **Case 3.** Node at a plane surface with convection	(4.42)[a]
	$(T_{m,n-1} + T_{m-1,n}) + 2\frac{h\Delta x}{k}T_\infty - 2\left(\frac{h\Delta x}{k} + 1\right)T_{m,n} = 0$ **Case 4.** Node at an external corner with convection	(4.43)
	$(2T_{m-1,n} + T_{m,n+1} + T_{m,n-1}) + \frac{2q''\Delta x}{k} - 4T_{m,n} = 0$ **Case 5.** Node at a plane surface with uniform heat flux	(4.44)[b]

[a,b]To obtain the finite-difference equation for an adiabatic surface (or surface of symmetry), simply set h or q'' equal to zero.

Figure 3.10. Summary of Nodal Finite-Difference Equations [53]

Along with the meshing process above governing equations are used to find the output data stored in the center of a single mesh volume. The algorithm involves these equations to solve the problem.

3.6 Boundary Conditions

In this section, the boundary conditions and scenarios used for the algorithm is presented as listed below:

- Environmental Conditions
- Space Boundary Conditions
    - Space Parameters
    - Equipment Parameters
    - Electrical Appliances
    - Human Parameters
- Analysis Scenario

The values taken from the BIM model and user input while creating the analysis setup are given. Within the scope of this analysis, the created BIM model provides the inputs.

- Environmental Conditions

Neighboring regions for the analyzed region are defined as conditioned. This approach aims to determine the plain operation of the systems in the region. The summer design temperature of the city of Ankara, where the station is located, is accepted as 34°C. Where the room is opened to the outside air, the boundary condition of 34°C temperature and 1 atm pressure is used [54].

- Space Boundary Conditions

Space boundary conditions are tabulated in Table 3.4. The tabulated values for geometric data and user inputs are taken for the base case. The cooling load of the room is calculated manually from cooling design software. In Chapter 4, these values change considering different scenarios.

Table 3.4 Space Parameters for Office

Subject	Value	Unit
Area	18	m²
Number of People	1	-
Number of Computers	1	-
Design Temperature	25	°C
Total Heat Gain	1054	W

- Equipment Parameters

Equipment boundary conditions are tabulated in Table 3.5. In the base case, the tabulated values are taken. The cooling capacity of the A/C unit is selected according to the cooling loads. In Chapter 4, these values change considering different scenarios.

Table 3.5 Equipment Parameters

Subject	Value	Unit
Cooling Capacity*	1100	W
AC Unit Type	Cassette	-
AC Unit Dimensions (LxW)	60/60	cm/cm
Number of Equipment	1	ea

*Cooling Capacity is always determined by the designer after cooling load calculations.

- Electrical Appliances

Electrical appliance conditions are tabulated in Table 3.6. In the base case, the tabulated values are taken. The values are taken from the standards. In Chapter 4, these values change considering different scenarios.

Table 3.6 Electrical Appliances

Subject	Value	Unit
Lighting	8.5	W/m²
Computer	690	W

- Human Parameters

Human conditions are tabulated in Table 3.7. In the base case, the tabulated values are taken. The values are taken from the standards. As the activity type for the base case, moderately active office work is considered in the office. Metabolic rates and clothing factors are taken as 1 and 0.6, respectively for a person sitting in the office in normal conditions as defined in the regulations. In Chapter 4, these values change considering different scenarios.

Table 3.7 Human Parameters

Subject	Value	Unit
Activity Type	Moderately Active Office Work	
Sensible Heat Gain	75	W/Person
Latent Heat Gain	55	W/Person
Metabolic Rate	1 (60)	Met Units (W/Person)
Clothing Factor	0.6	-

- Exterior Wall Parameters

Wall conditions are tabulated in Table 3.8. In the base case, the tabulated values are taken. Wall material parameters are taken from TS 825 [54].

Table 3.8 Exterior Wall Parameters

Subject	Value	Unit
Concrete	0.45	W/m²K

Overall boundary conditions for office space is shown in the below Figure 3.11.

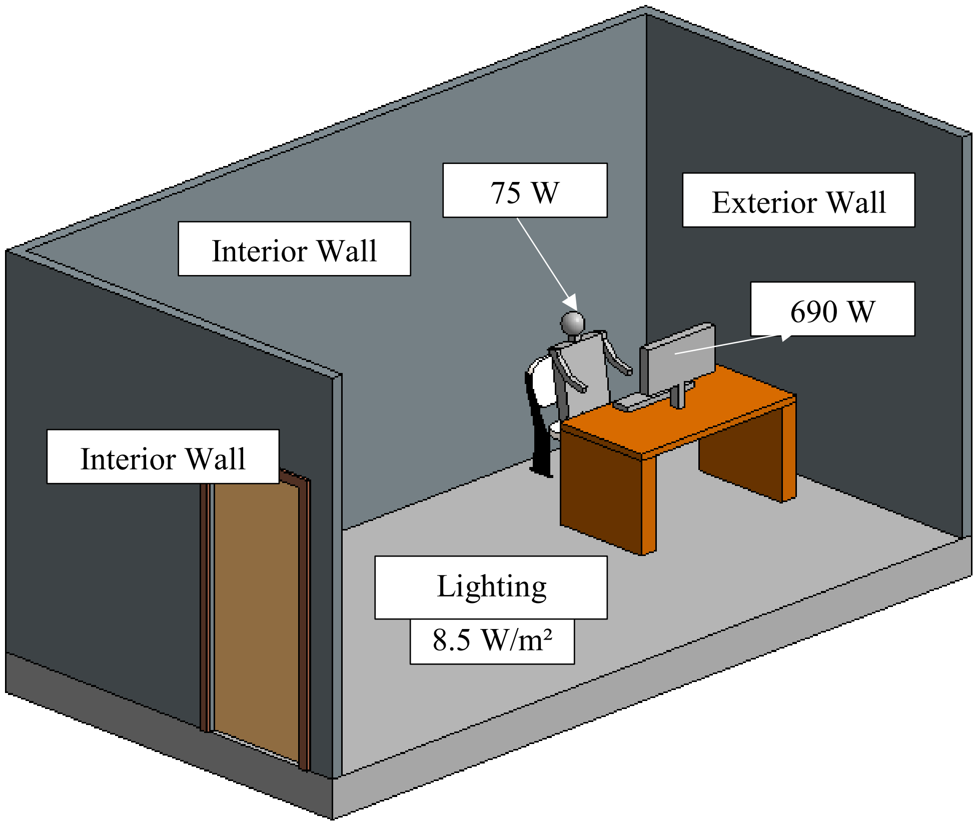


Figure 3.11. Overall Boundary Conditions for the Base Model

3.7 Placement and Optimization

As it is stated in the previous chapter, the placement or location optimization of an air conditioning unit is the main objective of this thesis. To achieve this a Dynamo script is constructed to locate the A/C units. This section demonstrates the approach for searching the optimum location for the installation of the Air Conditioning Unit in an office by utilizing BIM.

As it is stated, a split Air Conditioning unit is used in the general algorithm. First, there are input parameters that the designer should supply. The input parameters are requested from the designer via Autodesk Revit API with the help of Dynamo custom nodes. These parameters are the same as the input parameters defined in the previous chapters. Two additional input parameters are the office space in the BIM model and the location of the person sitting in the office. These inputs are to define the geometry and provide the algorithm the bounds of the meshes to be generated.

After selecting the office space, the mesh generator part in Dynamo code generates the 60x60x60 cm cubic meshes in the space. These meshes have center nodes that stores data for temperature, velocity, PMV, and PPD. After the meshing process is complete, the location optimization part of the algorithm works to find the optimal location for the cooling unit in the space.

Note that all A/C unit location combinations have 3 meters of height, which is the ceiling height of the office space.

The algorithm works as follows;

- Defining space and mesh bounds
- Generating meshes,
- Checking the human position, which is an input
- Placing the target node at the occupiable area, which is 60-120 cm of human position,
- Checking the heat loads, which is an input

- Placing the A/C into a cubic mesh on the suspended ceiling,
- Calculating the PMV and PPD values for the target node.

After the calculation for all possible nodes is finished, the Dynamo algorithm remembers the target PMV values for each possible A/C location. The flow of the algorithm is presented in Figure 3.12.

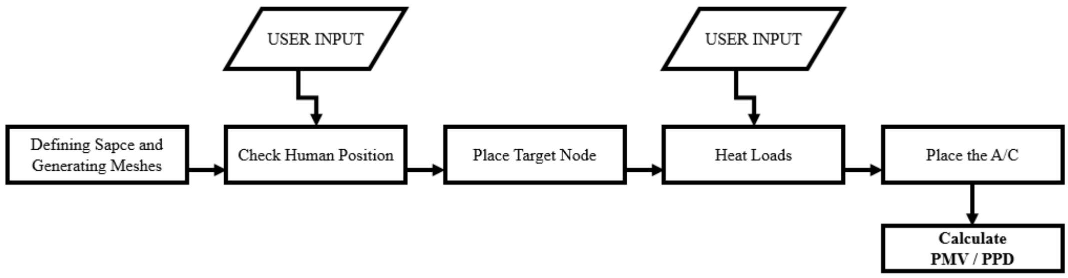


Figure 3.12. Workflow of Generated Algorithm

The method was created using Dynamo for Autodesk Revit and several custom nodes with input and output ports. Each custom node has an input, such as spaces or walls, and is designed to compute the appropriate data from the defined construction parts. Each component has several nodes that work together to complete a certain activity. The components are grouped into five categories. The first is BIM-based inputs such as spaces, equipment, or walls. Part 2 generates and enumerates the meshes in the space. User-adjustable inputs such as human position, number of people, and heat generating elements are covered in Part 3. Part 4 is the air conditioner placement and the parametric assessment, which uses the data from the input blocks to do particular calculations, and Part 5 is the output module, which displays the computed findings. The relationships between the blocks are depicted in the diagram in Figure 3.13. Detailed block diagrams are given in Appendix A.

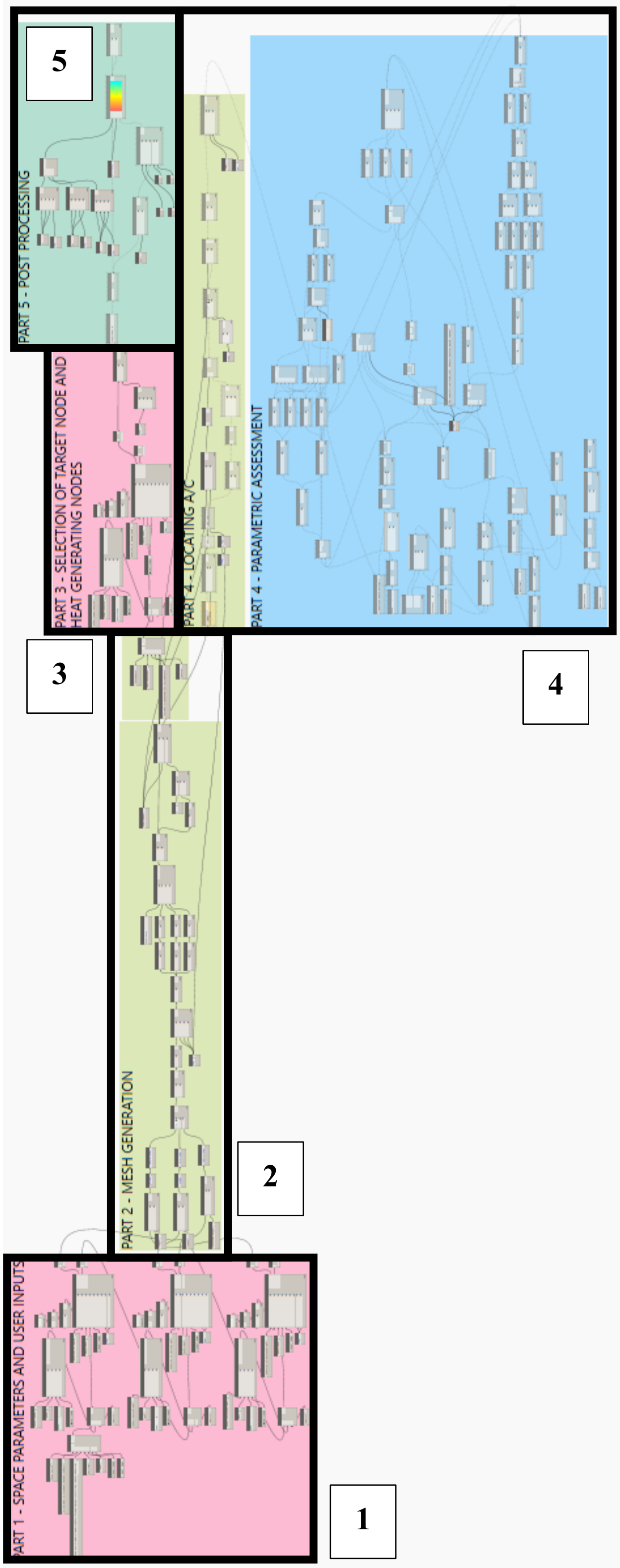


Figure 3.13. Dynamo Flowchart for the Algorithm

The detailed steps of the Dynamo script are as follows;

