

**AUGMENTING OCCUPANT THERMAL EXPERIENCE
WITH CYBER-PHYSICAL-SOCIAL SYSTEMS:
A CASE STUDY ON ADAPTIVE VENTS**

A Dissertation

by

Cem Keskin

Submitted to the

Graduate School of Sciences and Engineering
In Partial Fulfillment of the Requirements for
the Degree of

Doctor of Philosophy

in the

Department of Mechanical Engineering

Özyeğin University
June 2020

Copyright © 2020 by Cem Keskin

**AUGMENTING OCCUPANT THERMAL EXPERIENCE
WITH CYBER-PHYSICAL-SOCIAL SYSTEMS:
A CASE STUDY ON ADAPTIVE VENTS**

Approved by:

Prof. M. Pinar Mengüç, Advisor,

Department of Mechanical
Engineering

Özyeğin University

Prof. Gülgün Kayakutlu,

Energy Institute

İstanbul Technical University

Asst. Prof. Özgür Ertunç,

Department of Mechanical
Engineering

Özyeğin University

Asst. Prof. Altuğ Başol,

Department of Mechanical
Engineering

Özyeğin University

Asst. Prof. M. Berker Yurtseven,

Energy Institute

İstanbul Technical University

Date Approved: 11.06.2020

To my parents



SUMMARY

Buildings use more than 30% of global energy, while 36% of this energy comes from direct combustion of fossil fuels. Hence, buildings constitute a considerable share of CO₂ emissions and has a large contribution to climate change related problems. The highest share (almost half) of the total energy consumption in buildings is due to heating, cooling and air conditioning (HVAC). Particularly, the increasing demand for space cooling is pushing this share up. Thus, HVAC systems are considered as one of the key contributors of the total energy consumption and the adverse environmental impacts of buildings.

Recent developments in technology offer promising tools to leverage interactions between occupants and the building systems. The energy efficiency of HVAC operations is not only a technical concern, what is more is that it requires to modifications considering human behavior. The convergence of physical systems in built environment with the information and communication technologies, as well as the human dimension makes it necessary to co-evaluate these distinct realms during the design and operation of building systems. The cyber-physical-social systems (CPSS) approach has a promising potential to facilitate this interdependence.

A novel HVAC interface is presented in this thesis study. An Adaptive Vent System (AVS), is proposed to enable localized and customized thermal management in built environment for a better thermal experience of occupants and higher level of energy efficiency for building operators. The system is designed as a CPSS and composed of: (i) a novel diffuser design with individually operable flaps, (ii) thermal agents, (iii) a user interface, and (iv) a control and communication unit. It enables asymmetric air-inlet to manage indoor temperature distribution and aims to match varieties in temperature with

the differences in occupant demands. The system is intended to decrease the conditioned air volume that results in HVAC energy efficiency without sacrificing occupant comfort.

The design and operation of complex building energy systems like AVS is a challenging task. In order to assist this process, a methodological framework is presented that outlines the development process, from the early definition to prototyping and performance analysis. The framework is based on a novel CPSS modeling approach that combines hybrid dynamic modelling (for cyber and physical aspects) with human behavior modeling (for social aspects).

A prototype of the proposed AVS was deployed in an office of an academic building in order to conduct experiments and validate CPSS and computational fluid dynamics (CFD) models. Both experiments and simulation based assessments of system operation shows that system can generate temperature difference between opposite sides of a room in a controllable manner. It is also shown that this difference results in considerable change in thermal sensation of occupants and can pave the way for energy savings with localization inside the rooms. The core reason for efficient HVAC operation with AVS is the usage of less amount of thermally conditioned air by minimizing the conditioning of unnecessary parts of the room. Moreover, the system leverages occupant interaction by delivering advanced control options (enhanced perceived control) for more customized practices. The interplay between the building energy management and the localization and customization of thermal management can maximize demand flexibility of buildings, that is a key concern for demand side management and energy planning. Hence, the new AVS system is to leverage overall thermal experience in built environment in an energy efficient way and help decreasing the environmental impact of buildings.

ÖZETÇE

Binalar, dünya enerji tüketiminin %30'undan fazla bir kısmından sorumlu olmakla birlikte, binalardaki enerji tüketiminin %36'sı fosil yakıtların doğrudan yakılması şeklinde gerçekleşmektedir. Bu nedenle binalar, CO₂ salınımının önemli bir kısmını gerçekleştirmekte olup, iklim değişikliğinden kaynaklı sorunların oluşmasına da ciddi katkıda bulunmaktadır. Binalardaki enerji tüketiminin önemli bir kısmı (yaklaşık olarak yarısı) ısıtma, soğutma ve havalandırma (HVAC) işlemleri için gerçekleşmektedir. Artmakta olan soğutma talebi ise bu oranı daha da artırma eğilimindedir. Dolayısıyla, çevresel, teknik ve sosyal etkenlere tabi olan HVAC sistemleri, binaların toplam enerji tüketiminin ve olumsuz çevresel etkilerinin azaltılmasında önemli bir role sahiptir.

Son yıllardaki teknolojik gelişmeler, bina kullanıcıları ile sistemleri arasındaki etkileşimin artırılması için umut vaat eden araçlar sunmaktadır. HVAC işlemlerinin enerji verimliliği artık sadece teknik bir konu olmayıp, insan davranışlarına dair değerlendirmeleri de içermesi beklenen bir konu haline gelmiştir. Bu nedenle, binalardaki fiziksel sistemler ile bilgi ve iletişim teknolojileri ve insani boyut arasındaki yakınsama, bina sistemlerinin tasarım ve işletme süreçlerinde farklı düzlemlerdeki olguların birlikte değerlendirilmesini zorunlu kılmaktadır. Siber-fiziksel-sosyal sistem (SFSS) yaklaşımı, bu ilişkiselliği pekiştirme potansiyeli içermektedir.

Bu tez çalışması, özgün bir HVAC arayüzü sunmaktadır. Geliştirilen uyarlanabilir havalandırma sisteminin (UHS), bina ortamında daha iyi bir ısı deneyimi sunmak üzere sınırlandırılmış ve özelleştirilmiş ısı yönetimi sağlaması ve daha yüksek seviyede enerji verimliliği sunması hedeflenmiştir. Bir SFSS olarak tasarlanan söz konusu sistem şu bileşenlerden oluşmaktadır: (i) birbirinden bağımsız hareket edebilen hareketli kanatçıklara sahip özgün difüzör, (ii) ısı ölçüm birimleri, (iii) kullanıcı arayüzü ve (iv)

kontrol ve iletişim birimi. Sistem, oda içerisinde sıcaklık dağılımını kontrol etmek üzere asimetrik hava girişi sağlayabilmekte ve bu şekilde oluşturulan sıcaklık farklılıklarını bina sakinlerinin tercihlerindeki farklılıklar ile eşleştirebilmeyi mümkün kılmaktadır. Bu sayede, toplam şartlandırılmış hava miktarının azaltılması ve kullanıcıların konforundan taviz vermeksizin enerji verimliliğinin artırılması hedeflenmektedir.

UHS gibi karmaşık bina enerji sistemlerinin tasarımı ve işletilmesi oldukça zor işlemlerdir. Bu süreçleri kolaylaştırmak için, başlangıçtaki tanımlamadan ilkörnek geliştirme ve performans analizine kadar geliştirme sürecini ana hatlarıyla belirleyen bir yöntemsel çerçeve sunulmuştur. Bu çerçeve yapı, SFSS'lerin modellenmesi için hibrid dinamik modelleme (siber ve fiziksel olgular için) ile davranış modellemeyi (sosyal olgular için) bir araya getiren özgün bir modelleme yaklaşımı üzerine kurulmuştur.

DeneySEL çalışmalarını gerçekleştirmenin yanı sıra SFSS ve HAD modellerinin doğrulamasını da sağlamak üzere, bir akademik binada bulunan bir ofiste, geliştirilen UHS'nin bir ilkörneği kurulmuştur. Sistemin çalışmasını incelemek için yapılan deneyler ve simülasyonlar, odanın iki tarafı arasında kontrollü bir biçimde sıcaklık farkı oluşturabildiğini göstermiştir. Ayrıca, bu sıcaklık farkının, kullanıcıların ısı hissiyatında ayırt edilebilir bir fark oluşturduğu ve sağlanan sınırlandırma ile enerji kazanımları elde edilmesini mümkün kılacağı da gösterilmiştir. UHS ile gerçekleştirilen HVAC işlemlerinin verimliliğindeki ana etken, gerekli olmayan noktaların iklimlendirilmesinin en aza indirilerek, şartlandırılan hava miktarının azaltılmasıdır. Bununla birlikte sistem, daha özelleştirilmiş bir kullanım için gelişmiş kontrol seçenekleri sunarak (algılanan kontrol düzeyinin yükseltilmesi), kullanıcı etkileşimini artırmaktadır. Bina enerji yönetimi ile sınırlandırılmış ve özelleştirilmiş ısı yönetimi arasındaki ilişki, talep tarafı yönetimi ve enerji planlaması için kritik öneme sahip talep esnekliğinin ençoklanması

da sağlayabilmektedir. Bu açılardan bakıldığında UHS, binalarda ısııl deneyimi bütüncül olarak ve enerji verimli bir biçimde geliştirebilir ve binaların çevreye etkisini azaltabilir.



ACKNOWLEDGMENTS

I would like to present my special thank to my advisor Prof. Dr. M. Pınar Mengüç for providing freedom, continuous encouragement and his patience during this study.

I also would like to thank the my thesis committee members Prof. Dr. Gülgün Kayakutlu and Asst. Prof. Özgür Ertunç for sharing their valuable insights.

My utmost appreciation to my love Aysun Eyrek for her continuous support and unconditional love during the hardest times of this study.

I would like to thank my mother and brothers for motivating me since the very beginning of this study, and to my father for inspiring me studying hard in my childhood.

I would like to present my special thanks to Tufan Akba, Selim Kılıç, Güven Fidan and M. Rifat Öcal for their generous supports in troubled times.

I am also very grateful to ÖzÜ/CEEE family who were always so helpful.

TABLE OF CONTENTS

SUMMARY	iii
ÖZETÇE	v
ACKNOWLEDGMENTS	viii
1. INTRODUCTION	1
1.1. Environmental Challenges and Building Energy Efficiency	1
1.2. Research Objectives of the Thesis	5
1.3. Outline of the Thesis	6
2. CYBER, PHYSICAL and SOCIAL REALMS OF BUILDING ENERGY SYSTEMS	9
2.1. Cyber Context	9
2.1.1 Sensor Networks	10
2.1.2 The Cloud and Edge Computing	13
2.1.3 Wireless Communication.....	16
2.1.3 Model Predictive Control.....	18
2.2. Physical Context.....	19
2.2.1 Ventilation Systems	20
2.2.2 Indoor Airflow Regime.....	22
2.2.3 Thermal Comfort	30
2.3. Social Context.....	41
2.3.1 Qualitative Approaches.....	42
2.3.2 Quantitative Approaches.....	46
2.3.3 Behavioral Dimension of Thermal Comfort.....	49
3. METHODOLOGICAL FRAMEWORK.....	52
3.1. Step1: Definitions.....	52
3.2. Step 2: Conceptual Design	54
3.3. Step 3: Modeling.....	55
3.3.1 Hybrid Dynamical Modeling	56
3.3.2 Hybrid Dynamical and Behavior Modeling.....	57
3.4. Step 4: Prototyping.....	58
3.5. Step 5: Experiments	58
3.6. Step 6: Analysis.....	59
4. IMPLEMENTATION OF THE CPSS CONCEPT	61
4.1. Definition of AVS	61
4.2. Conceptual Design of AVS	63
4.2.1 Operable Flap Diffusers.....	65

4.2.2 Thermal Agents.....	66
4.2.3 User Interface.....	68
4.2.4 Control and Communication Unit (CCU).....	69
4.2.5 System Level Description	70
4.3. Modelling the AVS	72
4.4. Prototyping and The Test Room	75
4.5. Experiments.....	82
4.6. Analysis.....	84
5. CFD Analysis of Performance of AVS.....	90
5.1. The Model Development and Validation	91
5.1.1 The Geometry	91
5.1.2 Mesh quality	95
5.1.3 Boundary and initial conditions	97
5.1.4 Modeling Physics.....	99
5.1.5 Model Validation	103
5.2. Indoor Airflow Analysis	107
5.2.1 Air-jet characterization	107
5.2.2 Airflow Regime Identification.....	118
5.2.3 Thermal Comfort Analysis	127
5.2.4 Energy Analysis.....	138
6. DISCUSSION.....	143
7. CONCLUSION AND FUTURE WORKS	148
REFERENCES	151

LIST OF TABLES

Table 1: Mesh dependence analysis.....	107
Table 2: Archimedes Numbers for the cases in Figure 42 and Figure 43.....	116
Table 3: Coordinates of the lowest point of air-jets for different flap angles.....	117
Table 4: Comparison of experimental and simulation (CFD) data for sensors on head level.....	163
Table 5: Comparison of experimental and simulation (CFD) data for sensors on desks	164
Table 6: Comparison of experimental and simulation (CFD) data for sensors on ceiling level.....	165
Table 7: Comparison of experimental and simulation (CFD) data for sensors on floor level.....	166

LIST OF FIGURES

Figure 1: The Conceptual background of the thesis study.	5
Figure 2: Organization of the thesis study and the interdependence between sections (CPSS: Cyber-physical-social systems; BES: Building Energy Systems; CPSBES: Cyber-physical-social building energy systems; AVS: Adaptive vent system; CFD: Computational Fluid Dynamics).....	7
Figure 3: Common ventilation strategies deployed in modern buildings.....	21
Figure 4: Vertical cross-section and velocity profile of an air-jet with four regions that have different flow characteristics (Adopted from [99]). Note that the figure represents a free jet but the separation of the regions is similar for wall jets. For the corresponding formulations, see text (Eq. 2.1 to Eq. 2.2).	25
Figure 5: The relationship between velocity decay profiles and aspect ratio for a rectangular wall jet (Adopted from [103]).....	26
Figure 6: Nozzle geometry dependence of jet velocity profiles (Adopted from [102]).	27
Figure 7: Comparison of velocity and temperature decay profiles (Adopted from [104]).	29
Figure 8: Merging of three air jets thrown from circular outlets (Adopted from [103]).	29
Figure 9: Active and passive systems in thermoregulation models of human body and corresponding heat balance equations.	35
Figure 10: Variation of local skin temperatures with ambient temperature. Figure clearly shows the different thermal responses of each body segment. (Adopted from [117]). ..	38
Figure 11: The factors influencing behavior in the Theory of Interpersonal Behavior (Adopted from [124]).....	45
Figure 12: Drivers of acceptability in the Technology Acceptance Model.	46

Figure 13: Steps of the methodological framework.	53
Figure 14: Components and flow of the proposed modeling scheme (UCA: user control actions, EP: environmental parameters) (Adopted from [174]).	55
Figure 15: Overview of the proposed adaptive vent system components.	64
Figure 16: Preliminary diffuser design with operable flaps.	66
Figure 17: RC network model of the test room that is used for continuous dynamics..	73
Figure 18: Finite state machine for the discrete dynamics (M0=Nobody inside the room;, M1=Only Desk1 is occupied; M2=Only Desk2 is occupied; M3=both desk is occupied. (See text for the details).	74
Figure 19: Positions of the main system components in the test room. See text for detailed explanation of each component.	76
Figure 21: Pictures of operable-flap diffuser prototype: (a) back side (b) on the ceiling as mounted.	77
Figure 20: The picture (a) and the geometrical model (b) of the operable flap diffuser.	77
Figure 22: Pictures of thermal agents: (a) the temperature sensor (MCP9808) (b) the toy in which sensor is mounted.	78
Figure 23: The prototype of the user interface.	79
Figure 24: The flap control screen in the user interface.	80
Figure 25: Node-RED program that controls system operation	81
Figure 26: Additional sensors: (a) thermocouple on the wall (b) thermocouple on window (c) door sensor.	83
Figure 28: Simulation outputs and experimental results for the second experiment....	85
Figure 27: Simulation outputs and experimental results for the first experiment.	85
Figure 29: Simulation outputs and experimental results for the third experiment.	87

Figure 30: Inputs and outcomes for each step of CFD analysis of AVS operational performance.	92
Figure 31: The geometric model of the test room with the office equipment and the manikin.	93
Figure 32: Manikin geometry with dimensions: (a) Front view (b) Side view.	94
Figure 33: Positions of virtual probes that represent thermal agents and additional temperature sensors on the ceiling, head and floor level of the test room.....	95
Figure 34: Surface mesh on manikins body: (a) without surface wrapping (b) with surface wrapping.....	96
Figure 35: Representations of volume mesh: (a) around inlet and manikin, (b) around manikin surface, (c) around flap.....	98
Figure 36: An example for the evaluation of residuals.....	104
Figure 37: An example of the plot screen that is to follow the convergence of temperature and velocity measurements in selected probes.	105
Figure 38: The average of Mean Average Percentage Error (MAPE) values for sensor and virtual probe readings at different height levels.....	106
Figure 39: The geometrical model of an open flap.....	108
Figure 40: The dimensions of the simplified room geometry for air-jet characterization and the position of virtual line probes (each composed of 24 virtual point probes)....	109
Figure 41: Velocity decay profiles for different flap angles.....	110
Figure 42: Comparison of simulation results for velocity decay with the corresponding empirical formulations.....	111
Figure 43: Velocity profiles for different flap angles, inlet temperatures and inlet velocities.	112

Figure 44: Temperature profiles for different flap angles, inlet temperatures and inlet velocities.	114
Figure 45: Comparison of velocity and temperature decay profiles.....	115
Figure 46: A typical jet profile created by the flaps and the coordinates of the lowest point.	117
Figure 47: Positions of manikins (dark grey) and the mid-plane (pink).....	118
Figure 48: Indoor airflow regime for different flap configurations.....	119
Figure 49: Indoor airflow regime for different mass flow rates (MFR).	122
Figure 50: Indoor airflow regime for different inlet temperatures.	124
Figure 51: Indoor airflow regime for different flap angles.....	126
Figure 52: Regions where the air velocity exceed 0.3m/s and the resulting airflow on manikin surfaces.	128
Figure 53: Comfort regions for each body part in terms of equivalent temperature (Adopted form [192]).....	130
Figure 54: Comparison of equivalent temperature, air velocity on body surface and skin temperature of manikins under different mass flow rates (MFR).	131
Figure 55: Comparison of equivalent temperature for different flap configurations. .	133
Figure 56: Comparison of equivalent temperature, air velocity on body surface and skin temperature of manikins under different flap angles.	134
Figure 57: Comparison of equivalent temperature, air velocity on body surface and skin temperature of manikins under different mass flow rates (MFR).	136
Figure 58: Comparison of equivalent temperature, air velocity on body surface and skin temperature of manikins under different inlet temperatures.....	138
Figure 59: Comparison of equivalent temperature, air velocity on body surface and skin temperature of manikins for different clo values of manikin-1.	139

Figure 60: Percentage of the rated power (6.8 kW) of the reference fan-coil unit for different controller set levels.	140
Figure 61: Comparison of comfort levels of conventional (grey) and localized (green) conditioning (Controller Set Level is 4 for conventional system and 3 for localized conditioning).....	141



ABBREVIATIONS

Ar	Archimedes number
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ATU	Air terminal units
AVS	Adaptive vent system
BES	Building Energy Systems
CCU	Control and communication unit
CFD	Computational fluid dynamics
CO ₂	Carbon dioxide
CPS	Cyber-physical systems
CPSBES	Cyber-physical-social building energy systems
CPSS	Cyber-physical-social systems
DHA	Discrete hybrid automata
EP	Environmental parameters
FCU	Fan-coil unit
FSM	Finite state machine
GTR	Gray thermal radiation model
HVAC	Heating, ventilation, air conditioning
LMV	Local mean vote
LTS	Local thermal sensation
LTSV	Local thermal sensation vote
MFR	Mass flow rate
MPC	Model predictive control
MQTT	Message Queuing Telemetry Transport
Mtoe	Millions of tonnes oil equivalent
NASA	National Aeronautics and Space Administration (USA)
NGO	Non-governmental organizations
OFD	Operable-flap diffuser
PI	Proportional-integral
PID	Proportional-integral-derivative
PMV	Predicted mean vote
PPD	Percentage of dissatisfied
RC	Resistance-Capacitance
Re	Reynolds number
SPT	Social Practice Theory
SSR	Surface-to-surface radiation model
TA	Thermal agents
TCW	Thermal Comfort Wizard of Star-CCM+
T _{ext}	External temperature
TIB	Triandis' Theory of Interpersonal Behavior
T _{int}	Indoor temperature
T _{set}	Set temperature
UCA	User control actions
UI	User interface
VOC	volatile organic compound

1. INTRODUCTION

1.1. *Environmental Challenges and Building Energy Efficiency*

In recent years, we have started discussing about global environmental challenges with more frequency than ever. Climate change, CO₂ emissions, deforestation, ocean pollution, glacier melting, water scarcity, wild fires, and loss of species are just few of the topics that attracted our interest. Many people and institutions, including universities, governments, non-governmental organizations (NGOs), and companies have started developing strategies for these critical issues. The cause for the attention is the considerable effects of those to the daily life all around the world. According to historical global temperature dataset of NASA, eighteen of the nineteen warmest years between 1880 and 2019 has been experienced since 2001 [1]. The *United Nations World Water Development Report 2017* states that only the 20% percent of the wastewater is treated properly before being discharged to the environment which threatens availability of potable water [2]. These and many other arguments point out that our planet needs impactful and persistent actions to keep it sustainable.

Due to intense relationship with the drivers of environmental change, one of the key sectors to deal with the global environmental challenges is the energy. Today, hydrocarbon based energy resources still dominate the energy landscape. The total share of hydrocarbons (of oil, gas and coal) in global primary energy consumption in 2018 is 85 percent (11,743.6 Mtoe of 13,864.9 Mtoe) which is responsible for 33,890.8 Mtonnes of CO₂ emissions [3]. Furthermore, the demand increases as the population and the urbanization increases while the intertwined social institutions and the culture decelerates the change. Global final energy use in 2017 was around 400 EJ and buildings were responsible for about 30% (~120 EJ) of it [4]. Moreover, in 2016, 36% of the energy

usage in buildings was powered by direct combustion of fossil fuels in site whereas the rest was provided in the form of electricity and district heating [5]. Direct combustion was resulted in 2.9 Gt CO₂ emissions, which is the 35% of the total CO₂ emissions of buildings [5]. Thus, due to their significant share in global energy consumption and the high fossil fuel dependence of the current energy mix, buildings play a crucial role to deal with the global environmental challenges.

Total energy consumption in a building is directly related to the performance of the energy systems used for heating, cooling and lighting. These systems are categorized as the passive and active systems depending on their reliance on external energy sources. The systems that benefit natural forces to perform are passive systems [6]. Passive heating and cooling, façade systems, green roofs and shading systems are well known examples of passive systems. They don't need an energy input in the form of gas, biomass, electricity or any other type. Passive systems highly depend on architectural design elements (i.e. building orientation, window-to-wall ratio, among others) and are major determinants of building final energy consumption profile and energy efficiency [6]. The systems that need external power (via energy sources or backup systems) to perform its function are active energy systems [7]. The heating, ventilation and air conditioning (HVAC) and the artificial lighting systems are two typical examples of this kind as they typically need gas and electricity inputs to work, respectively. Moreover, the systems producing electricity, like wind turbines and solar panels, are also considered as active systems [8]. Since most of the services in buildings are intertwined with active energy systems by their design, efforts for energy efficiency in operation phase of buildings focus on active systems.

The services with the highest energy demand in buildings are heating, cooling, ventilation, infiltration, water heating, lighting, refrigeration, food preparation,

appliances and equipment [9,10]. The time dependent energy consumption profiles (hourly, daily and monthly) of each service for a specific building is driven by environmental, social and technical factors. Environmental factors include local climatic conditions, population density, building density, the distance to water bodies and green spaces, among others [11]. The technical drivers include the type, size and age of a building as well as its façade and roof structure, architectural design parameters, construction quality, service systems specifications, among others [12]. The social drivers include both socio-economic and occupant specific (behavioral) factors. Driven by these interdependent factors, energy consumption characteristics of an active system in a building is unique and requires custom evaluation for increasing its energy efficiency.

For most of the buildings, energy consumption of HVAC systems constitute the highest share (almost half) of the total energy consumption [10]. Moreover, the considerable increase in demand for space cooling in recent years tends to even raise this share [4]. Highly depending on each of environmental, technical and social factors, HVAC systems are one of the key elements of decreasing building total energy consumption. Accordingly, efforts increasing the energy efficiency of HVAC systems without sacrificing thermal comfort is a well-studied subject of building energy efficiency field. Some of the topics that need to be carefully studied for this purpose include: (i) development of novel designs of HVAC machinery with higher internal efficiency [13], (ii) implementation of advance schemes for controlling temperature, CO₂ level, air-bypass, among others [14], (iii) integration of renewable energy sources to traditional building systems [15,16], (iv) development of novel technologies (like radiant walls and ground heat exchangers) [17], and (v) design of customized and localized ventilation systems [18].

Following the developments in sensor and computation technologies in recent decades, physical products in our lives are transformed following two main trends: (i) they are controlled with more sophisticated algorithms (that makes them more ‘intelligent’) and (ii) they more intensively interact with each other and people. Accordingly, the cyber technologies bridge human experience and natural phenomena in a more intense and interactive manner in the buildings. This relies on a deeper semantic integration and synergetic interplay between *cyber*, *physical* and *social* realms [19]. Here the term “social” refers to any human related concern of systems including personal, inter-personal or society level perspectives. These concerns are expected to provide a deeper understanding of interaction of people with technological systems and to guide designers for developing technologies with high acceptance. Depending on these three distinct pillars, design and development of modern complex systems require holistic perspectives and integrative methodologies. Cyber-physical-social systems (CPSS) conceptualization is one of those that attracts attention of researchers for almost a decade.

Being an extension of well-studied topic of cyber-physical systems (CPS), CPSSs incorporate human intelligence and machine intelligence to deal with physical world [20]. Based on information fusion among human, computers and physical world, CPSSs exploit the diverse nature of its components to augment human experience in high performance buildings as well as other fields like (semi-)autonomous transportation and health [21]. Leveraging the interaction of people and automated processes not only develop personal experience, but also make it possible to operate systems more effectively. Thus, integrative nature of CPSSs makes it possible to use resources more efficiently in buildings by incorporating both technical and human driven interventions. Having highest share in building energy consumption, HVAC is the system that CPSS approach can leverage efficiency with the highest impact.

1.2. Research Objectives of the Thesis

Following the discussion provided above, this thesis study focuses on decreasing the environmental footprints of buildings by leveraging the adaptability of HVAC systems to occupant-driven and environmental factors with the CPSS perspective (Figure 1). More specifically, the study proposes an innovative adaptive vent system (AVS) that is intended to provide localized and customized thermal conditions and decrease the energy wastes of the HVAC operations. By doing so, the AVS is expected to augment occupants thermal experience that is based on co-evaluation of physical, technical and social modalities. To accomplish these objectives, a prototype of the AVS was deployed to an office in an academic building, following the living lab perspective.

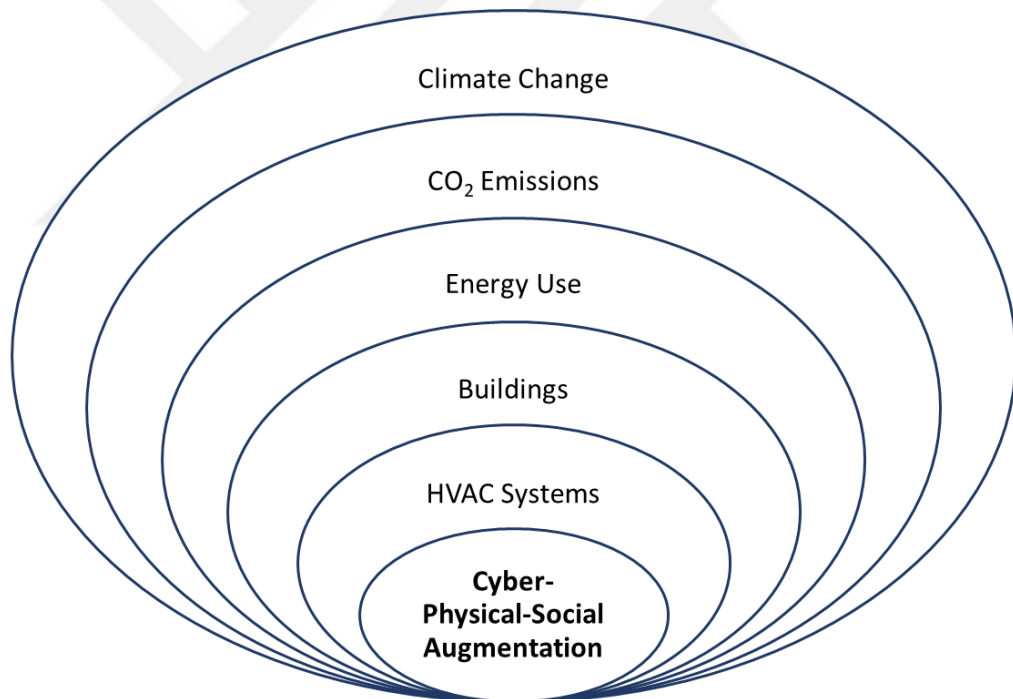


Figure 1: The Conceptual background of the thesis study.

The study also presents a design and development framework for cyber-physical-social building energy systems (CPSBES) as well as a novel modeling approach to support this framework. The framework guides researchers from early conceptualization to prototype deployment in terms of ontologies and data management. The proposed modeling

approach synthesizes hybrid dynamical modelling (cyber and physical content) and behavior modeling (social content) to effectively model the CPSBES designs. The performance analysis of the AVS was also supported with CFD simulations. Thus, the study aims to present a comprehensive approach that facilitates interdisciplinary research perspectives on building energy systems by focusing on the conflicts between energy efficiency and customized building operations.

1.3. Outline of the Thesis

This thesis study presents research effort with both theoretical and experimental perspectives in the following seven chapters. The organization of the study and the interdependence between sections of each chapter is shown in Figure 2.

Chapter 1 *Introduction*, presents the background and focus of the research effort and gives the outline of the thesis.

Chapter 2 *Review of Cyber, Physical and Social Realms for Building Energy Systems*, presents the review of the cyber, physical and social context related to building energy systems, mostly focusing on HVAC systems. The content of each realm establishes the foundation for the design, development and analysis of AVS in the following chapters.

Chapter 3 *Methodological Framework for Developing CPSBES*, outlines the design and development process of building energy systems as CPSS. The modeling phase of the framework (Section 3.3) presents a novel approach for modeling CPSS. The approach is an extended version of hybrid dynamical modeling and outlines how to co-evaluate the discrete (for cyber realm), continuous (for physical realms) and behavioral (for social realm) context for a specific design.

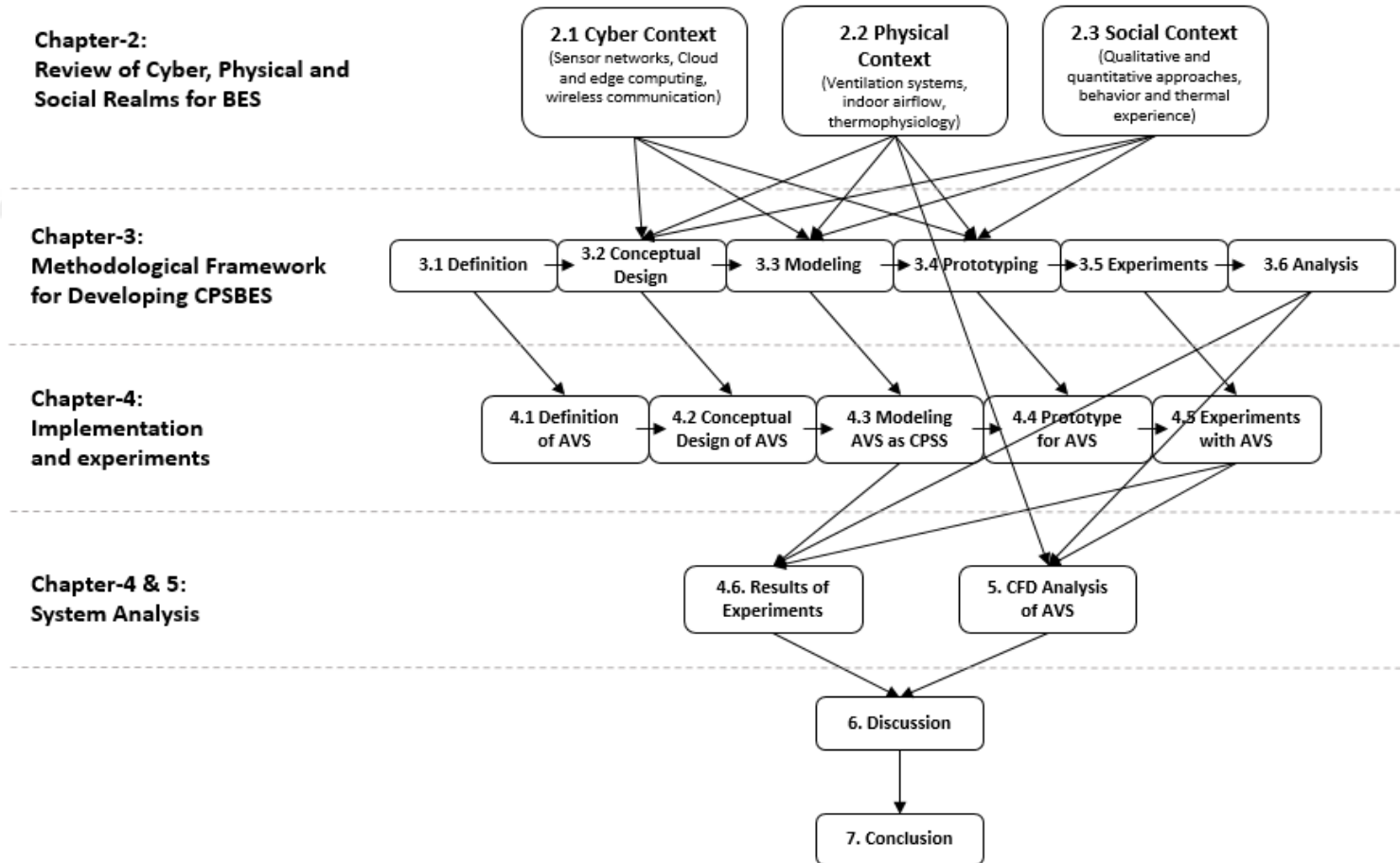


Figure 2: Organization of the thesis study and the interdependence between sections (CPSS: Cyber-physical-social systems; BES: Building Energy Systems; CPSBES: Cyber-physical-social building energy systems; AVS: Adaptive vent system; CFD: Computational Fluid Dynamics).

Chapter 4 *Implementation and Experiments*, explains the application of the proposed framework for the design and development of AVS and the experimental procedure for the validation of CPSS model of AVS is explained. Moreover, the chapter presents the outcomes of the experiments and compares the results of simulations (based on novel modeling approach) with experiments.

Chapter 5 *CFD Analysis of AVS*, presents the CFD based performance analysis of the AVS. CFD based indoor airflow simulations were match with thermoregulation model for human body in order to assess the thermal comfort performance of the system comprehensively.

Chapter 6 *Discussion*, presents the detailed evaluation of the AVS, based on the results of experiments and simulations. The design concerns of the AVS are revisited in the light of these evaluations.

Chapter 7 *Conclusion*, presents a summary of the study with the limitations and future research orientations.

2. CYBER, PHYSICAL and SOCIAL REALMS OF BUILDING ENERGY SYSTEMS

Bringing together the cyber, physical and social realms, the overarching nature of CPSS concept makes it a proper framework for leveraging energy efficiency of building energy system. Synthesis of domain specific aspect for each realm is impossible without a holistic perspective. Hence, CPSS modeling approaches can help researchers to systematically deal with complexity of software (cyber) and hardware (physical) entities as well as human behavior (social) [21]. In this manner, commonly used context-based ontologies for CPSSs map domain specific and general (cross-domain) ontologies as well as the interaction among them [22]. This helps researcher and developers to establish a foundation for the integration at the further design and development stages. Based on this foundation, this chapter reviews cyber, physical and social contexts related to building energy systems (specifically for HVAC systems) that will be interrelated in the next chapter to conceptualize a methodology for CPSBES design and development.

2.1. Cyber Context

The term ‘cyber’ refers to the technologies that facilitates computation and communication capabilities for the products and systems. The fundamental cyber technology applications in HVAC systems of modern buildings are sensor networks, edge and cloud computing, wireless communication and model predictive control. The vast majority of the data-driven advancements in building energy management depend on these technologies. As an example, the transformation from simple room thermostats to MPC based high-level set point generation for controlling thermostats would be practically possible with the implementation of each of these technologies at a certain level [23]. In other words, manipulating physical environment for energy savings and occupant comfort is only feasible (both technical and economical) with the involvement

of cyber technologies. The following subsections review these technologies in term of their functions and advances in the field of building energy management.

2.1.1 Sensor Networks

As like in many other systems, sensors have a crucial role in building operations. Important physical parameters related to the indoor environment and the human-centric parameters related to social life inside the buildings are observed by means of sensors. The automated building system operations are depending on human decisions and are supported by the information extracted from sensor networks. As more sensors are installed and their data is used effectively, built environment would be more comfortable and the energy wastes would be prevented [24].

Commonly deployed sensors for monitoring indoor physical environment are temperature, humidity, carbon dioxide (CO₂), volatile organic compound (VOC), air velocity and light intensity sensors [25]. These parameters determine the thermal comfort, visual comfort, indoor air quality and energy performance of the buildings. When compared the others, temperature sensors are the most deployed ones due to the high importance of temperature for building operations, energy efficiency and occupant comfort [26]. Temperature is the fundamental parameter for HVAC control and under the influence of environmental conditions and HVAC operations (heating and air-conditioning). In accordance, these sensors are highly available with variety of types (different sensing technologies), sensitivity and price tag. In most of the modern buildings, temperature sensors are coupled with humidity sensors to assess the indoor thermal conditions to provide feedback to HVAC system and have direct impact on energy performance of a building due to the high share of HVAC loads [27]. In recent years, in addition to temperature and humidity sensors, CO₂ and VOC sensors are getting popularity to monitor indoor air quality. These parameters are also outcome of the HVAC

system operation (ventilation) and important for energy performance [27]. For effective control of HVAC systems, in addition to meeting certain accuracy criteria, these sensors should also be deployed in proper positions that can represent indoor environment around the occupants [28,29].

Air velocity sensors are not commonly deployed in or around the occupied zones of the buildings but instead deployed inside the HVAC ducts to monitor the airflow. Two important reason for this limitation are: low air velocity values ($<0.5\text{m/s}$) that are difficult to detect with economically available sensor models, and (ii) measurement disturbances due to the occupant movements. Furthermore, due to their expense and similar values of air speed for each system mode, the mobile air velocity sensors are used during experiments and audits for control and maintenance of HVAC systems, instead of mounting airflow sensors to fixed positions for regular operation periods [30].

As well as indoor environment, building energy consumption is a function of outdoor environmental conditions. Outdoor temperature, humidity, air quality, irradiance, wind speed and wind direction are the important outdoor environmental parameters and have specific sensor types. The information coming from these sensors are used for the system control (HVAC, shading, among others) as well as predicting the system loads for short time intervals [31]. Typically, outdoor temperature forecasts are used for predicting HVAC loads, which has the highest share of building's total energy consumption [32].

Another important parameter related to indoor environment is lighting level. It is measured with lux meters and used for monitoring visual comfort and providing feedback to lighting automation system. Having a lighting level data, a lighting automation system balances natural and artificial lighting to save energy [33]. When coupled with outdoor

irradiance sensors, it can be used for dynamically controlling the solar shading systems, that have crucial role for visual comfort as well as cooling load savings [34].

Beside the parameters related to physical environment, social life inside buildings is also monitored for managing building systems. Presence, number, identity, location and the activities of the occupants are the parameters to monitor state of occupancy inside the buildings [35,36]. Presence is the easiest and most common parameter to detect and there are variety of sensor types for this purpose. PIR sensors, ultrasonic sensors, chair sensors, motion detectors are used for detecting if there is any person inside a room [25]. The human counters are more complicated and image processing-based sensors to determine the number of people inside a room [35,37]. Moreover, Bluetooth[®] low energy beacons and integrated sensors make it possible to monitor even position of people inside a room [36]. Occupancy information of a room is mostly used for making decisions on the system activation. Advance building control solutions follow occupancy patterns and manage lighting and HVAC systems in an adaptive manner to maximize energy savings [38,39]. Thus, these sensors are vital to operate building energy systems in an efficient way and prevent energy wastes. In parallel to recent developments in technology, there are research efforts to use wearables and smart phones to gather data directly from occupants [40]. Furthermore, smartphone based mobile applications are used for remote control of HVAC (or lighting) systems as well as following the performance evaluation of the system operation by occupants [41].