1. In the model, the designer selects the space that s/he wants to analyze with the help of a user interface (UI) presented in Figure 3.14. (Part 1)

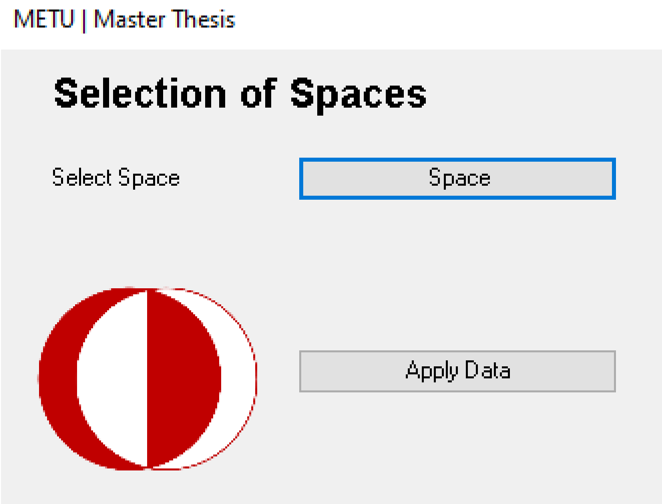


Figure 3.14. Selection UI for Spaces

2. The designer should define the vertical and horizontal walls by selecting them in Autodesk Revit model that enclose the specified space. (Part 1)
3. After defining the bounds of the space, the mesh generation script is run in Dynamo by itself. Then when the mesh generation is complete, a pop-up appears on the user interface as presented in Figure 3.15. (Part 2)

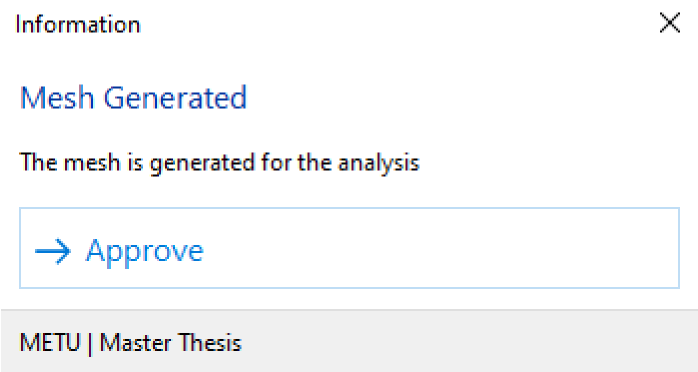


Figure 3.15. Information on Mesh Generation

4. After meshes are generated, the designer defines the target and heat-generating nodes by using the user interface as shown in Figure 3.19 for selecting the human position. (Part 3)

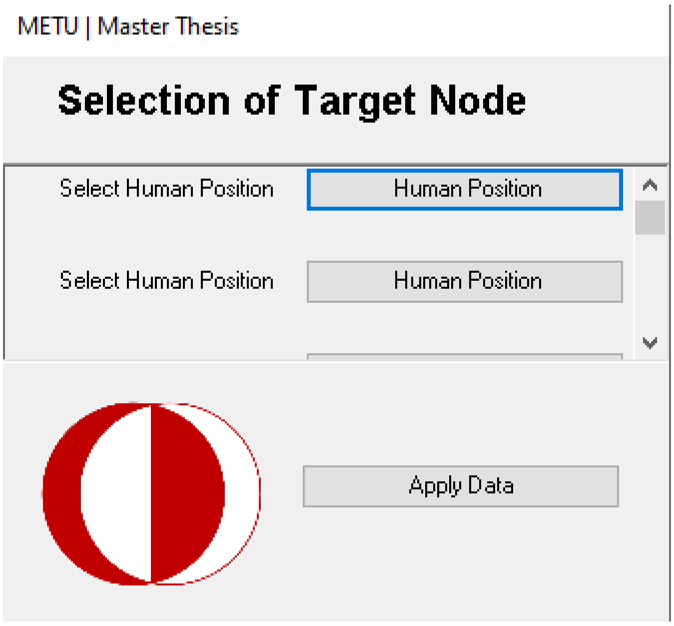


Figure 3.16. Selection of Target Node

5. After all boundary conditions are defined in the algorithm, the script places the air conditioner on ceiling nodes and calculates the PMV, PPD values for each node for each A/C location. All the equations, calculating the thermal comfort indices are included in this part. The PMV and PPD values are stored in cubic meshes in Autodesk Revit model. (Part 4)
6. The algorithm stops running after finding the PMV value that is closest to 0. (Part 4)
7. Last, based on the results found for PMV values, a colorful pattern is constructed in Autodesk Revit and the A/C is placed in the location where the PMV index value is closest to 0. (Part 5)

For different A/C unit locations, the pattern for the values for PMV and PPD occupiable area, which is the place of the person in the office space, is found. For the placement of the A/C unit to the first node, the inputs and results of the generated algorithm are shown in the figures below.

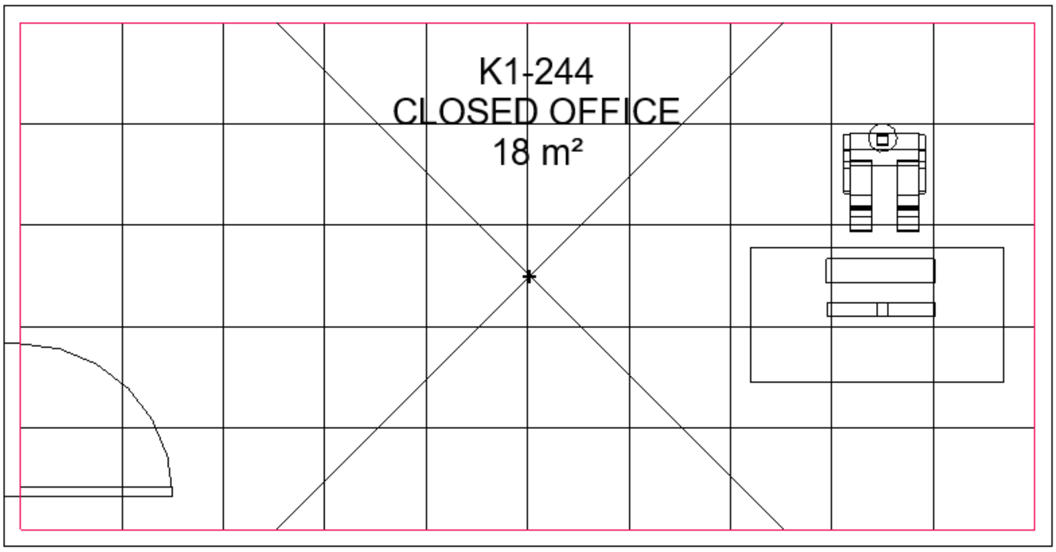


Figure 3.17. Model After Mesh Generation

After the mesh generation, the human position is given to the tool.

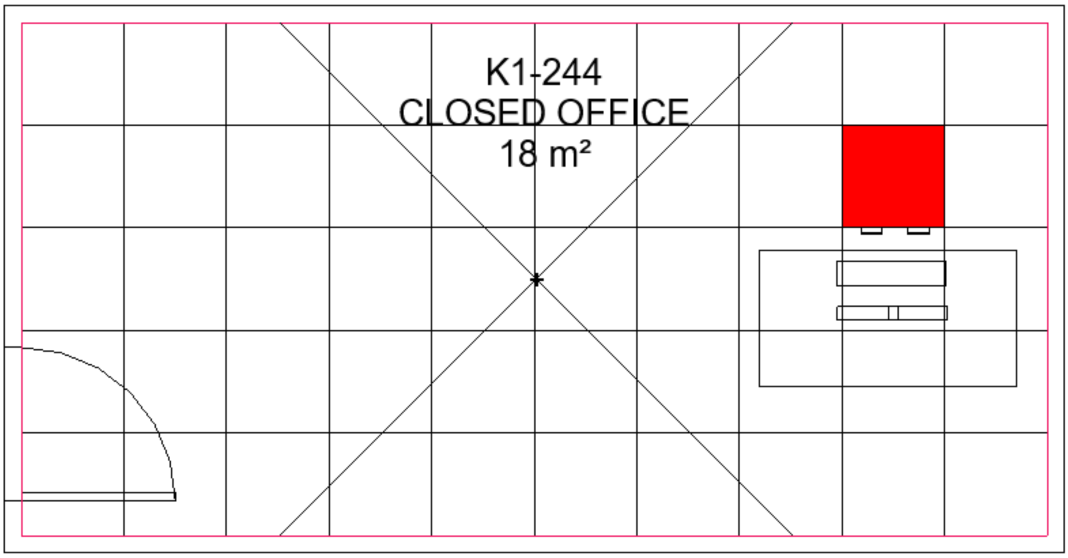


Figure 3.18. Input Given for Human Position, in Red

In Autodesk Revit environment the user selects the uppermost mesh of the human position, i.e. the mesh on the suspended ceiling. But the algorithm automatically defines the target node as the node that is between 60-120 cm, which is the occupiable area for a person sitting. This is shown in Figure 3.19, the section view below.

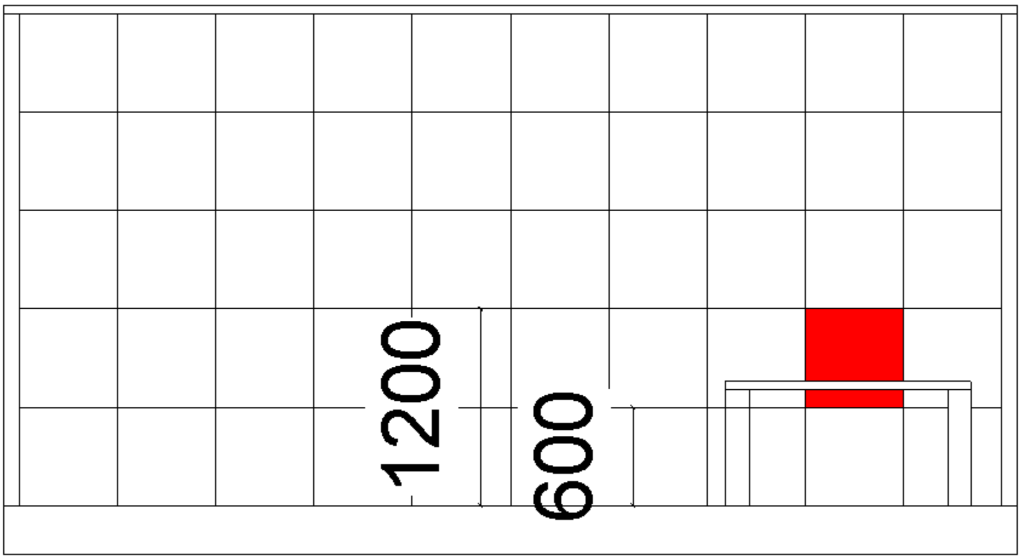


Figure 3.19. Human Position Selection in Section View, The Occupable Area

Then in the following process, the heat-dissipating elements are given to the tool as presented in Figure 3.20.

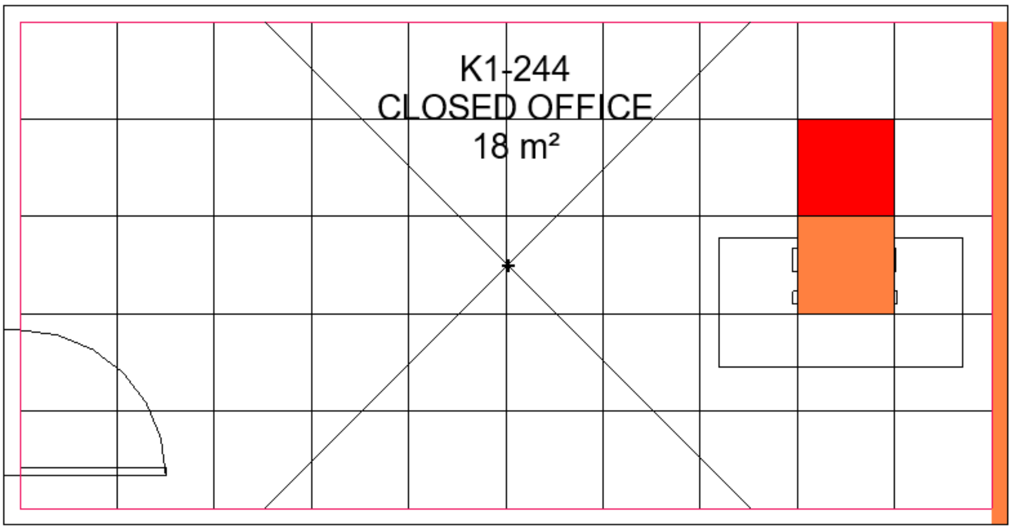


Figure 3.20. Heat Dissipating Elements, in Orange

Then the air conditioner is placed to the first node (as shown in blue) and the PMV and PPD values are found for the target node, presented in Figure 3.21.

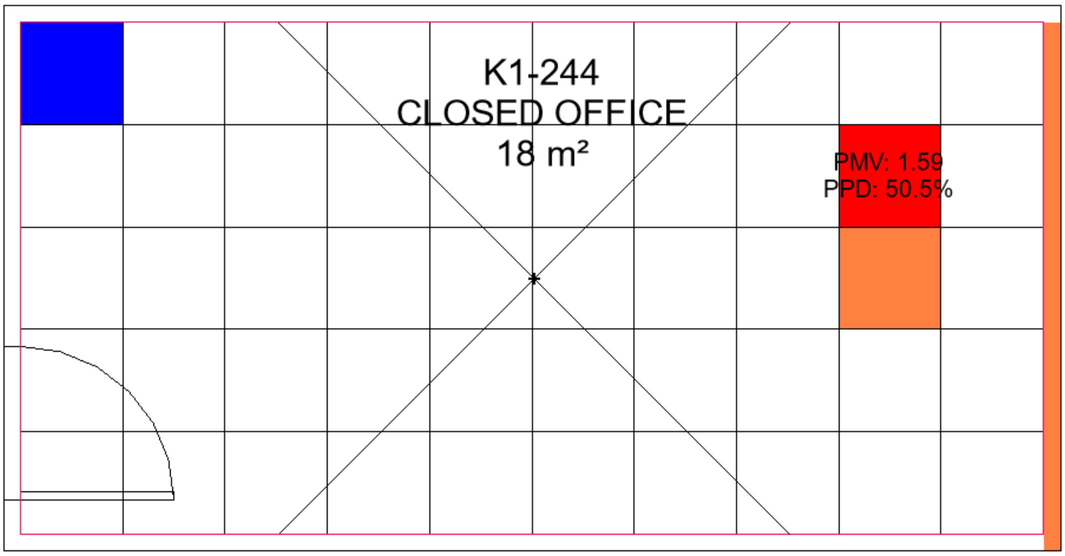


Figure 3.21. Air Conditioner Placement in the First Node, in Blue

After finding the results for the first operable A/C location, other locations can be analyzed. The result for the second possible location (as shown in blue) for the A/C is given below in Figure 3.22.

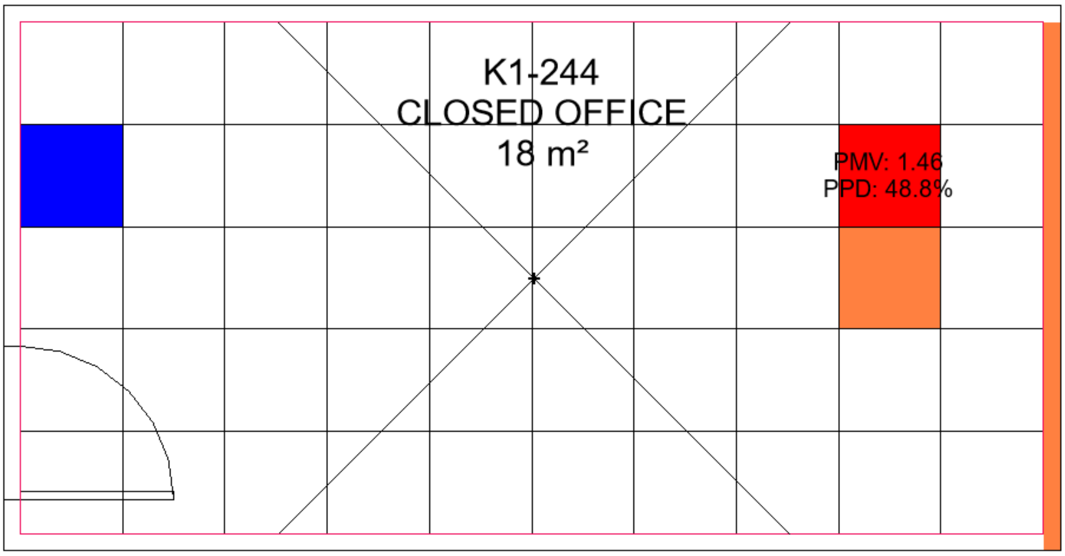


Figure 3.22. Air Conditioner Placement in the Second Node, in Blue

3.7.1 Design Optimization

The output shows the first possible ceiling node that gives the most optimal PMV and PPD values and gives the PMV pattern for the specified color range of the thermal sensation scale.

Design optimization of the A/C system layout is the optimization process used in the suggested methodology. The data from the parametric analysis modules are used to develop the best design layout by comparing several design choices. The collected variables from the BIM are fed into the algorithm, and the result is the best A/C layout configuration in terms of PMV values. The parametric analysis components built to extract design parameters from BIM were presented in the preceding paragraph. The extracted data is stored in Dynamo and is ready to be supplied into the algorithm's optimization section for the creation of design solutions. The input data specifies the design limitations and the coordinate range that must be used to locate the A/C configuration. The optimization method will assign each A/C a single position and find the positions that produce appropriate PMV and PPD values. The ensuring design solution will be the layout solution that has been recognized as the ideal option. It will meet all requirements to the greatest extent possible. The optimization algorithm has two targets that are chosen to improve design efficiency and accuracy. The final location of the A/C configuration to the specified space and human position is included in the output. The final stage is to reintroduce this data into the BIM model. The design optimization method will provide an A/C layout model that is connected with the physical model of the project and ready to be uploaded back into the Building Information Model. The result of the optimized solution is shown in Figure 3.23.

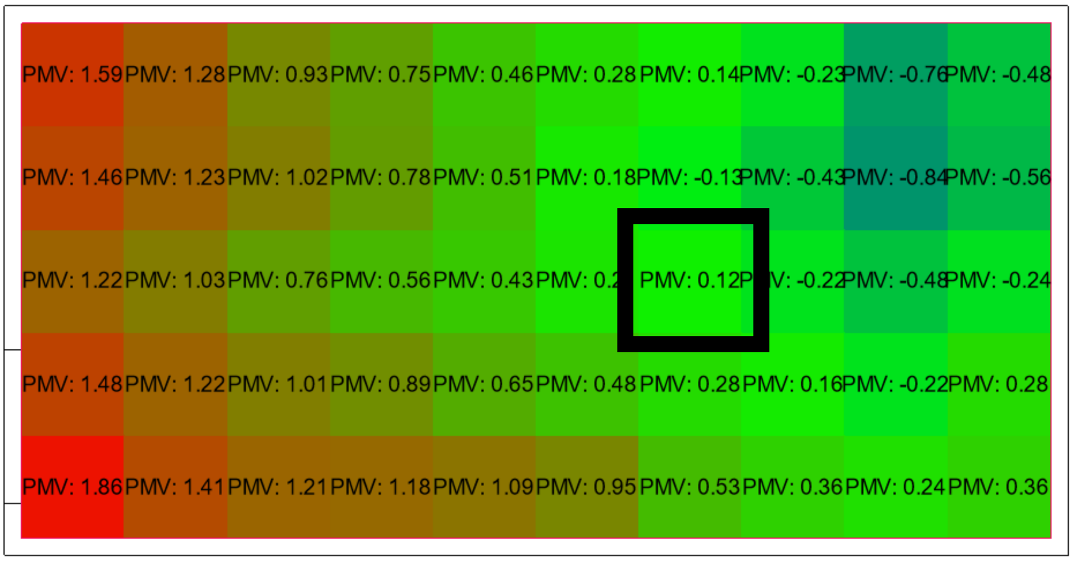


Figure 3.23. PMV Results for Optimization Algorithm

Then the output becomes the node that has the value closest to 0, which provides the optimal thermal comfort condition. The result tells the designer that the A/C unit should be placed in the node that gives the PMV value of 0.12 presented in Figure 3.24.

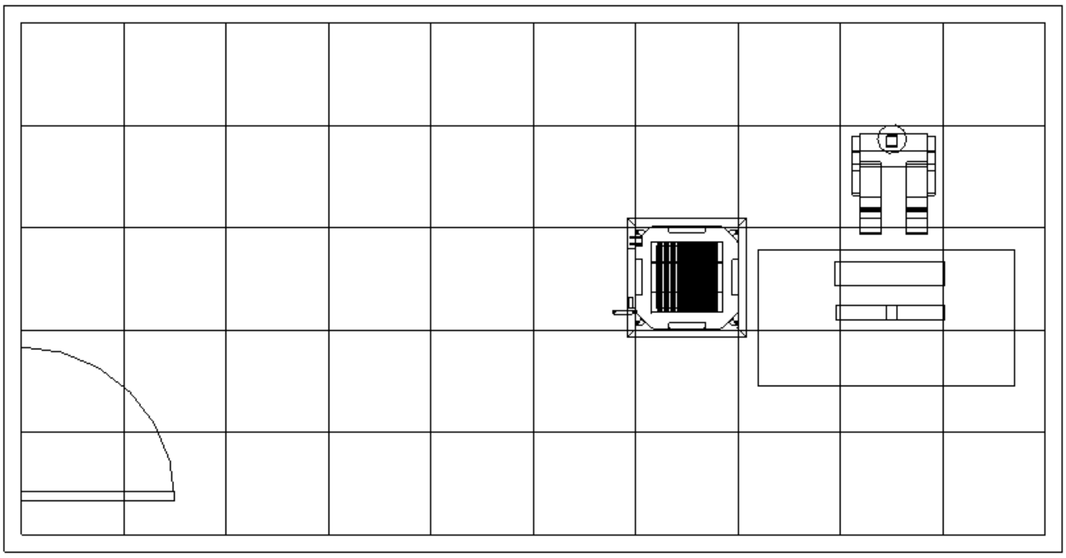


Figure 3.24. A/C System Placement in the Office

For cases having multiple office workers shown in Figure 3.25, the optimization algorithm finds the absolute total value of PMV indices. The algorithm solves the problem for each person's PMV value and divides the totals into the number of people. Then the algorithm determines the place of the A/C unit on the point which has the closest value to 0, as there cannot be any negative value after having taken the absolute values.

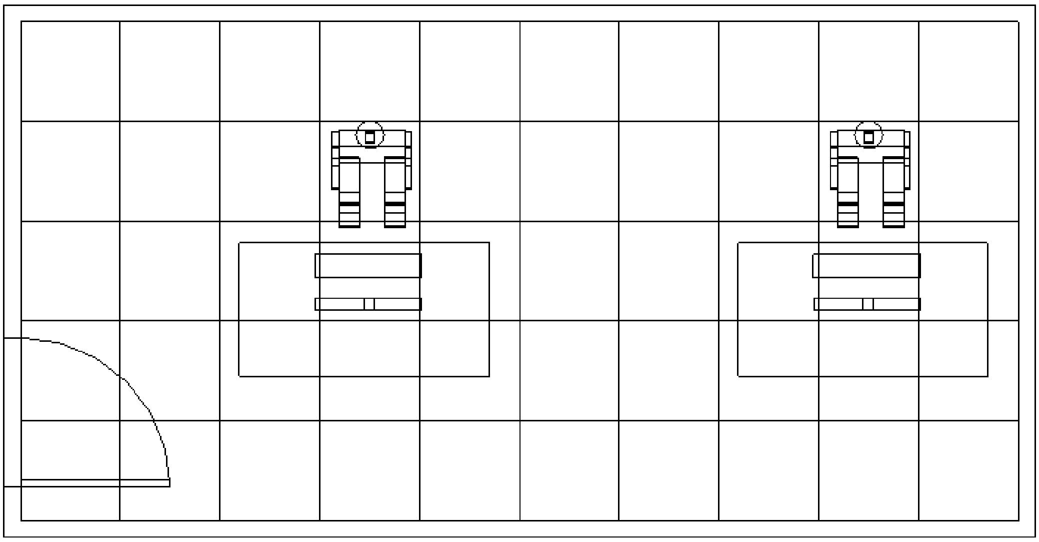


Figure 3.25. Office with Two People

The algorithm first solves the PMV value for the first person as in the case of the base model as seen in Figure 3.26. Then finds the PMV values according to the second person's location as in Figure 3.27. The combined solution (Figure 3.28) and final placement of the A/C can be determined as a result (Figure 3.29).