Beside building monitoring and control, increasing availability of fine-grained data related to physical dynamics of the building makes it possible to perform better building performance simulations since empirical determination of some difficult to measure parameters (like internal thermal mass, zone air infiltration rate, among others) become possible [42].

2.1.2 The Cloud and Edge Computing

The advances in digital technologies during last decades brought together the demand for large scale, reliable, highly available, automated and secure computational resources. Following the exponential increase in data-driven intelligent solutions in many sectors, companies started to offer these resources as a service and today the cloud computing paradigm is an essential technology of modern life. On the other hand, inevitable delays, errors and faults during any data transfer (to and from the cloud services) and processing, make it risky or impossible to deploy cloud-based solutions for applications that requires rapid (or real-time) decision making and actuation. To deal with these challenges, the edge computing paradigm is proposed [43]. These systems are back with cloud services but can operate independently at the positions that are physically closer to end-users. In this way, the essential and urgent computation is performed rapidly whereas the storage and high capacity computation is provided by cloud services [44]. As a result, the solutions based on integration of cloud and edge computation are ‘embedded’ in modern life. The synergy triggered by this integration revolutionized product and services in many sectors, as well as building systems.

Cloud computing is a service that provides large scale computer system resources including data storage (short or long term), computation (normal or high speed) and automated application processes (like on-demand machine learning services) [45]. Massive data warehouses operated by specialized companies provide large number of virtual or physical machines dedicated to customers. The companies offering these services deal with the challenges to keep these resources always available in name of their customers. Some of these challenges are (i) automation of system management, (ii) creation and management of virtual machines, (iii) cost effectiveness, (iv) energy consumption, (v) high availability and speed, (vi) integration with other service providers

and costumers, and (vii) cyber security, among others [46–48]. As a result of high demand for cloud services, data centers are responsible of 1.1-1.5% of global energy consumption [49].

Having a centralized structure, a cloud-based application inevitably has limitations for minimum response time. To complement this restriction, a new computing paradigm, called edge computing, is emerged and rapidly developed in last few decades, being subject to influence by smartphone market [50]. Similar to cloud computing, edge computing provides an infrastructure for management, storage and processing power but it is limited to narrower space [51]. Thus, the edge computing complements the response time shortcomings of cloud computing and make it possible for cloud service and utilities being immediately available (ultra-low latency) to end users [52]. Moreover, having connection and computation capabilities, devices facilitating edge computation can interact with each other in a heterogeneous manner (different type of devices) [53]. In this way, edge computing extends cloud computing with a decentralized structure and pave the way for a better interaction with social spaces [54]. It is important to note that edge computing is not the collection of sensors and actuators with limited computational capacity. Instead, it is a dedicated system with reasonable computation and communication capacity that these tiny gadgets can be connected.

The integration of cloud and edge services offers a reliable cyber infrastructure for CPSSs. In a typical application, large scale and noisy data produced by real life applications can be stored and analyzed by means of cloud services [55]. The models and parameters derived from these services can be transferred to edge services for quicker response and higher availability [56]. In this way, end users can take advantage of information or predictions derived from the analysis of long-term data which are computationally heavy and not needed to be performed frequently. Edge devices store

short term data and perform computations that are needed for managing operations. This strategy minimizes the amount of data transferred and bandwidth used [57]. However, designing and realizing such an integration is a challenge. It requires proper physical set-up and effective computational resource management for edge devices to meet end-user demands [58]. On the other hand, as the number of connected devices increase, cyber security risks are also increase and require custom solutions [59]. Moreover, as the real-life gadgets are connected to hybrid (cloud and edge) systems, proactive resource management (including the shifting the peak loads) and providing resource continuity become key enabler of successful implementations [60]. Beside technical challenges, developing business models based on sharing added value between cloud and edge service providers requires developing specific algorithms for dynamic pricing of resource allocation [61].

CPSS applications back with edge-cloud integrations attract attention among scholars and companies from different fields. Smart building is one those fields that involves high interaction and interactivity of people with the systems. Thus, the smart building solutions gather data related to both physical environment and occupant behavior which brings together the challenge of managing, storing and analysis of time dependent data [44]. If a project couldn't derive insights from this data and translate it to actionable abstractions, then the storing this dataset data on cloud and monitoring via interfaces is far from meeting the expectations from 'smart' gadgets. Instead, the decisions should be taken in a short time interval and the systems or occupants should be informed for better actions. As beforementioned, the edge computing is considered as a technology that can meet these expectations.

Real-time energy (electricity) monitoring of smart buildings is a characteristic application field for cloud and edge integration. The electricity and the demand related parameters

are preprocessed in the edge computer (i.e. short-term forecast for voltage and power consumption profiles) and then sent to cloud server for further analysis and storage, which minimizes latency and bandwidth related problems [62]. Moreover, once the building level computation architecture is resolved effectively, it can be extended to involve large number of buildings in a region for more efficient and reliable energy management. Hence, cloud and edge integration provide reliable and scalable solutions not only for the building itself, but also pave the way for smart grid and smart city solutions. On the other hand, efforts in this direction focused on managing and monitoring electricity but there is a shortage of studies that discuss edge and cloud integration for thermal management, i.e. HVAC control.

2.1.3 Wireless Communication

One of the most important enablers of smart solutions is wireless communication since the smart products or services mostly depend on communication with each other or with other services (i.e. cloud, edge, database, among others). Hence, removing the obligation for physical connection and providing fast, error-free and secure communication offers enormous flexibility for product design and efficiency for operation [63]. Even for buildings that involves systems mostly fixed in position, the required cabling for data communication of sensors and actuators is not only expensive but also make it impossible to deploy a gadget for certain cases. Thus, there are many modern communication technologies to make wireless communication fast, low-power consuming and error-free, i.e., WiFi, Bluetooth, Zigbee, Z-Wave, Lorawan, 6LowPan, Sigfox, NB-IoT, among others [43]. In this section, we briefly review just few of these technologies that are commonly used in built environment, namely Wi-Fi, Bluetooth and Zigbee.

Wi-Fi is the most commonly preferred wireless local area networking technology since 1990s that is based on radio waves delivered by an adaptor (a router or hotspot). It is used

by most of the computers, mobile devices and other connected devices to access internet. IEEE's set of 802.11 wireless standards declare the frequency (2.4 and 5GHz), throughput and range of network connectivity provided by this technology as well as the parameters that determine the limits for latency and power consumption [64]. Due to its high availability, reliability, data transfer rate (up to 54mbps) and security, Wi-Fi is the leading wireless communication technology for connected devices today. It is also widely used in built environment for device-to-device and device-to-cloud communication. Beside device communication, there are research activities on using Wi-Fi signals for occupancy detection and occupant positioning in built environment [65,66].

Another radio wave-based solution for short range device-to-device communication is Bluetooth and it is commonly used for personal area networks (PAN) since early 2000s. IEEE 802.15.1 standard determines its frequency to be between 2.4-2.4835 GHz and it's data transfer capacity is between 2.1 and 24MBps [67]. Due to its lower energy consumption compared to Wi-Fi and being independent of adapter or router, Bluetooth is used by many customer products (headphones, fitness trackers, smart watches, among others) as well as sensor networks. Following the popularity of IEEE 802.15.1 (also known as Bluetooth Classic), Bluetooth Smart (also known as Bluetooth Low Energy - BLE- or Bluetooth 4.2) standard is released in 2014 that meets more requirements of IoT such as ultra-low energy consumption, IP support and logical link control [68]. Inside built environment, both Bluetooth Classic and Smart are used for enabling communication between control and monitoring devices and connecting building systems to user interface on mobile devices today [25]. Beside connectivity, it is also used for occupant detection and tracking inside buildings [69].

Beside general-purpose wireless communication technologies like Wi-Fi and Bluetooth, there are more specific solutions for low rate and low power device-to-device

communication. ZigBee is one of the earliest and the most commonly deployed technology among those. Its specification is determined by IEEE 802.15.4 standard that declares communication in 2.4 GHz and maximum data transfer rate of 250 kb/s [70]. Its low complexity, mesh networking capability, low power demand make ZigBee a proper solution for smart home, building automation and medical device applications, among others. Being a proven technology for indoor environment, Zigbee is a low-cost and license-free alternative for Wi-Fi and Bluetooth for building monitoring and automation [71].

2.1.3 Model Predictive Control

Being initially implemented in process control of chemical and petrochemical industries in the last quarter of twentieth century, model predictive control (MPC) has attracted attention of researchers from both the industry and academia as an advanced multivariable control method [72]. The reason for the interest is the promising outcomes of finding solutions based on online optimization that evaluates system dynamics, constraints and control objectives [73]. MPC uses a model of the system to evaluate its response to certain inputs (in accordance with constraints) and then optimize a sequence of control actions to reach control objectives [72]. In other words, MPC takes advantage of the process model (system dynamics) to deliver a control signal that meets the pre-determined constraints and control objectives.

Control applications in built environment are investigated by scholars for MPC adaption. The control of various HVAC technologies with energy optimization is one of the well-studied topics. These research activities mostly focused on finding optimal temperature set points either only evaluating temperature information or with some additional parameters (i.e. outdoor weather conditions, occupancy profile, thermal comfort, occupant feedback, among others) [32,74]. Since there isn't a standardized developing

strategy (as like in PI and PID control) for MPC, different modeling and formulation strategies for MPC are also under investigation.

There are two main challenges of MPC applications in built environment: solving optimization equations and adopting physical models (system dynamics). For solving optimization equations by dealing with the uncertainties, fuzzy modeling [75,76], stochastic modeling [77,78] and adaptive modeling [79] approaches are implemented. For physical modeling, white-box (physics-based formulations), grey-box (empirical models) and black-box (statistical models) models can be used. Adopting simplified CFD based thermal comfort formulations would be an example of physics-based modeling for MPC applications in HVAC research [80]. However, deploying this kind of solutions that based on white-box models on embedded systems is a challenge due to their high computational requirements. Thermal network models, on the other hand, are commonly used examples of grey-box modeling for MPC whereas artificial neural networks are the well-studied examples of white-box modeling for MPC based HVAC research [74,81]. Thus, the first step of a successful MPC applications is determining proper optimization and physical modeling approaches. Then, the hardware for computation should be selected or developed.

2.2. Physical Context

The quality of life inside a building is highly related to the physical properties of the circulating air. Thermal comfort and the air quality are just functions of the temperature, velocity and particulate matter content of the indoor air. These properties are controlled by the HVAC system and for the assessment of those, one need to analyze the characteristics of the indoor airflow. The primary modeling and simulation tool for this is the computational fluid dynamics (CFD) and computational heat transfer (CHT). Being subject to their own limitations in accuracy and reliability, these numerical approaches

can provide a deep understanding of airflow patterns in a given zone under different conditions. However, due to the large and non-linear set of governing equations solved, CFD and CHT analyses have high computational cost. This leads researchers to use thermal network modeling for getting insight related to temperature changes of a given point using less computational resources. Thus, this section briefly reviews the physical concepts and the corresponding systems of indoor air flow, its relationship with thermal comfort, the thermal network modeling and the CFD/CHT analysis. In the rest of the thesis, CFD abbreviation is used to mean both the CFD and CHT simulations.

2.2.1 Ventilation Systems

As the buildings get larger, it becomes impossible to meet ventilation and air conditioning needs with natural ventilation modalities (windows, doors, tall ceilings). Being an essential component of modern buildings, modern HVAC solutions have evolved extensively during the last century with the deployment of variety of ever improving technologies. The ventilation strategy has always been an integral and crucial part of solutions that aims to meet health and comfort criteria. Beside these fundamental concerns, the design and deployment of these systems are also expected to meet variety of criteria and parameters for an effective and efficient service life. Ventilation efficiency, air diffusion performance index and temperature stratification are just few examples of these concerns [82].

Two fundamental factors that characterize a mechanical ventilation system are position and the geometry of air terminal units (ATU). In terms of position of ATUs, common ventilation strategies deployed in modern buildings are mixing, displacement and personalized ventilation (see Figure 3 for graphical comparison). In a mixing ventilation system, both inlet and outlet ATU are fixed into the ceiling. Air usually has a speed of larger than 1m/s at inlet and is intended to create a mixture of fresh and older air in

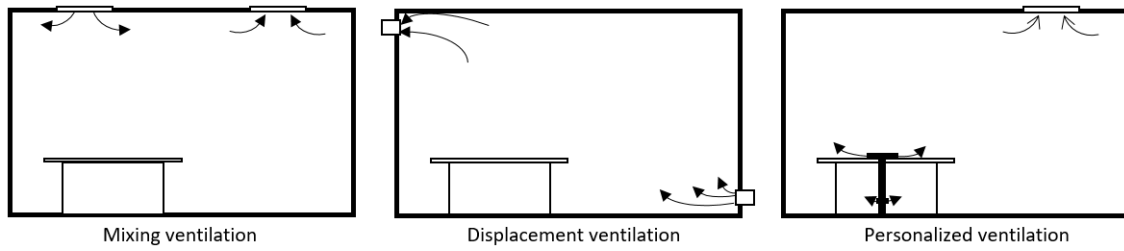


Figure 3: Common ventilation strategies deployed in modern buildings.

occupied zone by keeping contaminant density and movement as low as possible [83]. In a displacement ventilation system, inlet ATU are located at or near to floor where the outlet ATU are positioned near or on the ceiling. Hence, the air movement takes advantage of buoyancy forces for indoor movement and interact with other heat sources (computer, human, among others) effectively. This causes a requirement for comparatively lower air inlet speed [84]. On the other hand, personalized ventilation aims to deliver fresh and conditioned air just around the micro environment of occupants by means of furniture integrated mini ATU to provide local thermal comfort in an energy efficient way [85]. These strategies are based on delivering conditioned (heated or cooled) air and fresh air with separated ducts. However, the ventilation systems based on a strategy called ‘all air delivery’ offers to provide conditioned and fresh air within same ducts and becomes preferable in modern buildings.

The geometry of the ATU is another important concern for a ventilation system in order to characterize indoor airflow. The common geometries of ATU are nozzle, valve, displacement, grille, slot, square ceiling, round ceiling, vortex, conical and wavy types [86,87]. Combined with the air temperature and speed, the geometry and location of ATU determine the characteristics of indoor air flow that is explained with indicators like draft rate, temperature gradient and radiant temperature asymmetry [88].

2.2.2 Indoor Airflow Regime

The physics behind the indoor air flow is governed by heat transfer, buoyancy forces, Coanda effect and jet forces. Each of the conductive, convective and radiative heat transfer mechanisms are effective on indoor air movement. However, since the heat transfer processes are not fast and air is not mixed homogeneously, there is always air volumes with different temperatures and the hot air moves up by the time due to its lower density. In other words, buoyancy force inevitably results in temperature segregation on vertical axis inside the zones. Moreover, the air jet entering the room triggers the air movements inside the room and tends to stay attached to the ceiling (or walls). This phenomenon known as Coanda effect and very impactful on the airflow regime [89]. One can control these forces by changing air inlet temperature and velocity as well as the geometry of the inlet diffusers. Under the determinacy of these factors, the HVAC systems control the air quality, temperature distribution and velocity fields inside the zones. Accordingly, a clear understanding of indoor airflow requires solid knowledge on driving forces behind it. Hence, this subsection starts with an overview of them and the following subsections discusses air jet and air flow characterization based on these forces.

2.2.2.1 Driving Forces of Airflow in Built Environment

Air inside a room is subject to three types of heat transfer: conductive, convective and radiative. Conductive heat transfer to or from the indoor air is through the indoor surfaces of the room walls, floor and ceiling. The temperature change of indoor air due to the conductive heat transfer is division of heat transfer through a surface (due to the temperature difference between two side of walls) to the heat capacity of indoor air [90]. Convective heat transfer inside a room can be investigated under two categories: natural and forced convection. The natural convection is driven by buoyancy forces whereas the forced convection is driven by HVAC machinery (air inlet from diffusers). The surface

temperature of walls and windows, even that of human body can result in heat transfer by means of natural convection (plumes created by human body) [91]. While modeling the indoor air flow, this kind of heat transfer from the surfaces is approximated with empiric constants (e.g. 37.4 W/m^2 in average for the human body [92]). On the other hand, the heat transfer with forced convection is a more complex phenomenon and further discussed in the next section. Radiative heat transfer doesn't change indoor air temperature directly but instead change the temperature of indoor surfaces (including human body) and trigger natural convection on these surfaces [93].

As mentioned above, usually there are air volumes with different temperatures inside a room. This results in density differences and drives air flows due to buoyancy. Especially the air close to the hot or cold surfaces is subject to change in density and contribute buoyancy driven air flows. If the large buildings are designed properly, buoyancy driven air flows can provide natural ventilation and contribute decreasing cooling loads [94]. Beside these macro scale airflows, even the human body can trigger buoyancy driven micro airflows (plumes) when there is a considerable temperature difference with the surrounding air [95]. The volume of the air in this kind of flow is small when compared to air flows driven by mechanical ventilation inside a room. However, it has direct impact on thermal comfort due to the close distance to human body. Thus, Richardson number (Grashoff number divided by the square of the Reynolds number) is used to quantify the effect of buoyancy around human body [96].

Following the entrance of air to the zone, the pressure field between jet and ceiling is smaller than the one between jet and rest of the room. This pressure difference leads jet to curve towards surface [97]. This phenomenon known as Coanda effect and impactful for air circulation inside a room. The distance that the air stream attached to surface is related to balance between Coanda effect and the buoyancy forces as well as the throw

angle and momentum of a diffuser [98]. Especially for the heating mode and low throw angles with ceiling, this distance under the influence of Coanda effect is longer. Due to the higher density of cold air, the attached distance is shorter in cooling mode for a given diffuser. Thus, the Coanda effect is crucial for the formation of the entrance point and speed of supply air to the room, that is important for thermal comfort. In other words, the Coanda effect plays an important role on the formation of indoor airflow patterns and thermal comfort level.

Being subject to these factors, forced air entering to a room from diffusers with a certain momentum creates a jet. A jet of air is a type of flow characterized by the interaction of air leaking from an opening (primary fluid) with the already existing air volume (secondary fluid) [99]. It is called "free jet" if it moves without hindrance following the entrance and called "wall jet" (or plane jet) if attached to a surface [89]. Both flows have its own characteristics due to the different boundary type (free or wall). When the temperature of air jet is equal to temperature of indoor air, it is called "isothermal jet". In case of non-equivalence, it is called "non-isothermal". The velocity across a jet is zero at the boundaries. On the other hand, it is at the highest level at the center of a free jet and at the region next to the surface of a wall jet [99]. Depending on the design of air terminal unit (ATU) (diffuser), the geometry of the jet is formed: linear, compact, radial, conical and swirling jets are some of the well-known jet geometries [100]. Under the influence of buoyancy forces and Coanda effect, jet type and air velocity are most important parameters for indoor air flow regime since they determine the momentum of inlet air.

2.2.2.2 Air-jets and Airflow Patterns

The flow characteristics of an air jet initially depends on the type of the jet (free or wall). For modern HVAC installations, both types are applicable depending on the ventilation type. Free jet is a proper model for typical displacement ventilation systems whereas the

wall jet is for ceiling diffusers in mixing ventilation successfully. In accordance with the system design and the experimental set-up of this study, only a discussion for the characteristics of the wall jet in a mixing ventilation system is provided here.

The flow regime formed by the air leaving an air terminal unit of an HVAC system is affected by the dimensions of ATU and the thermal characteristics of air (isothermal or non-isothermal). The ratio of length to the width of a rectangular object is known as aspect ratio [101]. In this sense, air jets leaving an ATU with large aspect ratio (e.g. long slot diffusers) are known as two dimensional. In the opposite case where the air jets leaving an ATU with small aspect ratio (e.g. square ceiling diffuser) are called three dimensional [102]. There are three observable regions on the vertical cross-section of a three-dimensional isothermal wall jet whereas the forth one is called *terminal region* and out of the impact of jet (Figure 4).

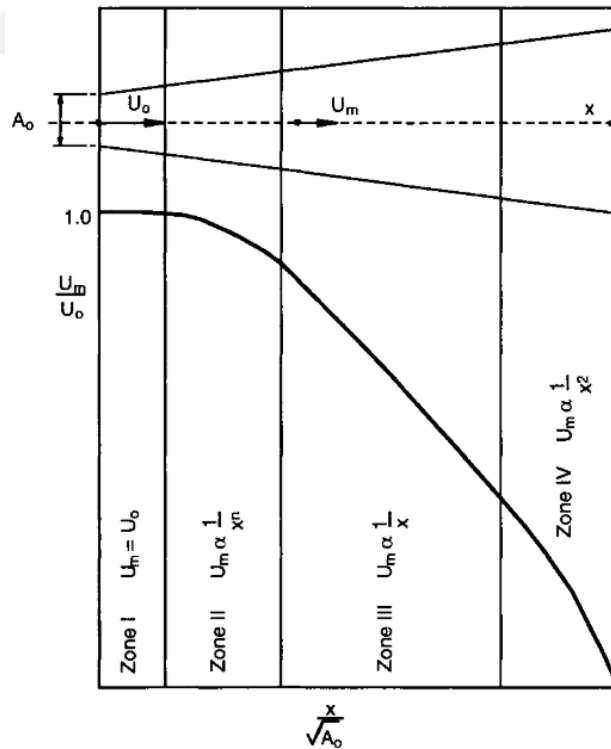


Figure 4: Vertical cross-section and velocity profile of an air-jet with four regions that have different flow characteristics (Adopted from [99]). Note that the figure represents a free jet but the separation of the regions is similar for wall jets. For the corresponding formulations, see text (Eq. 2.1 to Eq. 2.2).

The length and speed properties of each region is as follows [99]. In the first region, known as potential core, the air speed is almost equal to ATU exit speed and its length would be up to 7 times of the height (width) of ATU [99].

$$\text{Length of the first region} \leq 7h \quad (2.1)$$

$$\text{Velocity in the first region} = U_m = U_0 \quad (2.2)$$

The length and velocity profile of the second region, known as characteristic decay, is given by the following equations:

$$\text{Length of the second region} \leq 30 \cdot \sqrt{A_0} \quad (2.3)$$

$$\text{Velocity decay in the second region} = \frac{U_m}{U_0} = \frac{K_v}{\sqrt{x/h}} \quad (2.4)$$

where K_v is determined empirically to be around 3.5. In the third region, known as radial decay, the velocity profile is given by the following equation:

$$\text{Velocity decay in the third region} = \frac{U_m}{U_0} = \frac{14}{x^{1.15}} \quad (2.5)$$

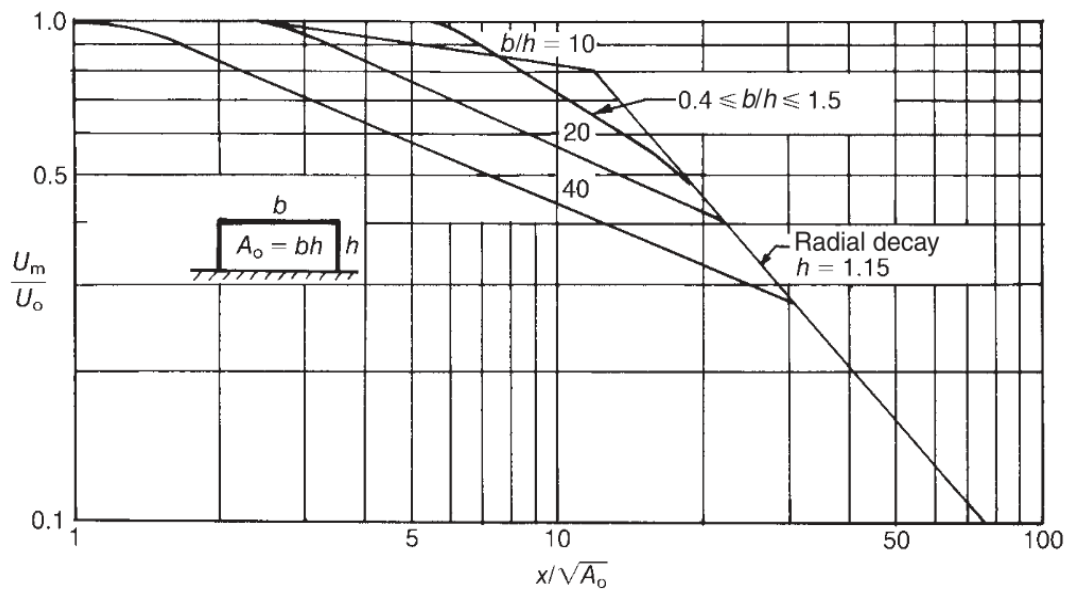


Figure 5: The relationship between velocity decay profiles and aspect ratio for a rectangular wall jet (Adopted from [103]).

As can be interpreted from the equations above, the velocity decay profile of a three-dimensional air-jet leaving a ATU highly depends on aspect ratio. For a rectangular wall jet, the relation is shown in Figure 5. Moreover, experiments suggest that, for the wall jets with different ATU geometry, there exist a very similar velocity decay profile as shown in Figure 6. When the HVAC system is only used for ventilation, that is heating or cooling is not activated, these formulas for isothermal flows can be used for evaluating flow regime where the inertia forces are dominant. On the other hand, when heating or cooling system is activated, the flow turns to be non-isothermal and the development of the jet is influenced by the buoyancy forces as well. This factor is quantified with a non-dimensional number called Archimedes number (Ar) as [103]:

$$Ar = \frac{g \cdot \beta \cdot \sqrt{A_0} \cdot \Delta T}{U_0^2} \quad (2.7)$$

where g is gravity force, β is the gas cubic expansion coefficient ($\sim 1/T_0$), A_0 is the effective area of supply opening, U_0 is the air supply velocity and ΔT is the temperature difference between supply air and indoor environment. As can be interpreted from Eq 2.7,

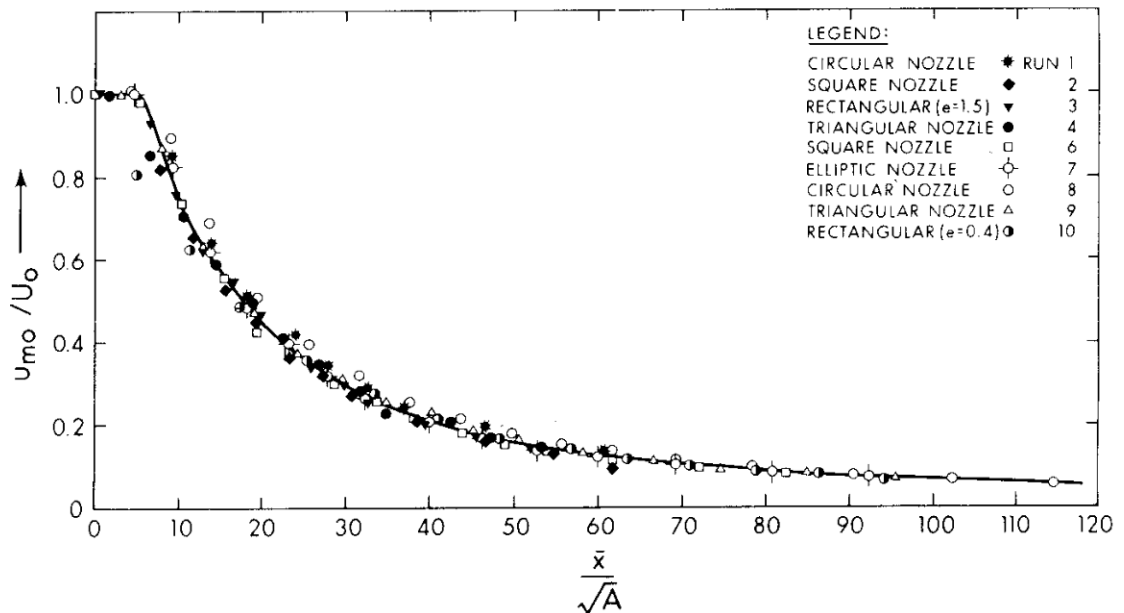


Figure 6: Nozzle geometry dependence of jet velocity profiles (Adopted from [102]).

containing the terms for inlet velocity and temperature change, Ar depicts the relation between the inertia forces and buoyancy forces acting on an air-jet. Hence the non-dimensional Ar is crucial to understand the path of an air stream. As an example, a cold air flow entering to a hot room tends to leave ceiling earlier when the Ar is large. This is due to the fact that buoyancy force dominates the flow since the density of the cold air is higher than hot air.

The temperature decay profile of an air jet is similar to velocity decay profile but quicker than that since energy diffusion is more intense than momentum diffusion. The relation between the velocity and temperature decay profiles can be formulated based on the experimental data as [104]:

$$\frac{U}{U_m} = \left(\frac{\theta}{\theta_m}\right)^2 = \left(e^{-0.8(\eta^+)^{1.4}}\right)^2 \quad (2.8)$$

where U represents non-dimensional velocity, θ represents non-dimensional temperature $((t_{ambient} - t)/(t_{ambient} - t_{inlet}))$ and η^+ is the shift in similarity variable at local maximum. The graphical comparison of velocity and temperature decay profiles based on an experimental data is given in Figure 7 [104].

As well as the characteristics of a single air jet and its impact on indoor environment, an understanding of interaction of two jets is also important. Experiments show that jets on a plane merge and behave as a single jet at a certain distance. The distance that they merge is depend on the areas of outlets, distance among outlets and the velocity of air jets at outlets [103]. The representation of an ideal case that has three identical air jets thrown from circular outlets (where $S/\sqrt{A_0} = 2.8$ and $Re = 8 \times 10^4$) on a plane is shown in Figure 8.

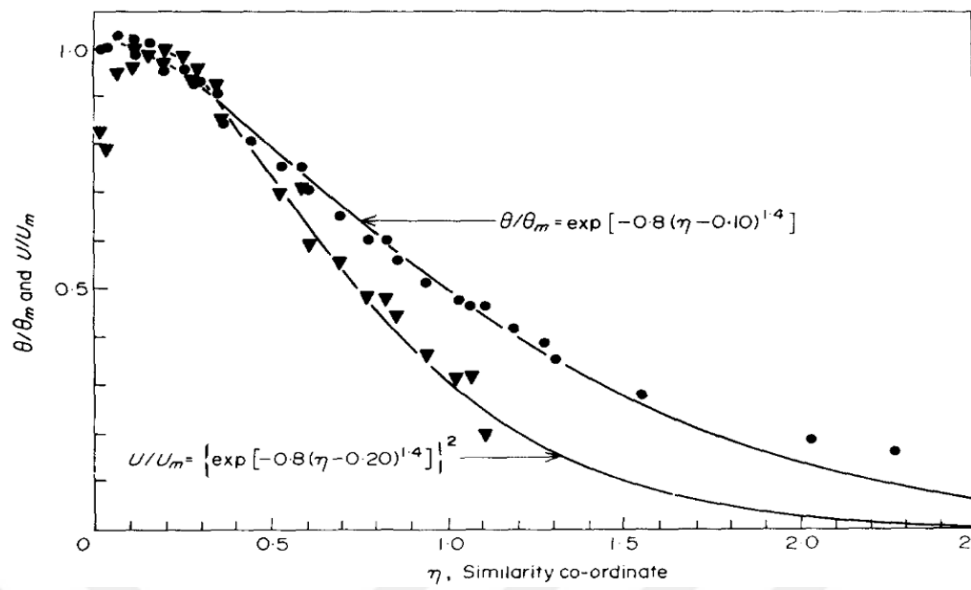


Figure 7: Comparison of velocity and temperature decay profiles (Adopted from [104]).

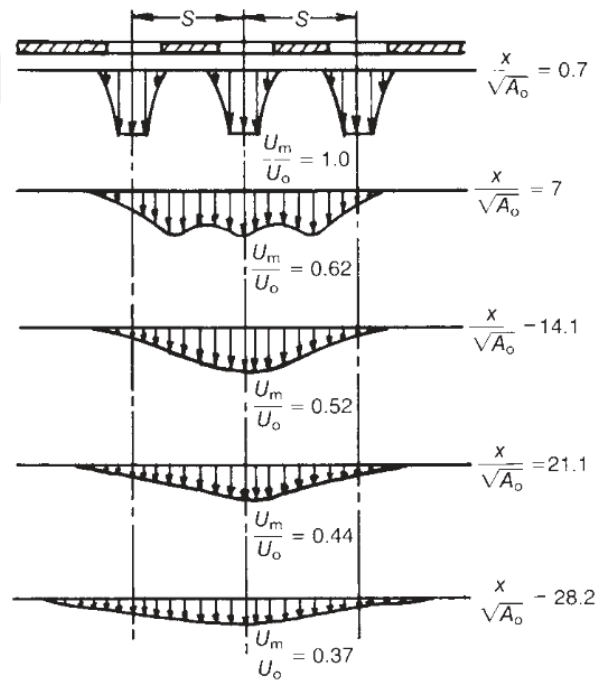


Figure 8: Merging of three air jets thrown from circular outlets (Adopted from [103]).

2.2.3 Thermal Comfort

Probably one of the most important parameters for a resilient indoor environment is the thermal comfort. People, in general, desire to live in environments where their thermal sensation is neutral, that is they do not want to have the feelings of extra warmth or coolness. From a heat transfer point of view, this would be possible only if the heat balance is established among human body (or its parts) and the environment. Regulation of heat transfer between the parts of human body and between body and environment has been under investigation for more than a century by physiologists under the light of laws of thermodynamics and heat transfer. We cannot have complete autonomy of our body temperatures, that is, we cannot change the temperature of any part of our body intentionally; this concept was discovered many centuries ago. However, the role of nervous system in the control of thermoregulation and the thermodynamic essentials of the control mechanism were initially understood in the early decades of the last century [105].

The science and technology related to heating and cooling of buildings have evolved since the second half of 19th century in line with the developments in the industrial systems. Even the pioneers of the building heating systems were aware of the importance of human dimension, the engagement of their expertise with the human physiology could not be formulated until mid-20th century [106]. In those years, with the pioneering studies of American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), the empirical formulations and practical guidance for thermal comfort within the form of annexes appeared. The first version of *ANSI/ASHRAE Standard 55: Thermal Environmental Conditions for Human Occupancy* was published in 1966. On the other hand, the research activities conducted in other fields also contributed to progress. As an example, the publication of a research report by NASA, named *A Mathematical Model of*

Physiological Temperature Regulation, was an important step for a better understanding and modeling of thermophysiology which also leveraged the studies on occupant thermal comfort in the following years [107]. In accordance, there are many ongoing research activities today to provide better thermal environments benefiting a deeper understanding of thermoregulation, thermal comfort, advanced HVAC design and related simulation software. Hence, for a reliable evaluation of thermal experience provided by a novel HVAC system, one needs to have a solid understanding of thermophysiology, thermal comfort standards, corresponding occupant behavior and the interaction among them. Hence, this section provides an overview of these topics.

2.2.3.1 Thermophysiological Modeling of Human Body

The ultimate goal of thermal regulation in the human body is to keep the temperature of core parts of the metabolism around 36.5°C. In order to meet this requirement, human body has to adopt itself to environmental conditions and deal with both internal and external thermal disturbances. Accordingly, thermophysiological models explain the mechanisms of heat exchange and temperature control within the human body as well as the thermal interaction of body with its environment.

Modern thermophysiological models consider human body as two interrelated systems: a passive system (controlled) and an active system (controlling) [108]. The passive system refers directly to human body and the models of it represent heat transfer among different parts of the body as well as the thermal interaction of parts of body with the surrounding environment. More specifically, the passive system models explain the dissipation of heat produced by metabolism by characterizing the heat storage and transfer properties of different parts of internal body and skin (including the effects of clothing). On the other hand, the active system regulates the temperature of different parts of body with the metabolic functions such as vasoconstriction, vasodilation, shivering and sweating that

controls blood flow rates and heat fluxes [109]. While selecting the thermal regulation actions, the signals for the mean skin temperature, the core temperature of head and the rate of change of skin temperatures are the main parameters [105]. On the other hand, these parameters are under the influence of both environmental (temperature, humidity, air velocity, temperature of a contact surface, among others) and personal (metabolic rate, skin surface area, fat percentage, gender, clothing, among others) factors [110]. Consequently, the interaction among active and the passive systems results in a complex thermoregulation scheme which needs to be addressed when considering human-building interactions.

An important concern related to modeling of the thermophysiological modeling is the partition of human body. The simplest thermal comfort models are empirical and consider the human body as a single part by ignoring the thermoregulation. More detailed models involve two or more parts that facilitate thermoregulation. The partition is based on the representation of limbs (head, arm, hand, foot, among others) and the layers of body (core, muscle, fat, skin) in a way that each part has unique heat storage and transfer coefficients. Hence, the multi-part models are expected to formulate the interaction among parts as well. The two common terms used for referring the partition are “segment” (generally the name of the limb) and “node” (layers of body). Simplest models are single-segment models without any layers, such as the well-known Fanger’s model [111]. More detailed models involve multi-segment (two-segment, six-segments, fourteen segments, among others) and multi-layer (two-node or multi-node) partitioning, like Stolwijk and Fiala’s models [107,108].

A well-studied multi-segment and multi-node model is Stolwijk’s model that was originally developed for NASA’s Apollo mission. It’s passive system involves six segments (head, trunk, arms, legs, hands and feet) with four nodes in each (core, fat,

muscles and skin) as well as a central blood compartment [109]. Following the Stolwijk's approach, modern mathematical representations of the heat balance in human body involves (i) 14 segments (head, trunk, each arm as lower and upper parts, hands, each leg as lower and upper parts, feet), (ii) 4 nodes for each segment and (iii) a central vascular system. Pennes' bio-heat transfer equation is used for modeling heat transfer in each of these 56 nodes (14 segments X 4 nodes for each) [112]:

$$k \left(\frac{\partial^2 T}{\partial r^2} + \frac{w}{r} \frac{\partial T}{\partial r} \right) + q_m + \rho_{bl} \cdot w_{bl} \cdot c_{bl} \cdot (T_{bl,a} - T) = \rho \cdot c \cdot \frac{\partial T}{\partial t} \quad (2.11)$$

where ρ is the tissue density (kg / m^3), c is the heat capacitance ($J/(kg \cdot K)$), and k is the conductivity ($W/(kg \cdot K)$), T is the tissue temperature ($^{\circ}C$), t is time (s), r is the radius of the node (m), g is the geometric factor coordinate system (1 for polar and 2 for spherical), q_m is metabolism (Wm^{-3}) and w_{bl} is rate of blood flow, respectively. Note that bl refers to properties of blood whereas bl, a refers to that of arterial blood. The first term in Eq. 2.11 represents the heat conduction (based on Fourier's law), second represents the metabolic heat generation, the third term represents the heat of blood and the fourth one represents the heat storage in the corresponding node. Heat exchange while blood is flowing over each component is the physiological mechanism of thermal regulation. In this heat balance equation, the stored heat in the blood should be considered specifically because of the assumption of the model that states the existence of "the central blood compartment" [108]. Blood flows coming from different parts of the body are assumed to mix here in a way that the highly efficient heat exchange may occur. Hence, the heat balance equation for central vascular system is formulated as [113]:

$$\dot{Q}_{ST,BLOOD} = \sum_{j=1}^{14} \left(\sum_{i=1}^4 \left(-\dot{Q}_{BLOOD_{i,j}} \right) \right) \quad (2.12)$$

where j denotes body segments and i denotes the nodes for each segment.

The heat produced by human metabolism ($\dot{Q}_{MET}$) is either stored in the body ($\dot{Q}_{ST}$) or dissipated by (i) the convective and radiative heat transfer on skin ($\dot{Q}_{SKIN}$), (ii) the evaporation of sweat on skin ($\dot{Q}_{EVAP}$), (iii) the respiration ($\dot{Q}_{RESP}$) and (iv) the metabolic work within muscles (W). Hence the corresponding heat balance equation can be written as follows [113]:

$$\dot{Q}_{MET} - \dot{Q}_{ST} - \dot{Q}_{SKIN} - \dot{Q}_{EVAP} - \dot{Q}_{RESP} - W = 0 \quad (2.13)$$

The active system in Stolwijk's model (and in many other modern thermophysiological models) controls the thermal regulation of body by controlling the metabolic heat and blood flow rate (the terms q_m and w_{bl} in Eq. 2.11, respectively). The corresponding control actions depends on the temperature signals (inputs) coming from each node. Deviations in the skin temperature of each segment ($T_{4,j}$ where $j = 1$ to 14) and the core temperature of the head ($T_{1,1}$) are the essential input parameters of control mechanism [108]. These inputs are compared with the corresponding reference values to determine deviations [109]. The deviation values of the elements are summed by hypothalamus to yield control outputs that are sent to local controller for regulating blood flow rates and heat fluxes (evaporation or shivering) (Figure 9) [114].