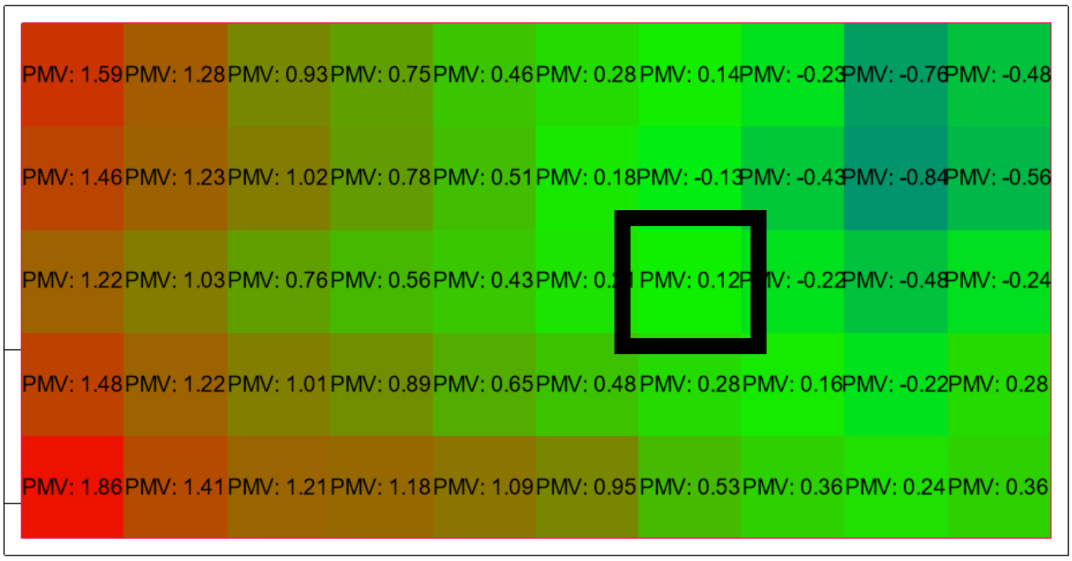


Figure 3.26. Solution for the First Person

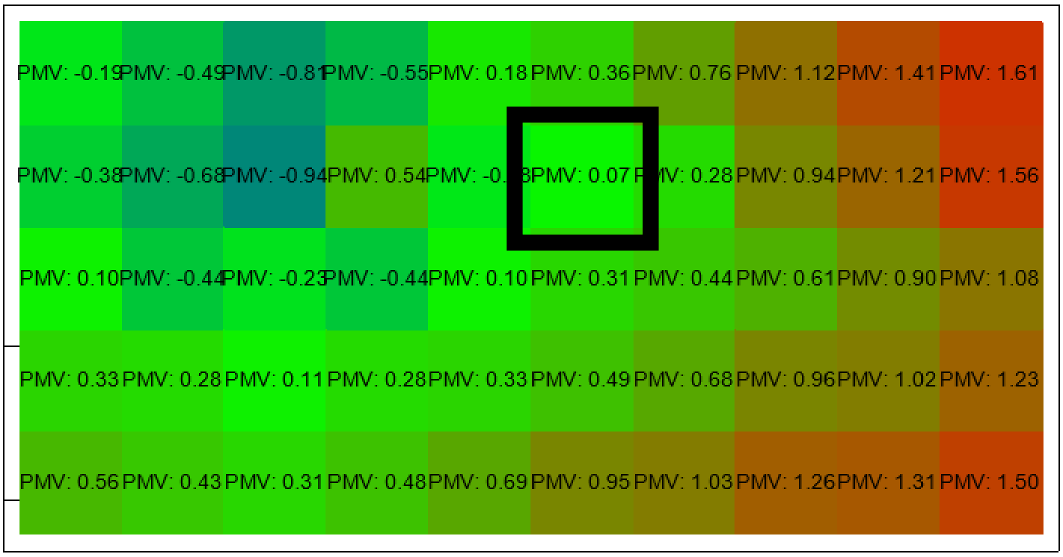


Figure 3.27. Solution for the Second Person

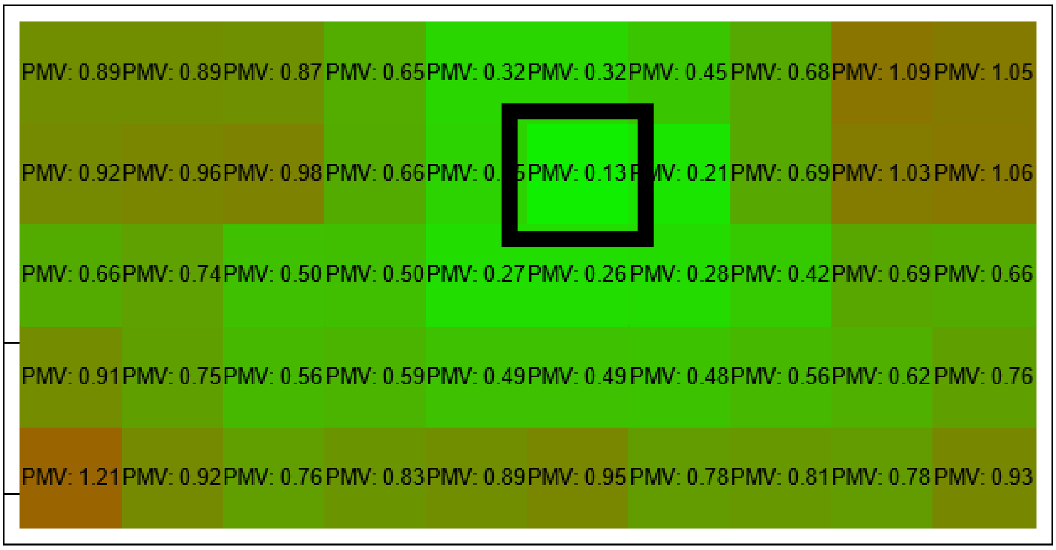


Figure 3.28. Combined Solution for Two People

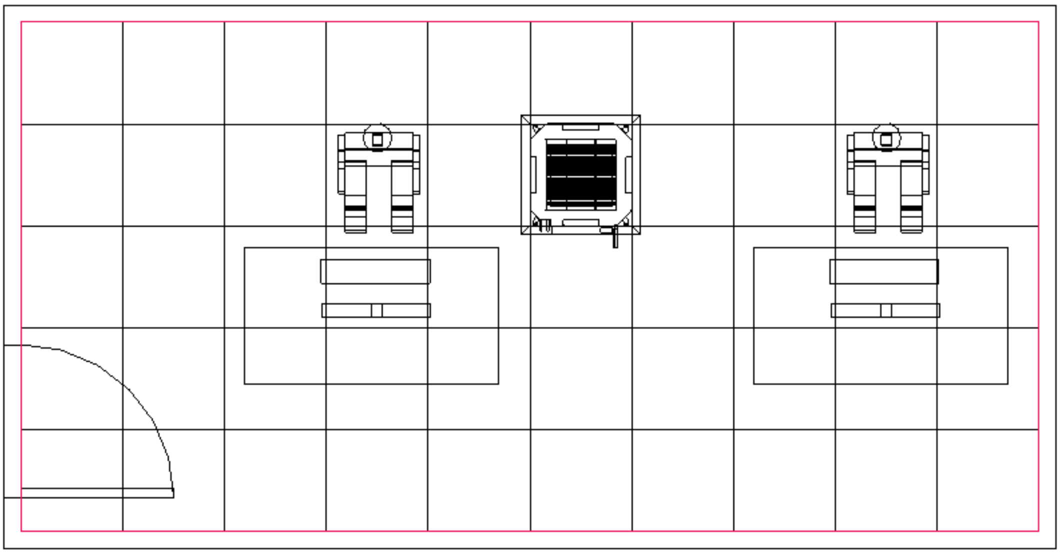


Figure 3.29. A/C System Placement in the Office for Two People

CHAPTER 4

IMPLEMENTATION AND VERIFICATION

To further analyze the generated algorithm different design cases are studied. For each design case the design optimization module is run and the results for different conditions of;

- Geometry
- Heat Load
- Human Position

are shown in the following scenarios.

Different design cases for implementation of the generated algorithm are presented in Table 4.1 and Table 4.2. For each case, room area, number of people, number of computers, cooling capacity, human activity type, metabolic rate, and clothing factor are kept different. The other changing parameters such as room design temperature, A/C unit type and count, lighting load per area, computer type, and wall types are kept constant for each case with values presented in Section 3.6. The first scenario is considered as the base scenario described in Chapter 3.

Table 4.1 Space and Equipment Parameters for Different Scenarios

Scenario No	LxWxH (mxmxm)	Area (m^2)	Number of People	Heat Gain (W)	AC Cooling Capacity (W)
1(Base)	3x6x3	18	1	1054	1100
2	3x6x3	18	1	1049	1100
3	3x6x3	18	2	1819	2000
4	9x9x3	81	4	3957	4000

Table 4.2 Human Parameters for Different Scenarios

Scenario No	Activity Type	Sensible Heat Gain (W/Person)	Latent Heat Gain (W/Person)	Metabolic Rate (W/Person)	Clothing Factor
1(Base)	Moderately Active Office Work	75	55	60	0.6
2	Seated, Very Light Work	70	45	45	0.6
3	Moderately Active Office Work	75	55	60	0.6
4	Moderately Active Office Work	75	55	60	0.6

The model for Scenario 2 and 3 ais presented in Figure 4.1.

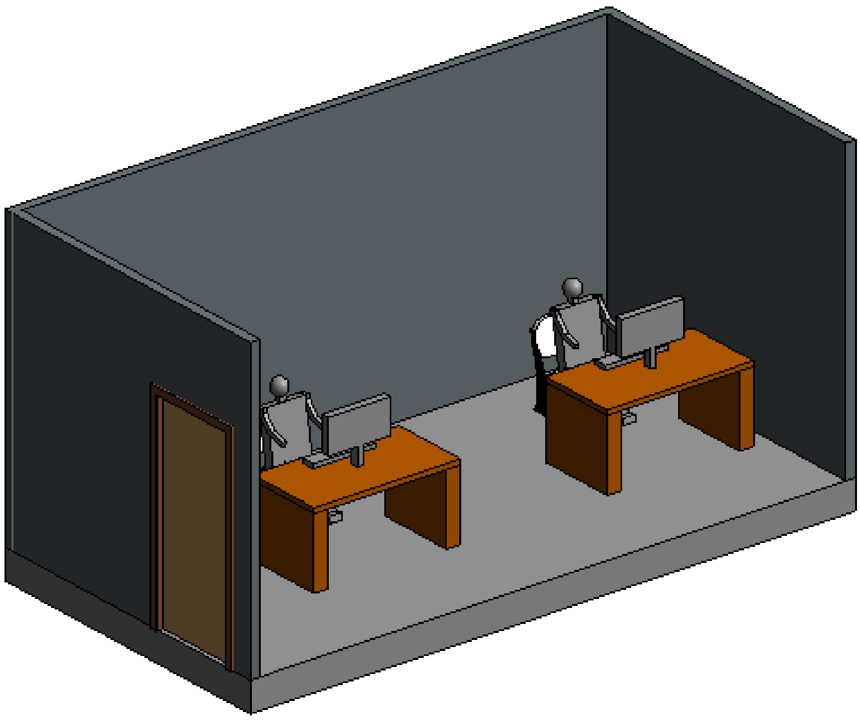


Figure 4.1. 3D View of Model for Scenario 2 and 3

The model for Scenario 4 is presented in Figure 4.2.

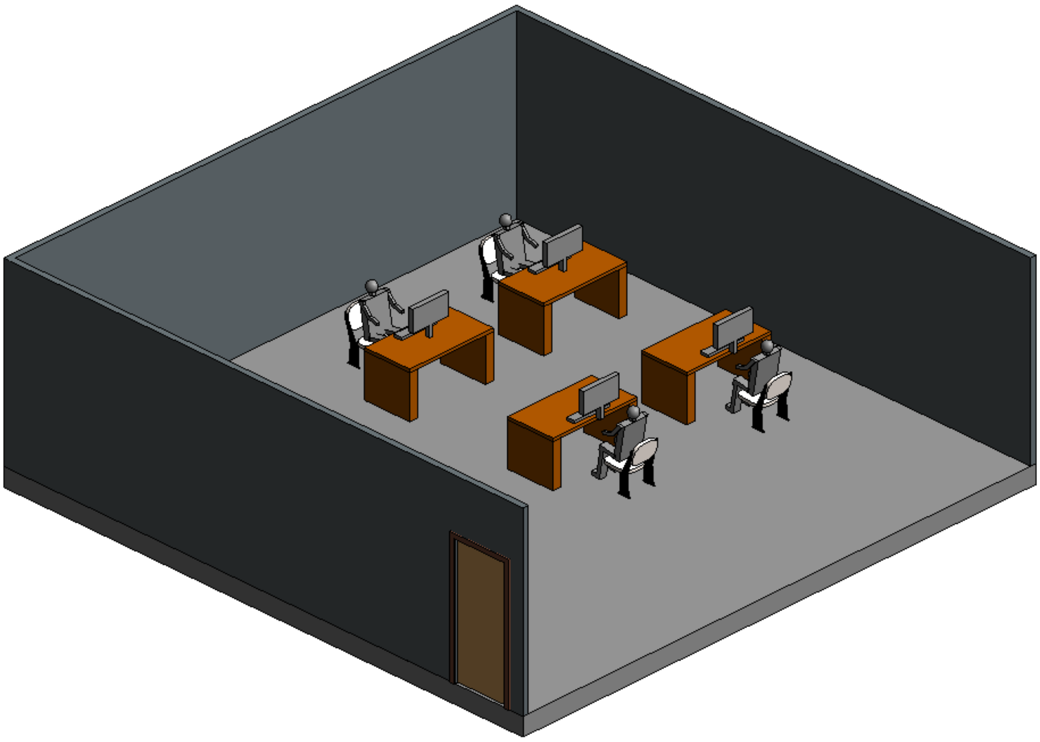


Figure 4.2. 3D View of Model for Scenario 4

As in the case for the base model, which is the first scenario, the mesh models are generated for analysis for other cases. Then, as described in the methodology, the human positions and heat-generating areas with boundary conditions are given to the algorithm for design optimization.

The results of the optimized solution for A/C placement, i.e. the PMV value closest to 0, for different scenarios are presented in Figure 4.3-4.6.

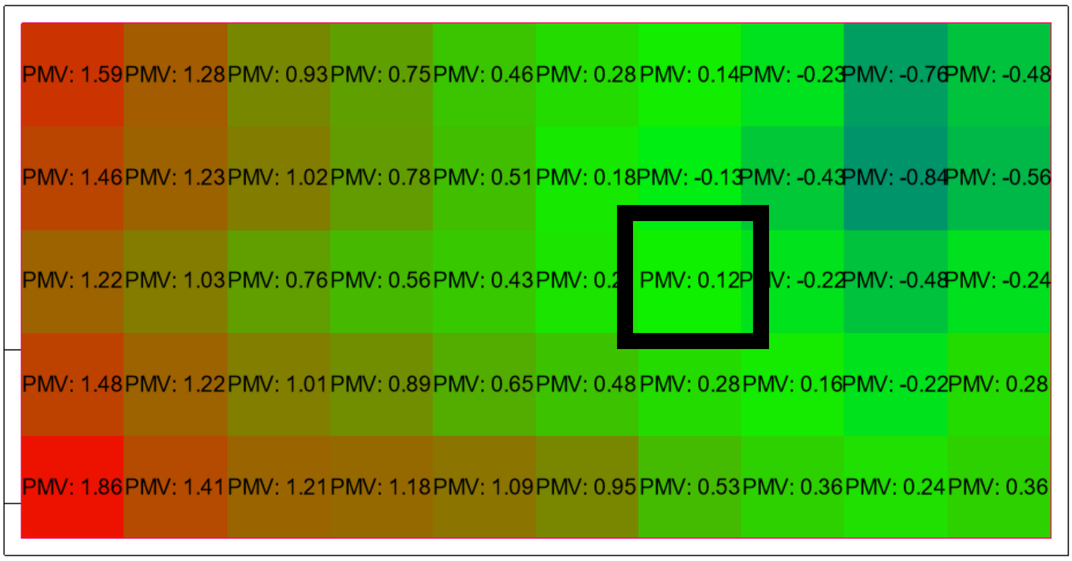


Figure 4.3. PMV Results for Optimization Algorithm for Base Model

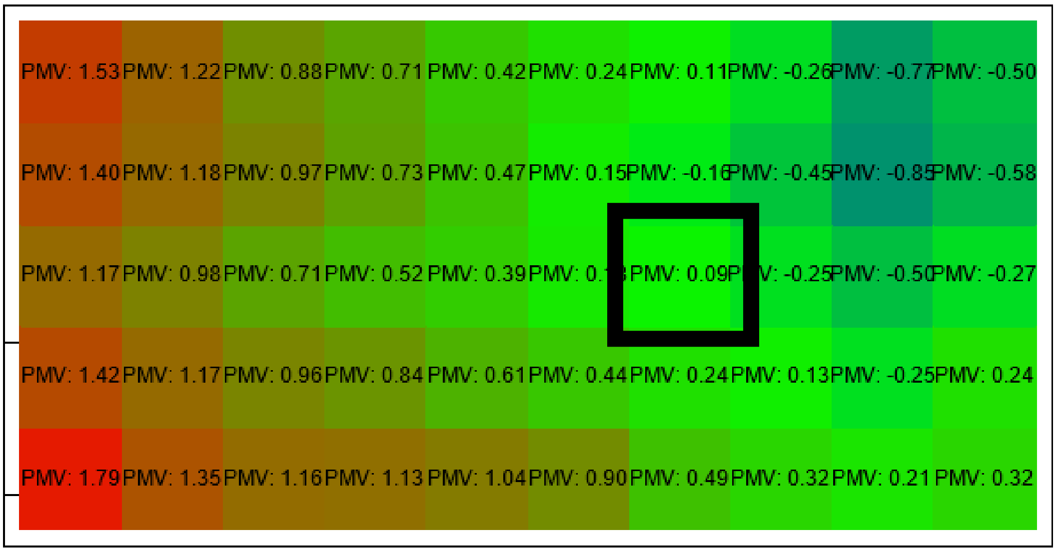


Figure 4.4. PMV Results for Optimization Algorithm for Scenario 2

For the second case, the result tells the designer that the A/C unit should be placed in the node that gives the PMV value of 0.09.

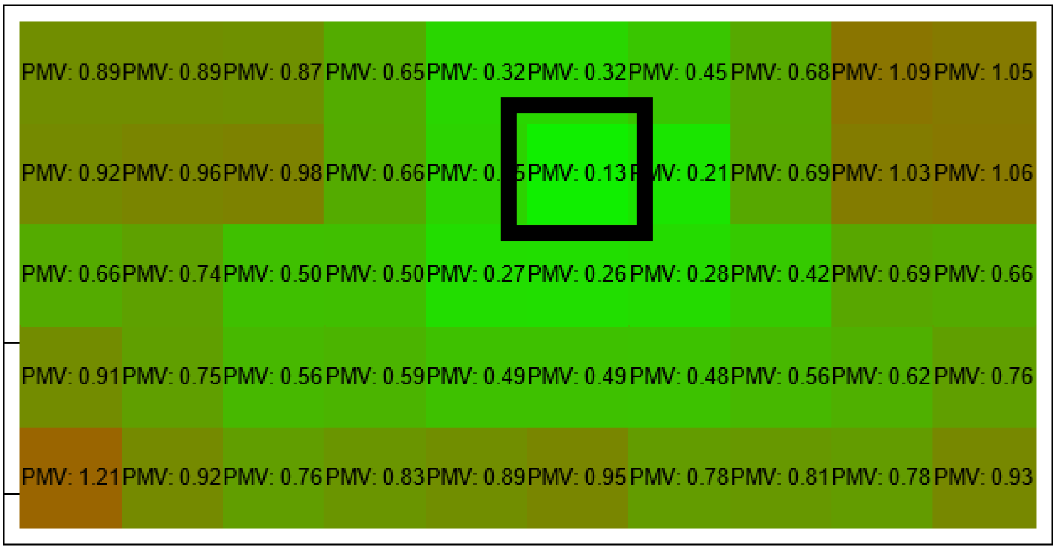


Figure 4.5. PMV Results for Optimization Algorithm for Scenario 3

For the third case, the result tells the designer that the A/C unit should be placed in the node that gives the PMV value of 0.13.

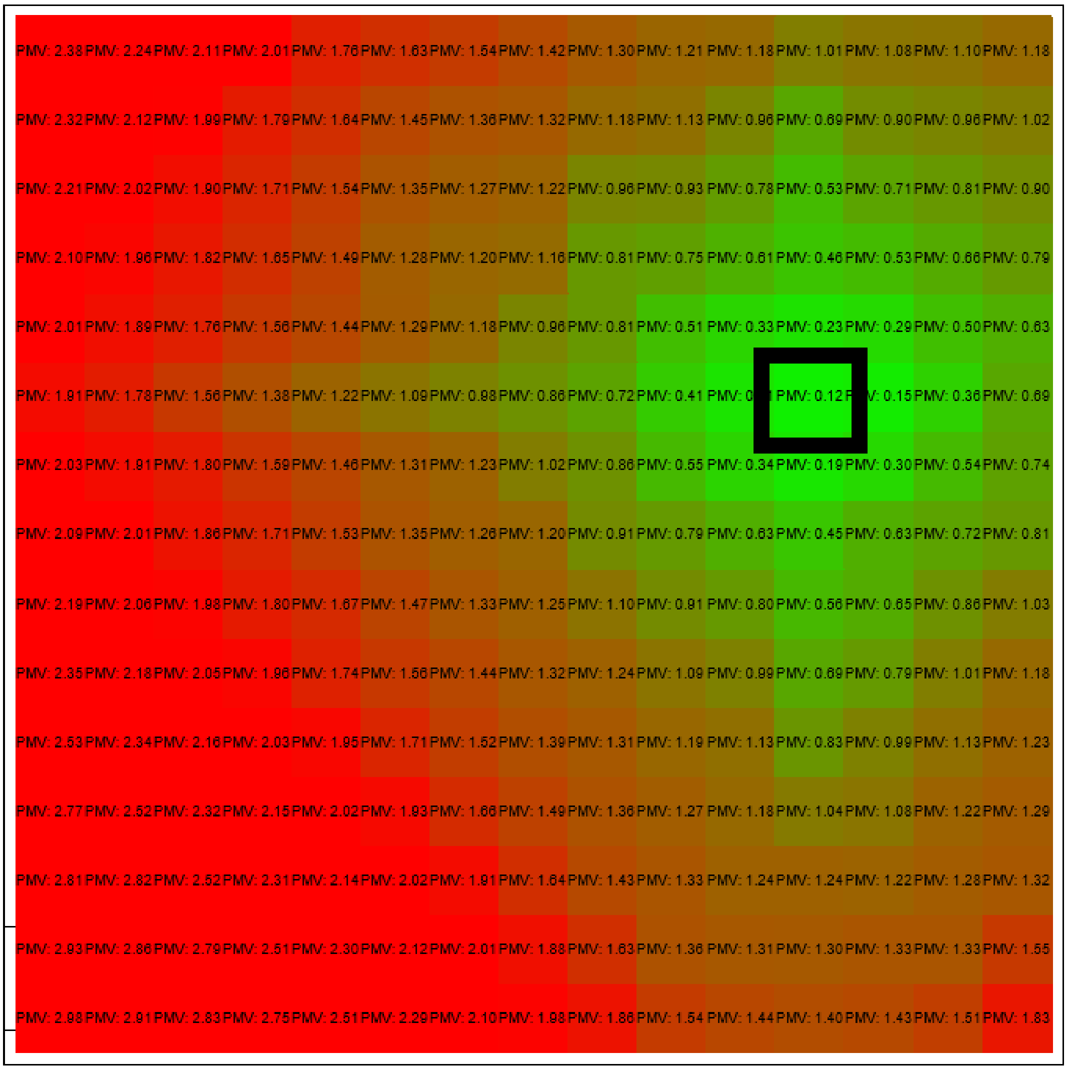


Figure 4.6. PMV Results for Optimization Algorithm for Scenario 4

For the fourth case, the result tells the designer that the A/C unit should be placed in the node that gives the PMV value of 0.12.