2.2.3.2 Thermal Comfort Standards

Even though thermophysiological models provide deep insight related to thermal interaction of human body with its environment, the analysis procedure and formulation is not easily applicable to building design process. Despite the increasing trend of using advanced simulation tools based on CFD methodologies for custom building designs, the main-stream building design practices commonly deploy software based on heat balance equations and product catalogs. In other words, the conventional building design practices have been deployed simplified thermophysiological formulations in order to meet well-

established standards. Accordingly, focusing on practical concerns during building design and operations, a well-known definition of thermal comfort is provided by ASHRAE as the “*condition of mind that expresses satisfaction with the thermal environment*” [115]. ANSI/ASHRAE Standard 55-2010 declares the factors affecting thermal comfort as (i) metabolic rate, (ii) clothing insulation, (iii) air temperature, (iv) radiant temperature, (v) air speed and (vi) humidity.

Most of the evaluation schemes, including ANSI/ASHRAE Standard 55, consider thermal comfort as a static phenomenon. Accordingly, the internationally accepted assessment frameworks (ISO 7730, ASHRAE Standard 55, CEN CR 1752, among others) of thermal comfort assume that occupants are positioned in a specific location for a while and reach thermal equilibrium. Built on these assumptions, Fangers’ thermal comfort model is the

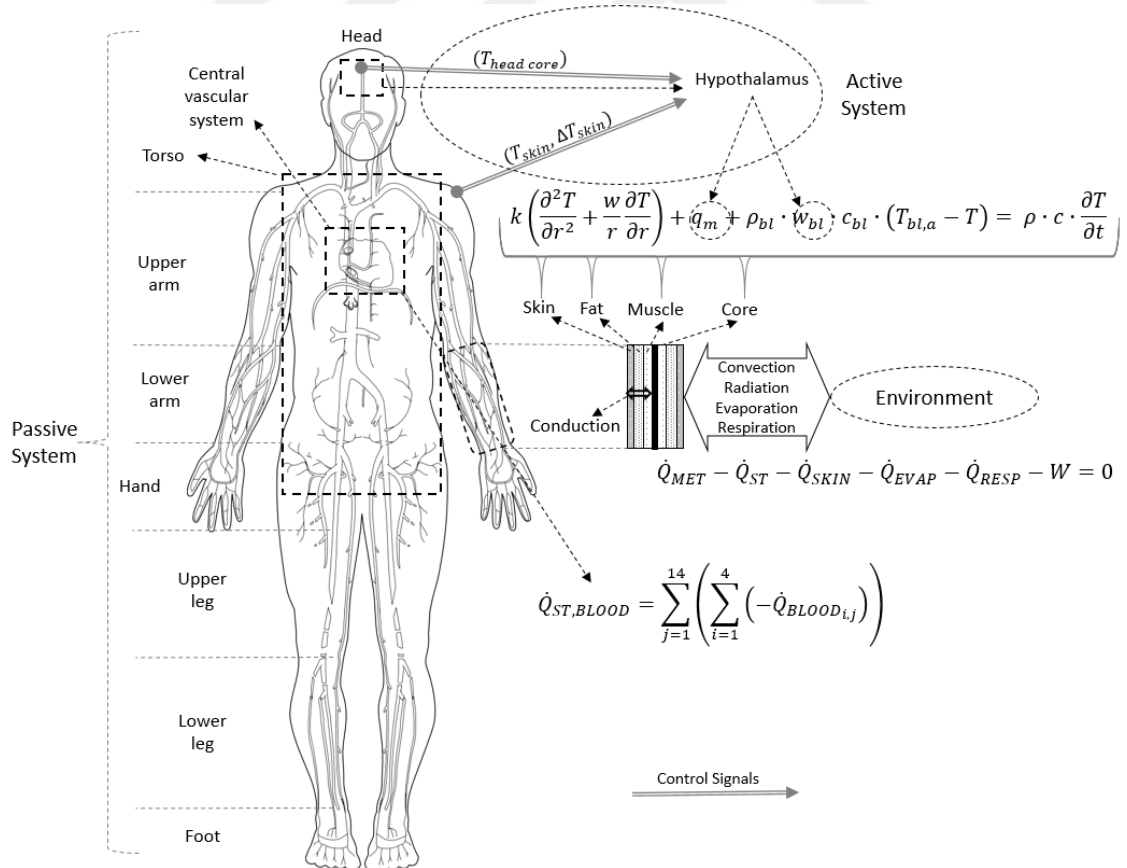


Figure 9: Active and passive systems in thermoregulation models of human body and corresponding heat balance equations.

mostly deployed formulation for the static evaluation of thermal comfort. It is based on a simplified (single segment and one-node) thermophysiological model and heat balance equations. Fanger's method introduces the concepts of *predicted mean vote* (PMV) and *predicted percentage of dissatisfied* (PPD) for the evaluation of the thermal comfort performance of zones in a convenient way. PMV is a 7-point thermal sensation scale (cold, cool, slightly cool, neutral, slightly warm, warm and hot) that represents the mean voting score of large number of occupants in a zone related to thermal conditions. We must note that PPD represents the percentage of people who are dissatisfied with thermal conditions. The PMV and PPD calculations in Fanger's Method is formulated in ISO Standard 7730:2005(E) as follows [116]:

$$\begin{aligned} \mathbf{PMV} = & [0.303 \cdot \exp(-0.036 \cdot M) + 0.028] \cdot \{(M - W) - 3.05 \cdot 10^{-3} \cdot \\ & [5733 - 6.99 \cdot (M - W) - p_a] - 0.42 \cdot [(M - W) - 58.15] - 1.7 \cdot 10^{-5} \cdot M \cdot \\ & (5867 - p_a) - 0.0014 \cdot M \cdot (34 - t_a) - 3.96 \cdot 10^{-8} \cdot f_{cl} \cdot [(t_{cl} + 273)^4 - \\ & (\bar{t}_r + 273)^4] - f_{cl} \cdot h_c \cdot (t_{cl} - t_a)\} \end{aligned} \quad (2.14.a)$$

where

$$\begin{aligned} t_{cl} = & 35.7 - 0.028 \cdot (M - W) - I_{cl} \cdot \{3.96 \cdot 10^{-8} \cdot f_{cl} \cdot [(t_{cl} + 273)^4 - \\ & (\bar{t}_r + 273)^4] + f_{cl} \cdot h_c \cdot (t_{cl} - t_a)\} \end{aligned} \quad (2.14.b)$$

$$h_c = \begin{cases} 2.38 \cdot |t_{cl} - t_a|^{0.25} & \text{for } 2.38 \cdot |t_{cl} - t_a|^{0.25} > 12.1 \cdot \sqrt{v_{ar}} \\ 12.1 \cdot \sqrt{v_{ar}} & \text{for } 2.38 \cdot |t_{cl} - t_a|^{0.25} < 12.1 \cdot \sqrt{v_{ar}} \end{cases} \quad (2.14.c)$$

$$f_{cl} = \begin{cases} 1.00 + 1.290 \cdot l_{cl} & \text{for } l_{cl} \leq 0.078 m^2 \cdot K/W \\ 1.05 + 0.645 \cdot l_{cl} & \text{for } l_{cl} > 0.078 m^2 \cdot K/W \end{cases} \quad (2.14.d)$$

$$\mathbf{PPD} = 100 - 95 \cdot \exp(-0.03353 \cdot PMV^4 - 0.2179 \cdot PMV^2) \quad (2.15)$$

where

M : metabolic rate (W/m^2);

W : effective mechanical power (W/m^2);

I_{cl} : clothing insulation ($m^2 \cdot K/W$);

f_{cl} : clothing surface area factor;
 t_a : air temperature ($^{\circ}\text{C}$);
 $\bar{t}_r$: mean radiant temperature ($^{\circ}\text{C}$);
 v_{ar} : relative air velocity (m/s);
 p_a : water vapour partial pressure (Pa);
 h_c : convective heat transfer coefficient [$\text{W}/(\text{m}^2 \cdot \text{K})$];
 t_{cl} : clothing surface temperature ($^{\circ}\text{C}$).

Despite being widely accepted and applied, Fanger's PMV/PPD based thermal comfort model has limitations to assess thermal comfort in real life conditions. As a result of using a simplified thermophysiological model, it is unable to provide insight related to different parts of the body that has different thermal responses [117] (Figure 10). Accordingly, a crucial concern that is not assessed by this model is local discomfort. Evaluating occupant's body as a whole, it is unable to provide insights regarding to unsatisfactory heating or cooling of a particular part of the body. Such a difference would be driven by variety of factors involving (i) draught (unintended heating or cooling of a part of the body due to air flow), (ii) radiant temperature asymmetry (due to hot or cold walls or windows), (iii) too hot or cold floor (unintended conditioning of foot) and (iv) vertical air temperature differences between parts of a body (like head and ankles) [116]. The effect of any these factors is under the strong influence of (i) the specific position and thermal preferences of an occupant, (ii) room geometry and indoor design, (iii) material properties (especially for walls and glasses) and (iv) type and design of HVAC system. These factors are crucial for evaluating thermal performance of a localized (also named as personalized or task ambient) conditioning systems. For the proposed AVS in this study, draught and vertical temperature differences between body parts are two essential concerns.

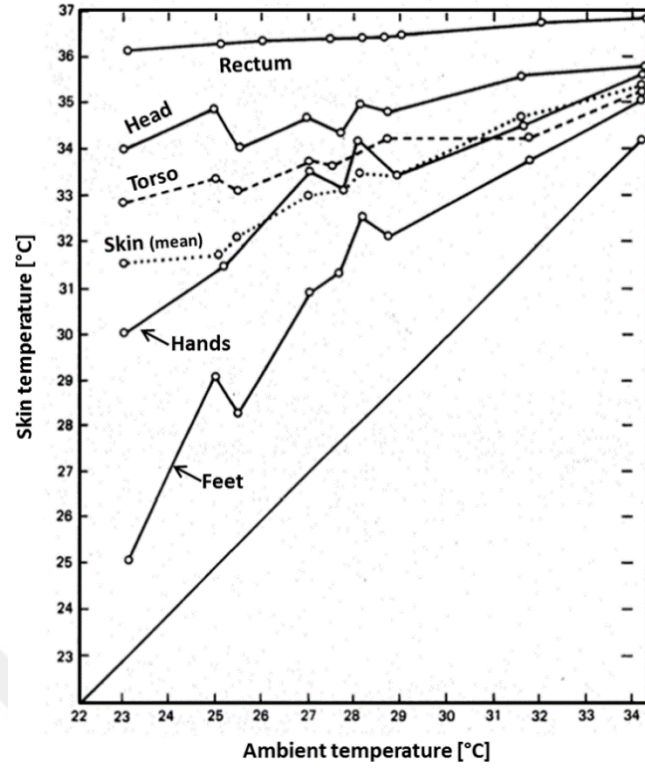


Figure 10: Variation of local skin temperatures with ambient temperature. Figure clearly shows the different thermal responses of each body segment. (Adopted from [117]).

The effect of drought on occupants' thermal comfort is commonly assessed with a model that is developed by Fanger et al. to complement PMV/PPD formulation. The model predicts the percentage of occupants (who are assumed to be sedentary and thermally neutral) dissatisfied because of draught as a function of mean air velocity, air temperature and the turbulence intensity [118]. Its formulation is provided in ISO7730:2005 as [116]:

$$DR = (34 - t_{a,l}) \cdot (\bar{v}_{a,l} - 0.05)^{0.62} \cdot (0.37 \cdot \bar{v}_{a,l} \cdot Tu + 3.14) \quad (2.16)$$

where

$$\bar{v}_{a,l} = 0.05 \text{ m/s for } \bar{v}_{a,l} < 0.05 \text{ m/s}$$

$$DR = 100\% \text{ for } DR > 100\%$$

and

$t_{a,l}$: local air temperature, between 20°C to 26°C;

$\bar{v}_{a,l}$: local mean air velocity, < 0.5 m/s;

TU : local turbulence intensity, between 10% to 60%.

On the other hand, the percentage dissatisfied due to the vertical temperature difference is empirically formulated as below (for $\Delta t_{a,v} < 8^\circ\text{C}$) [116]:

$$PD = \frac{100}{1 + \exp(5.76 - 0.856 \cdot \Delta t_{a,v})} \quad (2.17)$$

2.2.3.3 Local Thermal Sensation and Comfort

As shown in Figure 10, different parts of the body responses differently to a temperature value or to the changes in temperature. Furthermore, the response scheme depends on many physiological parameters that makes is highly personal. Ignoring this variety results in dissatisfied occupants who are not ‘predicted’ during design phase of HVAC systems. This is due to the fact that PMV and PPD based assessments suffer from providing insight related to local deviations from the mean thermal comfort levels of the zone. It is important to note that the term ‘local’ doesn’t refer to a sub-region in a zone as like the term ‘localized’ means but instead refers to a specific part of the body. DR and PD can determine dissatisfaction due to draught in a part of the zone, however, a more comprehensive approach is needed in order to assess the effect of changes in environmental conditions around the local parts of the body. In other words, the empirically determined comfort scale for each part of the body is a more reliable approach in order to evaluate the effect of environmental disturbances like draught, solar irradiation or cold surfaces in enclosed spaces [119]. Hence, researchers and engineers have developed approaches with ‘higher resolution’ that evaluate the thermal comfort for specific parts of the human body. These approaches are mostly supported by automotive industry and based on more detailed thermophysiological models (multi segment and multi-node) and heat balance equations. As mentioned at the beginning of Section 2.2.3.2,

the design practice in building industry mostly takes advantage of standards to eliminate computational complexity, however, more extensive approaches are needed to deploy for custom building and system design processes [120].

As like in Fanger's case, evaluation (voting) schemes for the local assessment of thermal comfort are based on laboratory experiments conducted with large number of people who are voting for the thermal satisfaction of different segments of their body. Local Mean Vote (LMV) is one of these approaches where the corresponding subjective judgement template and the analysis procedure is described in ISO-10551 standard [121]. Similarly, Local Thermal Sensation Vote (LTSV) is described in ISO-14505-2. Representing the outcomes with well-known thermal comfort voting scales (like ASHRAE's 7-level scale), these approaches take advantage of regression analysis for the assessment of local thermal comfort.

Benefiting experimental thermal comfort voting data for individual body parts, scholars developed formulations for predicting local thermal sensation. These models function as a link between thermophysiological knowledge and the thermal comfort assessment. Well-studied UC Berkeley model correlates physiological responses of human body with LMV by referring it as local thermal sensation (LTS). The formulation of UCB-model is as follows [122]:

$$LTS = 4 * \left(\frac{2}{1 + \exp\left(-C_1 * (T_{skin,local} - T_{skin,local,set}) - K_1 * ((T_{skin,local} - T_{skin,local,set}) - (T_{skin,mean} - T_{skin,mean,set}))\right)} - 1 \right) + C2_i \frac{dT_{skin,local}}{dt} + C3_i \frac{dT_{core}}{dt} \quad (2.18)$$

where the ASHRAE 9-point scale is used for quantifying LMV and

C_1 and K_1 : coefficients between 0 and 1 for the corresponding part of a body;

$T_{skin,local}$: local skin temperature of corresponding part of a body;

$T_{skin,mean}$: mean skin temperature of a body;

$T_{skin,local,set}$: local skin set point temperature for the corresponding part of a body;

$T_{skin,mean,set}$: set point mean skin temperature of a body;

$C2_i$: thermal capacity of the skin of corresponding part of a body;

$C3_i$: thermal capacity of the core of corresponding part of a body.

The coefficients in equations presented above are empirically derived by UCB researchers [123].

2.3. Social Context

Within the scope of this thesis study, the social context of CPSBESs refers to topics that conceptualize the occupants' energy related behaviors within buildings that has a high share in potential energy savings. There are three approaches in order to convey research on this field: (i) qualitative research, (ii) quantitative research and (iii) mixed methods [124]. While conducting qualitative research, scholars take advantage of behavioral science that focuses on human activities and aims to provide generalized explanation of human behavior. It is highly associated with the disciplines like psychology, economy, anthropology and cognitive science among others. Moreover, in many cases, there is a couple of a theory and a model which explains a specific human behavior interdependently or conjointly. Those for building energy efficiency are already outlined in a recent paper [125]. On the other hand, mathematical modeling methods and tools are widely deployed for quantitative analysis of human factor in buildings. This analysis is mostly for understanding the time and space dependence of occupants' presence and energy related actions. The increase in the availability of this kind of social data (online

performance rating, surveys, IoT, smart cities, smart homes, among others) results in the demand for analysis of those for innovative product and service solutions (see Section 2.1). The third approach, namely mixed methods, incorporate these two fundamental approaches in order to get a comprehensive insight regarding to subject under investigation. Here, an overview of qualitative and quantitative approaches that highlight the social context of AVS (as a CPSBES) are reviewed.

2.3.1 Qualitative Approaches

Behavior theories and models regarding to energy usage are foundations of qualitative research on human dimension of energy consumption in buildings. In accordance with the origins in social sciences, there are four main groups of theories and models: psychological, sociological, economical and integrated approaches [126]. Psychology theories and models focus on decision making processes of individuals under the influence of their attitudes, beliefs, perceptions, economic concerns, among others. Sociological theories and models are intended to understand effects of common symbols, culture and technological infrastructure on energy usage practices. Economic theories and models consider the energy as a meta of energy market and investigate the interdependence among energy behaviors and micro and macro economical determinants. On the other hand, integrated theories and models are not limited to any discipline but instead hybridize conceptualizations and methodologies from different disciplines and synthesize them for a more holistic perspective. The important theories and models are given in [125]. Here, only the Triandis' Theory of Interpersonal Behavior (TIB) and the Social Practice Theory are briefly reviewed since these are mainly used for conceptualizing the social context of AVS.

The perspective of sociology attaches great importance to social and technological factors and their interactions while evaluating decision making process of individuals. In other

words, beside technological and commercial dimensions, researchers should consider symbolic and cultural dimensions of everyday life and sustainability [127]. Accordingly, the Social Practice Theory (SPT) considers these dimensions as facilitators of the everyday practices and focus on the interplay between them and human behavior [128]. In SPT, the term "practice" refers to *"routinized type of behavior which consists of several elements, interconnected to one other: forms of bodily activities, forms of mental activities, 'things' and their use, a background knowledge in the form of understanding, know-how, states of emotion and motivational knowledge"* [129].

Moving the focus from individuals to social practices (any kind of daily activity), SPT considers perceptions, interpretations and actions as to be under the influence of the society level organization of practices and to be the key drivers of behavior change [130]. Hence, SPT based behavior studies focus on recreation/renovation of the practices in a social and collective manner. In other words, practices are accomplished by means of both 'doings' (practical activities) and 'sayings' (representations) [131]. Accordingly, behaviors regarding to energy consumption cannot be changed only with feedback and incentives (limited to activity), but a bundle of daily practices and culture (collectivity) must be changed [132].

Following SPT perspective, the *Sustainable LivingLabs* approach investigates occupant behavior in real-life environments in order to prevent isolation of any practical activity from its representations [133]. This is especially crucial for solutions based on product-service-systems where the companies aims to promote not only a product but also the services based on it, like pay-per-lux model for selling lighting equipment [134]. Here, the outputs (energy efficiency) of practical activities related to product (use of lighting equipment) are subject to influence of sayings (cheating on consuming light) in daily life (service phase of the solution).

Given the fact that social factors affect human behavior in buildings, the mechanism that explain the interaction of these factors is another research dimension. At this point, a comprehensive and well-studied theory of research on occupant behavior, namely Triandis' Theory of Interpersonal Behavior (TIB), place on account the concepts of 'intention' and 'habit' as the two essential antecedents of behavior [135]. Here, the term "intention" refers to both conscious and sub-conscious decision making of people whereas "habits" refers to routine behaviors. Moreover, 'facilitating conditions' are optional factors (both enablers and barriers) during the formation of a behavior [136]. Each of these two essential antecedents (habits and intentions) are also driven by other factors. Intentions are under the influence of three antecedents: attitudes (driven by evaluation and beliefs regarding to outcomes), social factors (driven by norms, roles and self-concept) and affective factors (driven by emotions). On the other hand, habits are driven by frequency of past behavior [137].

Taking advantage of a large bundle of determinants and the descriptive hierarchy among them (see Figure 11), TIB can provide deep insights regarding to human behavior and its antecedents (including both society and individual based ones). More specifically, it can help to differentiate the society and individual based factors [138]. Hence, it is used for supporting policy making in the domain of energy efficiency. Furthermore, it is also shown to be helpful to conceptualize and understand acceptance and adoption of energy technologies [139]. In such a study, economical and/or infrastructural factors can be considered facilitating factors (barriers or enablers) of energy technologies [140]. Similarly, most of the technological interventions (such as thermostats in offices) can be considered as facilitating conditions [141].

In parallel to behavior studies, innovation studies also provide valuable insights related to interaction of people with innovative BESSs. Most of the important concepts of

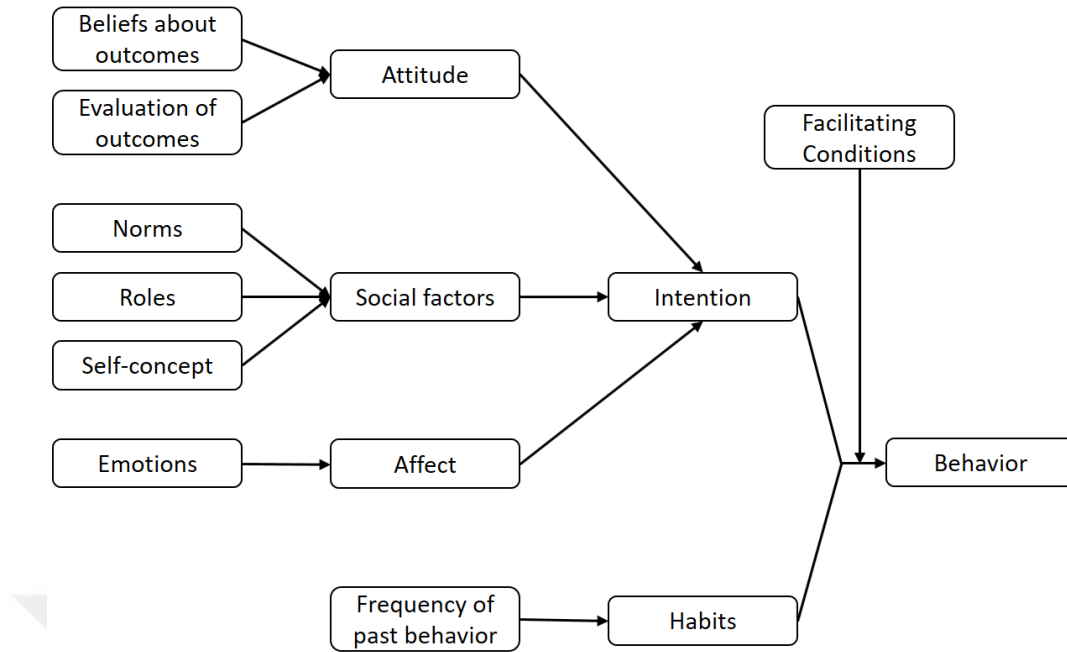


Figure 11: The factors influencing behavior in the Theory of Interpersonal Behavior (Adopted from [125]).

innovation studies (diffusion of innovations, rate of adoption, technology acceptance, among others) can explain response of individuals and societies to innovative BES based solutions and reviews in a recent study by our group [125]. One of the models of innovation studies, namely Technology Acceptance Model, explains acceptance of innovative technologies as being under the influence of two main drivers: social and practical (Figure 12). On the other hand, practical concerns are driven by factors like compatibility, costs, usefulness and reliability [142]. Compared to others, usefulness has been gathered highest attention among all factors to explain acceptance of modern technologies involving clean energy and energy efficiency. Moreover, there are frameworks that specifically explain the acceptance of energy technologies. Sustainable Energy Technology Acceptance Model is one of them and involves individual differences (trust to utility company, politic orientation, etc.), technology attributes (usefulness, cost, privacy) and demographics (gender, income, etc.) as the antecedents of acceptance of sustainable energy innovations [143].

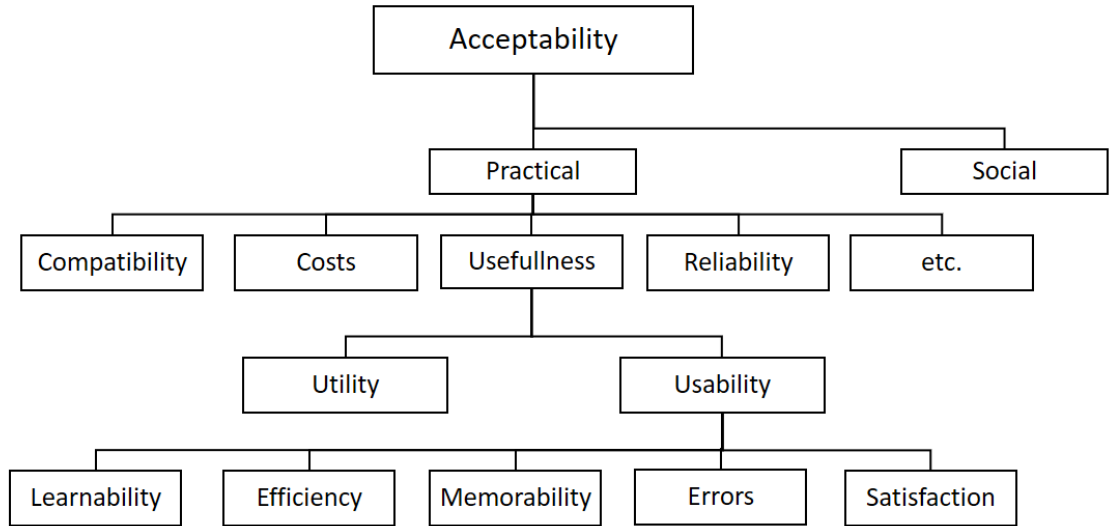


Figure 12: Drivers of acceptability in the Technology Acceptance Model.

2.3.2 Quantitative Approaches

In building energy efficiency research, quantitative research on human dimension is conducted depending on either (i) survey with occupants or (ii) occupant data acquisition from buildings. Survey is a reliable tool to support qualitative research activities but not proper for detailly characterizing the occupants' energy related behaviors. This is due to fact that occupant behavior is not a fixed but a versatile phenomenon [144]. Moreover, occupants can't remember all the energy-consuming actions with their exact timing even for a single day since most of them are performed unconsciously. In accordance, surveys for energy related occupant behavior should be designed inherently considering the reliability analysis that will assess multi-collinearity and multi-item integration intensity [145].

Data-driven occupant behavior modelling approach is based on the sensor data of buildings. The sensor types and their communication requirements are reviewed in Section 2.1.1. The modeling studies based on this data set aims to characterize occupant presence and movement as well as interaction with BESs [146]. Obviously, these modeling approaches are not deterministic but stochastic ones due to the diversity of

factors that drive human behavior. Energy related occupant behavior is under the influence of environmental, time-related, contextual, physiological, psychological, social and random factors [147]. However, if reliable patterns can be derived with data-driven approaches, outputs of these models can be used for many purposes including building energy performance simulations, demand side management, predictive control, policy development, among others. For a successful data-driven modeling study of occupant energy related behavior, there are two important decision points: selection of relevant parameters and modeling approach.

There are plenty of parameters that can be monitored with sensors for energy related behavior research. Occupancy pattern of a zone is an essential information for behavior research. Presence, number and/or position of occupants would be useful to evaluate the occupancy profile of a zone. Beside occupancy, set-point and set-back temperature values of thermostats are very important since the HVAC system constitute important share of building energy consumption. Other important factors for HVAC consumption are indoor air quality, door and window status (open or closed), blind and shading settings, ceiling fan activation patterns and clothing level [144,148,149]. Lighting system is another source of energy consumption where utilizing energy efficiency without sacrificing visual comfort is a challenge and has to be initiated at early design stages of building to be impactful [150]. Hence, illuminance settings, shading and blind usage as well as turning on/off habits are monitored for energy-related behavior characterization [147]. Beside HVAC and lighting, usage frequency and settings of appliances (printers, computers, kitchen-ware, among others) would also be monitored for a better assessment of daily activities [145]. Furthermore, direct measurement of energy consumption by means of (i) power analyzers and/or plug load meters for electrical energy and (ii) calorimeters for

heat energy are also important inputs for occupant behavior modeling. A comprehensive list of variables for occupant behavior modeling is provided in [151].

Modeling occupant behavior has been a challenge while modeling building energy performance due to the undeterministic nature of human activities. The convention is determining a set of levels for occupant related variables (schedules, temperature set point and setback values, open and close time ratio of doors and windows, among others) to get generic profiles for energy usage like low, standard and high energy consumers [152]. Then, these models are coupled with physical models of buildings to perform scenario analysis. On the other hand, thanks to the real data driven studies, more systematic approaches based on advanced statistical and data analytics methods are available. These studies drive more realistic occupant profiles and energy usage patterns. Some of the well-studied methods for advance modelling of the human behavior in building energy efficiency research are (i) fundamental statistical analysis (regression analysis, Kolmogorov-Smirnov test, Pearson's correlation, among others) [151,153], (ii) probability based models [154], (iii) fuzzy logic modelling [155], (vi) Bayesian models [156,157], (vi) Gaussian models [158], (vii) Monte Carlo based analysis [159], (viii) Markov chains [160,161], (ix) agent/multi-agent based modeling [162–164] and data analytics based modeling [165]. Even if these approaches are mostly used for occupancy modeling, they can be used to model other energy related behaviors including thermostat settings, door/window habits, fan usage, lighting habits, among others.

Bringing together relevant parameters and proper modeling methods, building energy simulations are essential tool for understanding and evaluating human-building interaction. They can be used for (i) optimizing parameters from variety of domains in the design phase and (ii) minimizing the energy performance gap of the design

simulations and actual operation data. Moreover, energy management teams always need these simulations as decision support tools in whole life span of a building.

Beside technical interventions, building energy simulations are also useful for understanding and estimating the potential of behavioral energy efficiency. In other words, these simulations can be used to evaluate the energy savings potential of behavior patterns. Two typical examples of these patterns would be “*the windows are getting tilted earlier when the office is occupied with 4 people*” and “*the percentage of blinds closed and ceiling fans running decreases with the number of people in each office*” [144]. As the examples illustrate, repeating habits of occupants can be used as scenarios for assessing the energy performance of a building (for a specific zone) in different operating conditions. Moreover, they can be formulated as derived parameters for continuous assessment of behavior-based interventions [166]. In turn, these assessments can settle a base for behavior change programs and facilitate behavioral energy efficiency improvements.

2.3.3 Behavioral Dimension of Thermal Comfort

Being under the influence of both subjective and objective factors, the assessment of thermal comfort is not a deterministic process. It requires the involvement of both physiology and psychology of occupants. In other words, given the same physical conditions, an occupant may experience different thermal comfort levels in different cases. As an example, interacting with pictures that have different compositions (criminal to peaceful) may result in a change of feeling of thermal conditions [167]. On the other hand, contextual factors such as occupants expectations, norms, culture or attitudes towards the thermal satisfaction has influence on thermal comfort [168].

Beside context dependent psychological factors, availability of control over thermal conditions is proven to be impactful for facilitating thermal satisfaction and behavioral adaptation [169]. In accordance, modern HVAC design standards and practices pay attention on occupant control on local environmental conditions. As an example, the ASHRAE Standard 55-201 has a statement for the availability of control option for air speed as either *(i) for every six occupants or less, or, (ii) for every 84 m² of living space* [115]. Being provided local control capabilities, occupants are observed to engage with HVAC management for a better comfort level and energy savings [170]. The occupants' evaluation related to availability and effectiveness of control options on HVAC system (an active system) is known as 'perceived control'. The studies on perceived control over thermal environment has shown that it is a powerful factor for enhanced thermal sensation, better productivity and more energy savings [171].

The availability of control for custom thermal environments facilitates behavioral adaption for thermal comfort and energy savings. Behavioral adaptation is a set of actions that allows occupants to adjust their conditions in accordance with their instantaneous thermal sensations [172]. These actions involve (i) active system control actions (changing thermostat settings, activating fans, changing dim level, among others), (ii) changes on passive systems (adjusting blinds/shaders, opening/closing windows or doors, among others), and (iii) changes on personal parameters (changing clothing level, changing location, among others).

When the studies on thermal comfort go beyond the thermophysiology and thermal characteristics of the indoor environment and involve behavioral factors for occupants, the phrase "thermal experience" would define human dimension of thermal conditions better than the "thermal comfort". The availability of control on the HVAC system, as an example, not only a concern related to comfort. It can be considered by an occupant, who

is a tech-sevy, as a part of ‘self-concept’ and can leverage the interaction with HVAC system beyond the thermal control (**Figure 11**). On the other hand, factors such as decoration may trigger (or obstruct) feeling of satisfaction for the indoor environmental conditions, so the thermal comfort. Hence, the term “thermal experience” enriches the expression for satisfaction level of the indoor thermal conditions by involving factors that are underestimated by thermal comfort standards. Thus, behavior studies on thermal comfort and energy efficiency in buildings focus on (i) identifying external factors that has influence on occupant behavior as well as (ii) unveiling behavioral drivers of human-system interaction.

3. METHODOLOGICAL FRAMEWORK

This chapter outlines the methodological framework required for the research questions explored in this study. It is aimed to demonstrate the progress of the conceptual and practical evaluation of the proposed system by identifying the important concepts and mapping the relationships among them. The proposed framework is intended to provide a systematic methodology to link the cyber, physical and social realms of CPSS with the co-involvement of hybrid dynamical modeling and human behavior modeling. Hybrid dynamical and the behavioral modelling have been extensively studied in the literature to investigate the characteristics of the cyber-physical systems and the human behavior, respectively. However, their interaction and joint usage have not been discussed yet. Thus, based on the review provided in previous section, a novel method is presented here to integrate these distinct realms by integrating conventional hybrid dynamical modeling with human behavior modeling.

The methodological framework involves six steps to outline the design of AVS from early conceptualization to performance analysis as shown in Figure 13. It is the third step that the novel modeling approach is explained extensively (Section 3.3). The details of each step is presented in the following subsections. Even this thesis study applies the approach to the building energy efficiency field and specifically for the AVS, it can be applied to other research fields that involves intense interaction of cyber, physical and social realms.

3.1. Step1: Definitions

The initial step for the CPSS design is the clarification of the value expected from the system that is necessary when designing complex projects, such as the systems to prevent wasting resources. On the other hand, narrow definition of intended system would limit the intellectual horizon and creativity of the developer(s). Defining the real benefit

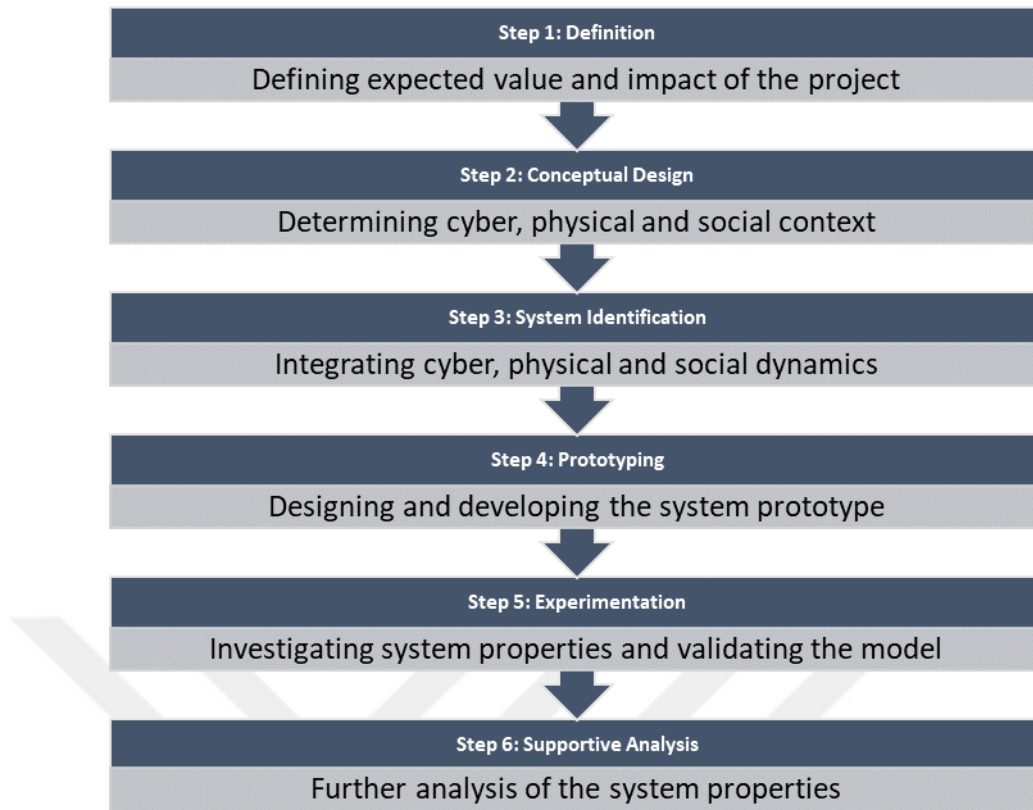


Figure 13: Steps of the methodological framework.

perceived by potential users, that is known as ‘value’, instead of defining the specification of a product or service is crucial to get an acceptable solution with project [173]. A clear definition of the expected value facilitates addressing needs, requirements, acceptability, risks and impact of the proposed CPSS during its design and development.

Beside clarification of the expected value, definition of an energy system as a CPSS (CPSBES) should involve the fundamental concerns regarding to cyber, physical and social realms. Potential concerns for each realm are reviewed in Chapter 2. The selected ones are needed to be explained in terms their contribution to value defined. Moreover, characteristic value offered by a CPSS emerges from the integration of these three realms and should be figured out. In other words, interaction among cyber, physical and social realms and the benefit of their unification should be translated to expected outcome of the

research. On the other hand, this is the stage that abstractions are under evaluation. Hence, the details of technical and social concern are not needed to be defined.

3.2. Step 2: Conceptual Design

The second step of the methodological framework aims to develop a conceptual design of the CPSS. The parameters belong to cyber, physical and social realms are listed separately and the interaction among them is determined. The means of the interaction would be material flow, heat or electricity conduction, data transfer or a human action. The overall design is expected to deliver the value expected defined in the previous step in a conceptual manner. Moreover, the governing equations, models or theories among these parameters should also be identified for a complete integration. Either qualitative or quantitative tools can be involved at this stage. Once this early design based on parameters is developed, those can be translated to system components (both hardware and software) that eventually will compose the CPSS.

The conceptual design of a CPSBES would require a deep understanding of human interaction with building energy systems. Some of the potential components and the governing equations, models or theories for CPSBES are reviewed in Section 2. There is also a large pool of staff and methodological tools that are out of the scope of this study and so not reviewed there. On the other hand, some of the technically advance tools may not be well accepted by occupants. Hence the designers should consider human dimension for each of technical staff. Here, behavioral concerns related to building energy consumption may help designers. The relationship between human behavior and innovation is briefly reviewed in Section 2.3.1 (like Technology Acceptance Model) and detailly discussed by the author in a dedicated paper [125].

3.3. Step 3: Modeling

The third step of the conceptual framework is the modeling of proposed CPSS using the conceptual design developed in Step 2. CPSS approach presents a competitive framing for environmental sustainability solutions including building energy efficiency. However, there is only limited number of methodological framing for modeling CPSSs. Hence, a modeling approach is presented here to facilitate the integration of cyber, physical and social aspects. The approach is based on the integration of hybrid dynamics (for cyber and physical aspects) with behavior modeling (for social aspects) [174] (Figure 14). This approach makes it possible to investigate the joint performance of each aspect as a unique system as well as interaction among them. Hence, this subsection starts with a brief review of hybrid dynamical modeling and then the three steps of the proposed modelling approach is explained.