As it was stated in Section 2.3.3, design engineers tend to conduct CFD analysis to see the thermal comfort indices on people. The calculation of thermal comfort indices is difficult without using computational software or an algorithm. Moreover, in literature studies, validations were done by using CFD analysis, as well. CFD analyses are conducted by validated simulation software such as Ansys Fluent or Autodesk CFD.

To verify the results obtained from the generated algorithm, a couple of CFD analyses are performed. Autodesk CFD simulation software is used to verify the results.

The verification methodology is followed by the steps described in the flowchart in Figure 4.7.

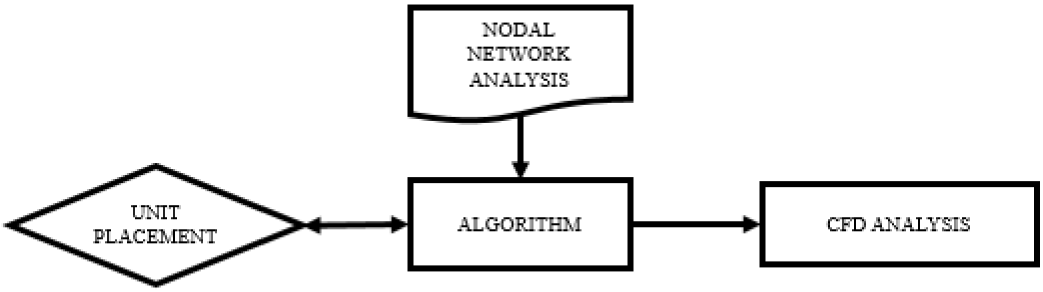


Figure 4.7. Verification Methodology

After the placement process is finished and the most optimum location of the A/C unit is fixed, the model is processed in Autodesk CFD software. In the following process, all the materials and boundary conditions that have been supplied in the algorithm have been provided in the CFD analysis as well, which is provided in Section 3.6. The model run in the software is shown in the below Figure 4.8.

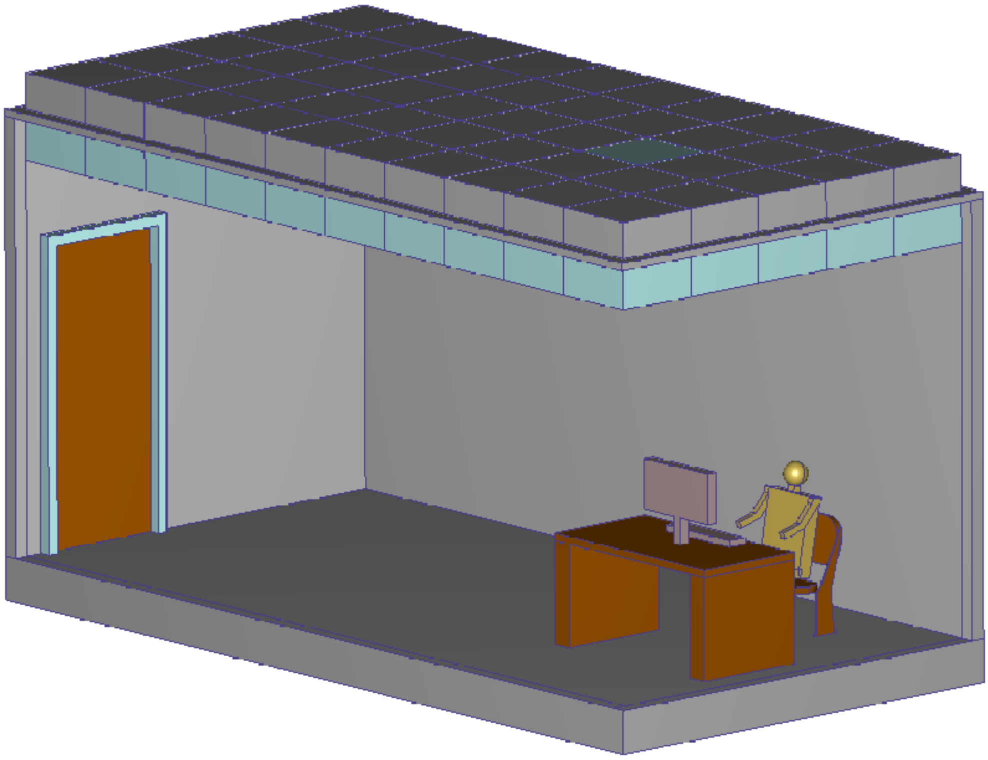


Figure 4.8. CFD Model of the Office

The boundary conditions and the materials are given to the CFD software as shown in Figure 4.9.

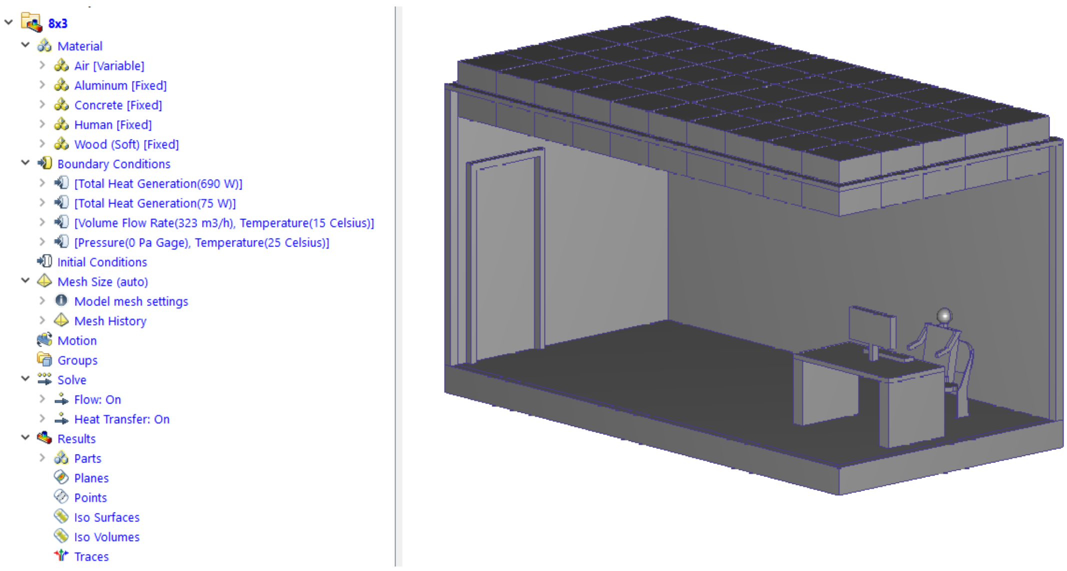


Figure 4.9. Boundary Conditions in CFD Analysis

The result of the analysis held for optimal A/C location determined by the generated algorithm is shown in Figure 4.10 below. The results are given for the sitting human in the occupiable area.

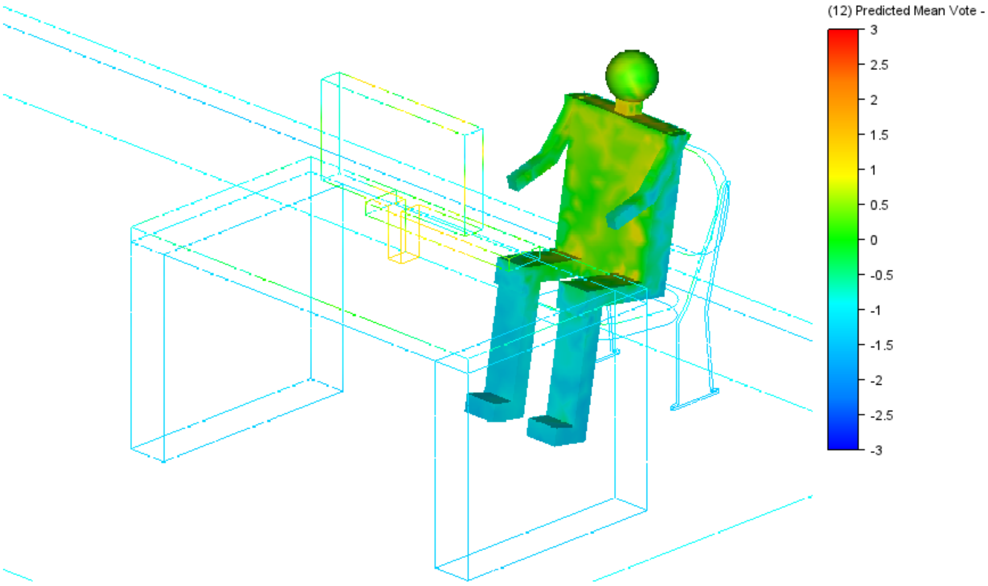


Figure 4.10. PMV Values for Optimal A/C Location, PMV=+0.12

To verify the algorithm for different A/C unit conditions for the base model, different CFD studies are carried out to obtain the same PMV values for the conditions determined as "non-optimal" by the generated algorithm. The results are given for the sitting human in the occupiable area.

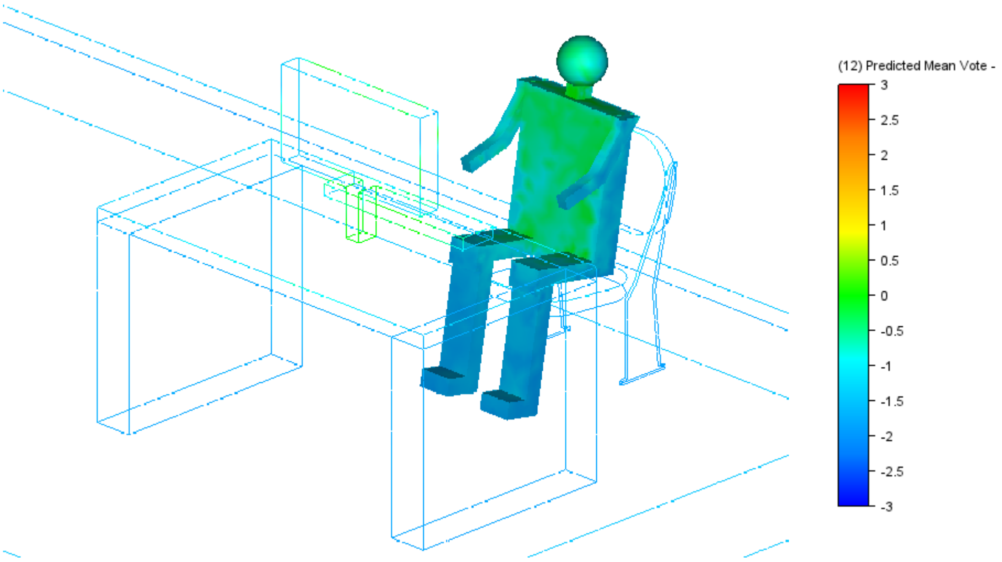


Figure 4.11. PMV Values for the Nearest Possible A/C Location, PMV=-0.84

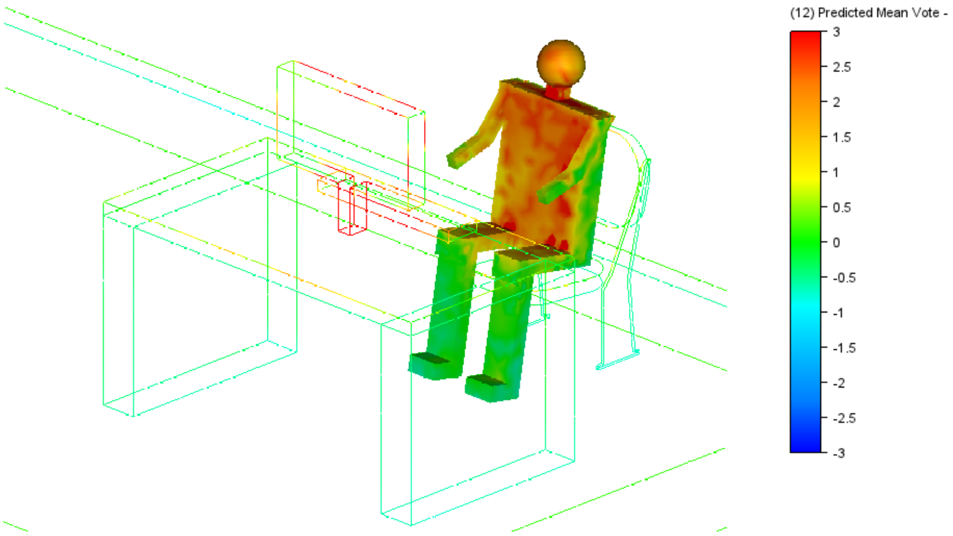


Figure 4.12. PMV Values for the Farthest Possible A/C Location, PMV=+1.86

From the CFD analysis of the base model, the results are coherent with the solution obtained from the generated algorithm. Table 4.3 shows the comparison of PMV values found in the algorithm and CFD results on human beings for the 3 cases analyzed. The error margin between the generated algorithm compared with the actual CFD results are about 1%. This value tells that the algorithm gives appropriate results and can be used without conducting a CFD analysis for the specified geometry.