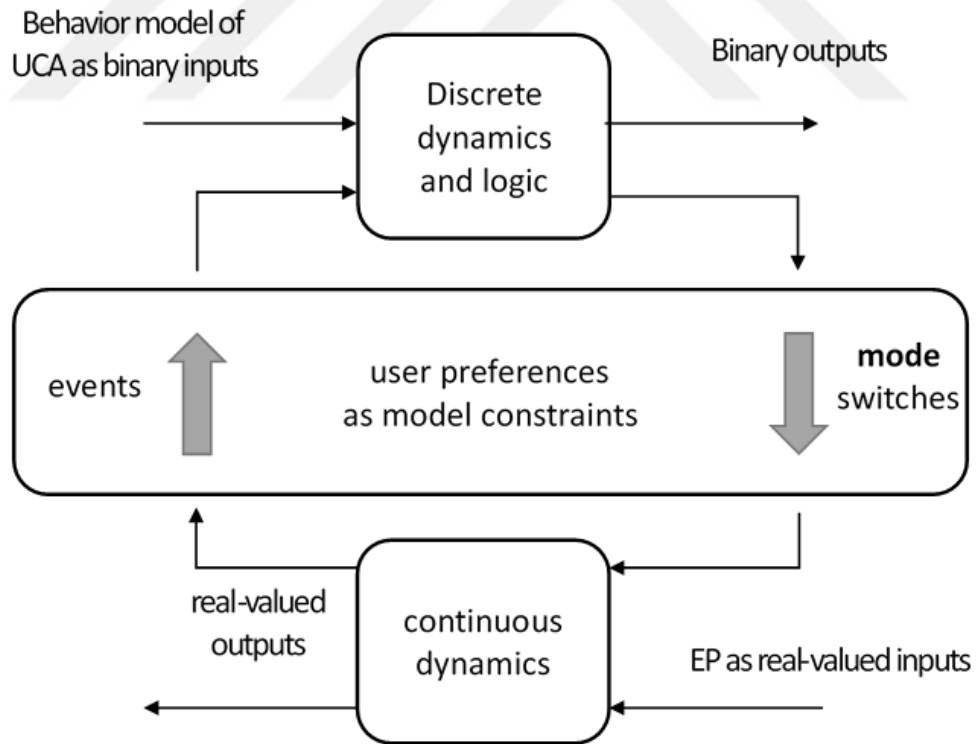


Figure 14: Components and flow of the proposed modeling scheme (UCA: user control actions, EP: environmental parameters) (Adopted from [174]).

3.3.1 Hybrid Dynamical Modeling

Most physical laws can be expressed in mathematical expressions, which can be reduced to differential or difference equations in order to solve them numerically. Accordingly, majority of the system modelling and control efforts focused on adopting these representations for effective applications [175]. However, being limited to continuous-time dynamics, such numerical approaches may not meet the requirements for cyber-physical systems (CPS) which include components governed by discrete-time dynamics, such as programmable chips based on finite state machines, if-then-else conditions, among others [176]. Thus, the hybrid systems theory is deployed by scholars to formulate the continuous- and discrete-time dynamics of CPSs together [177,178]. Over the last two decades, this formalism was developed to include both virtual system modelling and real-life applications in order to support interdisciplinary design decisions [179,180].

Continuous-time dynamics in hybrid dynamical modelling is typically represented using first-order differential equations in which the variable is belong to a subset (C) of n -dimensional Euclidean space (R^n) and a set-valued mapping function (F) as [181]:

$$\dot{x} \in F(x), \quad x \in C. \quad (\text{Eq 3.1})$$

On the other hand, a variable of discrete-time dynamics belongs to a subset (D) of n -dimensional Euclidean space (R^n) and a set-valued mapping function (G) as [181]:

$$x^+ \in G(x), \quad x \in D. \quad (\text{Eq. 3.2})$$

In this representation, $\dot{x}$ refers to time derivative of x when the time is continuous whereas x^+ refers to time derivative of it when the time is discrete for the given dynamical system. In the representation of continuous dynamics, (C) is called the flow set whereas (F) is called the flow map. In the representation of discrete-time dynamics, (D) is called the jump set and (G) is the jump map.

This representation of hybrid dynamics is called hybrid inclusions and can be used for modelling variety of systems including building energy systems. In an HVAC study, x would be temperature. In such a formulation, continuous dynamics can refer to governing heat equations whereas the discrete dynamics can refer to mode switches of a thermostat [182].

3.3.2 Hybrid Dynamical and Behavior Modeling

Following the conceptualization described above, as a first step of the proposed modeling approach, the control parameters and the corresponding control logic proposed for the system operation are match with discrete and social dynamics. Following the definition provided above, this refers to defining the control parameters as elements of the jump set ($x \in D$) in Eq. 3.2 whereas the control logic statements are elements of jump map ($G(x)$) in Eq. 3.2. Some control parameters would be linked to occupant interaction (so the human behavior) via user interface. Moreover, some control parameters are just linked to state changes in cyber components.

Second, physical parameters (like temperature) and the related governing equations of the proposed system are match with continuous and social dynamics. Referring to Eq. 3.1, physical parameters are elements of flow set (C) whereas the governing equations are elements of the flow map $F(x)$. Physical parameters are also linked to human behavior since the occupants are subject to effects of them. On the other hand, constraints defined for flow set (like upper limit for pressure) may result in state changes of cyber components in accordance with control logic statements.

Third, user preferences (ones out of control action defines in initial stage) defined as the elements of social aspects but linked to continuous or discrete dynamic formulations as constraints. For an HVAC system, scheduling options are good examples for this process

since they are not element of continuous or discrete dynamics, but may influence system operation as defined by users.

The three steps of the modelling approach presented above can be used to investigate the characteristic of CPSBESs. Then, it is possible to analyze different characteristics of the system using engineering simulation or modelling tools (such as Matlab Hybrid Toolbox). This stage is expected to be result in rigid abstraction that guide prototyping. If the outcomes of the early investigation are satisfactory, prototype of the system can be developed. Having a working prototype, it would require iterations to optimize system parameters and scenario analysis to identify system limits.

3.4. Step 4: Prototyping

The fourth step of the conceptual framework is developing a prototype of the system for real life tests and model validation. Components of the system were determined in conceptual design stage (Step 2). Following the specification declared there, one can develop both hardware and software that are essential for the system evaluation. Development of each of these components would require specific attention whereas sectoral regulations or conventions may limit the technical opportunities. Moreover, rapid prototyping technologies (such as 3D printers) can accelerate this procedure. On the other hand, depending on the system requirements, it would be needed to design and deploy additional components to test facility for experimentation that are not involved in actual system design.

3.5. Step 5: Experiments

Once the prototypes are ready, the next step of the methodological framework is designing and conducting experiments with them. Experiments are essential for identifying system performance in terms of design concerns as well as calibrating and

validating the model developed in Step 3. Thus, the experiment design should be in accordance with the system definition (Step 1) and conceptual design (Step 2) of the system. In other words, the proposed experiments are expected to validate the hypothesis done at the early design stage of the system. and enable further analysis of the performance of the system.

Prototyping and experimenting for CPSBES would be a challenge in practice. There are two opportunities: deploying a dedicated test chamber or using living labs. The former is an expensive option that requires special planning and management, human resources, dedicated time of researchers as well as budget. It is useful when isolated experiments are necessary for system development, such as observing the air flow characteristic. On the other hand, the latter one may save both time and money since the prototypes are deployed to real buildings. This approach makes it possible to test the proposed solutions in real life environment. However, the observed outcomes are result of many uncontrolled factors and the data would be noisy. These factors would limit the model validation accuracy.

3.6. Step 6: Analysis

Even if the experimental results validate the hypothesis, one can still need to perform simulations and further analysis to evaluate system performance. The model developed (Step 3) and validated (Step 5) during system development is the main tool for these efforts. Furthermore, one can take advantage of other engineering tools (i.e. multi-physics simulations, mathematic based system identification tools, among others) for further analysis. If the experimental results don't validate the hypothesis (that is the value expected is not created), it is needed to redefine the value expected or renew the conceptual design.

Despite extended hybrid modeling approach can help extensively, deployment of other tools would be beneficiary for deeper analysis of CPSBESs. As an example, computational fluid dynamics can provide detailed insight related to heat and mass transfer whereas agent-based human behavior modeling can provide extended understanding of occupant behavior.



4. IMPLEMENTATION OF THE CPSS CONCEPT

Following the methodological framework presented in Chapter 3, implementation of the proposed CPSBES design and development approach is applied to AVS here. Starting from early definition, each subsection here explains first to fifth steps of the framework. The sixth and the last step including the further analysis is presented in Chapter 5.

4.1. Definition of AVS

As mentioned in Section 1, buildings have a significant share in global energy consumption and the HVAC system is the most crucial building energy system to decrease this share. On the other hand, any attempt to decrease HVAC energy consumption should also pay attention to keep occupant thermal comfort in desired level. In other words, HVAC system improvements should focus on solutions that leverage both energy efficiency and occupant comfort. For today's highly complex buildings, this is only possible with the involvement of holistic approaches that incorporates cyber, physical and social realms.

For the conventional HVAC systems, an important source of energy waste is the energy spent for conditioning spaces that are unoccupied or the occupants don't ask for a change in thermal conditions. Here, the terms 'space' doesn't necessarily refer to term 'zone' (multi- or single-room) in HVAC terminology, but any place inside a building. Specifically, it involves sub-parts of rooms that are without physical separators (like walls, glass, air curtains, among others). As mentioned in Section 2.2.1, personalized ventilation approach is intended to provide thermal conditioning to personal spaces (spaces just around the occupants) which is also referred as "task conditioning", "localized thermal distribution" and "personalized air-conditioning" [183]. Besides providing custom thermal environments, these systems are proved to be able to (i)

improve the air movement and the ventilation effectiveness, (ii) reduce building energy use, (iii) lower the life-cycle building costs, and (iv) improve the occupant satisfaction and the productivity [184]. However, these systems have limitations for their applicability. It is a challenge to install corresponding hardware to places close to occupants, such as air ducts and outlets on desks or heaters on chairs. Their design, on the other hand, requires more detailed engineering that results in higher installation costs. On the other hand, their installation would limit the flexibility for using an indoor space since their reinstallation is a costly operation. More importantly, cold feet and draft discomfort may result in thermal dissatisfaction due to the short distance between body parts and air terminal units.

Based on the discussion provided above, a solution can be developed to provide localized and customized conditioning in a practical manner to prevent energy wastes due to conditioning unnecessary spaces. In order to overcome challenges presented here, AVS is intended to manage indoor temperature distribution by providing asymmetric air inlet to the zones. By doing so, it is expected to create spaces (sub-zones) with different thermal characteristics that can be match with occupant preferences. If only the necessary parts of the room are conditioned, total volume of the air used for meeting thermal comfort expectations of the occupants is decreased, which results in energy efficient HVAC operations.

Realizing the energy savings without sacrificing occupant comfort by using proposed AVS can only be facilitated with the detailed consideration and involvement of physical, cyber and social concerns. In terms of physics dimension, characteristics of the air-jet leaving air inlets and the air flow regime inside the room are determinants of indoor air temperature distribution. Thus, their control is essential for system performance. Yet, due to the chaotic nature of turbulence around air inlet, it is beyond the capabilities of

conventional control approaches to manage such a phenomenon. However, advanced control approaches, like predictive control, can make it possible by taking advantage of recent advances in cyber technologies to overcome this challenge. Some of these advancements are single board computers with reasonable computational capacity, lightweight machine-to-machine communication protocols, cloud infrastructure, cheap and reliable sensors, among others. Once the control of temperature distribution inside a room is facilitated with the involvement of cyber advancements, this can pave the way for occupants to control thermal environment next to them and prevent serious amount of needless conditioning in the rest of the room. Offering such a new practice to occupants can augment both occupant thermal satisfaction and engagement for savings.

Following the discussion provided above, the proposed AVS can be defined as “a CPSBES that can provide localized and customized indoor thermal conditioning by managing air flow with asymmetric air inlets in order to augment occupant thermal experience and leverage energy efficiency.” When realized, total energy consumption and CO₂ footprint of a building can be decreased while meeting occupants’ thermal comfort preferences.

4.2. Conceptual Design of AVS

In order to realize the definition provided in previous subsection, the proposed AVS can be abstracted into four major components: (i) operable flap diffusers (OFD), (ii) thermal agents, (iii) user interface and (iv) a control and communication unit. Moreover, integration of a cloud platform and additional sensors to the system would be an option (see **Figure 15** for the overview of the system components). Being fundamental physical component, OFD is under the charge of controlling the air directions in air inlet positions. Thus, it determines the characteristics of the air-jet and the indoor airflow regime, so the temperature distribution. Thermal agents are simple temperature sensors coupled with a

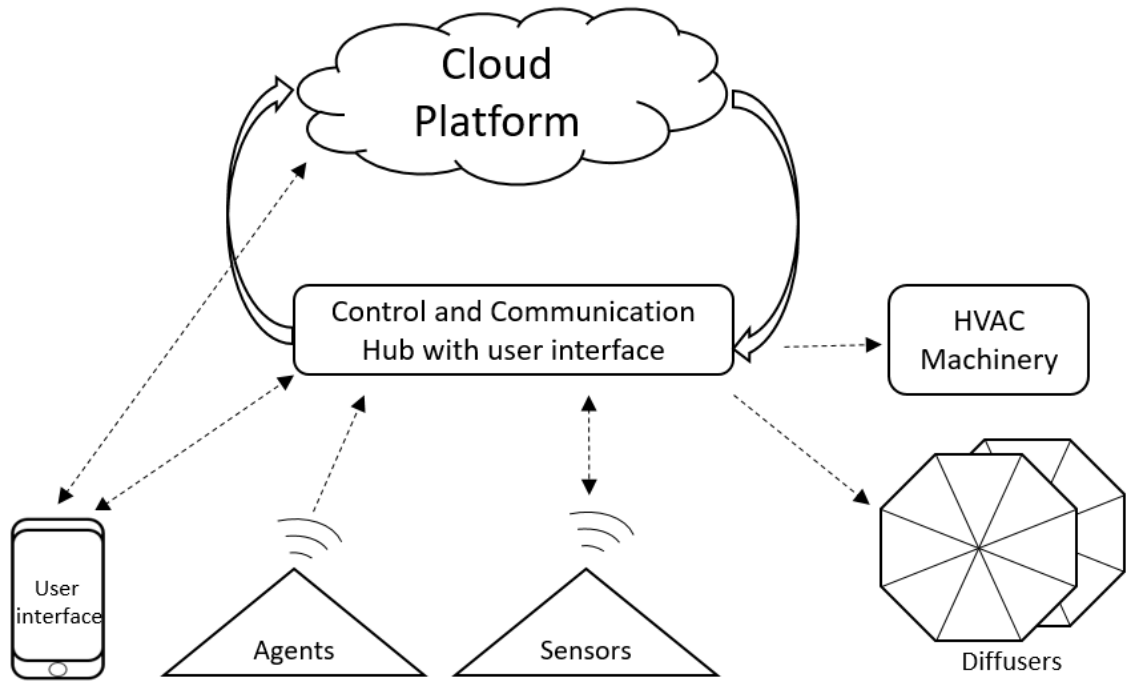


Figure 15: Overview of the proposed adaptive vent system components.

communication unit and let the controller monitor temperature at several points inside the room. The user interface let the occupants to set their general preferences (i.e. min/max temperature set points) and enter state change demands (i.e. increase/decrease temperature) to the controller. Control and communication unit controls HVAC machinery (air speed and temperature) and diffusers (air inlet/outlet directions) depending on the data coming from thermal agents and demand coming from user interfaces. Moreover, it manages wired or wireless communication among system components.

Optional components can enhance system performance. Additional sensors (i.e. door/window sensors, occupancy sensors, calorimeters, among others) can provide more detailed information about indoor environment to the controller for a better management. Integration with a cloud platform, on the other hand, can enable higher computational task and remote system management (software or model updates, system performance monitoring, long term data storage, among others). Detailed design concerns regarding to major components of the proposed design of AVS are given below.

4.2.1 Operable Flap Diffusers

Air inlet to the zones is characterized by air inlet speed and temperature, indoor temperature and diffuser geometry as mentioned in Section 2.2.2.1. Conventional diffusers are designed to let air symmetrically enter to the zone in order to create homogeneous temperature distribution. In order to reinforce homogeneity, those are distributed evenly on walls or ceilings. Thus, as the HVAC machinery send air to these diffusers, temperature measurements at different points of a horizontal plane are expected to be similar. However, this is a rare case during practical operation due to the environmental disturbances, like opening a window or cumulation of people at a point. In short, conventional diffuser designs offer a fixed scheme for thermal conditioning which is assumed to be homogenous all around the zone.

On the contrary, the proposed AVS is intended to manage temperature distribution inside a room dynamically in order to match the temperature dissimilarities with variety in temperature preferences of occupants. A practical way for this intention is providing an asymmetric air inlet to the zone in a controllable manner. This can be realized with a diffuser design that has individually operable flaps. Letting air to primarily flow towards the sub-regions where occupants ask for change in temperature, AVS prioritize conditioning these parts of the room (or zone). A diffuser design that can perform in this way is shown in Figure 16. It is an octagonal and the flaps are opened turning around the hinges at one side of the flap. Figure 16 shows two of the flaps are open and let the airflow in specific direction whereas the others block the airflow.

During the practical operation of such a system, due to the heat diffusion and the secondary air flows (flows triggered by air jet), unintended parts of the room are also subject to a change in temperature. However, it would not be as much as the intended sub-regions since the primary air is directed towards these parts (where occupants ask for

change in temperature). Thus, the proposed system makes it possible for occupants to primarily change the temperature around them and limit the change in the other parts. This is a new practice for occupants while controlling temperature inside a room and offers a promising potential in order to leverage human-building and inter-occupant relations. Since occupants would imagine laminar airflow blowing out of open flaps, the design of diffuser flaps is important to facilitate convenience while occupants chose flaps to open and their opening angle.

4.2.2 Thermal Agents

Temperature is the essential parameter for the HVAC system control, so the sensors for measuring it are among the major components of HVAC control. Conventional systems use thermostats that includes (i) a sensor unit that measures temperature (and humidity in most cases), (ii) a controller that keeps temperature at a set point and conduct communication with HVAC machinery, and (iii) a user interface to let occupants to

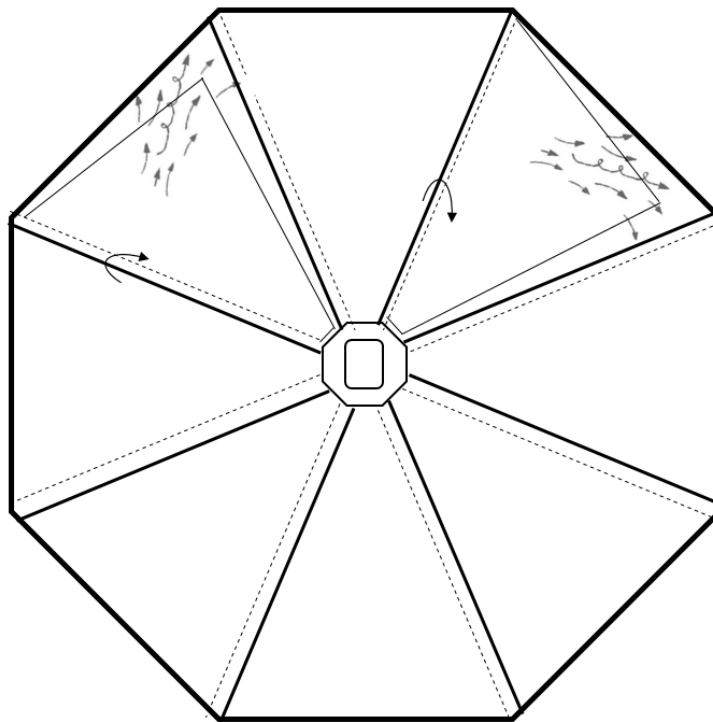


Figure 16: Preliminary diffuser design with operable flaps.

declare setpoints, fan speed and timer settings. The thermostat measures local temperature around it and control parameters of machinery by assuming a homogenous temperature distribution inside the zone. Such an approach would be correct for small rooms; however, it results in uncontrollable temperature distributions due to the door and window openings, variety in occupant intensity, furniture (thermal mass) locations and design, sun radiation, among others.

Unlike conventional HVAC control, the proposed AVS requires temperature readings with higher spatial resolution. In other words, in order to manage temperature distribution inside a room, there should be more than one temperature measurements to provide feedback to controller. However, it is not needed to include controllers to each of these temperature sensors since the control action is performed by a dedicated unit. Hence, the AVS includes TAs that is composed of a temperature sensor and a communication module to measure temperature and transfer this data to the controller. The controller of the system manages temperature distribution inside the room in accordance with the data coming from several TAs. Due to their dedication for temperature data gathering and being distributed inside the room, they are called ‘agents’.

The number of the TAs in a room can be determined in concordance with parameters like number of diffusers on the ceiling, arrangement of the furniture, number and positions of occupants, outline (wall) geometry of the room, among others. Moreover, TAs shouldn’t be located close to heat sources (such as human body, laptop fan outlet) to prevent misrepresenting temperature measurements. On the other hand, the selected communication technology would limit the number of agents in practical design. As an example, if Wi-Fi is preferred, the router will limit the number of devices that can be connected. Hence, the IT infrastructure of the building should be investigated before AVS design for deployment. The maximum connection distance and the power requirements

of the selected technology are two important criteria for TAs in order to provide a reliable and efficient communication.

4.2.3 User Interface

Most of the modern HVAC systems provide essential control opportunity to occupants by means of screens on thermostats. Users can set temperature set points, fan speed, heating capacity and timers. However, they are not user friendly in most cases and this limits the interaction of occupants with HVAC systems. Moreover, a change in a multi-occupant room affects all people inside room even if only one of them needed a change in thermal conditions. Being referred as “thermostat wars”, this phenomenon is a bottleneck in occupant experience of current HVAC deployments and obviously the problem is related to overall system design, not limited to any single component. Thus, offering an opportunity to customize thermal environment around occupants requires a better interaction design between occupants and the HVAC system. Otherwise, it can limit user acceptance.

Following the system definition provided in Section 4.1 and other system components presented above, the user interface of the AVS system is expected to leverage occupant interaction with HVAC system. In addition to conventional control parameters like fan speed and heating (or cooling) capacity, it is the interplay where the occupants can (i) see the temperature around them and other occupants (corresponding TA readings) as well as average room temperature, (ii) set a change in temperature, fan speed or heating (or cooling) capacity, (iii) choose flaps to open and the angle of opening. In other words, occupants can determine basic set-values for temperature, air speed and air flow direction for specific parts of the room. Some other functionalities such as scheduling, alarm setting or providing feedback can also be offered to occupants using UI for a better interaction. Furthermore, it has a crucial role for behavioral concerns because beside managing the

system, it can be used for facilitating behavior change toward energy efficiency by means of persuasive technologies. Similarly, occupant interaction with the system should be designed in a way to maximize user engagement with the energy saving potential of the system. Mobile devices like smartphone and smartwatch are proper gadgets for this task with high availability in modern life. Similarly, web browsers on personal computers can fulfill this task.

4.2.4 Control and Communication Unit (CCU)

Conventional thermostats have simple controllers that performs control actions following the algorithm programmed. Control actions would be as simple as on/off at a certain temperature or be complicated like determining fan speed and air inlet temperature with predictive approaches. Yet, Proportional-Integral (PI) and Proportional-Integral-Derivative (PID) temperature control algorithms are commonly used in the products on the market whereas there are attempts by companies to deploy advance control approaches.

Beside temperature, fans speed and heating capacity control, CCU of AVS is expected to perform two additional tasks. First, it controls flap angles when occupant didn't set these parameters but asking for conditioning in a specific part of a room. In such a case, CCU is also expected to close flaps that don't contribute to thermal conditioning of selected part in order to prevent energy wastes. Despite having a simple definition, performing such a task with a limited computational capacity is a challenging task. It would require deployment of advance control approaches like model predictive control (MPC). A neural network based MPC can perform control actions taking advantage of a black-box model trained with the data related to results of previous control actions. Such a control action can be performed with single board computers available today (Section 2.1.2).

The second role of the CCU is the management of device-to-device communication. Since the OFDs, TAs, UIs and additional sensors are distributed in a room, their communication is needed to be managed effectively and securely. A selection among available communication technologies (see Section 2.1.3) and protocols (i.e. MQTT, BACNet, I2C, among others) is needed to facilitate networking between devices. Since battery life is an important design concern for wireless sensors, the energy efficiency of the communication process is important and can be dynamically optimized by CCU. As an example, the data transfer would be set to lower rate when room is empty, or HVAC is not active.

In order to perform all these control and communication actions effectively, CCU needs to host a database. There are custom databases for embedded devices that are suitable for this kind of operations. As expected, these require a reasonable amount of system specification (CPU, RAM and memory) that is beyond the capacity of most of the microcontrollers. However, commonly available single board computers can perform these actions if programmed effectively as embedded systems.

4.2.5 System Level Description

In accordance with the definition of the AVS (see Section 4.1) and the description of fundamental components described above, a system level description is provided here in order to clarify the overall characteristics and the operation of this CPSS.

The AVS aims to provide localized and customized thermal environment to occupants by managing temperature distribution inside room by means of controlling airflow. When an occupant asks for a change in temperature change in a specific part of a room, he/she sets fan speed and heating capacity as well as determines which flaps to be open. For a typical room, those are the ones that head toward occupants. It would be possible to open one

or more flaps due to the design of diffuser. If the occupant is alone in the room, the other flaps would be completely or partially closed due to the specific case; however, the main idea is to send larger ratio of conditioned air towards occupant. With the help of such a prioritization, the conditioned air is initially met with the part of the room where occupant asks for a change. The rest of the room is conditioned with the secondary air induced by air jets leaving open flaps. CCU keeps track the change of temperature around the occupant by means of nearest TA (predefined during system installation) and perform control actions like machinery on/off. On the other hand, since the system aims to operate at lowest fan speed in order to minimize energy consumption, the control algorithm can keep this parameter as low as parameter.

The fundamental information flow for the basic operation of the system is shown in Figure 15. The cyber components are TAs, CCU and additional sensors (occupancy, door/window, among others.). These components control system operation by performing corresponding computations and communication. Furthermore, integration of CCU with cloud services would an option for a better system management (such as firmware update) and additional functionalities (like performance reporting.) OFD is the fundamental physical component of the system that manipulates airflow. A clear understanding of the physics of the airflow around flaps and inside the room requires detailed modeling of heat and mass flow. Equations for conservation of mass, momentum and energy as well as thermal comfort formulations can provide a detailed analysis of air flow where specific tools like CFD can leverage this procedure. The social component that facilitates interaction of system with occupants is the UI. Beside entering control parameters, occupants can get feedback related to temperature trend around them and resulting energy consumption of their preferences. Hence, UI is the main tool for interaction between occupant and AVS.

Here it is important to note that AVS is not a complete HVAC system that involves ducts, machinery or dampers. It is simply a “HVAC interface” between corresponding building infrastructure and occupants. Running a dedicated software on CCU, several functionalities can be deployed benefiting advance control methodologies and interface design tools. However, user experience should be on the focus of any functionality. The system is intended to allow occupants to customize their experience and get full control of the system for a better acceptance.

4.3. Modelling the AVS

The hybrid dynamics of AVS system is modeled using a well-studied approach called discrete hybrid automata, DHA. DHA deploys linear difference equations (LDE) for modelling continuous dynamics whereas the finite state machines (FSM) are used for modelling discrete dynamics [175]. LDE and FSM are synchronized by the same clock which provides discrete timing based on natural numbers. Moreover, they interact with each other by means of events and mode switches.

In order to model the continuous dynamics of the AVS, a well-known thermal modelling approach called Resistance-Capacitance (RC) network modelling is used. RC network models take advantage of circuit diagrams and state-space equations for identifying thermal dynamics in a medium [74]. For indoor thermal environment, it doesn't provide any information about airflows but still usable for analyzing temperature profile. Conventional usage of RC networks deploys a single point to represent room temperature with corresponding resistance and capacitance values representing whole room. However, it can be extended to represent temperature of a sub-zone if resistance and capacitance values are adopted.

RC network for the test room is demonstrated in Figure 17 where T_{int_1} and T_{int_2} represents temperatures on the two desks that are located at opposite positions. T_{h_1} and T_{h_2} values represent hot air inlets towards corresponding directions whereas T_E is indoor surface temperature and T_{ext} is outdoor surface temperature. On the other hand, R_x and C_x values represent corresponding resistance and capacitance values. Following this network model and notation, temperature change in a given point can be formulated as follows:

$$\dot{T}_{int_x} = \frac{T_E - T_{int_x}}{C_{int_x} \cdot R_{C,int_x}} + \frac{T_{h_x} - T_{int_x}}{C_{int_x} \cdot R_{h_x}} \quad (\text{Eq. 4.1})$$

Using the Euler approximation in the form of

$$\dot{T}_{int_x} = \frac{T_{int_x}(k+1) - T_{int_x}(k)}{s} \quad (\text{Eq. 4.2})$$

we can convert this differential equation to the following difference equation:

$$T_{int_x}(k+1) = T_{int_x}(k) + s \cdot \left[\frac{1}{C_{int_x} \cdot R_{C,int_x}} (T_E - T_{int_x}(k)) + \frac{1}{C_{int_x} \cdot R_{h_x}} (T_{h_x} - T_{int_x}(k)) \right] \quad (\text{Eq. 4.3})$$

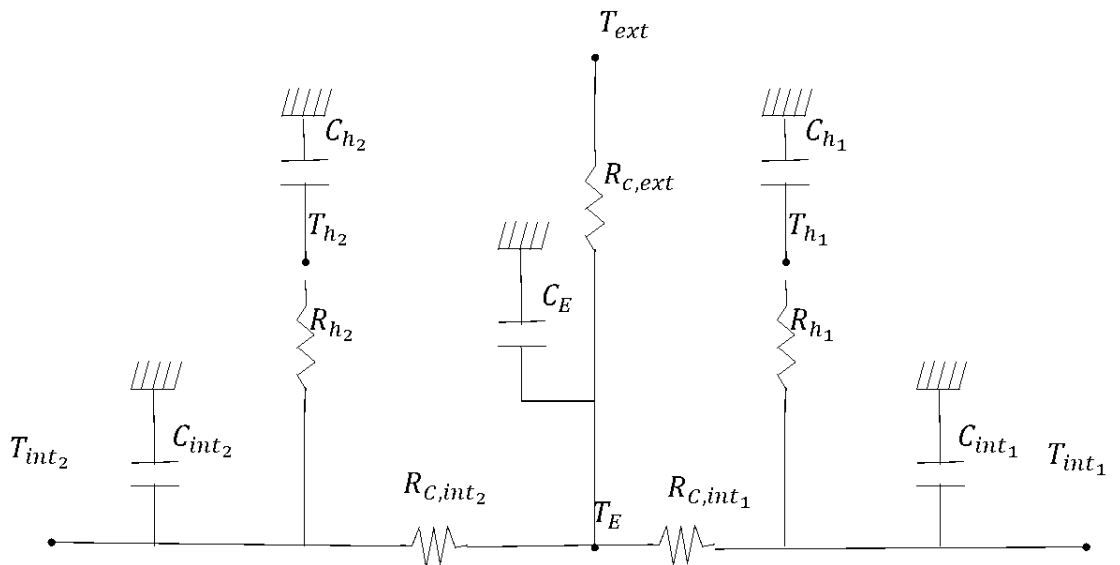


Figure 17: RC network model of the test room that is used for continuous dynamics.

The FSM for AVS is shown in Figure 18 which represents state transitions for the experiments. Accordingly, M0 represent the case that both desks are empty, so the system is closed. M1 is the case that only the Desk 1 is occupied so the diffuser blows only in that direction. M2 is the case that only the Desk 2 is occupied so only the flaps releasing air towards that direction are open. M3 is the case that both desks are occupied so the flaps heading both direction are open. Temperature change in each mode is governed by Eq. 4.3 but the T_{h_1} and T_{h_2} values are different for each case.

The fundamental behavioral concern for building energy management is occupancy [161]. Hence, the behavior modelling of the AVS for experiments was based on occupancy models. A time dependent data set for occupancy can be formulated with a unit step function as follows:

$$u(t) = \begin{cases} 0, & \text{if occupant is not present} \\ 1, & \text{if occupant is present} \end{cases} \quad \text{Eq. 4.4}$$

Moreover, as defined in third stage of proposed modeling approach, occupant preferences can be set as constraints for discrete or continuous dynamics. Accordingly, temperature set-values of occupants defined as follows:

$$T_x < T_{set_x} \quad \text{Eq. 4.5}$$

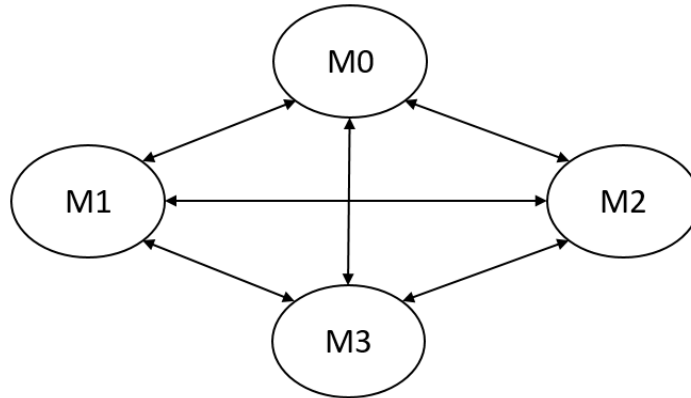


Figure 18: Finite state machine for the discrete dynamics (M0=Nobody inside the room;, M1=Only Desk1 is occupied; M2=Only Desk2 is occupied; M3=both desk is occupied. (See text for the details).

So, the temperature of a point (T_x) is limited to reach values higher than T_{set_x} . Since T_{set_x} is set by occupant by means of user interface, it is an element to observe the occupant behavior. During the simulation, when the (T_x) value reaches the set value, the FSM switches the mode (changes T_{hx} values) that closes the flaps blowing towards that direction. Hence, the parameters representing the physical conditions (continuous dynamics) inside the room ($C_{int_x}, R_{C,int_x}, R_{hx}$) are updated.

The enhanced hybrid dynamical model for the simulations was developed using HYSDEL modeling language. The HYSDEL is a high level programming language develop specifically for modeling hybrid dynamics and has a syntax similar to natural languages [175,185,186]. The HYSDEL code for the model presented above is given in Appendix-A. Due to the convenience of the modeling language, one can easily recognize the part for continuous dynamics in lines 28-30 and the part for discrete dynamics in lines 19-27 of the HYSDEL model. Moreover, occupant temperature preferences were defined in lines 22-23 whereas occupancy state is used in lines 25-26. In accordance with the design of these tools, for simulating the experiments, the HYSDEL model was converted to a MLD model using *mld()* function. Then, *pwa()* function is used for converting MLD model to piecewise-affine equivalents. Having the HYSDEL model, the *sim()* function of Matlab is used to run the simulations.

4.4. Prototyping and The Test Room

In order to validate the models developed in Section 4.3 with experimental data, a test room is prepared. Accordingly, the prototypes of each component of AVS is deployed into a room in Engineering Faculty Building of Özyeğin University. In other words, a living-lab is created for both experimentation and real-life testing of the proposed system. The room involves (i) a novel design of OFD at air-inlet that has 8 individually operable

flaps, (ii) a manually operable 4-way diffuser at air-outlet, (iii) 8 thermal agents, (iv) a user interface hosted on a tablet computer, (v) a single board computer as CCU, (vi) door and window sensors, (vii) 23 additional temperature sensors that measures at ceiling, head and floor level air temperatures as well as wall and window temperatures. The locations of the main components are shown in Figure 19 and detailed description of each component and the test room are given below.

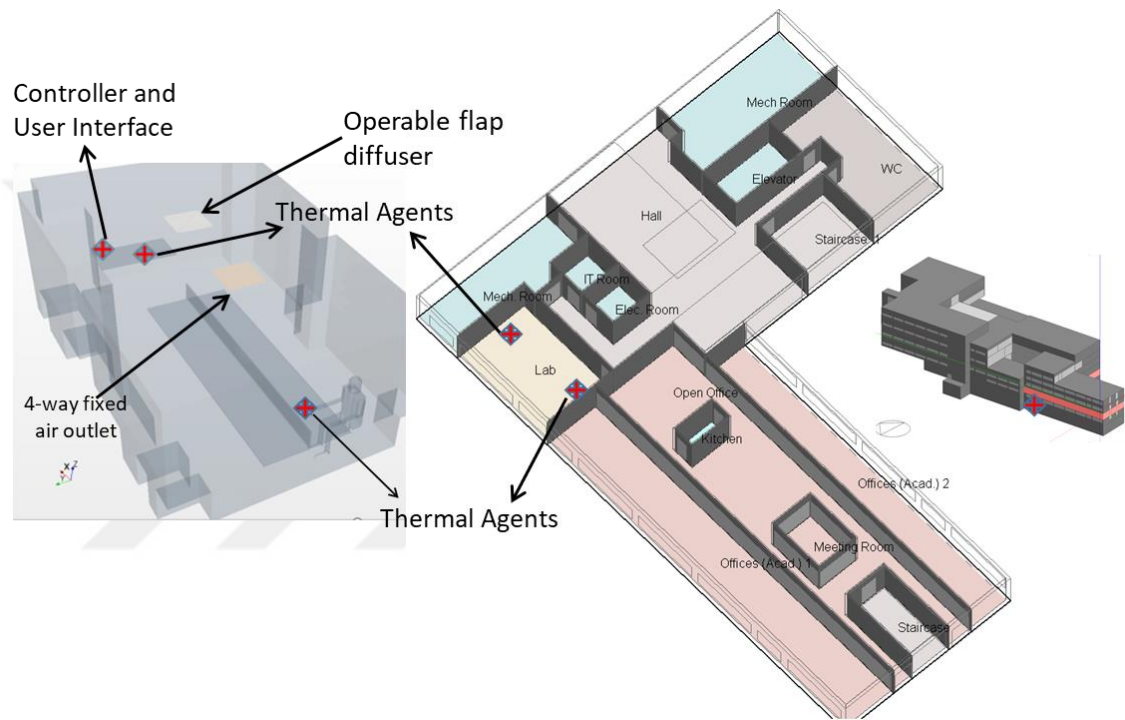


Figure 19: Positions of the main system components in the test room. See text for detailed explanation of each component.

A novel ceiling air diffuser with 8 individually operable flaps was designed and produced. Then it is replaced with the typical 4-way square diffuser of the room. Flaps are in shape of trapezoid and their stack forms an octagon outline (Figure 20 and Figure 21). The hinge of each flap of the OFD is attached a servo motor (Tower Pro SG90 9G Servo Motor) that is controlled with a microcontroller (DOIT ESP32-DevKit development board). The motor controller communicates with CCU using an onboard Wi-Fi module and MQTT protocol. MQTT is a ‘lightweight’ machine-to-machine connectivity protocol and allows CCU to send position change commands for each flap to motor controller. Motor

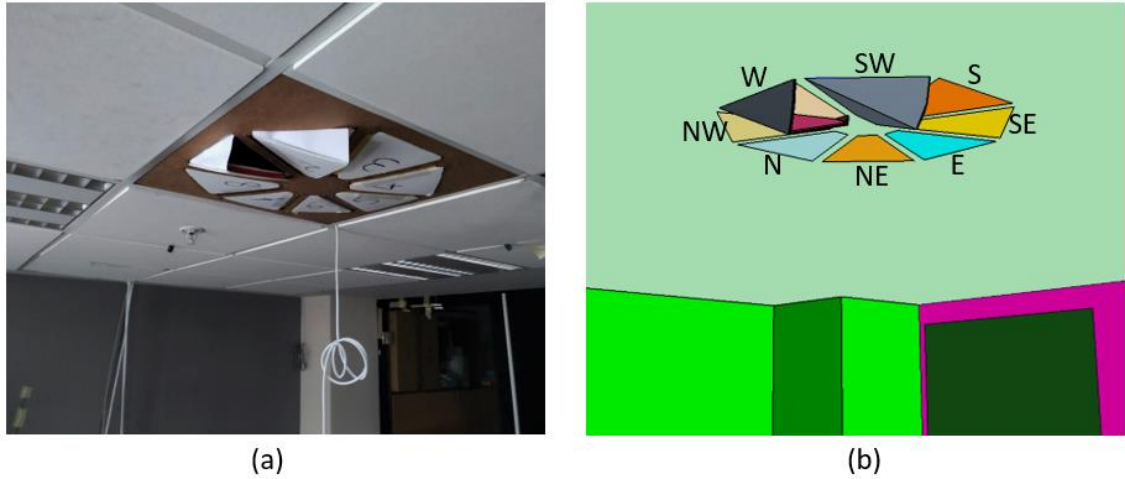


Figure 21: The picture (a) and the geometrical model (b) of the operable flap diffuser.



Figure 20: Pictures of operable-flap diffuser prototype: (a) back side (b) on the ceiling as mounted.

controller is programmed in a way that it allows each flap to have 3 levels of opening (3 different angles with respect to normal of a ceiling) or to be closed.

The hinge of each flap is along one of the long sides of trapezoid that allows other long side to move up and down. This makes it possible for occupants to easily understand which flaps are open and what is the angle of opening for each flap. This allows them to recognize flow direction of primary air intuitively that makes it possible for them to choose flaps to open when they are setting HVAC system. On the other hand, an off-the-shelf 4-

way manually controllable ceiling diffuser was mounted to the air outlet, but its flaps are kept fixed during experimentation.