Table 4.3 Comparison of Algorithm and CFD Results for the Base Model

Case	PMV Algorithm	PMV CFD*	Margin (%)
Optimum	+0.12	+0.05	1.16
A/C Nearest	-0.84	-0.91	1.16
A/C Farthest	+1.86	+1.78	1.33

* PMV results in CFD analysis are based on average PMV values on the solid human model.

For further verification, optimum results for Scenario 3 and 4, which have multiple people are analyzed in the CFD software. The same CFD verification methodology is used in these cases. Table 4.4 shows the comparison of PMV values found in the algorithm and CFD results on people for the cases analyzed. The error margin between the generated algorithm compared with the actual CFD results are about 1% but gives higher error margins when the room area is enlarged. This value tells that the algorithm gives appropriate results and can be used without conducting a CFD analysis for the specified geometry, however, when the office space is getting larger, the margin for error gets higher which is a limitation.

Table 4.4 Comparison of Algorithm and CFD Results for Scenario 3 and 4

Case	PMV Algorithm	PMV CFD	Margin (%)
Scenario 3	+0.13	+0.21	1.33
Scenario 4	+0.12	+0.25	2.16

CHAPTER 5

CONCLUSION

5.1 General Conclusion

HVAC systems play a major role in building energy consumption and occupant comfort. Especially the cooling systems are important in hot conditions, which directly affects the occupants' performance in offices. In this study, an algorithm is developed to ensure the cooling design engineer foresees the necessary location of the cooling device to maximize human thermal comfort without conducting time-consuming analyses. Traditional cooling system location relies on engineering judgment and designers' experience and the design process is time-consuming if the engineer wants to design the system appropriately in terms of human comfort. If BIM is used, the building model stores data that can be manipulated through external tools. This leads engineers to foresee the thermal comfort conditions in 3D. However, human comfort-focused cooling system design still relies on external software such as CFD. By integrating decision-making optimization algorithm into BIM, the designer uses the minimum time to locate the air conditioner complying with both thermal comfort criteria and general cooling requirements based on standards.

5.2 Contributions

The purpose of this thesis is to create an integrated decision-making model for determining the best position for an air conditioner based on thermal comfort parameters. Most importantly, design optimization of A/C unit position combined these criteria into a single decision support system, resulting in a novel approach to equipment placement for human comfort-focused cooling system design. With the aid of the produced algorithm, cooling system designers may easily and swiftly facilitate conceptual designs and make judgments. A CFD study is not required at the early design stage. The summary of the contributions of the thesis are as follows;

- Traditional, thermal comfort-focused A/C design is combined with the concept of BIM by the generated algorithm.
- A combined evaluation and optimization model for A/C design was developed, which provides decision-makers with a user-friendly model that is simple, efficient, and reliable.
- Time consumption of thermal comfort assessments for A/C system location is greatly reduced. Table 5.1 shows the modeling and simulation durations for both the traditional methods and the assessment with the help of the developed algorithm. The time required to generate an optimal layout for A/C placement is reduced to 5-6% compared to traditional methods. As it was stated, in traditional methods, the designer has to change the location of the A/C unit in CFD analysis to see the results. Meanwhile, the generated algorithm gives the optimal location in the first assessment study.

Table 5.1 Thermal Comfort Assessment Comparison

Type of Room (LxWxH) (m)	Modeling Time (hour)	Simulation Time in CFD (hour)	Simulation Time in Generated Algorithm (hour)
6x3x3	1.5	~4*	0.25
9x9x3	1.5	~6*	0.30

* Simulation time in CFD includes geometry importing, defining boundary conditions, meshing, solving, and post-processing. The simulation time is presented for only one CFD solution, in which the A/C is assumed to be in the optimal location. If the A/C placement does not give satisfactory results designer should conduct further analysis which takes more time.

- Implementing scripts in Dynamo for Autodesk Revit to regulate numerical methods inside the BIM model without the need for external tools.

Thus, regarding the findings in the literature, this thesis fills the absence of study regarding all concepts such as BIM-based numerical node method algorithm that is coded in Dynamo for Autodesk Revit for optimizing air conditioner location for the cooling systems in offices. Detailed analyzes should be done with CFD programs. In this study, an algorithm that will guide the designer in the preliminary design phase has been developed by integrating numerical methods that make general approaches without detailed CFD analysis, together with software development tools, into the BIM system. Thus, it is aimed to ensure that the comfort-oriented design process is performed more effectively.

5.3 Limitations

The major goal of this study was to create the basis and develop a technique for increasing the efficiency of human-focused cooling system design and improving human comfort in the workplace. There are flaws in this concept that can be addressed to solve other design and configuration difficulties. These flaws can be addressed by expanding the suggested technique, as described in the following section on future work.

The following constraints were present in this idea and can be developed in future work;

- The algorithm is limited to single cooling equipment, not including the whole cooling system.
- The algorithm is limited to steady-state analysis of human comfort. The code runs neglecting the human behavior, transient conditions, and change in environmental effects.
- The meshing process for this thesis only allows rectangular-shaped geometries as different shapes need further and different methods of discretization.
- The cooling equipment can only be placed in the suspended ceiling.
- The mesh sizes are as same as the dimensions of the cooling equipment.
- Equipment can only be located on designated meshes, it cannot be placed in among all possible locations.
- Evaluation of energy consumption is not valid as just one cooling equipment is used and it is pointless to derive energy consumption indices.
- Air velocity is neglected in the numerical node method. In the future, it can be integrated for high flow regimes in offices or halls.

5.4 Future Works

Following are some recommendations for further research based on the study's results and limitations;

- The generated algorithm can be updated to evaluate a more comprehensive and systematic design for thermal comfort for all cooling systems.
- The energy consumption indices are not included. Possible design considerations can be integrated to evaluate the indices.
- Multi-equipment or different cooling systems such as air handling units connected to air terminals can be integrated into the script to obtain the optimal human comfort level. To give an example, for multiple equipments of central cooling systems, the script should manage comprehensive airflow data as the diffusers dissipate airflow inside the room, while the other air terminals take the exhaust airflow. The nodal network analysis will not be sufficient and additional simplified Navier-Stokes equations should be integrated to manage airflow data.
- An intelligent neural network methodology can be developed from the results of the available methodology much faster as the data can be collected for the machine learning would cost less time compared to regular CFD analysis.
- The developed algorithm can be further expanded to an automated design study in which the designer does not intervene in the procedure by means of unsupervised or supervised learning.