The prototype TAs have digital temperature sensors, namely Microchip MCP9808 on their board (Figure 22). These sensors have $\pm 0.25^\circ\text{C}$ accuracy and are located inside the small toys to protect them from damages. These toys have extra holes on them for enabling air flow across it and measure temperature correctly. Eight of them are located on desks inside the room for a high-resolution (spatially) monitoring of the indoor temperature distribution. These calibrated sensors were connected to the microcontrollers (NodeMCU ESP8266) with cables. Sensors' chip and the microcontroller communicates via cables using I2C protocol whereas microcontroller and CCU communicates via Wi-Fi using MQTT protocol. Microcontrollers are always active and 'listening' CCU for data demand. Whenever data is asked by CCU, temperature is measured by the sensor and sent to be processed and stored. In a regular operation, CCU asks for data in each minute but whenever occupant interrupt the regular process to change any setting, new values are also recorded. TAs are located on a corner of each desk in order to keep them away enough from occupant to prevent effect of heat dissipation from his/her body on sensor readings.

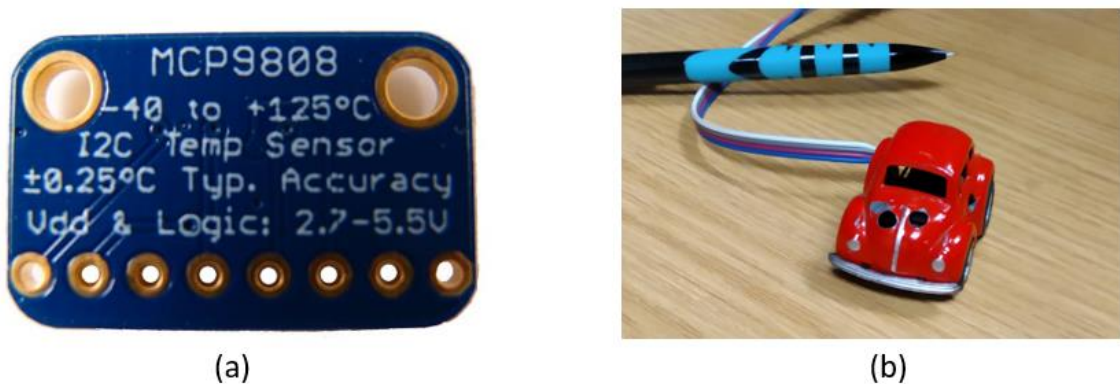


Figure 22: Pictures of thermal agents: (a) the temperature sensor (MCP9808) (b) the toy in which sensor is mounted.

UI of the prototype is an interactive dashboard (Node-RED) hosted on a dedicated tablet computer. Occupants can also reach it using their web browsers on their personal computers or smartphones if they are connected to same Wi-Fi network with CCU. UI consists of several screen to perform different functionalities. The “control screen” enables interaction with OFD and HVAC machinery. Thus, it involves slide bars for setting flap positions, fan speed and heating capacity. The “general view screen” shows all sensor readings by grouping them according to their positions and types. It involves graphs showing (i) temperatures on ceiling, floor, desk and head levels, (ii) wall temperatures, (iii) door/window positions, and (iv) occupancy status of each desk. An “occupant screen” involves graphs showing neck (floor), desk and head level temperature trends for the desk of an occupant. Each occupant (desk) in the room has a dedicated screen to monitor localized thermal environment (Figure 23 and Figure 24).

CCU of the prototype is a single board minicomputer (Raspberry Pi Model 3B+) that has BCM2837 SOC (1.4GHz) as CPU, 1GB SDRAM as memory and 32GB SD card as hard drive. Moreover, it has onboard hardware for dual band and Wi-Fi and Bluetooth 4.2

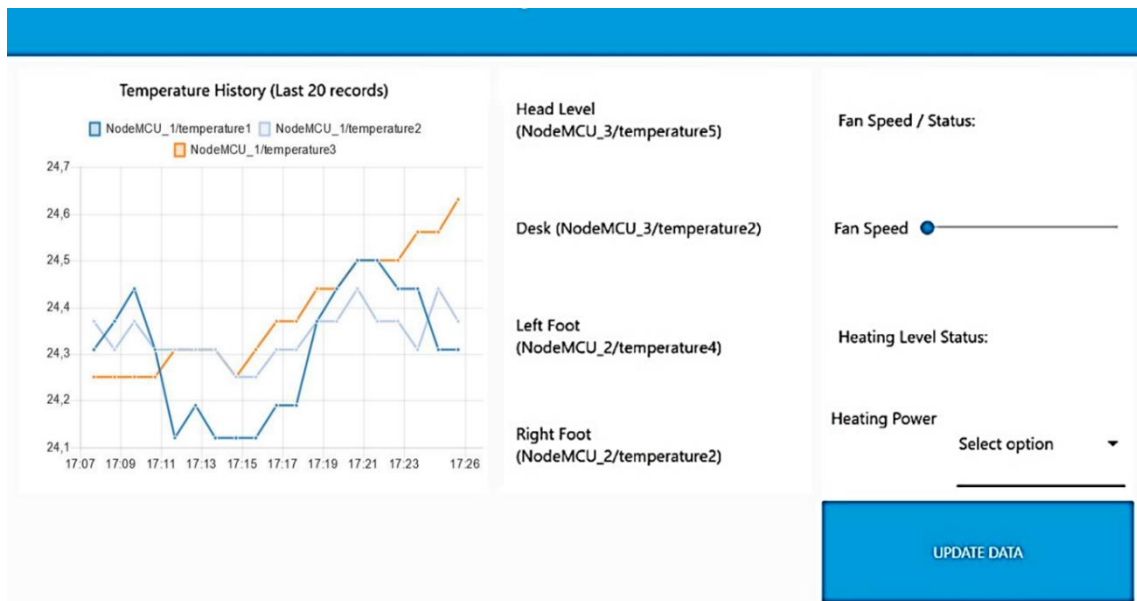


Figure 23: The prototype of the user interface.

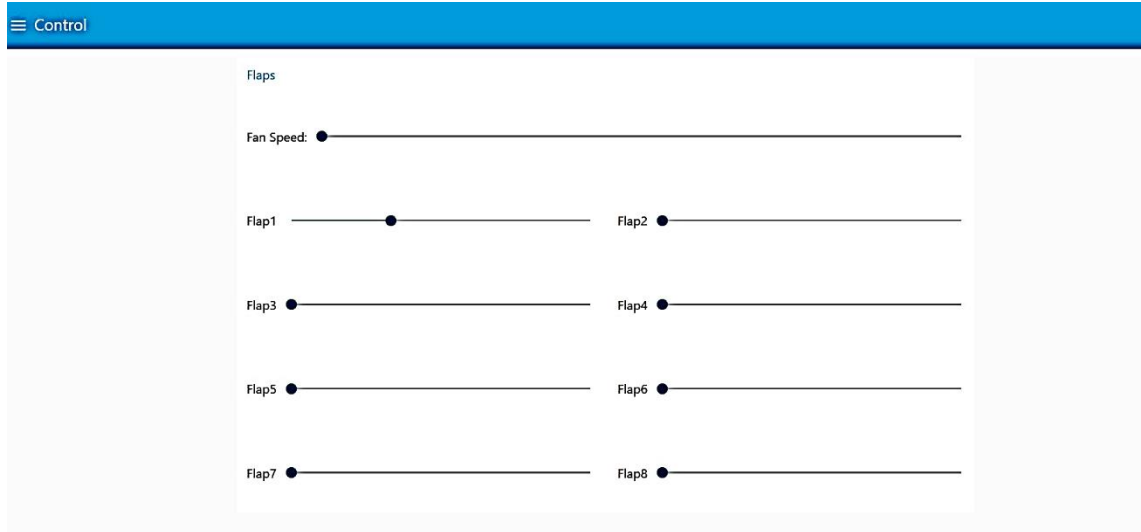


Figure 24: The flap control screen in the user interface.

connectivity. It runs Raspbian operating system that conducts all system management duties at the background. Thus, it can run several services and software for reliable operation of CCU. A lightweight IoT development tool originally developed by IBM's Emerging Technology Services team, namely Node-RED was used as the core development environment. Having an extensive applications library, Node-Red enables and manages information flow among software, services and devices. Figure 25 shows the main functions of Node-Red software for AVS operation. Fundamentally, it receives real time sensor data from microcontrollers, match them with a time-stamp and transfer to database server (regions 2, 4 and 6 in Figure 25). The UI of the AVS was also developed and applied using the dashboard toolset of Node-Red (Region 1 and 3 in Figure 25).

During system operation, when the occupant changes flap configurations or HVAC machinery settings on UI, Node-Red sends this data to corresponding microcontrollers in the test room, using MQTT protocol on Wi-Fi (Region 5 in Figure25). Thus, beside built-in functionalities, the Node-Red software plays an integrative role for system operation in parallel to definition of CCU.

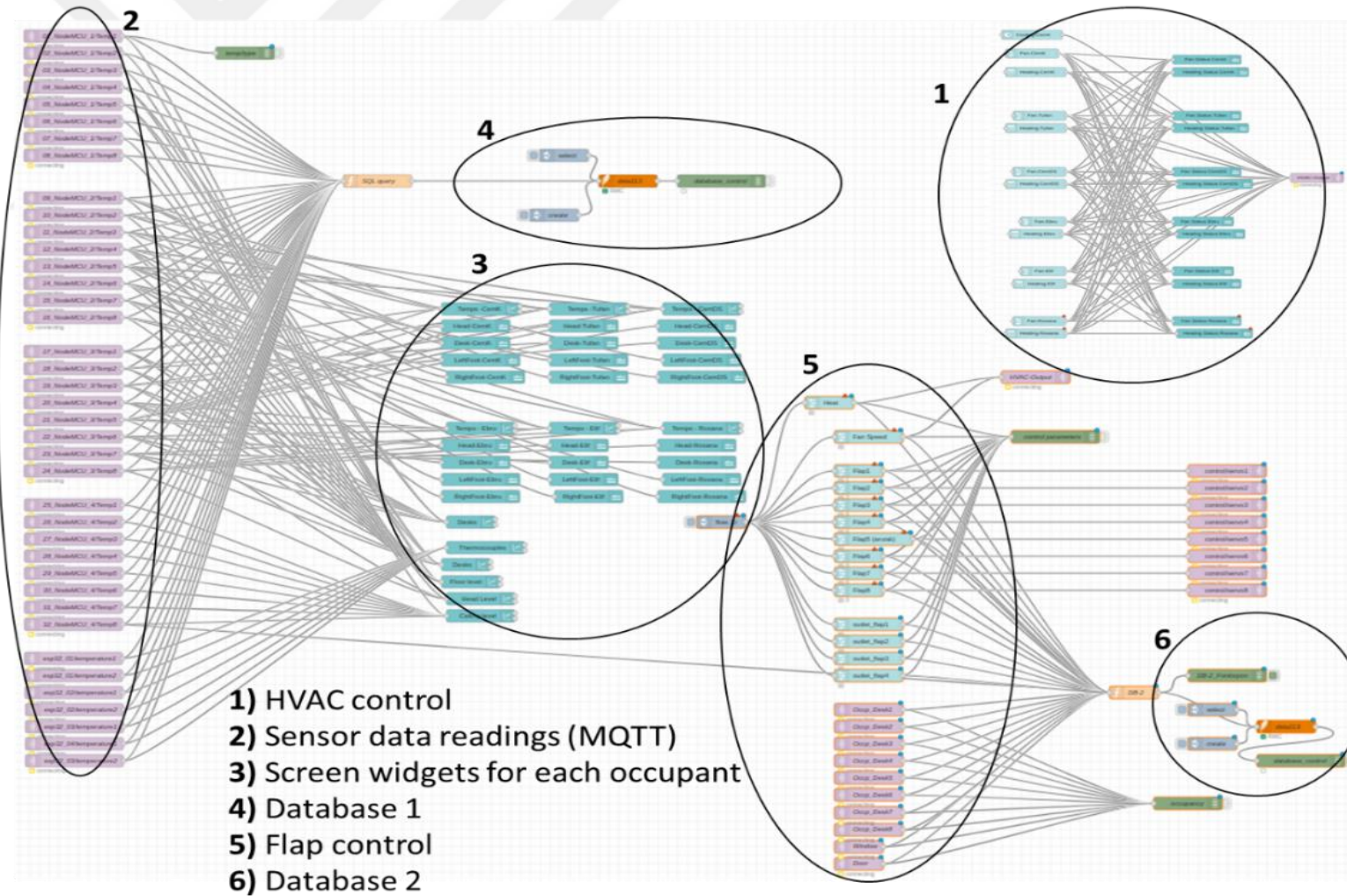


Figure 25: Node-RED program that controls system operation

CCU functions as a database server (SQLite) that stores all collected data and serves them to other services like dashboards on UI and temperature control software (Python script). Hence, all sensor readings and data related to flap positions are gathered and stored in this unit. Third, it manages communication among devices by hosting a MQTT broker (Mosquitto). Note that, While selecting wireless technology (see Section 2.1.3), each of the Zigbee, Bluetooth and Wi-Fi were tested for device-to-device communication. The availability of well-documented and reliable MQTT software libraries made Wi-Fi advantageous, especially in terms of development time. Hence, as mentioned in previous paragraphs, the system components communicate with CCU using Wi-Fi.

The test room is $4.4m \times 6.2m \times 2.45m$ in size and houses 8 desks. Only one of the walls (west) has windows with glazed area ratio of 45%. The room has false ceiling and floor that enables insulation for heat losses. There is an all-air delivery system deployed in the room and 2 diffusers (one for air inlet and one for air outlet) on the ceiling. A fan-coil (GEA Flex-Geko GE31.UWW4.AO) installed above the false ceiling conditions (both heating and cooling) inlet air whereas the hot and cold water was fed to the fan-coil by a campus-wide energy distribution center. Additional sensors were deployed to the test room in order to support experiments. Accordingly, temperature sensors (Microchip MCP9808) were located to the floor level (11 sensors), the ceiling level (7 sensors) as well as the air inlet and outlet ducts (1 for each). K-type thermocouples (with MAX6675 modules) were mounted on 4 walls of the room and the window. Moreover, status (open/close) of door and window is also monitored Figure 26.

4.5. Experiments

The experiments and the corresponding simulation scenarios was intended to observe the characteristics of the temperature distribution inside the room due to the different flap

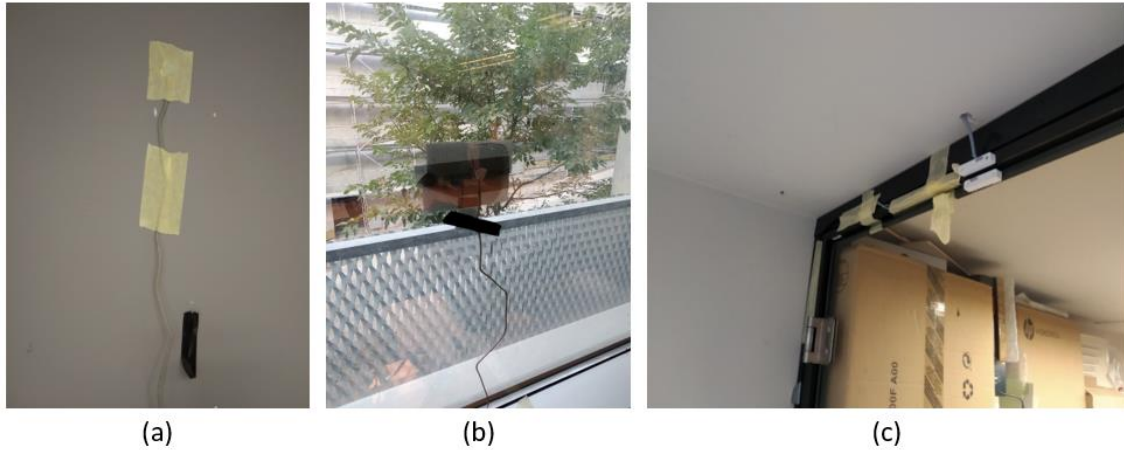


Figure 26: Additional sensors: (a) thermocouple on the wall (b) thermocouple on window (c) door sensor.

positions. The two main questions were (i) ‘Is it possible to create temperature differences in a controllable way,’ and, (ii) ‘How long it is possible to keep the temperature difference between two points’. As one can notice, these questions took aim at the limitations of conventional HVAC design targeting the homogeneity of indoor temperature.

Accordingly, experiments were conducted in mornings when the room reached temperature stability during the night since HVAC system was not active and there was enough time (several hours) to eliminate observable temperature differences ($<0.5^{\circ}\text{C}$) in demo room. This made it possible to eliminate as much as possible the effects of conditions before experiments and also clearly observe the performance of OFD. Moreover, during the experiments room was kept empty, so the heat input from people is ignored. Similarly, the experiments were conducted in early hours of the day and in winter, so the heat inputs related to sun radiation were also ignored. Accordingly, these two heat resources and corresponding resistance and capacitance values are not included in the thermal network. This enabled observing clean effect of flap orientation since it was the dominant heat source.

4.6. Analysis

The analysis of results of each experiment was conducted with a two-step procedure. Initially, the experimental results were investigated in terms of establishing and the control of temperature differences between selected points (two desks at the opposite sides of the room). For this step, the primary concern was the evaluation of temperature difference among selected points. The amount of the difference as well as the time intervals for the formation and disappearance of it were the factors to assess timely evaluation of temperature distribution inside the room. Secondly, the AVS model presented in Section 4.3 was investigated to determine if it is capable of representing the time dependent change of temperature differences among points of concern. For this assessment, graphical fit method was used: the resistance (R) and capacitance (C) values of the model were set manually to observe if the model can fit to experimental data.

The first experiment investigates the case that only Desk 1 was asking for an increase in temperature. Thus, two OFD flaps releasing air towards that direction were opened (system mode M1) and the fan-coil was set to middle capacity (Level 2 of 3 possible fan speed levels that conditions 360 m^3 air per hour. After the system activation, the temperature around Desk 1 (readings of sensor 1) increased gradually whereas the temperature around Desk 2 stayed almost constant. Accordingly, the parameter fit of the proposed model for system Mode 1 was successful in terms of temperature change trend Figure 27. Thus, the first experiment showed that the temperature difference can be created in a controllable fashion. However, time duration of the first experiment was short, so a second experiment is conducted for a longer case.

The second experiment was designed for a case that Desk-2 was asking for an increase in temperature. Hence, two corresponding flaps were opened, and the system set to middle

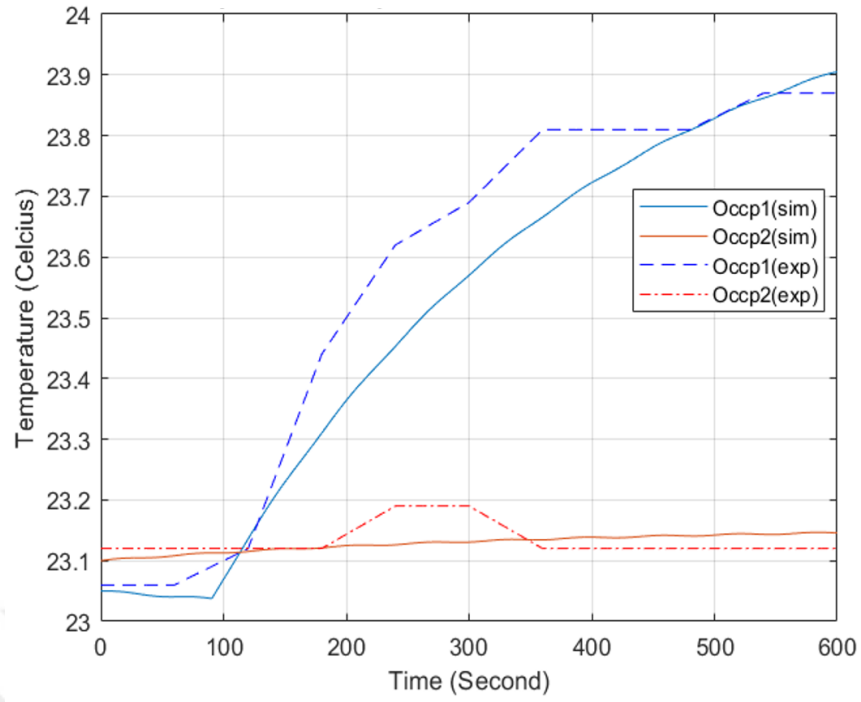


Figure 28: Simulation outputs and experimental results for the first experiment.

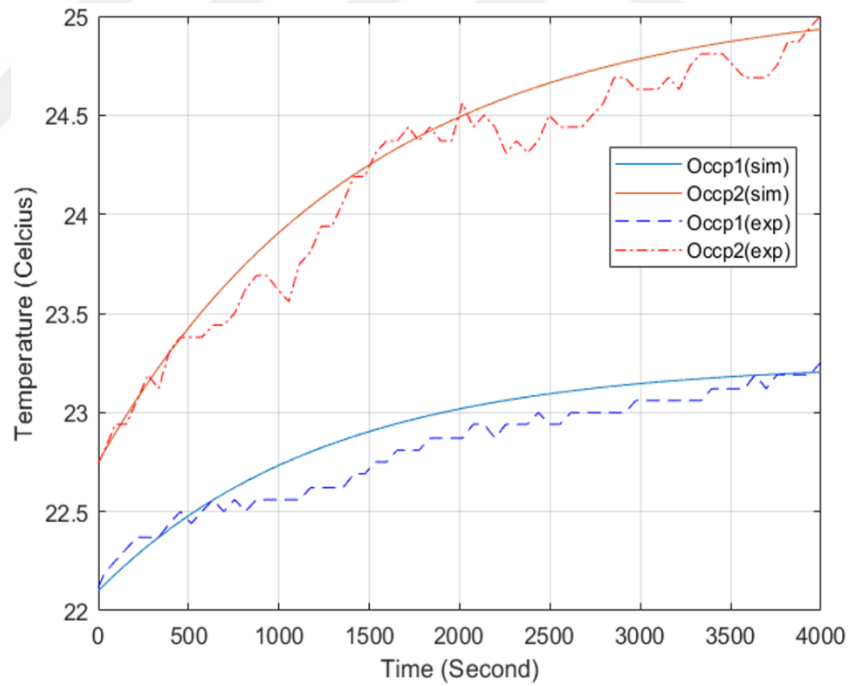


Figure 27: Simulation outputs and experimental results for the second experiment.

capacity. At the time of system activation, temperature difference between two desks was smaller than 0.5°C but it increased up to 1.5°C at the end of the first hour. An important difference with the first experiment was that the temperature of the opposite desk

increased obviously. The simulation output after the parameter fit for second experiment (Mode-2) was also in agreement with experiments (Figure 28). Thus, the second experiment and the corresponding simulation showed that temperature difference between two desks can be kept an hour. This period is long enough for indoor thermal management. Hence, the second experiment answers the second question given above related to time-dependent performance of the system.

The third experiment is intended to observe system dynamics for a change in system state. Thus, a system mode change from Mode-2 to Mode-1 was proposed more than half hour later than experiment initiation. The fan-coil was working in lowest speed (Level 1 of 3 possible fan speed levels). This is realized in test room by changing the open flaps: the ones heading to Desk-2 were closed and the ones heading to Desk-1 were opened. In simulations, only the occupancy profile is changed and the update (switching the state) of all other model parameters is performed automatically in parallel to logic defined in HYSDEL model. Note that, the R and C parameter got in previous experiments were used here (a new graphical fit procedure was not applied). Experimental and simulation results demonstrate that the temperature trends Desk-1 and Desk-2 was twisted just after state switch (Figure 29).

The result of experiments and their harmony with the simulations indicate the promising performance of the AVS for managing temperature distribution in an adaptive manner. In other words, it is possible to say that localized and customized thermal conditions can be created and controlled with the proposed system and can be fitted to customer preferences better than homogenous conditioning of whole room. The consistency of the experiments and the simulations also shows the effectiveness of the modelling approach that integrates hybrid dynamical and behavior modeling.

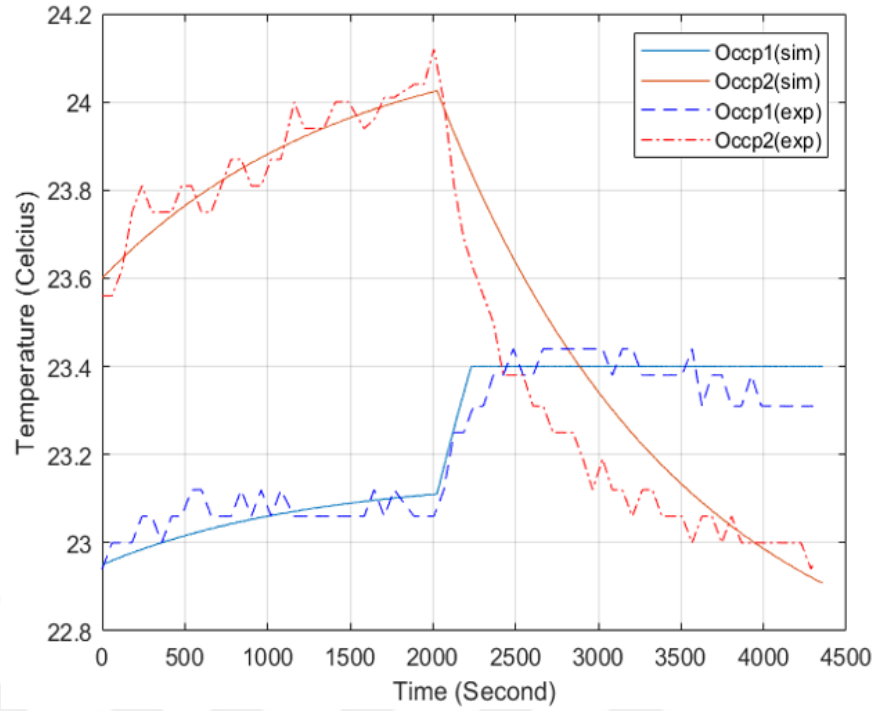


Figure 29: Simulation outputs and experimental results for the third experiment.

Beside validating the AVS concept and modelling approach, experimental results and simulations also provide insight about the operation of the AVS. In the first experiment, the distance between OFD and the wall next to the Desk-1 is two times more than the distance between OFD and the wall next to Desk-2. Therefore, the sub-region of Desk-1 is larger than the that of Desk-2. The larger volume refers to larger amount of air mass that “absorbs” the vast amount of the heat energy of the incoming air and so limits the rise in the opposite direction (around Desk 2). On the other hand, in the second experiment, the change of the flaps resulted in different temperature trend in opposite desk. Since the distance between OFD and the wall next to de Desk-2 is short, some portion of the air leaving OFD is deflected from wall due to its higher momentum and head towards Desk1. Accordingly, at the end of an hour, there was an observable increase ($\sim 1^{\circ}\text{C}$) in the temperature of the air around Desk1 but still difference with the Desk2 was obvious, as expected. This shows us the important design criteria for the proposed system:

relative positions of diffusers and walls has a strong impact on temperature distribution inside a room for a given flap configuration.

It is important to note that the experiments were conducted at the middle (Level 2) and low (Level 1) fan-foil speeds. As mentioned in Section 1, the conventional HVAC system operations aim to create homogenous indoor environment and accordingly air is released symmetrically in all directions. Thus, a higher volume of air is conditioned and released toward all parts of the room. However, if a system like AVS can deliver air only to the regions that occupants ask for thermal conditioning, it is possible to save the energy used for needless parts of the room. This cannot be completely prevented due to the heat diffusion and inevitable mass transfer but it is possible to limit these wastes. In practice, if a system can achieve this, it is possible to use heat machinery with lower capacity which would result in direct savings. As an example, the heating capacities of the fan-coil installed in demo room (GEA Flex-Geko GE31.UWW4.AO) in low, middle and high speeds are 4.5/6.0/8.6 kW respectively, referring to product catalogue. Hence, enabling user-system interaction with UI and enabling practical management of air-flow by means of OFDs, AVS can meet thermal requirements with less conditioned air. This may result in 30% energy savings when worked at fan speed 2 instead of 3 and 25% energy savings when worked at fan speed 1 instead of 2.

The comparison of calibrated model outputs and experimental results are in good agreement as shown in Figure 28 to Figure 29. It is important to note that these figures present responsive temperature profiles for a HVAC system. The time delay for the thermal response shown is very short. This is due to the fact that AVS releases air streams towards measurement points (Desk 1 and Desk 2). If an average air speed of 0.5 m/s is considered, it takes just few seconds for hot air streams to reach sensors. Hence, the sensor

measurements start to increase just in a short time. For a conventional HVAC system, this requires longer time interval since hot air initially spreads on ceiling and then slowly diffuses to occupied zone (see Figure 3 for the comparison of conventional and personalized ventilation strategies).

Having a hybrid dynamics based model representation of the system, it is possible to conduct several scenario analysis to get better insight related to system operation. However, the thermal network models unable to provide information for the micro-climate inside the test room. Being based on an innovative approach for ventilation systems, a better understanding of system operation can only be established with deeper investigation of the indoor airflow and the resulting thermal comfort. Hence, a CFD based indoor airflow and thermal comfort assessment for the test room is presented in the next chapter including the energy analysis.

5. CFD Analysis of Performance of AVS

The heat transfer among the occupant and the indoor environment is governed by the conductive heat transfer, convective heat transfer, radiative heat transfer, metabolic heat production, evaporation over the skin and the clothing (see Section 2.2 for details). The corresponding heat transfer coefficients are functions of factors including temperature and velocity of indoor air, geometry of air terminal devices and zone surfaces, humidity of air, occupant's skin temperature, among others. Thus, the analysis of the formation of indoor airflow regime and the local temperature and speed of air as well as the effect of those on the occupant's thermal comfort and the related energy consumption of the HVAC system is a complex analysis. Hence, it requires design and deployment of variety of experiment scenarios which would require too much time and money. Nevertheless, when compared with the experimental studies, CFD analysis offers cheaper, quicker and more comprehensive analysis of fluid flow and heat transfer in variety of research fields, including indoor airflow and thermal comfort. Hence, a number of CFD simulations were conducted for further analysis of the performance of the AVS system.

In order to start running CFD models and their validation, four types of analyses are consecutively conducted for the numerical investigation of the characteristics and the performance of the AVS system: (i) air-jet characterization, (ii) indoor air-flow regime identification, (iii) thermal comfort analysis, and (iv) energy performance analysis. The analysis of air-jet characteristics aims to show the effect of air inlet temperature, speed and flap angle on the formation of air-jet properties (spatial distribution of velocity and temperature fields) in a room size empty box. Then, it was possible to conduct further analysis related to resulting air-flow regime inside the test room induced by air-jets, involving temperature and velocity fields. Once the flow related analysis is completed, the next step was investigating the thermal comfort performance of the AVS-system. The

last step was the analysis of the energy performance of the system under variety of environment and comfort conditions. The Figure 30 shows the inputs, methods and the outcomes for each step of CFD analysis. Whole model development and analysis procedure is conducted with corresponding tools of the propriety CFD software Simcenter STAR-CCM+ (version 12.04).

5.1. The Model Development and Validation

As mentioned above, the initial step for the numeric analysis of indoor airflow was development of CFD models that has crucial effect on the reliability of the analyses. Hence, a detailed description of the CFD model is provided in terms of (i) geometries of the virtual test room and the virtual manikins, (ii) meshing procedure, (iii) boundary and initial conditions, (iv) physical modelling, and (v) the validation of the model.

5.1.1 The Geometry

As mentioned in Section 4.4, the prototype of the proposed AVS system was deployed to an office room in Engineering Faculty Building of Ozyegin University (Istanbul/Turkey). The geometry of the indoor environment is outlined by 4 asymmetric side walls, symmetric ceiling and floor, 2 windows, 8 desks, 5 monitors, 7 caission and a paper cabinet (the chairs were got out of the room during the experiments). Both the air inlet and outlet terminals are located on ceiling. Hence, the essential components listed above are involved in 3D-model of the room which was created with the 3D geometry design interface of the Star-CCM+. The exact positions of the architectural elements and the furniture are shown in Figure 31. On the other hand, the geometrical model of the OFD was identical to the prototype as shown in Figure 21.

It is important to note that room has a false ceiling with a height of 60cm which accommodates FCU and its ducts as well as cabling for lighting system and sensors.

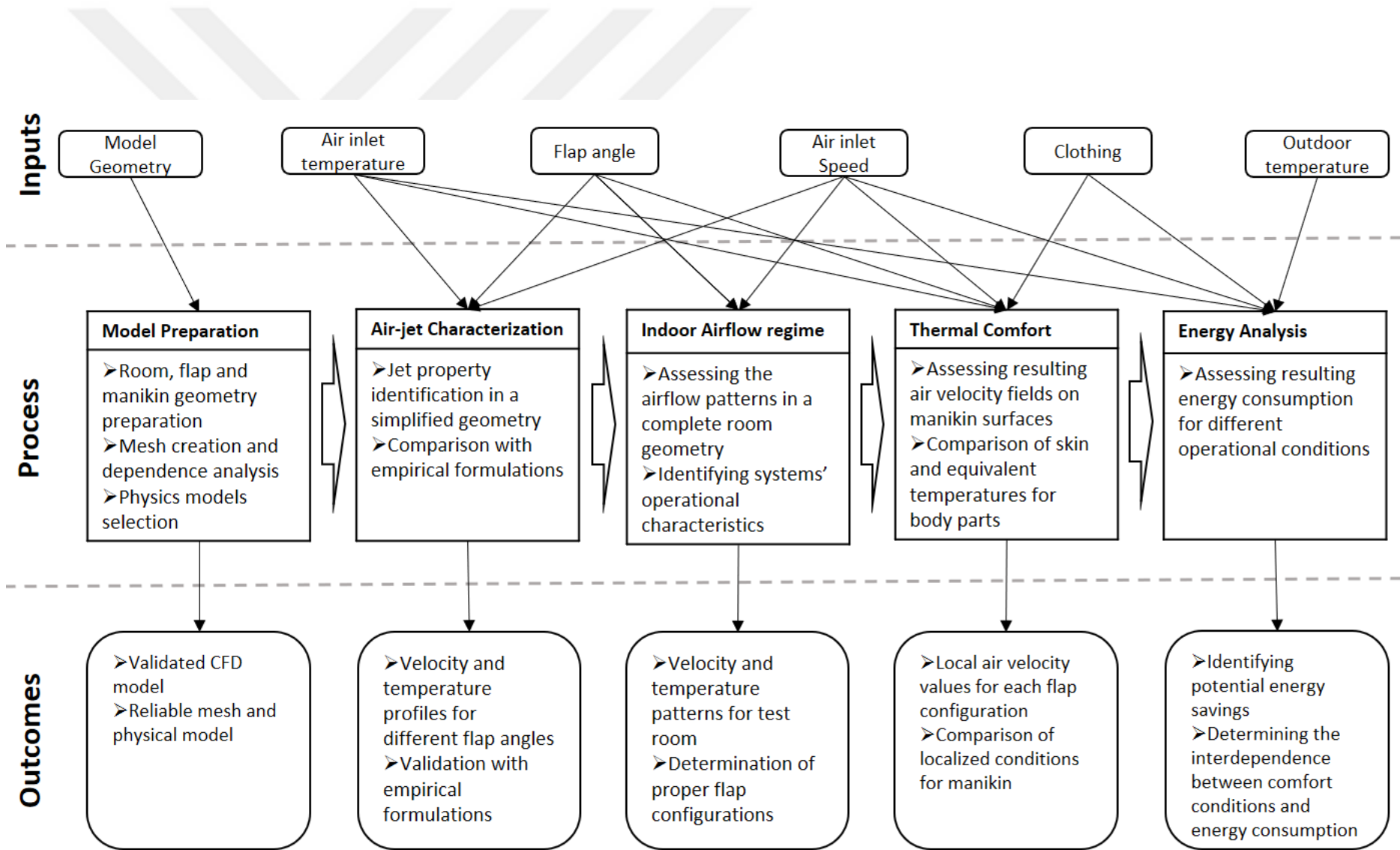


Figure 30: Inputs and outcomes for each step of CFD analysis of AVS operational performance.

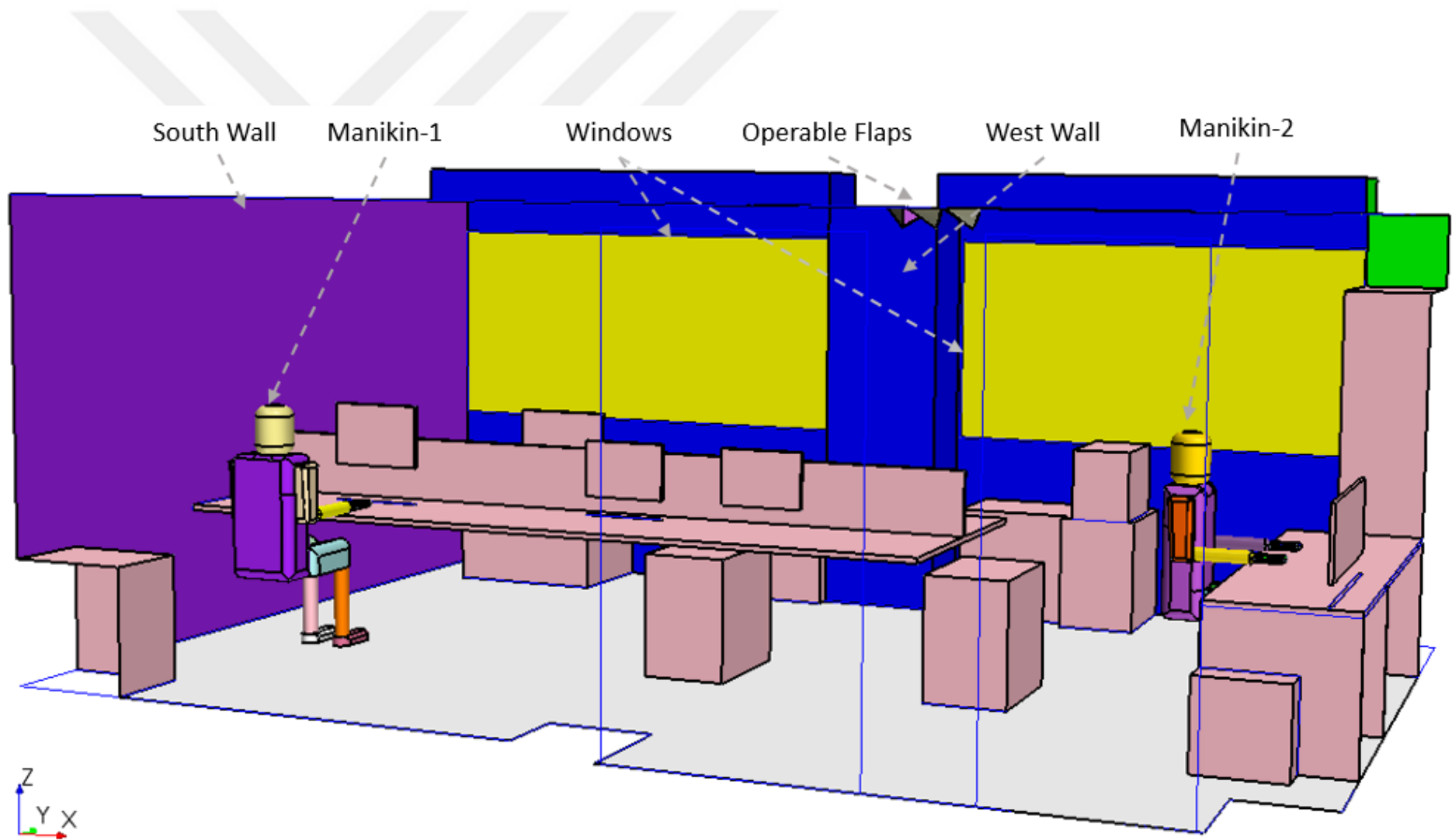


Figure 31: The geometric model of the test room with the office equipment and the manikin.

Moreover, room has a false floor of 12 cm height that shelters network cabling. The false ceiling is composed of 60x60 cm chipboards whereas floor is composed of plywood and wall-to-wall carpets.

Another important component for CFD geometry was the outline of virtual manikins. It was created with the geometry design interface of the STAR-CCM+ (Figure 32). It is intended to represent each of the 14 parts of the body of a sedentary person roughly but separately for the thermo-physiological modelling. The manikin geometry has a height of 1.33m, width of 0.49m and depth of 0.62m that represent a person with height of 1.8m. Furthermore, as mentioned in Section 4.4, beside the thermal agents on the desks, the test room includes additional sensors on ceiling, head level and floor. Each of these sensors were represented in model geometry as a virtual point probe that is a measurement point without volume. Position of the sensors in the room and virtual model are almost identical and presented in Figure 33.

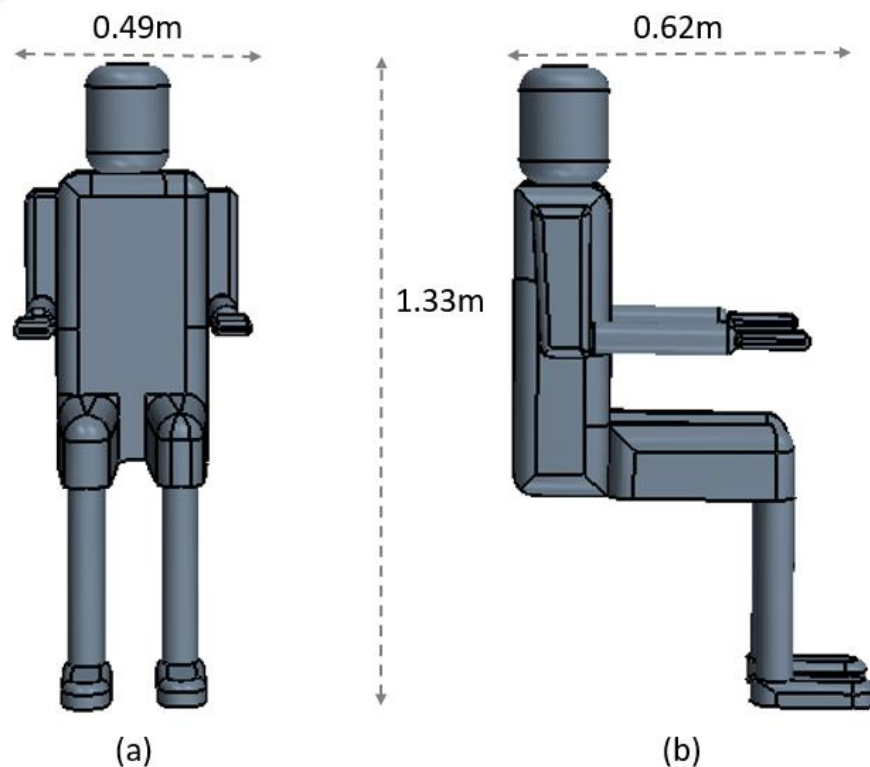


Figure 32: Manikin geometry with dimensions: (a) Front view (b) Side view.

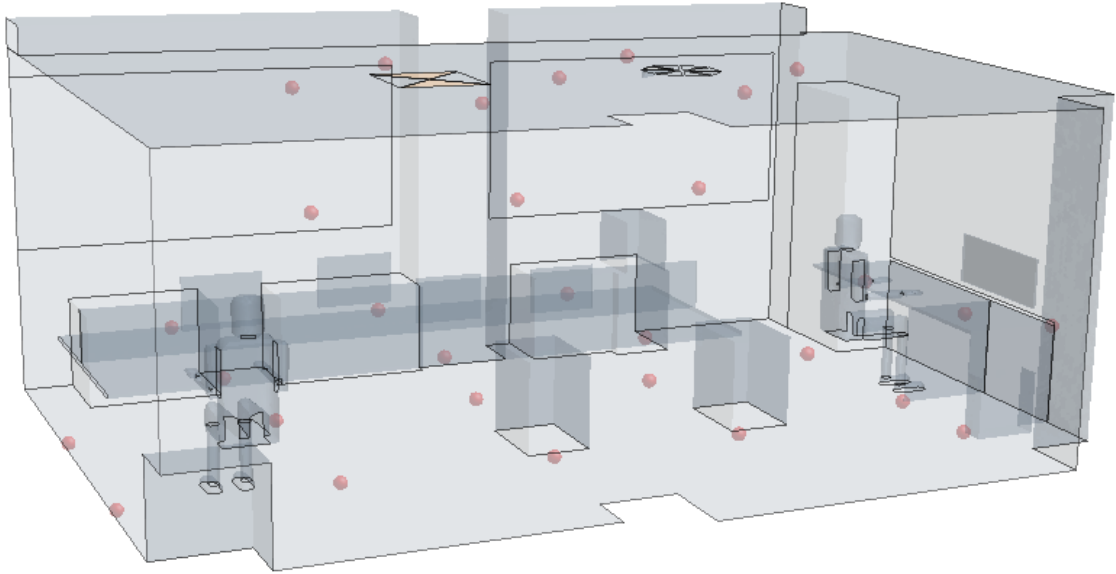


Figure 33: Positions of virtual probes that represent thermal agents and additional temperature sensors on the ceiling, head and floor level of the test room.

5.1.2 Mesh quality

Besides having realistic geometric representation, having a high quality computational domain discretization is crucial for the performance of the CFD models. Automated meshing functions of CFD software performs lots of optimization and quality control procedures but still users are expected to tune some settings for a reliable mesh. Most of the CFD models involves some geometry parts with higher importance for the development of physical phenomenon under investigation as well as the convergence and accuracy of results. Hence, creating a non-uniform grid structure is a common practice for CFD modelling.

For indoor airflow modelling, the region around the air inlet devices is one of them and is subject to special attention for meshing. Moreover, the computations related to the airflow next to the human body are crucial for the reliability of calculations of the heat transfer among body and indoor environment, so the thermal comfort calculations. Hence, the mesh size, type and quality of the surface and volume meshes of virtual manikin and air inlet device had custom settings. Accordingly, these surfaces initially were subjected

to surface wrapping procedure as a local refinement strategy in order to deal with challenges related to complex geometries they have. Figure 34 shows the default and wrapped surface meshing on virtual manikin. Moreover, the cell size on and around them is kept smaller when compared to other surfaces of the room (room walls, furniture surfaces, among others).

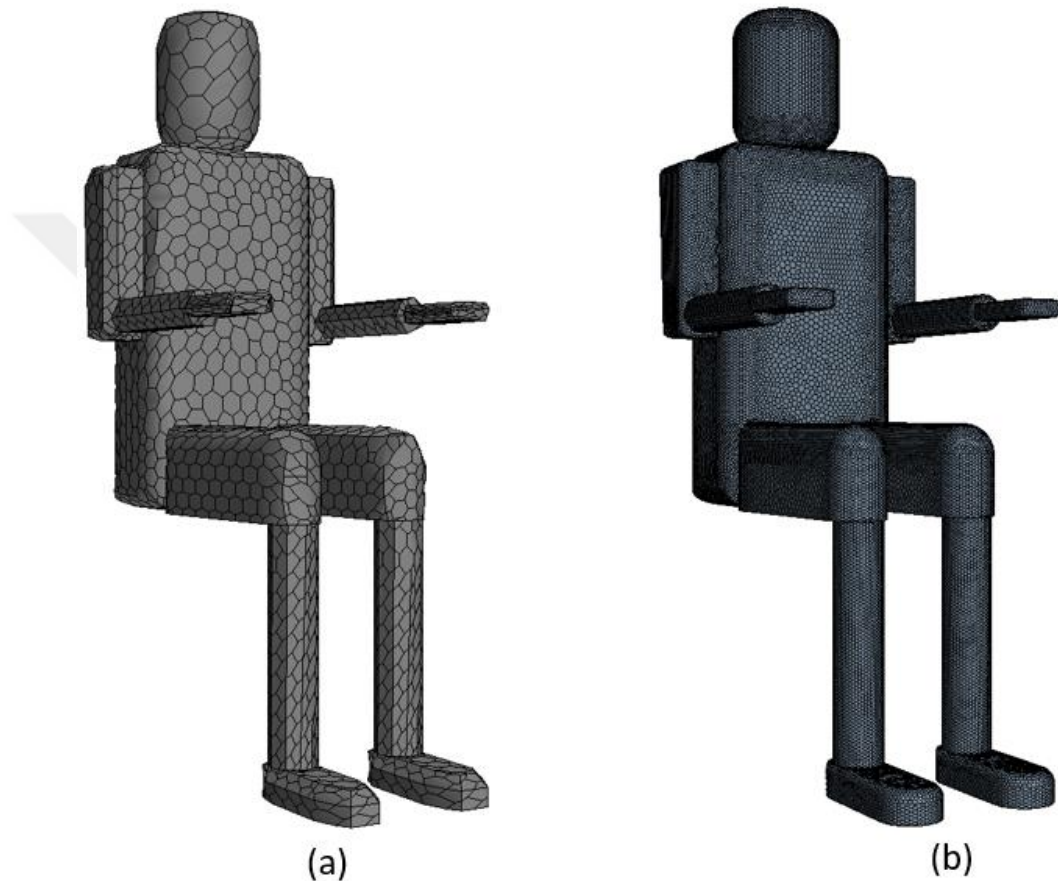


Figure 34: Surface mesh on manikin's body: (a) without surface wrapping (b) with surface wrapping.

Having a fine surface mesh is an essential step for a reliable volume mesh. As the next step of meshing specification, these fields also had higher number of prism layers than other surfaces (20 instead of 10). All prism layers are assigned to have thickness of 2 mm. The remaining flow domain was filled with polyhedral meshes with the base size of 5.0cm whereas the growth rate was set to 1.2 (the selection procedure for the base size is

explained in Section 5.1.5). As a result, a topologically valid mesh structure is attained where the whole flow domain included approximately 3.5 million cells, 17 million faces and 11 million vertices. Figure 35 shows the details of mesh around manikins, inlet and inside the room). Apparently, straight surfaces have refined cells on them and good attachment with volume mesh. However, the cross-section parts among body parts have weaker mesh structure which is the hardest and inevitable challenge of virtual manikin modelling.

5.1.3 Boundary and initial conditions

Star-CCM+ allows defining three types of inlet boundaries for flows with unique control options: velocity inlet, stagnation inlet and mass flow inlet. However, the Thermal Comfort Wizard (TCW) of the Star-CCM+ is designed in a way that it only allows using inlet type “mass flow inlet”. This type of inlet is sensitive to the density of the fluid (controls velocity automatically when density changes) and is compatible with both segregated and coupled solvers. On the other hand, flow-split outlet and pressure outlet are two pre-defined outlet types with different control options. Pressure outlet is the typical type used in indoor air flow simulations due to the extensive control options for pressure, temperature and turbulence. It is deployed in the AVS model by setting (i) environmental pressure as the pressure specification and (ii) boundary normal as the direction specification.

The other surfaces in model are set to boundary type “wall” with different thermal specifications. Another limitation by TCW of Star-CCM+ for the boundary types is the requirement of specifying human body parts as walls with “temperature” thermal specification. This specification allows body surfaces to have an initial temperature setting that changes during simulations as the thermophysiological heat balance equations

for corresponding body parts are solved. TCW algorithm defines convective and radiative heat transfer coefficients for these parts in accordance with the surface temperature.

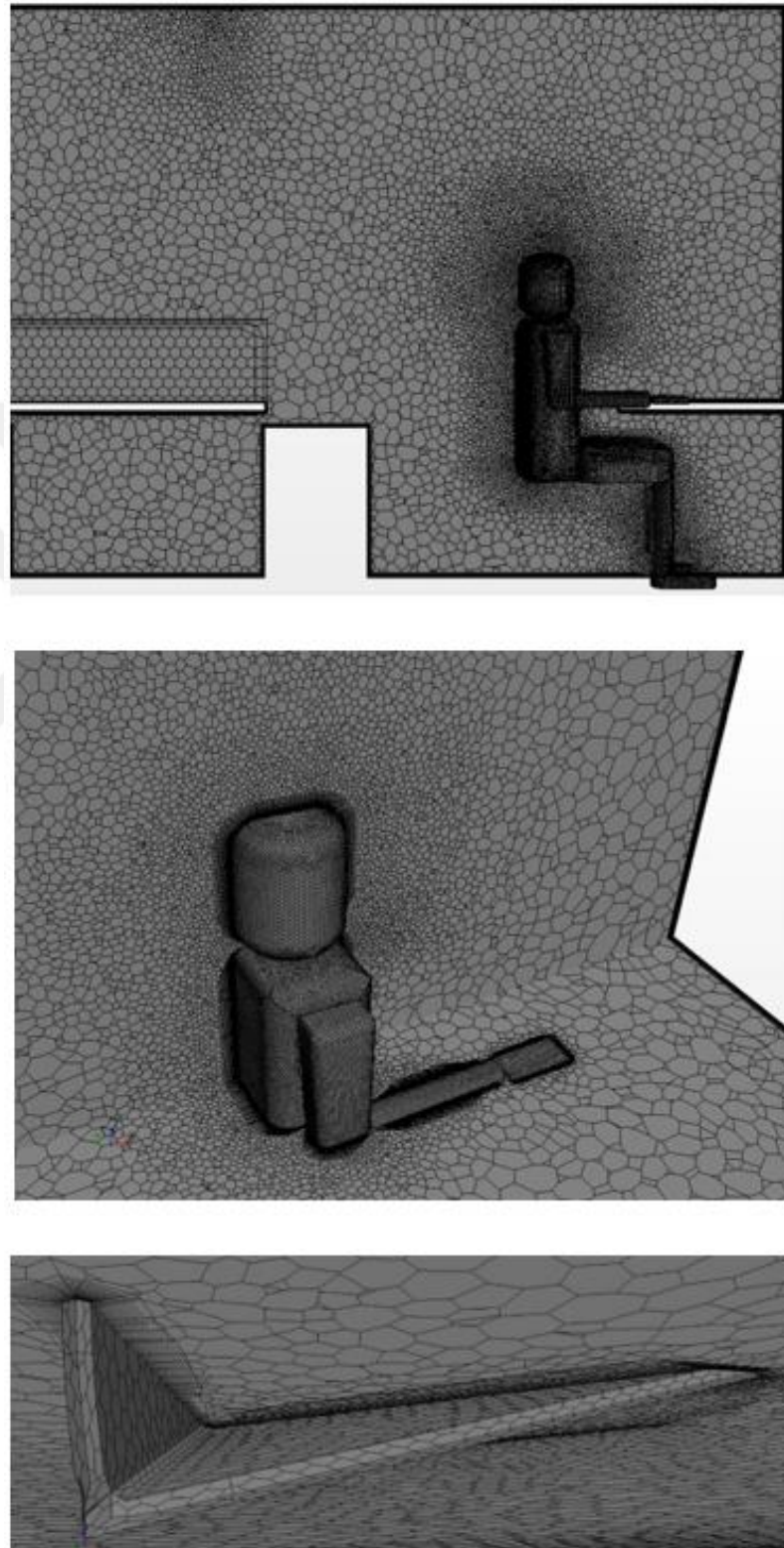


Figure 35: Representations of volume mesh: (a) around inlet and manikin, (b) around manikin surface, (c) around flap.

The air inlets and the virtual manikin surfaces have to be defined in accordance with the TCW requirements; however, there are no limitations for the other surfaces of model. The outdoor (west) boundaries of the room (façade and window) are defined as walls that have thermal specification of “convection with conduction”. Referring to construction materials data of the test room, façade (BIMS block, insulation material and plaster with total thickness of 0.28 m) and windows (double-glazed with total thickness of 0.028 m) were defined to have thermal conductivity of 0.15 W/(m·K) and 0.65 W/(m·K), respectively. Referring to the literature, the heat transfer coefficient for the external convection is defined as 23 W/(m²·K) for wind speed of 4 m/s [120]. Outdoor temperature was set to be 10 °C. The TCW calculates the heat loss from these surfaces. On the other hand, as explained in Section 5.1.1, the test room has false ceiling and floor with the highly isolative materials. Thus, these surfaces are defined as adiabatic walls.

5.1.4 Modeling Physics

Indoor airflow problems are subject to conservation of momentum through Navier-Stokes equations. Hence, conservation laws can be formulated as follow for numerical assessment of airflow regime [84]:

- Conservation of mass (continuity equation):

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0 \quad (\text{Eq. 5.1})$$

where density (ρ) is constant for incompressible flow that also makes its time dependence (the first term) zero. Hence, it can be reformulated for incompressible fluids as follows:

$$\frac{\partial(u_i)}{\partial x_i} = 0 \quad (\text{Eq. 5.2})$$

- Conservation of momentum:

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} + \frac{\partial(\rho u_j u_i)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_i} + \rho g_i + F \quad (\text{Eq. 5.3})$$

in which p is static pressure, τ is the viscous stress tensor, ρg_i represents gravity forces and F represent external body force.

- Conservation of energy:

$$\rho \frac{De}{Dt} = [-\nabla(pu)] + \left[\frac{\partial(u\tau_{xx})}{\partial x} + \frac{\partial(u\tau_{yx})}{\partial y} + \frac{\partial(u\tau_{zx})}{\partial z} + \frac{\partial(v\tau_{xy})}{\partial x} + \frac{\partial(v\tau_{yy})}{\partial y} + \frac{\partial(v\tau_{zy})}{\partial z} + \frac{\partial(w\tau_{xz})}{\partial x} + \frac{\partial(w\tau_{yz})}{\partial y} + \frac{\partial(w\tau_{zz})}{\partial z} \right] + \nabla(k\nabla T) \quad (\text{Eq 5.4})$$

The physical model of the test room in Star-CCM+ is set to solve segregated flow model in order to deal with the governing equations of airflow. A predictor-corrector approach is used to link the momentum and continuity equations. Segregated fluid temperature model solves the total energy equation with respect to temperature. For both of the flow and energy equations, second order upwind convection discretization approach was deployed. On the other hand, the SIMPLE algorithm was used for controlling the solution updates. In order to deal with the indoor turbulent airflow, Reynolds-averaged Navier-Stokes (RANS) approach is coupled with k-epsilon turbulence model (Realizable K-Epsilon Two-Layer) in which averaged variables are used to treat temporal variations. These are also coupled with Exact Wall distance and Two-Layer All y+ Wall Treatment models.

In order to enable thermal comfort assessment with TCW, a radiation models has to be deployed. Hence, the generic Radiation model of the software is deployed with Surface-to-Surface Radiation (SSR) and Gray Thermal Radiation (GRT) model options in order to deal with radiative heat transfer inside the room. SSR eliminates the involvement of flow medium (air) to the radiation calculations as the physics suggest. It performs computation for radiative heat transfer only between surfaces in accordance with the

specified coefficients (emissivity, reflectivity, and transmissivity and radiation temperature on surface.) On the other hand, GTR eliminates the frequency dependence of thermal radiation properties for an approximated but reliable calculation of radiative heat transfer with lower computational cost. Nevertheless, the validation experiments were performed in winter-time and early hours of the day which made radiative effects ignorable. Hence solar radiation model was not deployed. Moreover, none of the surfaces was assigned radiative thermal specification (such as environment boundary condition that integrates convective and radiative heat transfer) which made the effect of radiative heat transfer on thermal comfort calculations ignorable.

TCW is based on a one-dimensional thermo-physiological occupant model (referred as TIM) developed by company. It provides evaluation of thermal comfort for 14 parts of the body: head, torso, two upper legs, two lower legs, 2 hands, two upper legs, two lower legs and two feet. Moreover, like many other modern thermophysiological models, it separates each of these parts to segments, namely, (i) core, (ii) muscle, (iii) fat and (iv) skin. These 56 segments (14 parts x 4 segments) and the central vascular system comprises the passive system of TIM. Heat production, storage, transfer and balance for each component of passive system is regulated by the active system (see Section_2.2.3.1 for details of this mechanism and the Star-CCM+ documentation for the company's formulation for it).

Before initiating simulations, TCW asks the declaration of surfaces of body parts (sub-surfaces of virtual manikin), height of occupants (to estimate mass of body parts), clothing level of occupant (clo) and activity level (in terms of metabolic rate) in order to assign corresponding parameters based on literature. Then, corresponding heat balance equations are assigned to 'imaginary' components of passive system (segments) and the regularity algorithm is assigned for active system. The heat transfer between body and

indoor environment is calculated on the interface among them and the human response to given thermal conditions is calculated based on TIM algorithm. In other words, neither heat nor mass flow equations are deployed as like in conventional CFD modelling. Instead, airflow model for indoor environment is coupled with TIM, based on the heat transfer on interfaces.

TCW provides several outputs in the form of automatically created reports that present details of the calculations (like calculated heat production of segments, blood volume flow and heat transport, heat flux from the skin, among others.) Having such a comprehensive modeling scheme, the thermal comfort evaluation of the TIM is presented as LMV ratings for each of 14 body parts of each occupant. The corresponding output report also presents skin and equivalent temperature information. Furthermore, based on the pre-defined boundary and initial conditions of the room (or car, plane, any closed enclosure), it provides an estimation for the energy consumption of an HVAC system that delivers final thermal conditions in the room. Hence, one can correlate HVAC settings (air inlet temperature and speed) with resulting thermal comfort level and energy consumption, for a given set of initial and boundary conditions (temperature, humidity, heat transfer coefficients of room walls and windows, among others).

Another important selection among physics models is the gas model due to the nature of the given problem (airflow). Ideal gas model was deployed in simulations that treats the density of the gas a function of temperature and pressure, being subject to the ideal gas law. For the simulations, air is treated as an incompressible gas without any limitation on density. Its specific heat was set to 1003.62 J/kg-K whereas the thermal conductivity was 0.0260305 W/m-K. Beside these essential models, optional Gradient and Gravity models were selected as well as Three Dimensional in accordance with the nature of given problem.

Simulations were run for steady state conditions and the standard initialization scheme was deployed. There were two criteria for deciding on the convergence of the results: order of magnitude of residuals and the elimination of fluctuations for selected parameters. The solutions were considered to be converged when residuals (continuity, $x/y/z$ momentum, kinetic turbulence energy, turbulence dissipation rate and thermal comfort) were in the order of 10^{-4} or smaller, whereas the energy residual was expected to be in the order of 10^{-6} or smaller. Another criteria for the evaluation of residuals was the elimination of imbalances (sharp and random changes of residual values). Figure 36 shows the evaluation of residuals for a typical case. Moreover, a plot screen was created in order to monitor measurements by virtual probes for selected parameters per iterations. The selected parameters were temperature and velocity values on selected virtual probes. The fluctuations of these measurements are expected to vanish for a decision on convergence. Figure 37 shows the plot screen for a typical case in which temperature and velocity “measurements” converge to a fixed value.

5.1.5 Model Validation

The performance of the CFD model created following the considerations presented above was tested by comparing them with the experimental data. The case scenario and the dataset of the first experiment used for calibrating the hybrid model was considered for validation. However, instead of two nodes used there, data for all temperature sensors (29 sensors) in the test room is compared with the corresponding virtual probe data (see Figure 33 for the sensor positions). This made it possible to assess the model performance all around the room. Moreover, since the time dependence of the change of the temperature at a point is as important as the exact value, the validation is performed with an unsteady model. The sensor and simulation data for each of 29 measurement points

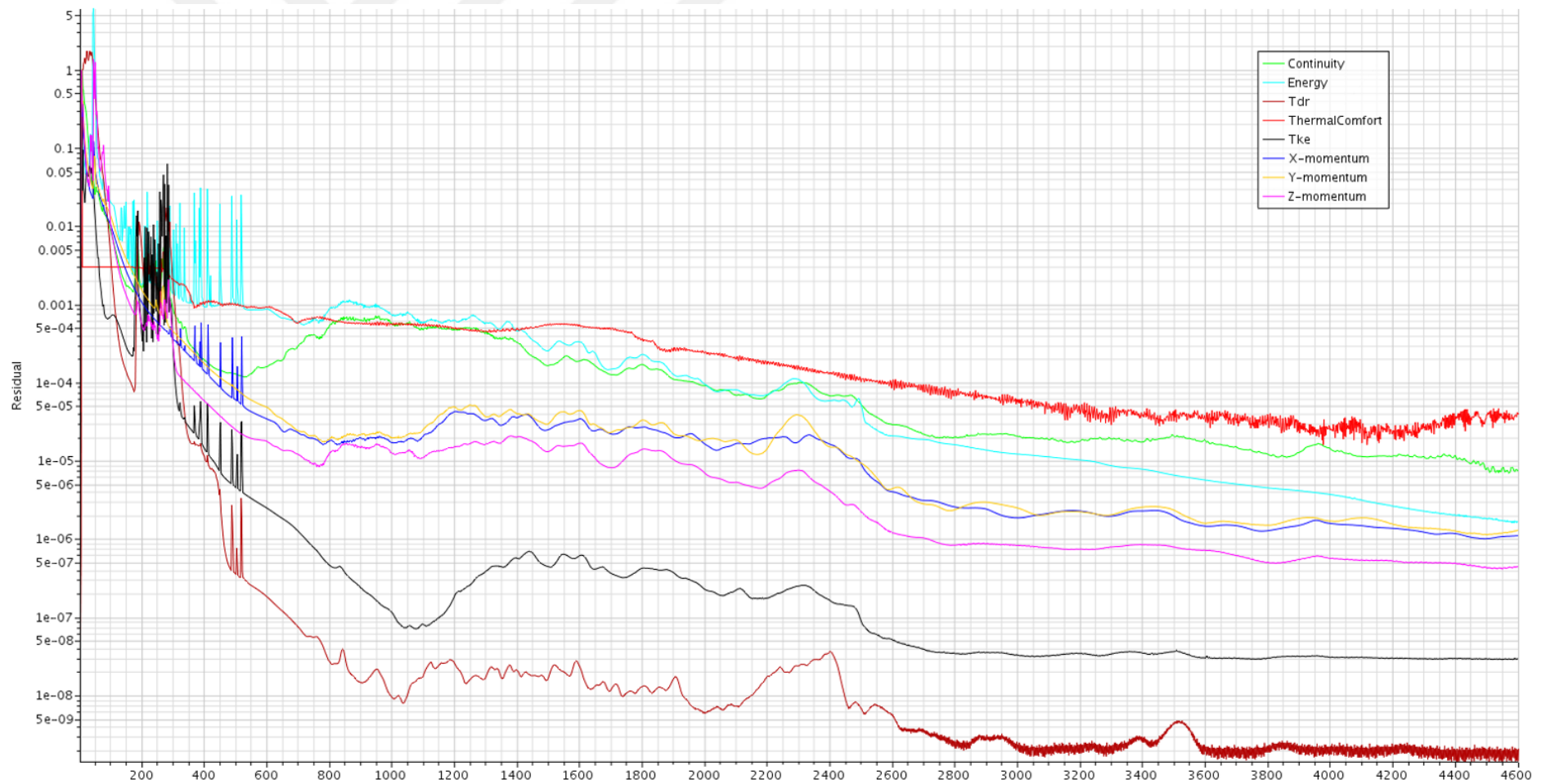


Figure 36: An example for the evaluation of residuals.

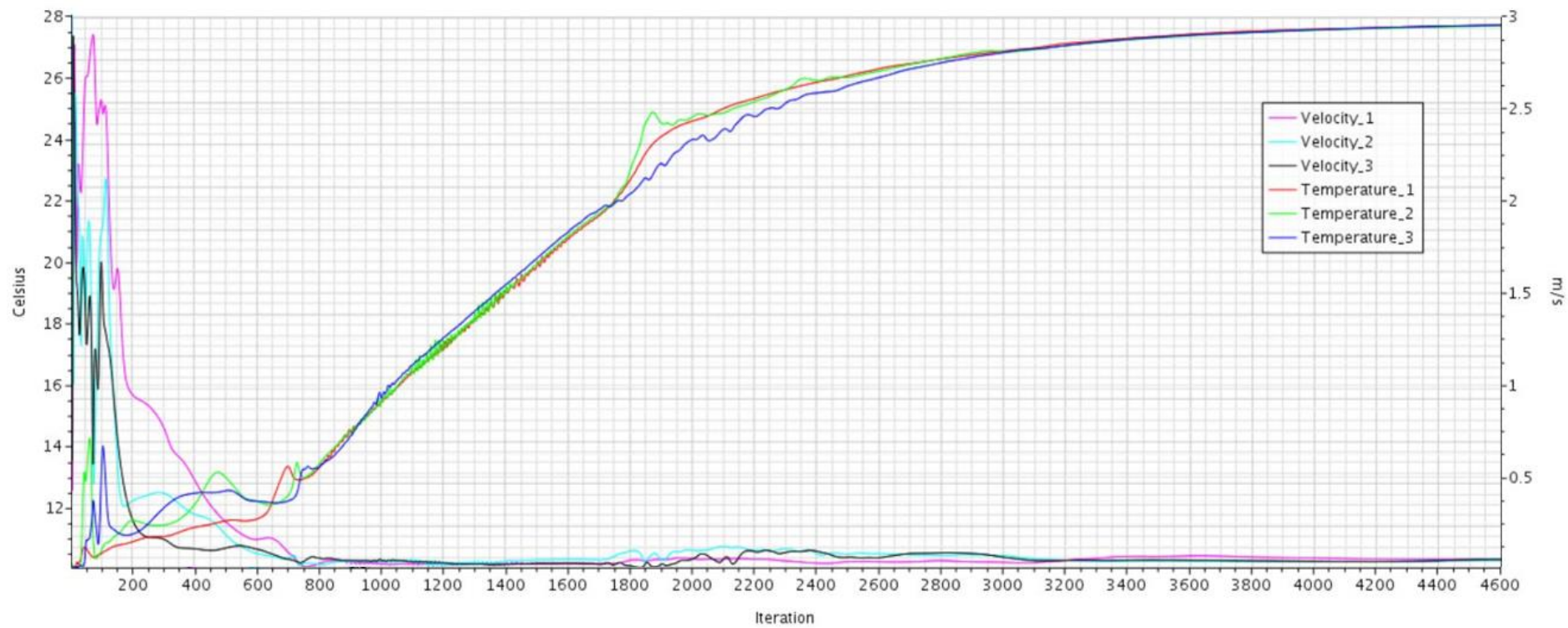


Figure 37: An example of the plot screen that is to follow the convergence of temperature and velocity measurements in selected probes.

are presented in Appendix-A. Moreover, the mean average percentage error (MAPE) value was calculated for each measurement point using the following formula:

$$MAPE (\%) = \frac{1}{n} \sum_{i=1}^n \left| \frac{y_{model\ output,i} - y_{experimental\ data,i}}{y_{experimental\ data,i}} \right| \times 100 \quad (Eq.5.5)$$

Figure 38 presents the average of MAPE values for different height levels.

An important concern for the model performance is the mesh quality. It is under the influence of the size and the total number of cells within the computational domain. The parameter called ‘base size’ is the setting that fundamentally determines the cell size and number. The base size of 5cm was selected for simulations as a result of an iterative procedure (see Section 5.1.2 for details of mesh settings).

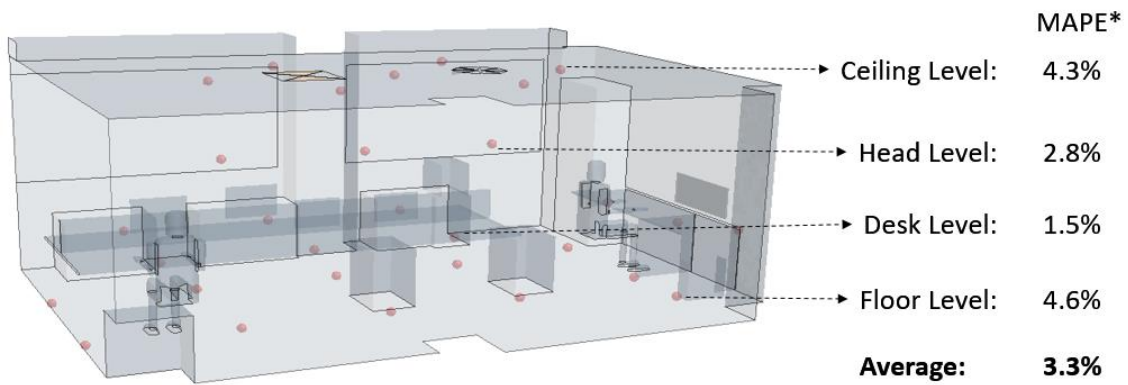


Figure 38: The average of Mean Average Percentage Error (MAPE) values for sensor and virtual probe readings at different height levels.

The base size for polyhedral meshing as well as the number of prism layers and their thickness are determined with an iterative procedure for deciding on the balance between accuracy and computational cost. Accordingly, the change in error of the temperature predictions for thermal agents were evaluated with respect to computational cost. Table 1 presents the change in prediction accuracy with respect to total number of cells as well as the time for 100 iterations (as a representation of computational cost). Based on Table 1, base size of 0.05m was selected.

Table 1: Mesh dependence analysis

Base Size	Total Number of Cells	Accuracy	Time for 100 iterations
0.08 m	~0.89m	7.4%	213s
0.06 m	~1.9m	3.1%	398s
0.05 m	~3.5m	1.3%	614s
0.04 m	~6.1 m	1.2%	947s

5.2. Indoor Airflow Analysis

Having a reliable CFD model, next step was running simulations for different conditions in order to assess the system performance. Following the roadmap presented in Figure 30, the result of each analysis is presented below.

5.2.1 Air-jet characterization

The airflow regime is a representation of the velocity and temperature distribution in a room which is under the influence of variety of factors including air inlet and outlet conditions, room size, furniture geometry and position, occupant position and mobility, among others. Moreover, the air-jet created by the air inlet device has the strongest influence on the airflow pattern as the main source of air motion and thermal interactions. Hence, a clear understanding of the properties of the air stream entering to a room is essential for further investigation on indoor airflow regime and studies on this topic is often called as air-jet characterization.

Air-jet characterization studies (both experimental and numerical) generally conducted in empty and geometrically symmetric rooms in order eliminate the influence of factors apart from the physical properties of the inlet air stream (velocity, temperature, inlet geometry, among others). When such an approach is preferred, inlet boundary conditions have the dominance on the reliability of results. Hence, advance techniques, including

particle image velocimetry and infrared thermography, have been used in experimental studies for monitoring inlet conditions. On the other hand, the numerical studies have been focused on the effect of modelling air inlet devices, turbulence models and mesh quality around inlet boundary [187]. Making stress on proper monitoring and declaration of inlet boundary conditions, the main expectation from these studies is to provide reliable qualitative and quantitative information related to the physical properties of flow around air inlet devices. These outcomes are usually compared with the outcomes of the analytical and experimental approaches describing the flow properties of air-jets (Section 2.2.2.2).

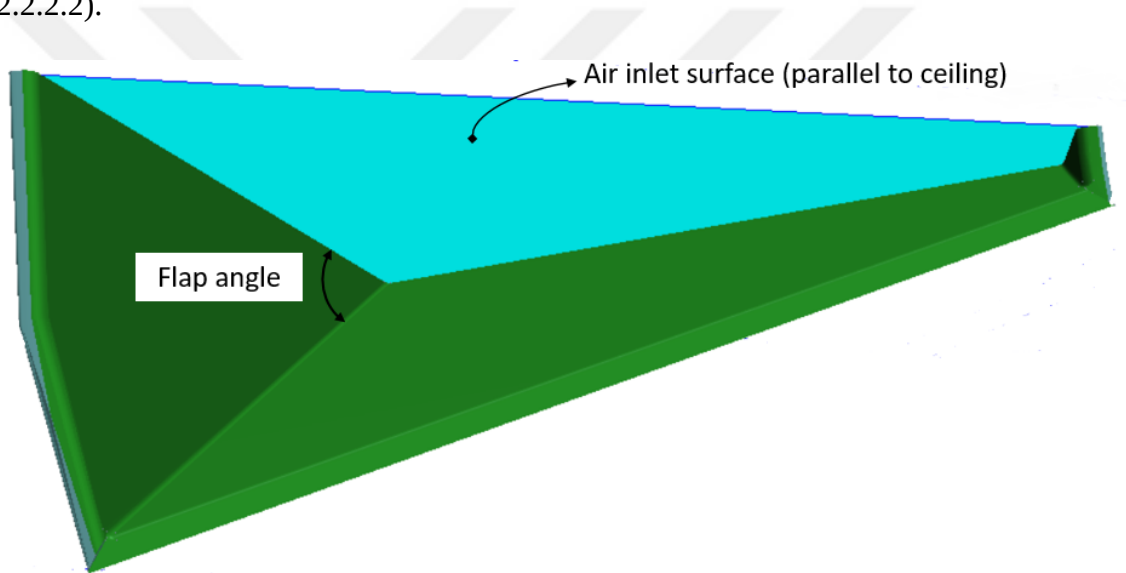


Figure 39: The geometrical model of an open flap.

For the CFD based numerical investigation of air jets created by AVS proposed in this thesis study, the flaps of the air inlet device were modelled geometrically as they are (see Figure 21 and Figure 39). There are simpler approaches in the literature, like defining estimated velocity inlet profiles (speed and direction), to deal with the challenges of modelling and simulating well-studied air inlet terminal geometries [187]. However, having a novel design of an operable flap diffuser, an exact 3-dimensional model was necessary for the air inlet diffuser in this study. On the other hand, following the conventional modelling approach for outlet terminals, the typical 4-way diffuser deployed

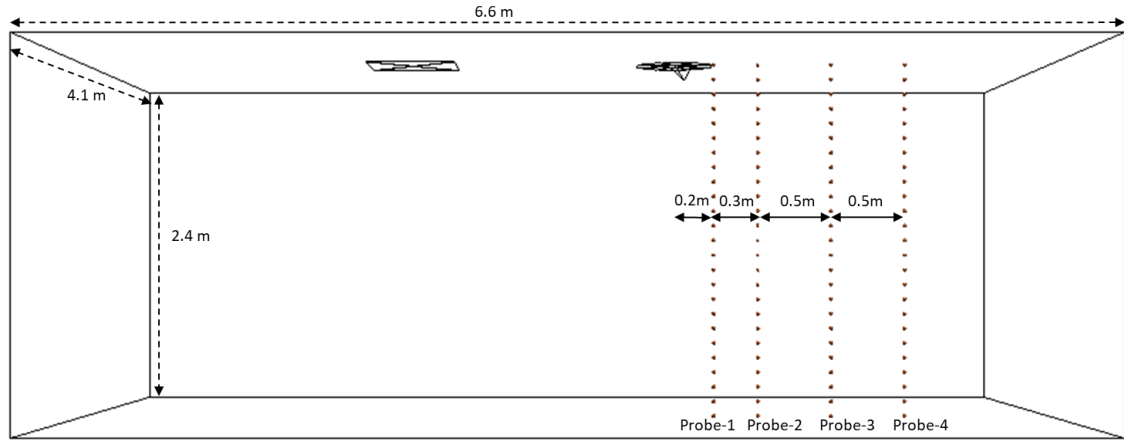


Figure 40: The dimensions of the simplified room geometry for air-jet characterization and the position of virtual line probes (each composed of 24 virtual point probes).

in the room was defined as a pressure outlet and modelled only as a 2-dimensional surface. Having these inlet and outlet boundaries, the original room geometry is simplified as an empty box having comparable dimensions with the room (Figure 40). Initially, isothermal flow simulations were conducted for different flap angles for investigating velocity profiles and compare with analytic formulations given in Section_2.2.2.2. Then, in order to get velocity and temperature characterization charts for non-isothermal conditions, 18 steady state simulations were performed for 2 representative flap angles, ($z=-25^\circ$ and $z=-45^\circ$), 3 temperatures (30°C , 35°C and 40°C) and 3 velocity values (0.5m/s , 1m/s and 2m/s) of inlet air. For an effective comparison, boundary conditions (other than inlet) and the initial air temperature value (10°C) were same for each case. The vertical profiles of the parameters were monitored with virtual line probes located at different distances on the normal line of hinge of operable flap (see Figure 40). Each line probe involves 24 point probes separated equally (each 0.01m) on a vertical line along the room height (2.4 m). Furthermore, a case with flap angle $z=-35^\circ$ was also simulated (35°C and 1 m/s) for the enrichment of velocity decay analysis.