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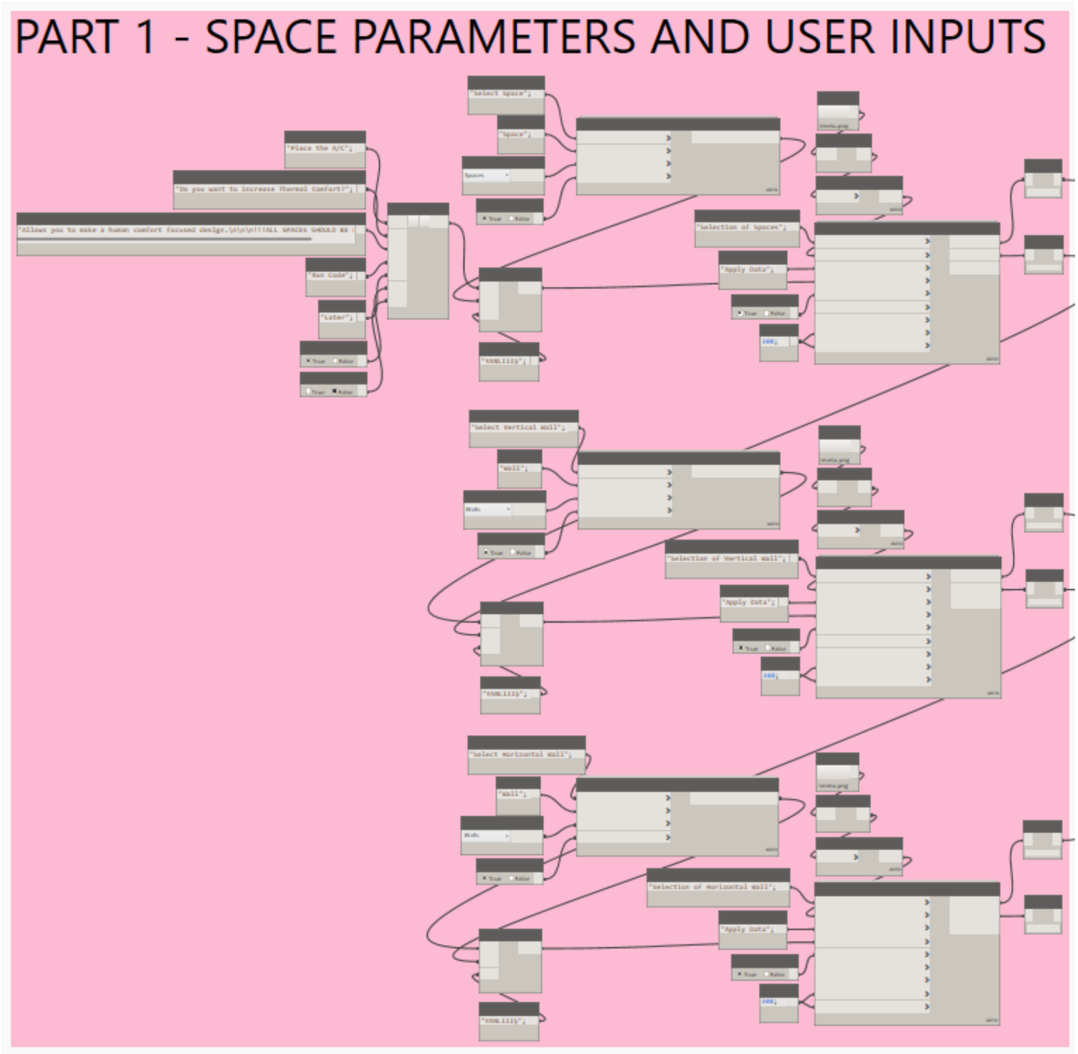
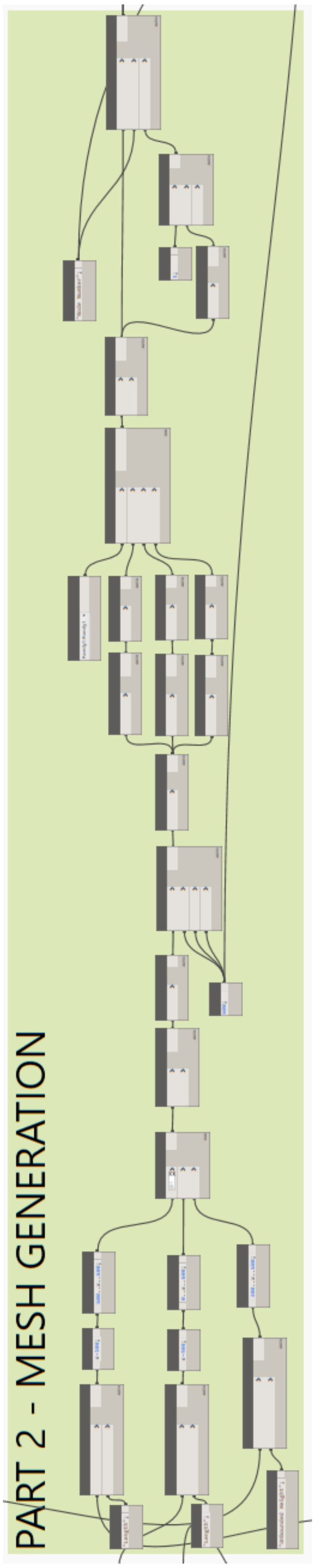
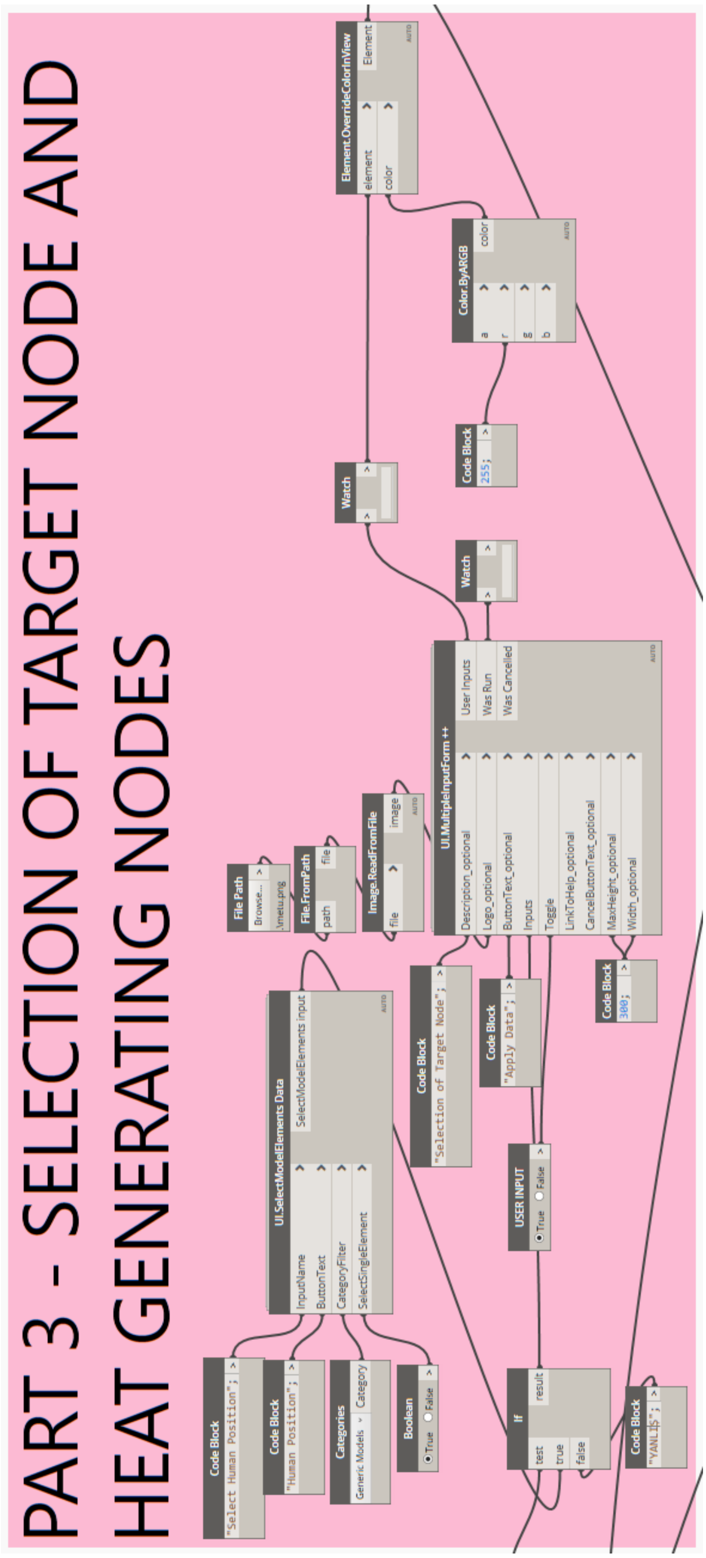
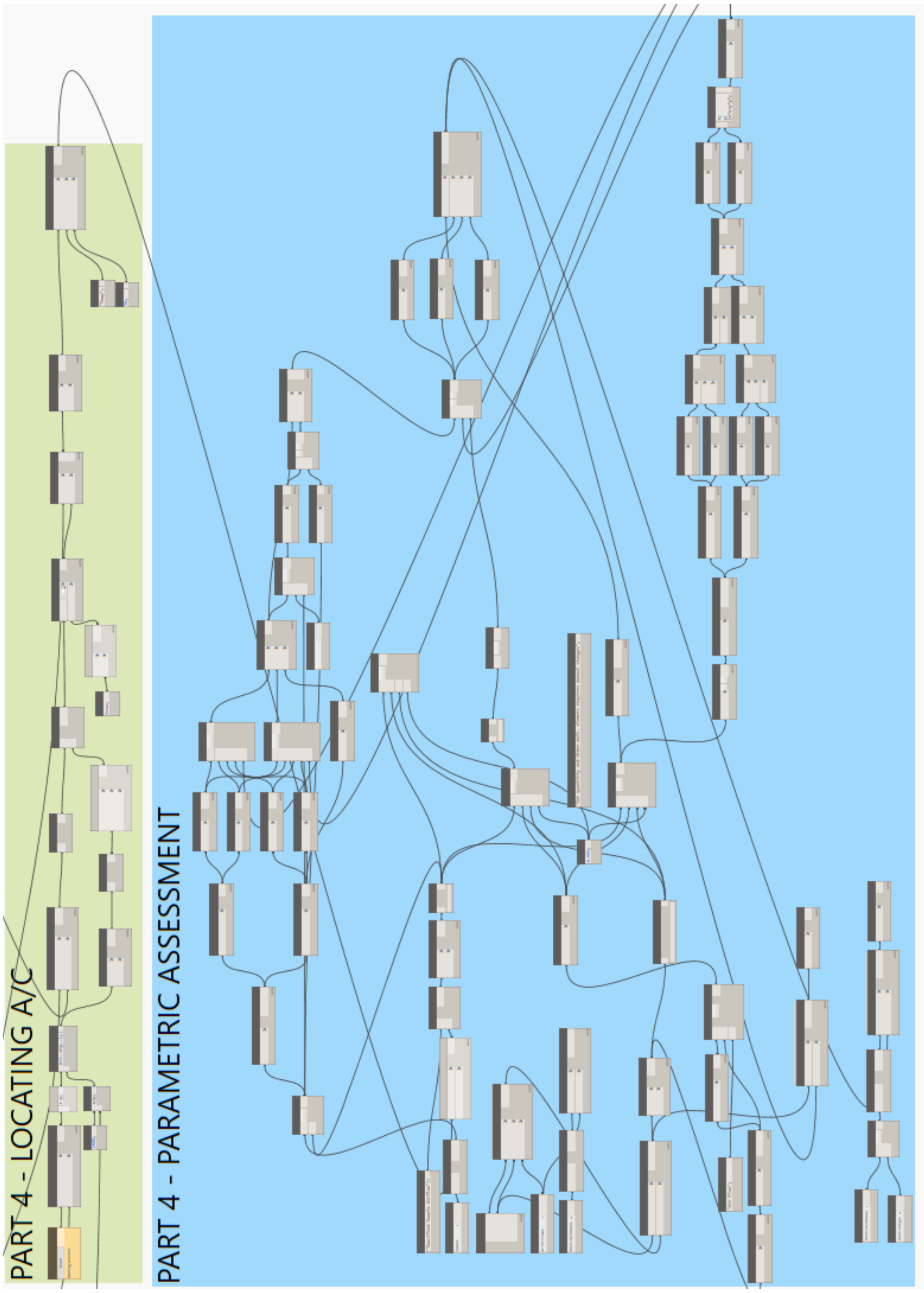
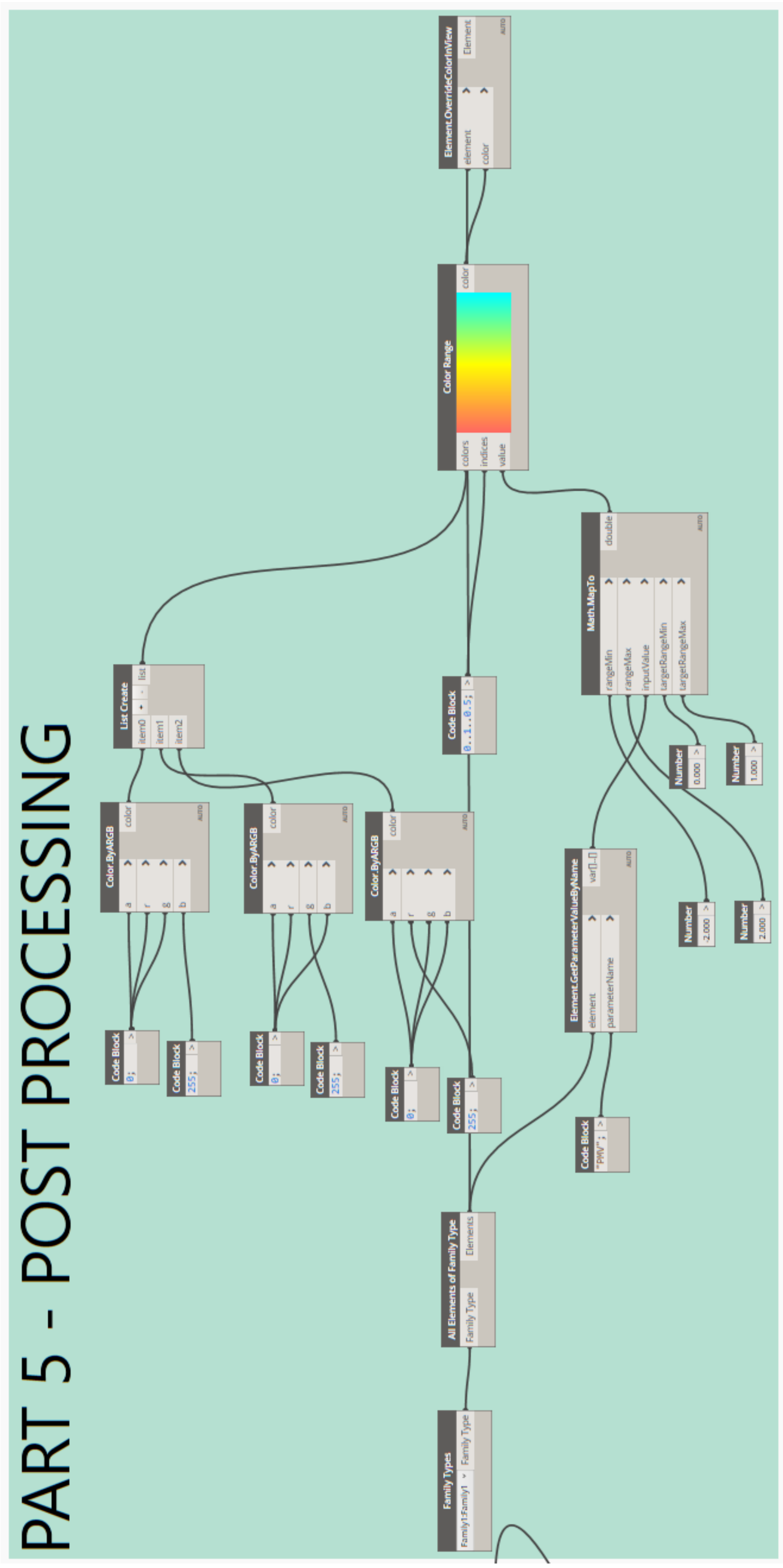
A. Parts of the Generated Algorithm




PART 2 - MESH GENERATION


PART 3 - SELECTION OF TARGET NODE AND HEAT GENERATING NODES
Code Block
"Select Human Position";
Code Block
"Human Position";
Categories
Generic Models
Category
Boolean
True
False
UI.SelectModelElements Data
InputName
ButtonText
CategoryFilter
SelectSingleElement
SelectModelElements input
File Path
Browse...
File.FromPath
path
file
Image.ReadFromFile
file
image
Code Block
"Selection of Target Node";
Code Block
"Apply Data";
USER INPUT
True
False
If
test
true
false
result
Code Block
"YANLIS";
UI.MultipleInputForm ++
Description_optional
Logo_optional
ButtonText_optional
Inputs
Toggle
LinkToHelp_optional
CancelButtonText_optional
MaxHeight_optional
Width_optional
User Inputs
Was Run
Was Cancelled
Code Block
300;
Watch
Watch
Code Block
255;
Color.ByARGB
a
r
g
b
color
Element.OverrideColorInView
element
color
Element


PART 4 - LOCATING A/C
PART 4 - PARAMETRIC ASSESSMENT



PART 5 - POST PROCESSING
Element.OverrideColorInView
Color Range
Math.MapTo
List Create
Color.ByARGB
Color.ByARGB
Color.ByARGB
Code Block
Element.GetParameterValueByName
All Elements of Family Type
Family Types