Figure 41 shows the velocity decay profile of air jets created by different flap angles in isothermal conditions. Since the flap outlet area is smaller, jet entrance velocity to the

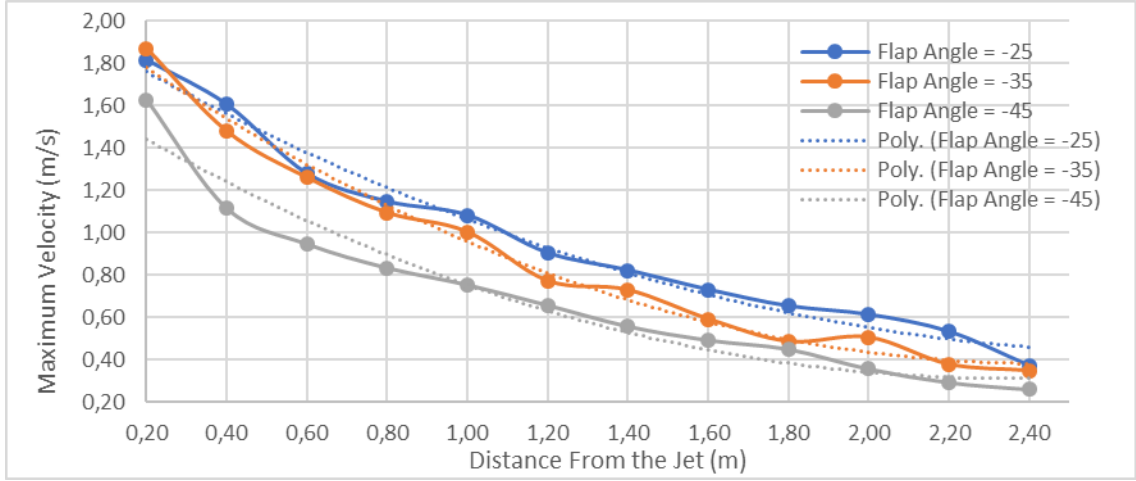


Figure 41: Velocity decay profiles for different flap angles.

room is higher for small flap angles. As the flap angle increases, jet gets smaller velocity peaks and decay faster. The jet velocity decay profiles for each flap angle is in accordance with the decay profile given in Figure 6. for triangular nozzle. Furthermore, non-dimensional velocity decay profiles are compared with the empirical formulations given in Section 2.2.2.2. Figure 42 shows the normalized maximum velocity ratios for the normalized distances from the flap (in logarithmic scale). For the given inlet boundary conditions, the first region ($U_{max} \sim U_{inlet}$) for the jet is very narrow (shorter than 2 times characteristic length). The region up to ten times of the characteristic length represents the second region (characteristic decay region) of the jet and can be formulated in terms of Eq. 2.4 as:

$$\frac{U_{max}}{U_0} = 1.4368 * x^{-0.5} \quad (\text{Eq. 5.6})$$

The region between 10 and 23 times of the characteristic length can be considered as the third region (radial decay region) of the jet and can be formulated in terms of Eq. 2.5 as:

$$\frac{U_{max}}{U_0} = 7 * x^{-1.15} \quad (\text{Eq. 5.7})$$

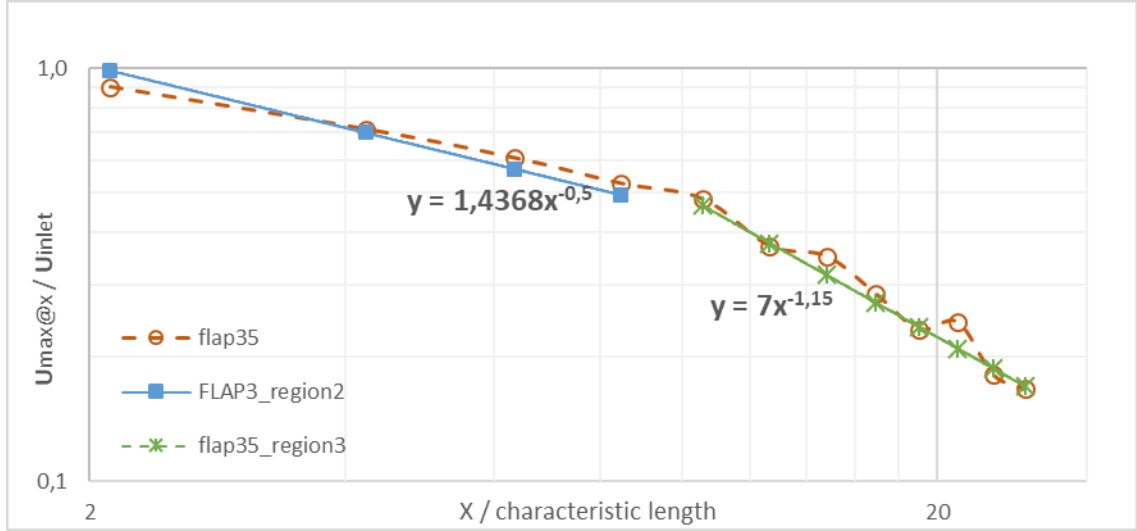


Figure 42: Comparison of simulation results for velocity decay with the corresponding empirical formulations.

Here, the coefficients in Eq. 5.6 and Eq. 5.7 are not equal to corresponding ones in Eq. 2.4 and Eq. 2.5 since they are adopted for a better fit with simulation data. This was necessary due to the change in geometry. However, the good accordance between simulations and analytical formulations is a proof of reliability of developed model. The Figure 42 is also in good agreement with Figure 5.

Having insight for isothermal cases, next step was analyzing non-isothermal simulations. Figure 43 shows the vertical velocity profiles observed in non-isothermal simulations. The profiles show that the air velocity within the jet varies considerably with respect to distance from inlet and the height. Profiles clearly demonstrate the downward shift of air stream between height 2.4 m and 0.5 m of the observed area as the inlet z-direction changes ($z = -25^\circ$ to -45°). Moreover, none of the parameters change the velocity profiles significantly below the height of 0.5 m. Thus, this part can be considered as to be out of jet regions created with given inlet velocity and temperatures. Another important property that can be observed in Figure 43 is that the amplitude of the velocity peak increases almost proportionally with the inlet velocity, regardless of the temperature. On the other hand, as the inlet temperature increases, the height of peak velocity points increases,

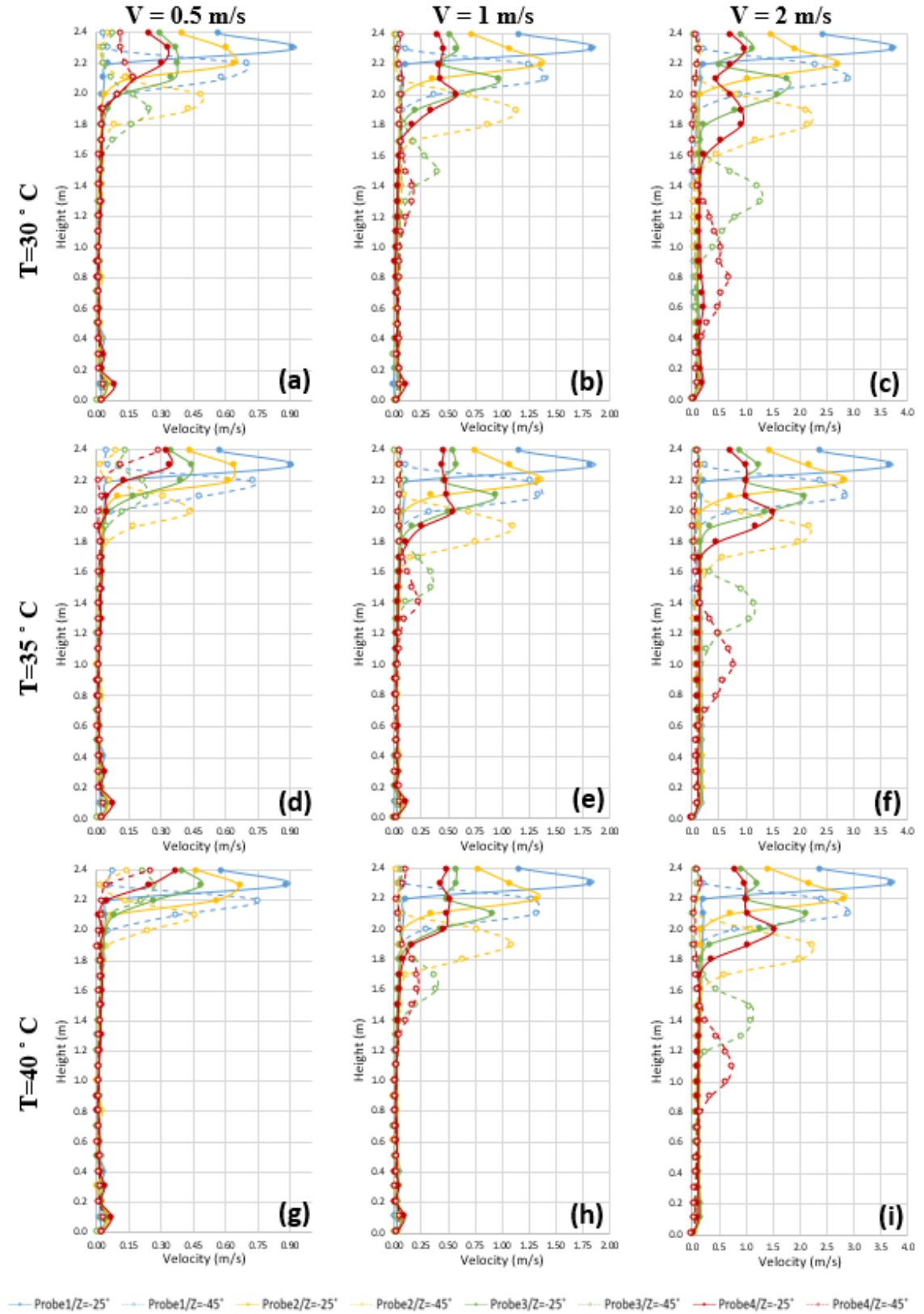


Figure 43: Velocity profiles for different flap angles, inlet temperatures and inlet velocities.

especially for lower speeds. In all likelihood, this is due to the increasing influence of buoyancy force that is driven by the temperature (density) gradient.

Figure 44 shows the temperature profiles monitored in simulations. As like in the velocity profiles, the air temperature within the jet changes significantly. The effect of the buoyancy force can be identified with the rise in the height of temperature peaks in parallel to increase in inlet temperature. This is more obvious for cases with lower inlet velocity. It is also possible to observe the right inclined profiles for almost each case as a representation of vertical temperature segregation. In discordance with velocity profiles, an observable amount of change in the temperature of points closed to floor can be seen, especially for the cases with larger inlet (flap) angles and lower inlet velocity (see Chart-c in Figure 44, as an example). Moreover, a downward shift and enlargement in width can be seen in temperature profiles, again especially for larger inlet angles (compare Chart-d and Chart-f in Figure 44).

For the case in Chart-c of Figure 44, secondary temperature rise can be interpreted. Referring to velocity profile of corresponding case, it is possible to say that these peaks are not included in corresponding air-jets but are result of induced (secondary) airflows. More interestingly, the separation between cases with narrow and large inlet angles (the groupings among cases represented with continuous lines and dashed lines) is obvious especially for cases with higher inlet velocities. Hence, it is possible to say that the change in air inlet angle, speed and temperature can create variety of localized thermal environments that can be match with different occupant expectations.

Having insight related to temperature and velocity profiles, it is informative to investigate the interdependence among them. Referring to related discussion in Section 2.2.2.2, the Figure 45 demonstrates the velocity and temperature decay profiles for a case with flap

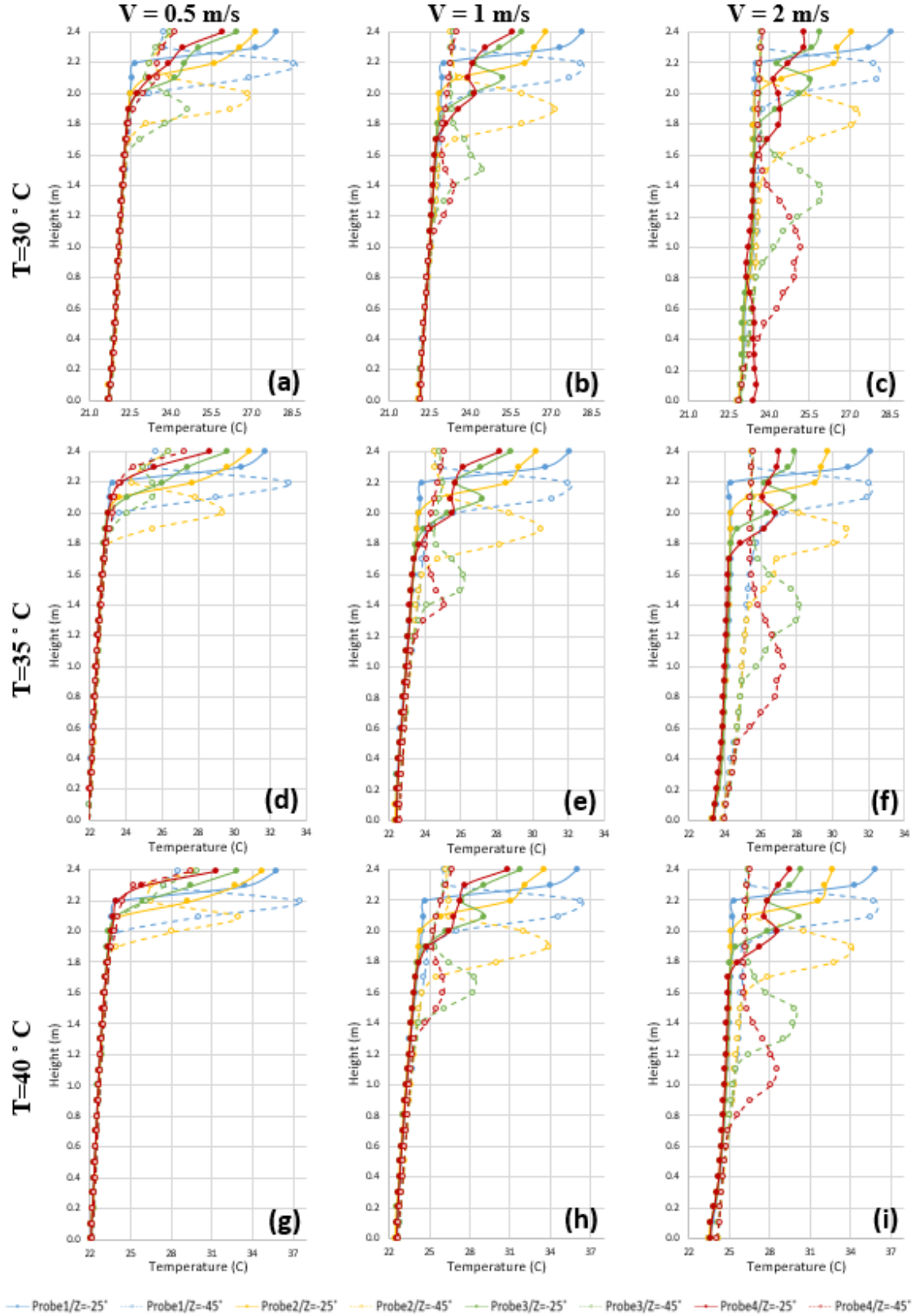


Figure 44: Temperature profiles for different flap angles, inlet temperatures and inlet velocities.

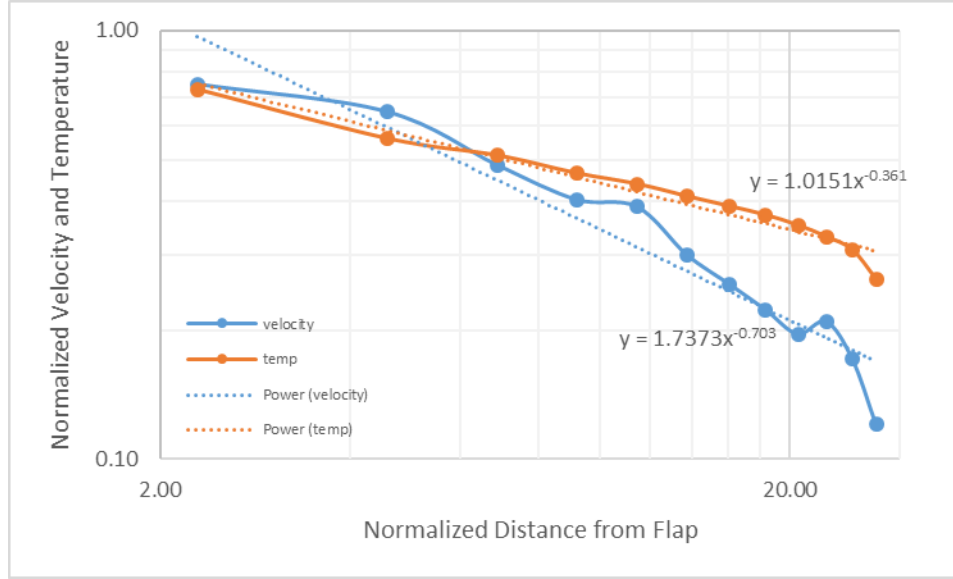


Figure 45: Comparison of velocity and temperature decay profiles.

opening of 25° , velocity inlet of 1m/s , temperature inlet of 35°C and ambient temperature of 23.69°C (average of related data in Chart-e of Figure 44). The trend equations for the curves validates the Eq. 2.8 with a small deviation which shows the slowness of temperature diffusion when compared to velocity diffusion.

As mentioned above, the effect of buoyancy forces can be observed in the Figure 43 and Figure 44: air-jets with higher temperature move closer to the ceiling as a result of temperature (so the density) gradients within indoor air. As mentioned in Section 2.2, the ratio of buoyancy and momentum forces can be quantified with the dimensionless number called Archimedes Number (Ar). Using the corresponding geometrical information in 5.1.1 as well as the initial and boundary conditions information provided above, Ar values can be calculated with Eq.2.7 for a better understanding of flow dynamics (Table 2). As an example, for the cases with $V_{inlet} = 1\text{m/s}$ (increases to 2.44m/s at flap outlet), Ar is equal to 0,009, 0,012 and 0,014 for inlet temperatures 30°C , 35°C and 40°C , respectively (for $z=-25^\circ$). Thus, as the inlet buoyancy forces prevail momentum forces, velocity and temperature peaks are occurred at positions closer to ceiling. Similarly, for the cases with $T_{inlet} = 40^\circ\text{C}$ (for $z=-45^\circ$), Ar is equal to 0,129, 0,032 and 0,008 for the

inlet velocities 1m/s, 2m/s and 3m/s (increases to 0.87m/s, 1.74m/s and 3.48m/s, at the flap outlet), respectively, due to the increasing effect of momentum forces.

Table 2: Archimedes Numbers for the cases in Figure 42 and Figure 43

V_{inlet}	Archimedes Numbers		
	30°C (z=-25°/z=-45°)	35°C (z=-25°/z=-45°)	40°C (z=-25°/z=-45°)
0.5m/s	0.038/0.089	0.047/0.109	0.055/0.129
1m/s	0.009/0.022	0.012/0.027	0.014/0.032
2m/s	0.002/0.006	0.003/0.007	0.003/0.008

It is important to note that, Ar values mentioned here are smaller when compared to typical room air diffusers that generally have Ar values between 20 and 240 [188]. However, for the air terminals with high inlet velocity (typically ones with small cross-sectional areas as like nozzles in airplanes), Ar ranges around 10^{-2} and 10^{-3} [189]. Considering the physical meaning of this non-dimensional number, such a small magnitude refers to dominance of momentum forces. Hence the calculated values here are relatively small but in expected range when the flap and room geometry and the boundary conditions are considered. Moreover, they can explain the formation of separation among ceiling and jet. This is a limiting factor for the realization of Coanda effect explained in Section 2.2.2.1, which requires higher Ar numbers.

The analysis results given above provides information about the velocity profiles created by flaps in vertical and horizontal directions separately. For a better understanding of jet flow in room, one needs to validate the both horizontal and vertical position of at least the lowest point of the jet. The Figure 46 shows the velocity profile of the jet and trajectory parameters for flap angle of 25°, air inlet velocity of 1m/s, air inlet temperature of 35°C. Moreover, the lowest point in the figure can be calculated using Eq. 2.9 and Eq.2.10 (Section2.2.2.2). Based on this notation and equations, Table 3 shows the

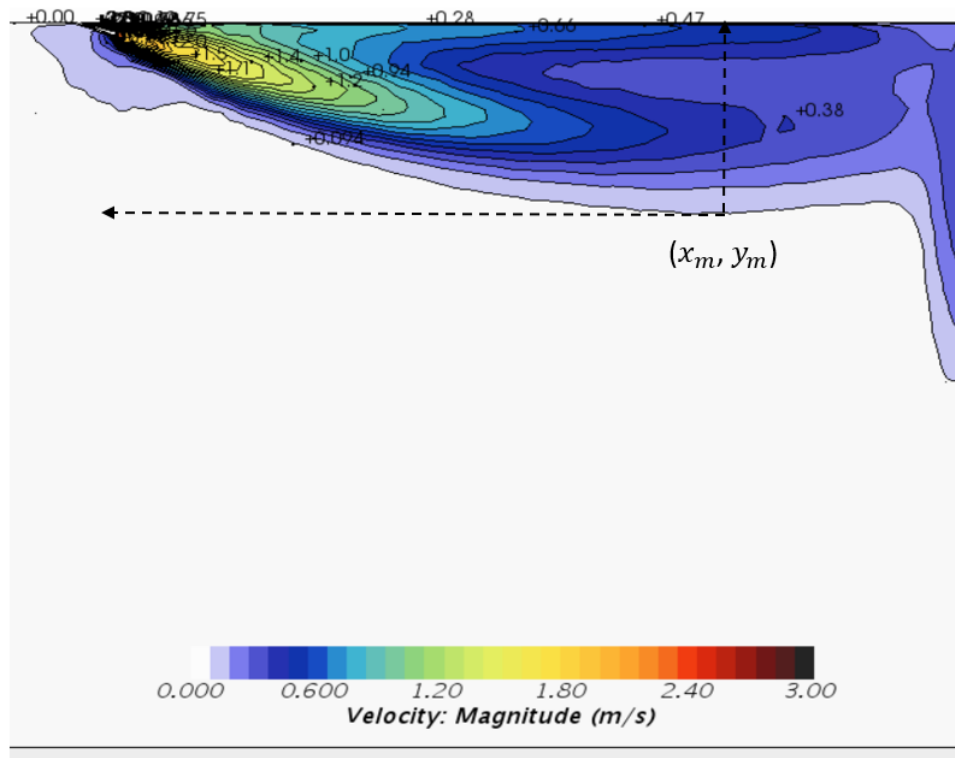


Figure 46: A typical jet profile created by the flaps and the coordinates of the lowest point.

simulated and calculated values for the lowest point of velocity profile for selected scenarios. Reference temperature values are average room temperatures calculated with volume average reporting property of Star-CCM software. Archimedes numbers are taken from Table 2. Empirical calculations and simulations for these non-isothermal flows are in agreement with the average error of 7.9%. This error would be related to asymmetric flap geometry, presence of a wall close to diffuser (due to the room geometry) and the comparatively larger flap angles.

Table 3: Coordinates of the lowest point of air-jets for different flap angles

Jet lowest point	Empirical			Simulations			Error		
	Flap Angles			Flap Angles			Flap Angles		
	25	35	45	25	35	45	25	35	45
Depth(m)	0.68	0.92	1.18	0.63	0.85	1.15	0.08	0.08	0.03
Distance to flap (m)	2.20	1.97	1.78	1.97	1.78	1.63	0.11	0.10	0.08

5.2.2 Airflow Regime Identification

Having a better understanding of jet behavior in an empty box in previous subsection, the resulting airflow regime inside the test room is investigated below. The simulations presented here are based on the room geometry described in Section 5.1.1 and the manikin geometry was included for a complete representation (Figure 47). Note that, this section investigates the airflow regime created by a single flap. So, the air velocities at inlets and in the occupied zone are higher than usual for some cases. In practical operation of AVS, typically more than one flap is open, so the total MFR is divided into different flaps. In this way, air velocity within the occupied zone can be set to be lower than certain limits defined in standards. This section is only for identifying airflow regime created by a single flap of AVS at different operation settings, regardless of the thermal comfort concerns.

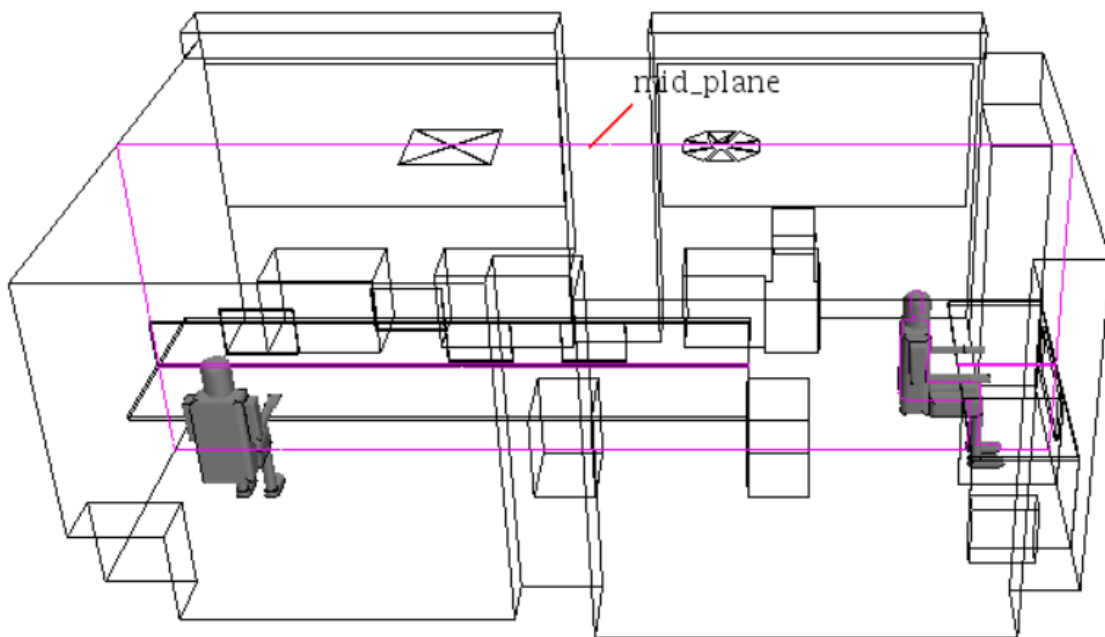


Figure 47: Positions of manikins (dark grey) and the mid-plane (pink).

Figure 48 presents the velocity and temperature fields on the mid-plane of the room for different flap configurations (see Figure 47 for the position of mid plane with respect to inlet and outlet air terminal devices). In the first case, flap configuration is intended to imitate regular vortex diffusers used in buildings with a moderate flap angle ($\phi = 30^\circ$)

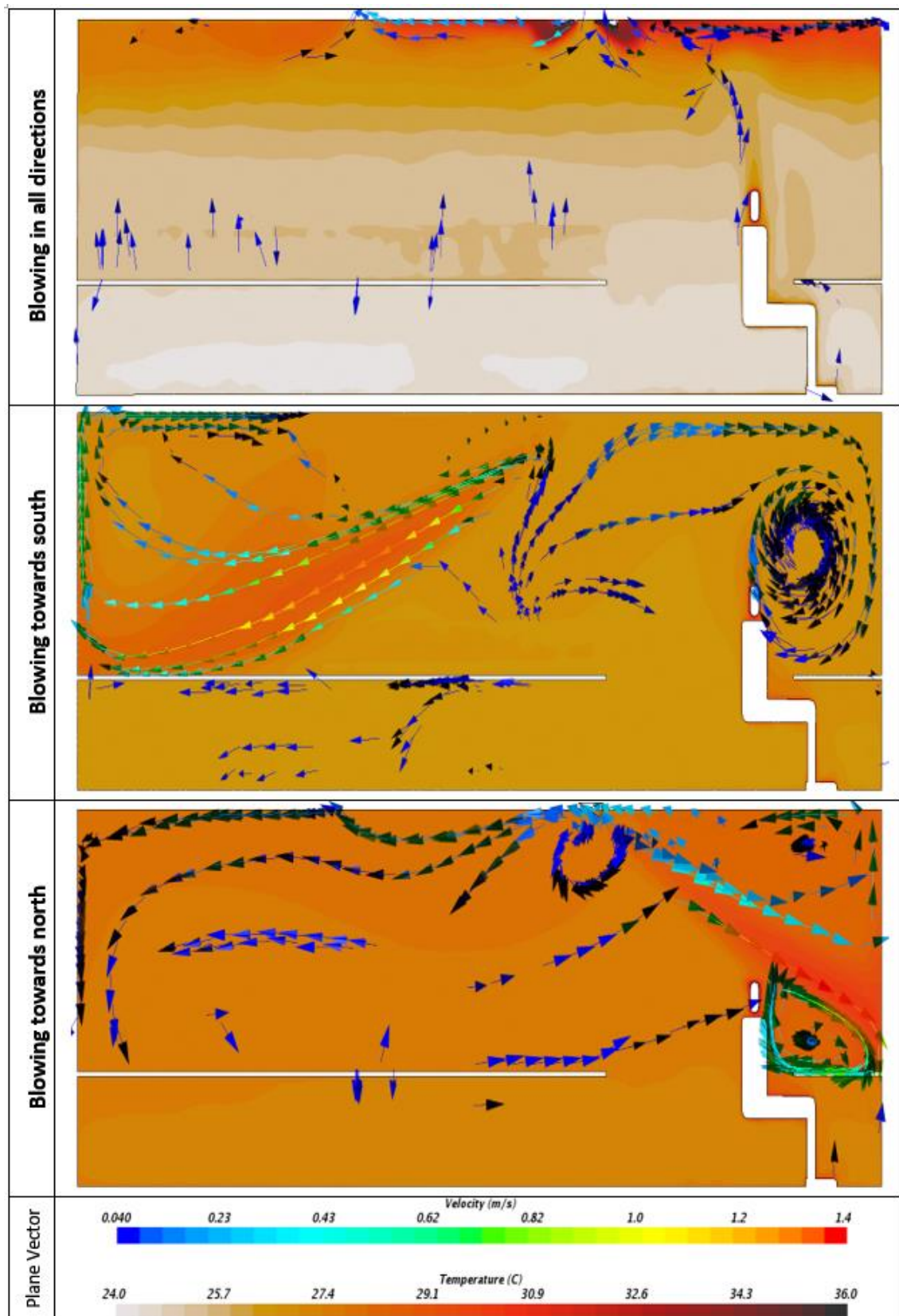


Figure 48: Indoor airflow regime for different flap configurations.

and be a reference case for comparison with the single flap configurations in the second and the third case. In the second and third cases, the flaps blowing towards south and north (Flap-W and Flap-E in Figure 21) were open, respectively, with the same flap angle ($\theta = 30^\circ$). In all cases, total mass flow rate was set to be 0.04kg/s which yields 0.025m/s in each inlet of first case and 2m/s in the inlets of second and third cases (remember that air speed would be different than inlet velocity when leaving the flap due to the flap geometry shown in Figure 21). Note that, velocity is relatively small in first case since the total mass is divided into 8 inlets. Hence, the velocity vectors in the first case are relatively weaker and cumulated on the ceiling. This in accordance with the design criteria for mixing ventilation that is designed to eliminate the risk of draft in the occupied regions (roughly up to the height 1.8m) of the room [190]. Moreover, a short-cut stream with a relatively higher velocity can be seen due to the pressure field coupling of air inlet and outlet terminals (throw and suction, respectively). On the other hand, there is an obvious stream heading in the opposite direction (towards right) with a moderate speed.

Having higher inlet velocities, it is possible to observe the jet profiles clearly in the second and third cases of Figure 48. In the second case, the primary air stream is directed by table-top and left wall towards outlet. The velocity of the air receiving outlet from this trajectory is relatively high whereas the short-cut stream (between inlet and outlet) is even unrecognizable on mid-plane. This is due to the dominance of air inlet momentum over the pressure outlet. The secondary air stream induced by the first one is seen to have a weaker but remarkable velocity field. On the other hand, the primary air stream in the third case moves just above the head and receives occupant after directed by wall and table-top. Moreover, the secondary air stream has very low but recognizable flow over the back of the occupant. The air flow in the south side of the room has lowest velocity

and at ignorable levels in the occupied zone. The short-cut stream is also recognizable with a low speed.

The temperature fields represented in Figure 48 shows the dependency of temperature distribution on flap configuration and room geometry. For the same mass flow rate and inlet temperature, mid-planes have distinct temperature characteristics. In the third case, the distance between flap and the wall in the jet direction is relatively small. This results in change in direction of air stream and head it towards the opposite direction with a relatively higher velocity and temperature. The temperature and velocity of these streams decay along the air flow path outlined by room geometry. This is also the case in second case but due to the higher distance between flap and corresponding wall, the average temperature is lower. Both cases result in higher velocity and temperature fields in occupied zone when compared to first one. The selected mass flow ratio for the comparison is small for each of eight flaps reach enough velocity to diffuse occupied zone.

The second and third cases presented in Figure 48 showing the interaction of air-jets of AVS with the occupied zone of a room for representative cases. They are obviously different than the first case that is a typical scenario for “diffusion” strategy. In the following paragraphs, more details of air-jet penetration to occupied zone will be investigated for different inlet velocity and temperatures. Having a cross section with an occupant, the right part of the room will be under focus to give insight regarding to interaction of jet and occupants under different operating conditions.

Figure 49 shows three cases for Flap-E with different mass flow rate values. Obviously, the right side of the mid-plane always has higher speeds compared to south side due to the orientation of selected flap. Moreover, all parts of the room receive higher speeds as

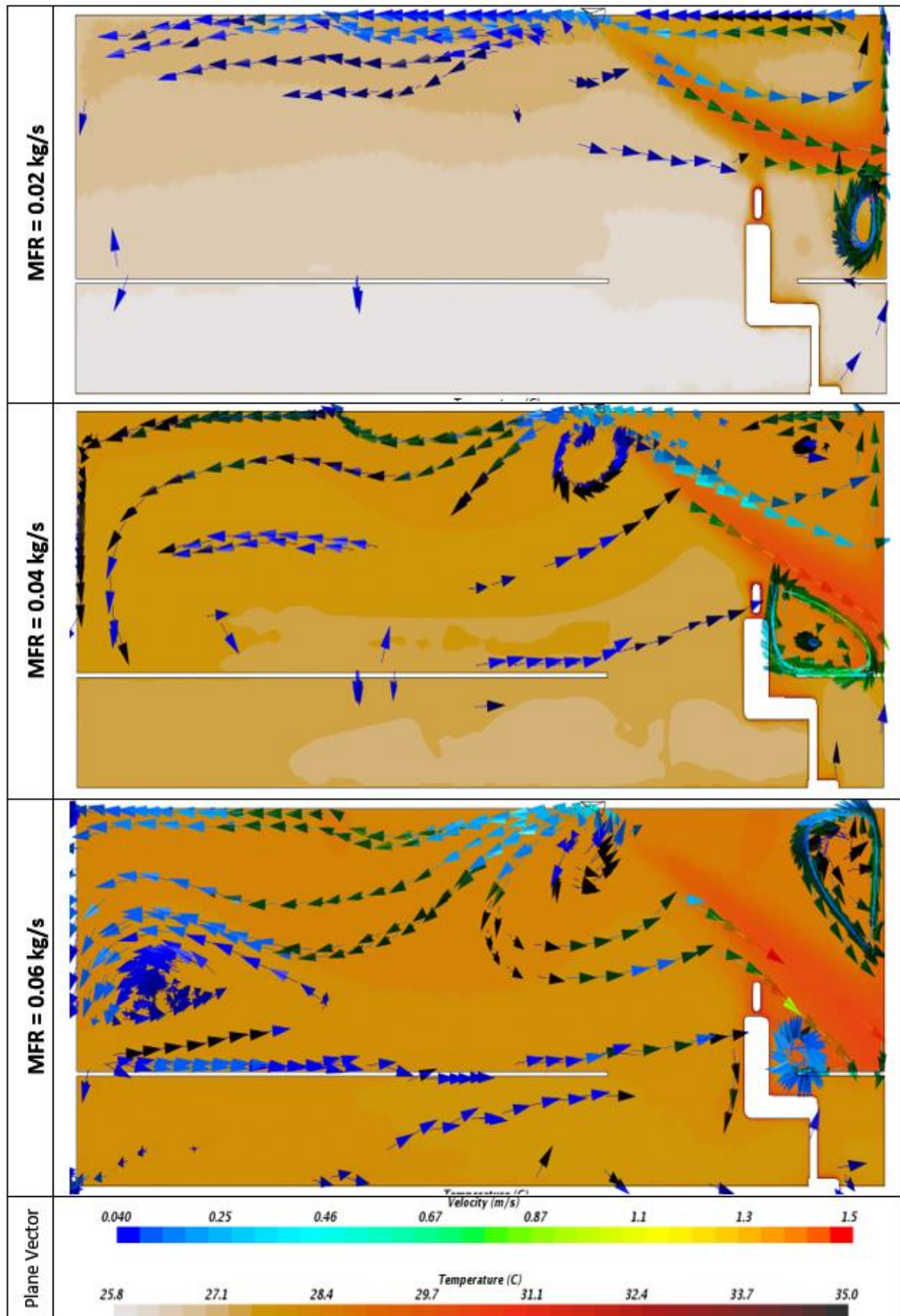


Figure 49: Indoor airflow regime for different mass flow rates (MFR).

the mass flow inlet increases. The speed of airflow next to the wall is a typical representation of this as well as the more intense vectors below the table. Also, the increasing speed and decreasing radius of the air circulation in the upper-right corner of the plane is noticeable. For the given flap configuration (single flap with $\varnothing = 30^\circ$), airflows that have mass inlet flow rate more than 0.02 kg/s creates considerable air speeds within the occupied zone of the room. This is an important concern for comfort concerns which will be discussed in detail later. However, referring to Figure 49, one can argue that the MFR and the flap configuration (number, orientation and flap angle) has crucial importance to provide localization without overreaching comfort limits.

The temperature fields presented in Figure 49 demonstrate temperature differences created between opposite sides of the room for all cases. Moreover, as the mass flow rate (so the inlet velocity) increases, room temperature also increases slightly. This is in parallel with the discussion for Figure 44 in terms of the effect of velocity on temperature characteristic. In both figures, for the cases with higher velocity in the opposite direction result in higher average room temperature. For all cases shown in Figure 49, the temperature stratification is clearly observed. On the other hand, as the inlet MFR increases, the occupant interacts with air stream that have higher temperature and velocity where the increase in velocity is more noticable.

Figure 50 shows the velocity and temperature fields created by Flap-E on the mid-plane for different inlet temperatures ($T_{\text{inlet}}=35^\circ, 40^\circ$ and 45°) where the flap angle $\varnothing = 30^\circ$ and the inlet mass flow rate (MFR=0.04 kg/s) were identical. Even the general outline of the velocity fields is similar, there are two noticeable differentiations. First, the velocity of the airstream that reaches to occupant by moving tangent to right wall and the table-top has higher velocity for lower temperatures. Accordingly, vortices in the upper-right wall have smaller radius. This is a result of difference in density gradient where the dense air

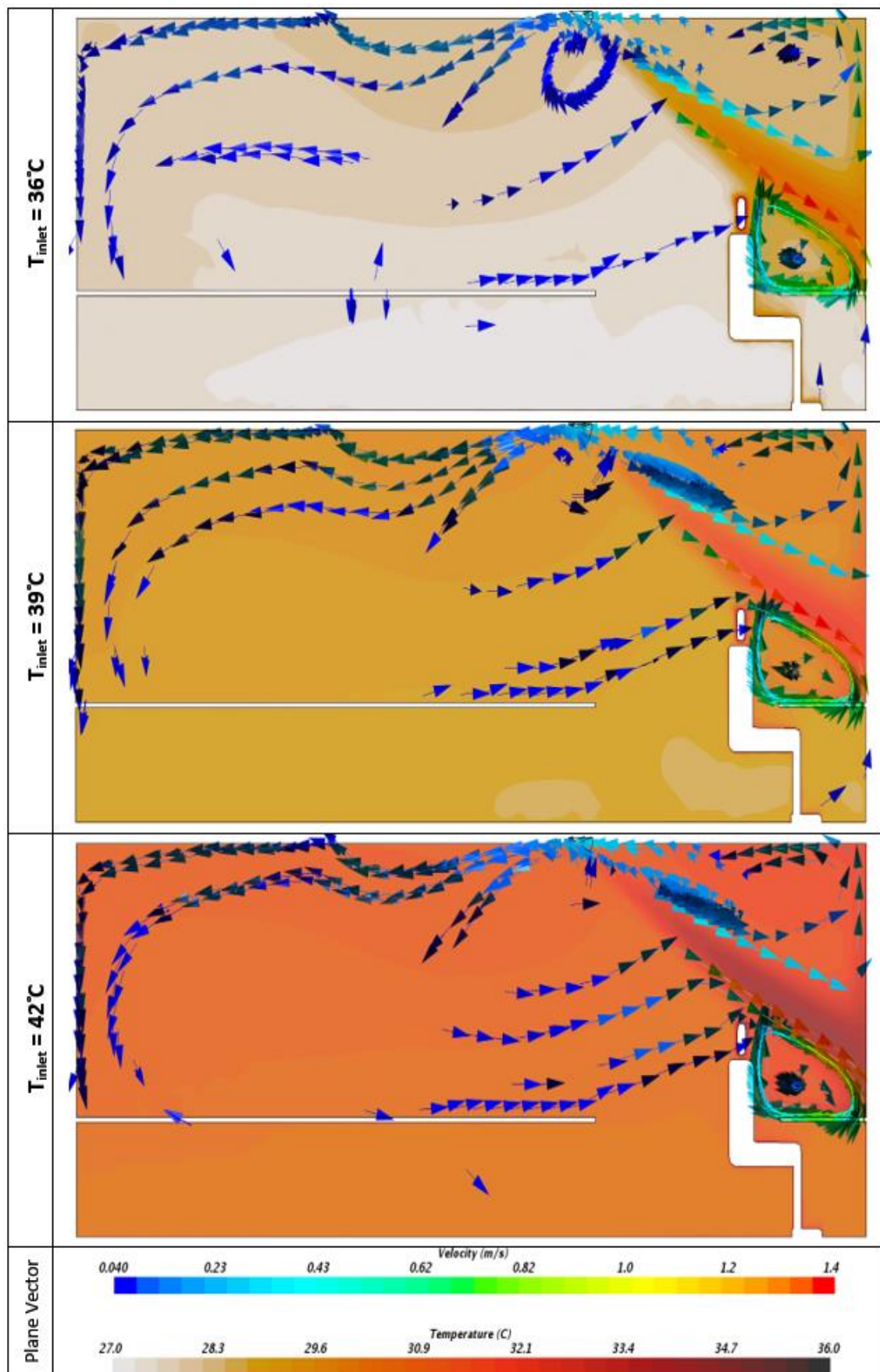


Figure 50: Indoor airflow regime for different inlet temperatures.

temperature reaches higher height on the right wall and splinter off several directions. Hence, the total volume reaching occupant towards table-top decreases. This is in accordance with the velocity profiles provided in previous sub-section (see Figure 43 where the effect of density can be seen more clearly due to the better orientation of the monitoring plane with air-jet.) Second, the left side of the room has air streams with higher velocity that results in increasing speed of airflow on the back of the occupant. This is a result of air streams divided at the higher height and distributed over room volume. Hence, the Figure 50 shows how the temperature of inlet air effects the formation of velocity fields and how it can change comfort conditions within the room.

Figure 51 shows the change of velocity and temperature fields inside the room for different flap angles whereas the inlet air has same temperature and mass-flow rate for each case. (Remember that as the flap angle gets larger, air-jet leaving flap has lower velocity due to the change in geometry, see Figure 21). Obviously, flap angle directly effects the jet orientation and so the penetration of the primary air to the occupied zone. As the flap angle gets larger, the air jet leaves flap with a smaller speed but directly heads towards occupied zone. Moreover, the jet in the Case-3 is divided to branches by the head of occupant which is an undesirable case (draft discomfort, see Section 2.2.3.2). The flow moving tangent to the back of the occupant then divided into opposite directions and flowed along the floor. Such an interaction with the environment results in serious loss of momentum of the initial stream on the right side of the room and thence the opposite side of the room has air streams with lower velocity and temperature. Note that, this is the only case that has right-to-left air flow on the floor. On the other hand, the first case is also interesting in terms of the result of interaction of air stream with the occupant. It can be observed that a relatively higher speed of air reaches occupant's front side after crossing to wall but the flow towards opposite direction is limited by body. This

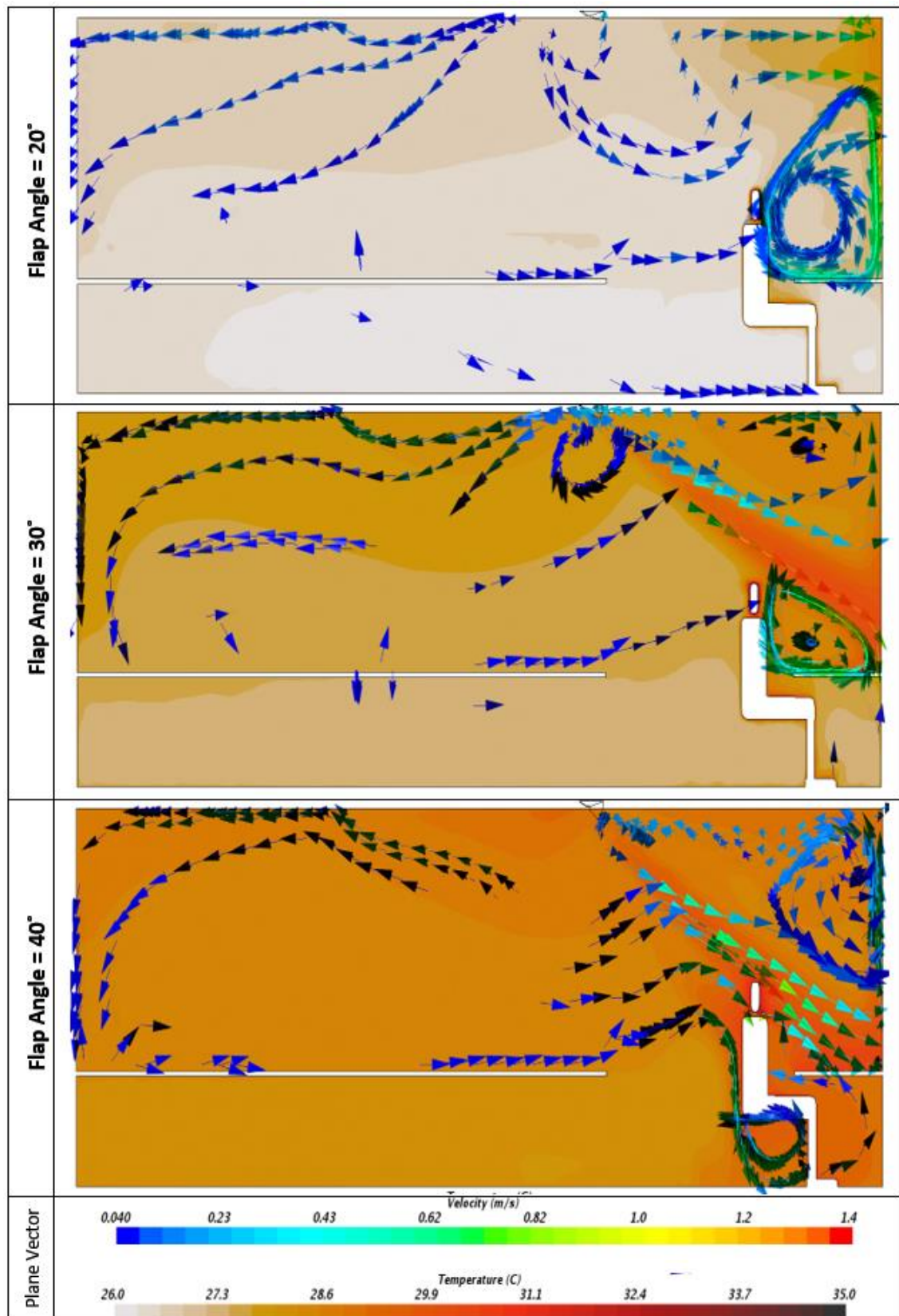


Figure 51: Indoor airflow regime for different flap angles.

diminishes the air-jet momentum. Hence, the first case has highest temperature difference among left and right sides of the room.

The results presented in this sub-section are consistent with the design concerns of AVS that is intended to manipulate indoor airflow with individually operable flaps. On the other hand, results tend to highlight that it possible to create draft discomfort in occupied zone if the system is operated with a single flap since the whole volume of conditioned air is injected via smaller surface. Hence, the following subsection discusses the resulting thermal comfort of occupants in different parts of the room as well as the different parts of the occupant's body for a variety of operating conditions that have different flap configurations.

5.2.3 Thermal Comfort Analysis

A comprehensive analysis of the air-jets and indoor airflow created by the operable flaps is presented in previous subsections, following the discussion in Section 2.2.2. As defined in Section 4.1, the core design concern for the AVS is providing localized and customized thermal comfort to building occupants in an energy efficient way. Hence, a comprehensive analysis of thermal comfort created by AVS is presented here in light of literature review presented in Section 2.2.3. The AVS is intended to deliver asymmetric air entrance from inlet diffuser to create and control non-homogenous thermal environment inside a room. The discussion in the previous section shows that this can be realized, however, there is a risk of giving rise to draft discomfort in occupied zone (see Section 2.2.3.2 for the effect of draft on comfort). Especially for cases with only one flap is opened, air stream would reach occupant with more than 1m/s where the corresponding standard (ISO-14505) suggests to be 0.3 m/s at most. Hence, the temperature comparisons for evaluating the performance of a HVAC system should account for indoor air velocity limits. Accordingly, the flap configuration of cases presented in this sub-section were

involved two or three open flaps. Moreover, the air velocity created by the airflow regime on body parts were monitored using the built-in “Cell Relative Velocity” function of Star-CCM and presented for each case. The Figure 52 shows a case in which three flaps were open (SE, E and NE) whereas the inlet air has 0.088 kg/s mass flow rate and at 43°C. The velocity field for air flow shows the points where air speed exceeds 0.3 m/s whereas the manikin surfaces shows resulting air speed on the corresponding part of the virtual manikin. The left wrist of the manikin is seen observed to overreach air speed limit due to the air stream on the desk.

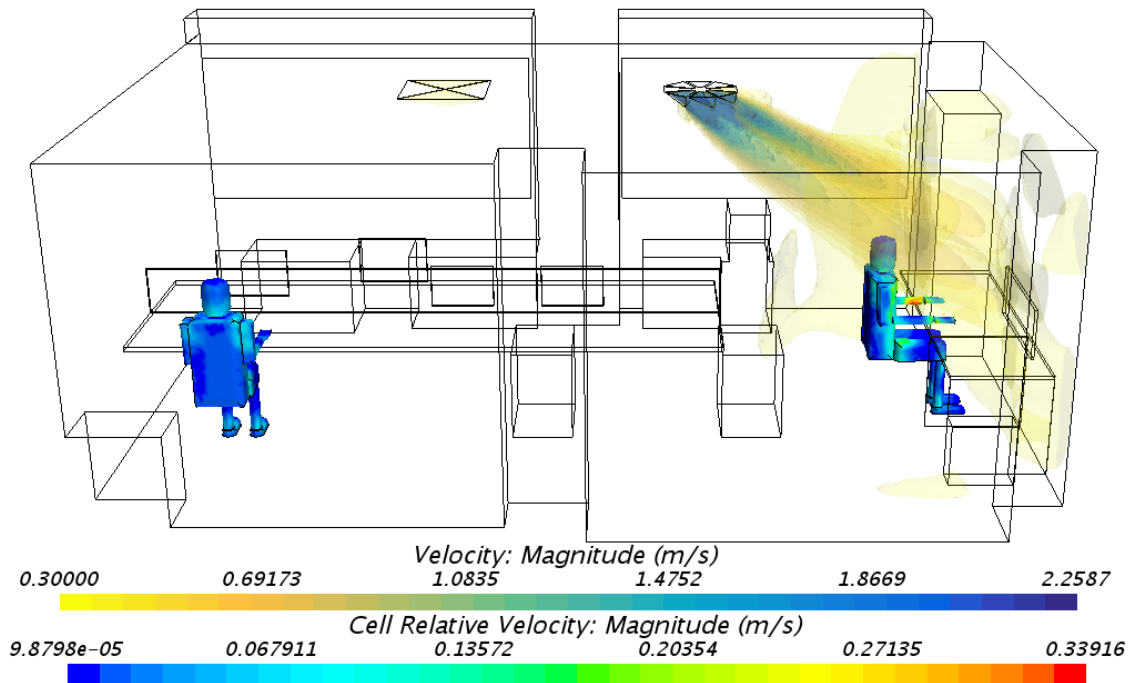


Figure 52: Regions where the air velocity exceed 0.3m/s and the resulting airflow on manikin surfaces.

It is important to note that, mass flow rates (MFR) is the only available control parameter to determine the air inlet velocity in Star-CCM+ Thermal Comfort Wizard. Hence, a reference fan-coil unit was chosen (GF31.UWC1.A00A1) to make realistic assumptions related to air flow rates in the simulations [191]. This fan-coil is very similar to the one installed in the test room in terms of heating/cooling capacity but has higher number of

speed control levels (5 instead of 3). The MFR for each control level (1 to 5) of the selected fan-coil is 0.0496 *kg/s*, 0.0714 *kg/s*, 0.088 *kg/s*, 0.1117 *kg/s* and 0.1676 *kg/s*, respectively (converted from m^3/h values in the catalog using the density of air at 43°C). The preferred total MFR for a simulation was divided into number of open flaps in the simulation scenario to determine MFR as the inlet boundary condition of the open flaps.

Beside the velocity limits, the way dealing with the temperature for the thermal comfort is another crucial factor where reporting the room air temperature around body is not enough. In parallel to design concerns of AVS, temperature evaluation was performed here for the fourteen individual parts of the virtual manikins, using the one-dimensional human thermoregulation model of Star-CCM+. The model provides both skin and equivalent temperature (*Teq*) data of each body part for post-processing. *Teq* is a parameter commonly used to assess thermal comfort in confined living environments that has asymmetric climatic conditions (such as vehicle compartments and desks with personalized ventilation). ISO-14505 standard defines it as: “temperature of a homogenous space, with mean radiant temperature equal to air temperature and zero air velocity, in which a person exchanges the same heat loss by convection and radiation as in the actual conditions under assessment” [192]. Hence, it is proper for assessing the thermal comfort performance of AVS. The results for *Teq* are presented here with bar charts that are coupled with “boundary lines” for thermal comfort. Figure 53 shows these equivalent temperature intervals for fourteen parts of the human body as thermal comfort regions, namely, ‘too hot’, ‘hot but comfortable’, ‘neutral’, ‘cold but comfortable’ and ‘too cold’ [193].

Since the risk of draft is an essential concern for thermal comfort assessment, it is crucial to monitor the speed of air next to the occupant’s skin. The analysis presented in Section

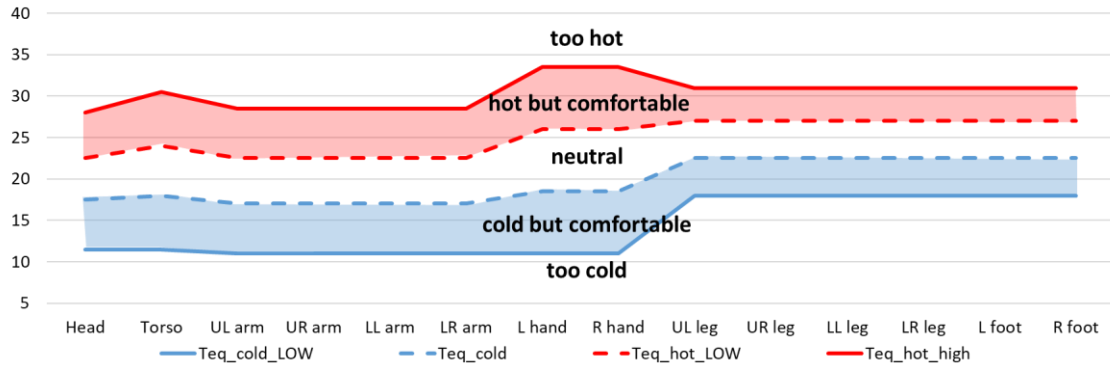


Figure 53: Comfort regions for each body part in terms of equivalent temperature (Adopted form [192]).

5.2.2 shows that improper flap configuration and HVAC machinery settings would result in high velocity (>0.3 m/s) air streams in occupied zone. Hence, for each case presented here, the air velocity on virtual manikin surfaces are monitored using the built-in “Cell Relative Velocity” function of Star-CCM+. This field function monitors the “near” wall velocity of fluids. Hence, it is useful for monitoring air velocity next to manikin surfaces. On the other hand, heat flux distributions on the virtual manikin surfaces are presented for each case in order to monitor the effect of AVS settings on different parts of the body. The following paragraphs discusses numerical results for selected cases that reveal operational characteristics of the AVS. To this end, thermal comfort comparisons for different inlet temperature, mass flow rate, flap angle and flow direction are presented. An all-opened flap configuration of AVS can be used to mitigate a conventional swirling air diffuser that is commonly used in buildings. It enables symmetric air inlet and can be considered as a base scenario for different operational mode of AVS. Since the flap configuration is fixed, control parameters would be air inlet velocity and temperature, as in conventional systems. Figure 54 compares the thermal comfort outcomes of different flow rates when the all flaps of the AVS is opened with the same angle ($\varnothing = 30^\circ$) and the inlet temperature is 43°C . For all cases, air streams reach manikin body with velocities smaller than 0.2 m/s. This is in accordance with the essential design concern of a

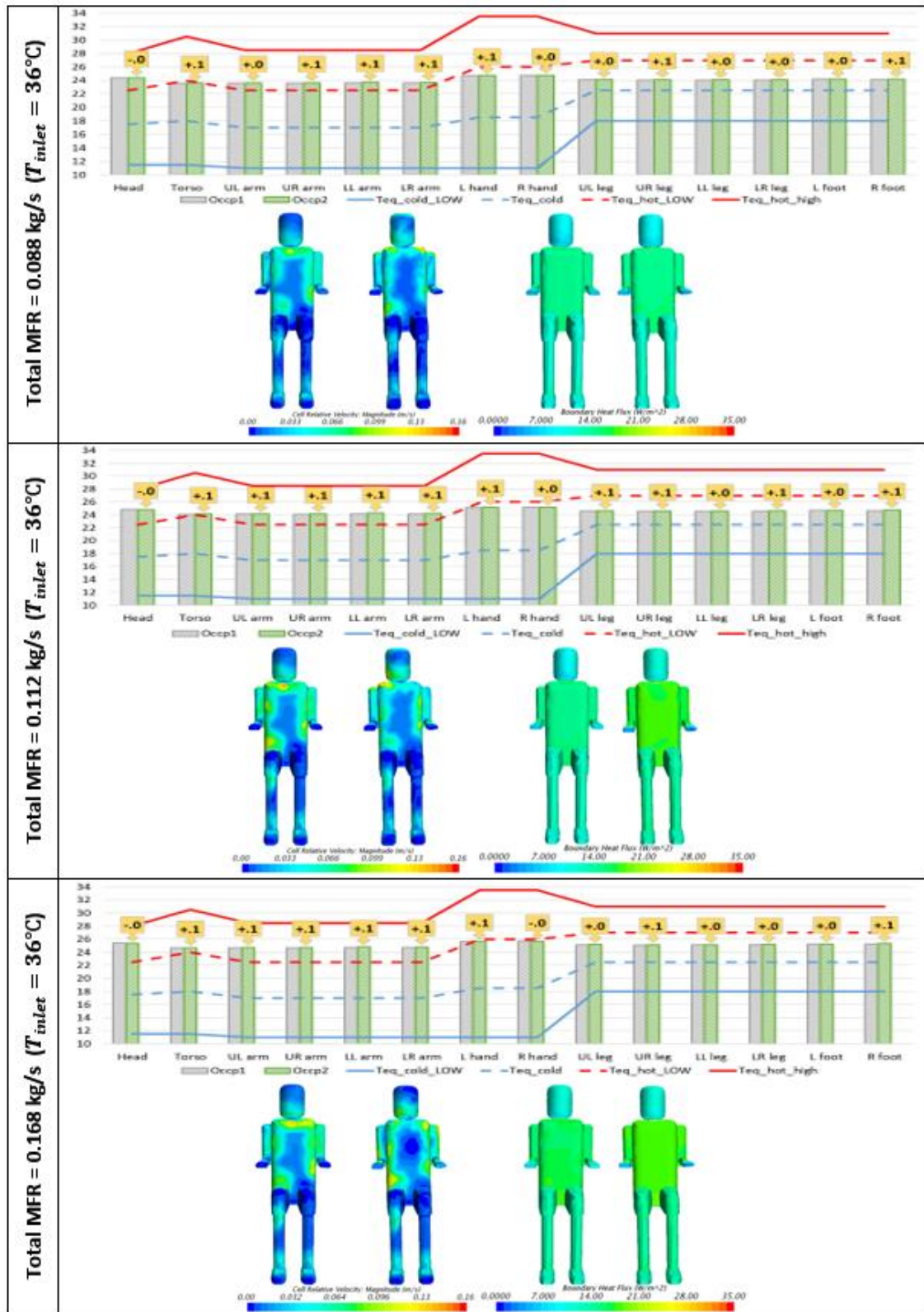


Figure 54: Comparison of equivalent temperature, air velocity on body surface and skin temperature of manikins under different mass flow rates (MFR).

conventional HVAC system that primarily aims to eliminate draught within the occupied zone. On the other hand, skin temperatures of both manikin is almost same in each case and slightly increases as MFR increases. Similarly, T_{eq} values are very similar for parts of the manikin bodies but for the case with highest MFR, the upper body parts of the second manikin are slightly warmer.

The inevitable inhomogeneities mentioned above are generic for conventional HVAC systems. Due to the several factors including room geometry, presence of other heat sources and door/window openings, a complete homogeneity cannot be reached in practice. Nevertheless, these systems don't have any tool to overcome this situation if occupants are dissatisfied. On the other hand, proposed AVS design aims to control these inhomogeneities in accordance with occupant preferences in order to maximize thermal satisfaction. The main tool for this is individually operable flaps that can deliver asymmetric air inlet. As an example, only the flaps blowing towards a specific part of the room can be manipulated (open, close or set of a specific angle) to change conditions around that part of the room.

Figure 55 depicts the comparisons of temperature distributions and thermal comfort variations for three flap configurations. The Case-1 in Figure 55 presents the base scenario in which all flaps of the AVS are open with $\phi = 30^\circ$ and total mass flow rate is 0.112 kg/s. There is only limited difference of equivalent temperatures between conjugate body parts of virtual manikins. On the other hand, Case-2 presents a case with a flap configuration that three flaps blowing towards right part of the room (SE, E and NE) are open with $\phi = 35^\circ$ and the total mass flow rate is 0.087kg/s. The right side of the room is slightly warmer, and the equivalent temperatures of body parts are higher approximately 0.5°C in average. Moreover, the difference is higher (approximately 1C in average) in the third case in which 2 flaps heading towards left part of the room are open

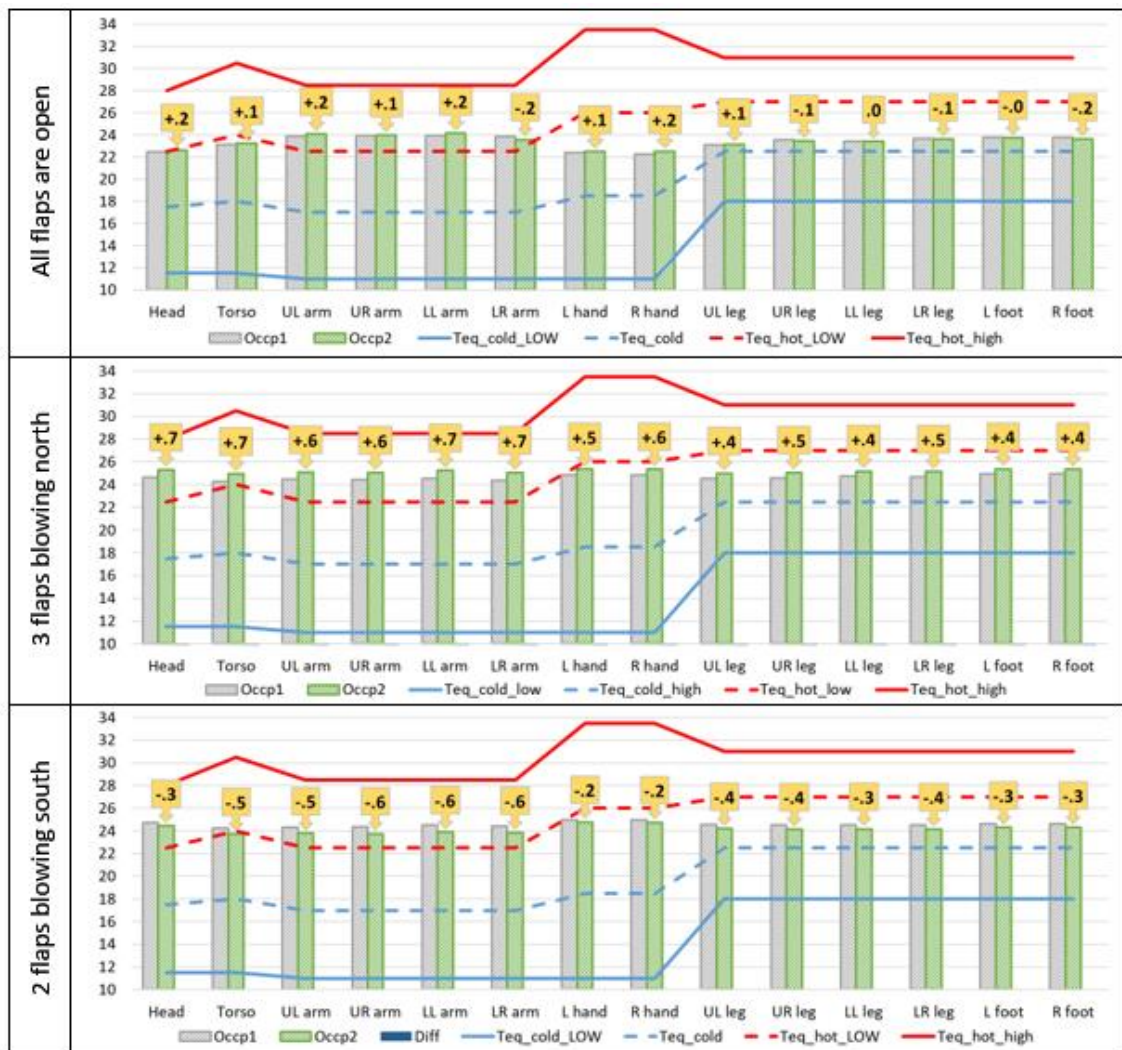


Figure 55: Comparison of equivalent temperature for different flap configurations.

($\phi = 35^\circ$ and the total mass flow rate is 0.087 kg/s) The obvious and intended differences in the second and the third cases represent the capability of AVS to create thermal localization and customization. The following paragraphs presents the extend of this capability in terms of thermal comfort outcome of different operational cases.

The flap angle is an important parameter for the path followed by air jet and the resulting airflow regime. Together with the room geometry, it effects the speed and temperature of the air stream reaching occupant. Figure 56 presents two comfort conditions created by different flap angles while both case have same inlet temperature and flow rate. Three flaps blowing towards right part of the room (SE, E and NE) were opened with $\phi = 25^\circ$

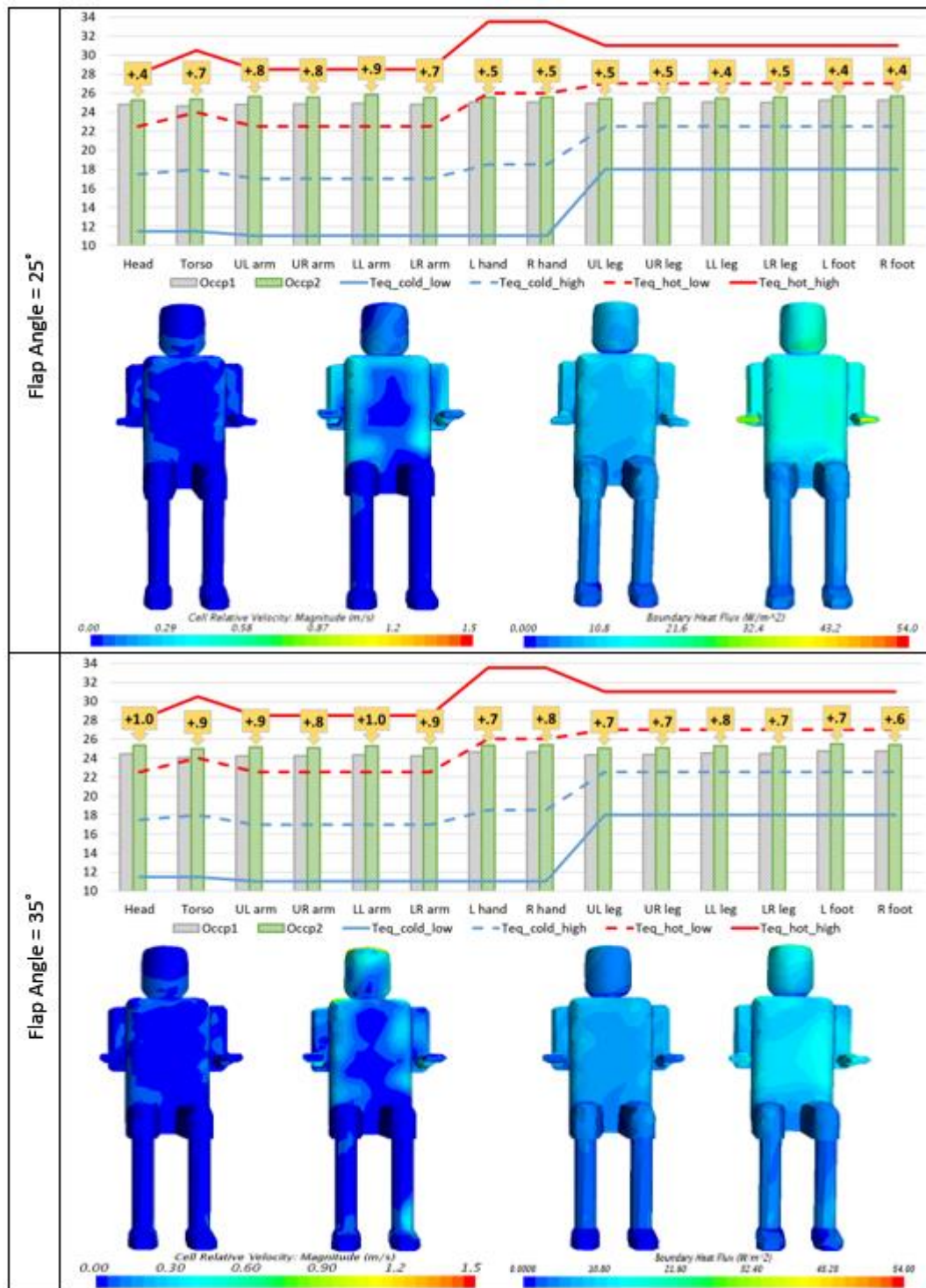


Figure 56: Comparison of equivalent temperature, air velocity on body surface and skin temperature of manikins under different flap angles.

(Case-1) and $\emptyset = 35^\circ$ (Case-2). Having a narrower flap angle, the air stream in the first case doesn't interact with the second manikin but reaches him with a moderate speed flowing over right wall and table-top. Hence, the front side of the virtual manikin faces relatively higher air velocity (maximum 0.44m/s). On the other hand, air-jet directly touches to the head of second manikin with a speed of almost 1.5 m/s which is a very high level of draft for indoor environment. These two cases show the effect and importance of air-jet direction for the interaction with occupants. On the other hand, being out of the trajectory of the air-jet and the primary airflow, first manikin receives slower air flows in both cases. Temperature fields in the both cases of Figure 56 resulted in higher temperature for the second manikin. In the first case, especially the upper part of the body has higher (more than 0.6°C) temperature compared to first manikin. In the second case, the head of the second manikin has overreaching temperature difference due to the draft effect whereas the other parts of the body have reasonable (around 0.7° C) temperature (T_{eq}) differences with the other manikin. In both cases, arms of second manikin reach upper limit of 'hot but comfortable' region whereas the lower parts of the manikins are around the lower limit of the region.

Figure 57 presents the comparison of two mass flow ratios (0.087 kg/s and 0.1117 kg/s for first and second cases, respectively) for the same inlet temperature ($T=43^\circ\text{C}$) and flap configuration (flaps SE, E and NE with. $\emptyset = 35^\circ$). As expected, as the MFR (so the inlet velocity) increases, the speed of air receiving second occupants body increases. The speed of air on the second manikins head increases from 1.1 m/s to 1.5 m/s whereas the larger ratio of the upper body surfaces receives air streams with high velocity (>0.3 m/s). On the other hand, as the MFR increases, the temperature difference between the conjugate parts of the manikins slightly increases for almost all parts of the body. In accordance,

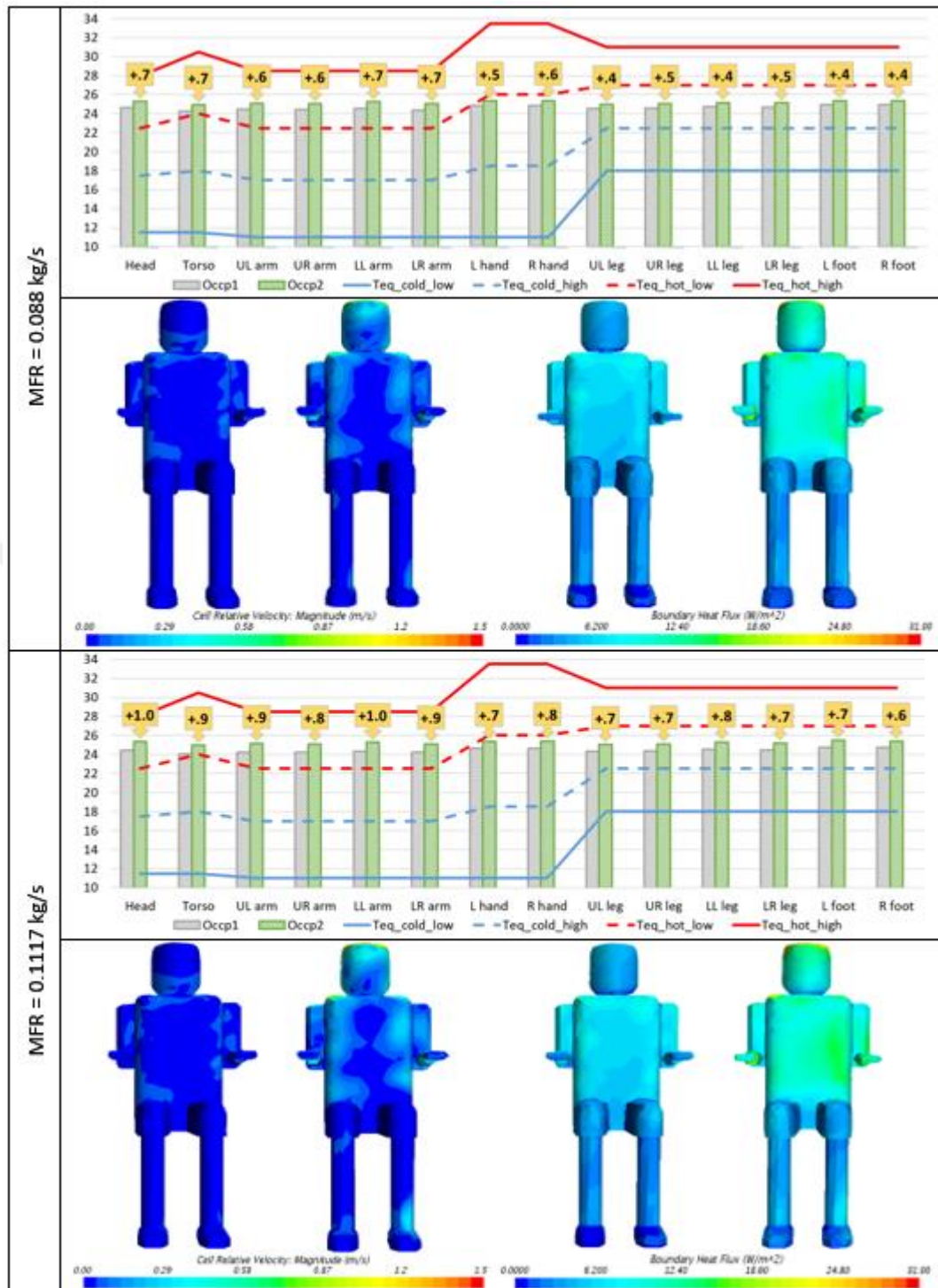
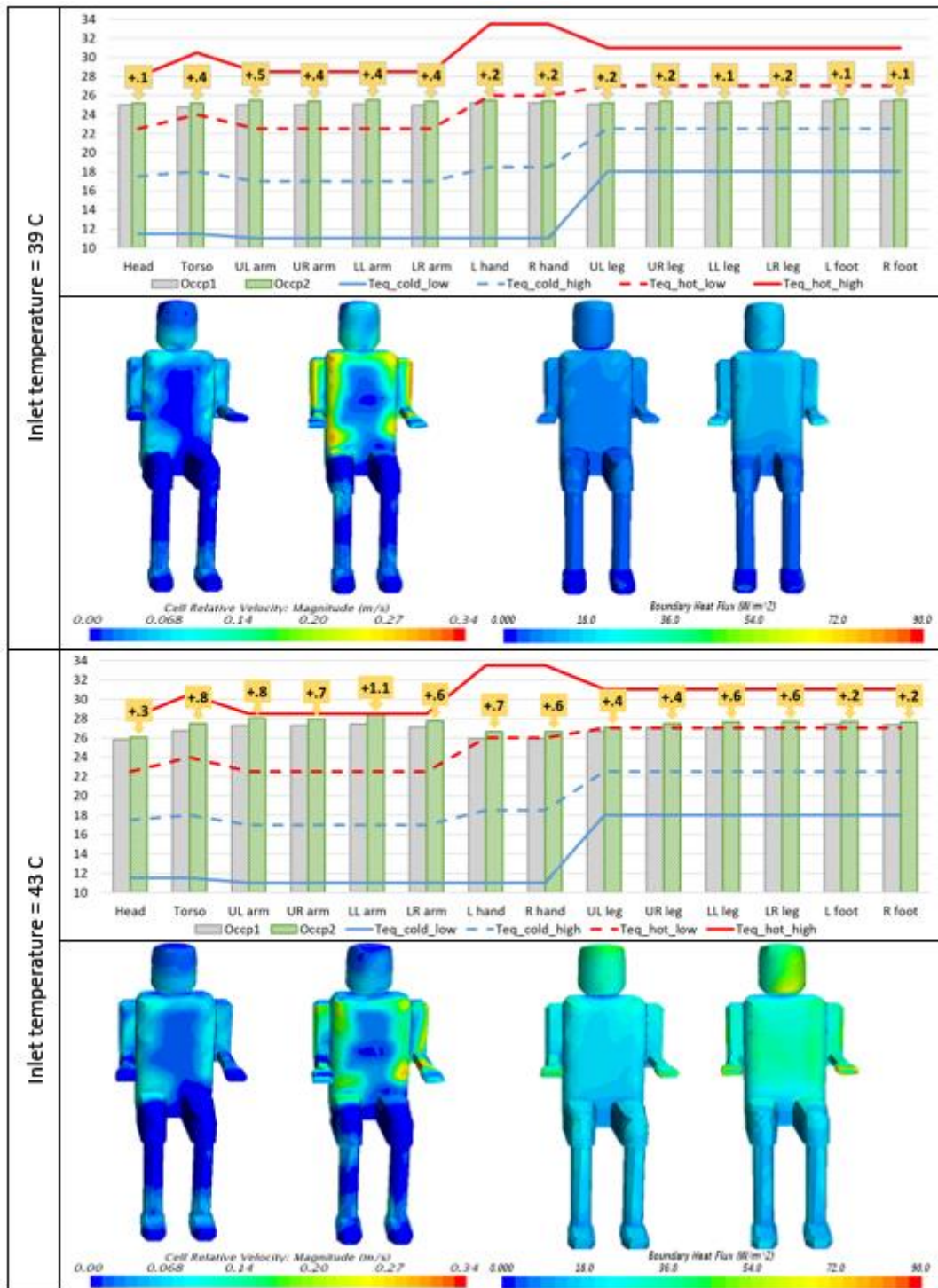


Figure 57: Comparison of equivalent temperature, air velocity on body surface and skin temperature of manikins under different mass flow rates (MFR).

the equivalent temperatures of the all body parts increase and the upper body parts get closer to higher limit of comfort zone.

Another important parameter for the system performance is, obviously, the inlet air temperature. Figure 58 shows the comparison of resulting comfort conditions for 39°C and 43°C where the total MFR is 0.087 kg/s and the flap angle is $\varnothing = 35^\circ$ for flaps SE, E and NE. As the figure shows clearly, the increase in temperature results in very similar air velocity distribution on the manikin's surface but with a small amount of increase on both of the manikin surfaces. On the other hand, both of the manikins has higher surface temperature for all body parts (almost 1.5°C higher). Moreover, the temperature difference between the body parts increases for both manikin (the range of the temperature scale increases from 0.7°C to 1.9°C). Accordingly, the equivalent temperature increases for all body parts as well as the temperature difference between conjugate body parts of the manikins (~0.5°C).

Figure 54 to Figure 58 present variations in comfort conditions for different operational settings of AVS. In other words, the figures show the characteristics of the adaptability of the proposed system for different occupant demand. A traditional way of thermal adaptation for daily life is the change of clothes. In winter (heating season), it is a common practice to put on thicker clothes that have higher thermal insulation (clo) value to keep body temperature higher. When the people dissatisfied with the thermal conditions in a room, they would change their clothing. Accordingly, Figure 59 compares the different comfort conditions experienced by first occupant when the clo value is changed. The flaps are set to blow toward occupant-2 with MFR=0.088 and ($T_{inlet}=43^\circ\text{C}$) and the clo value for the second occupant is kept same. As expected, the surface temperature on occupant-1 increases whereas the that of occupant-2 is almost same. Equivalent temperature for occupant-1 increases ~1°C in average for different parts of the body.



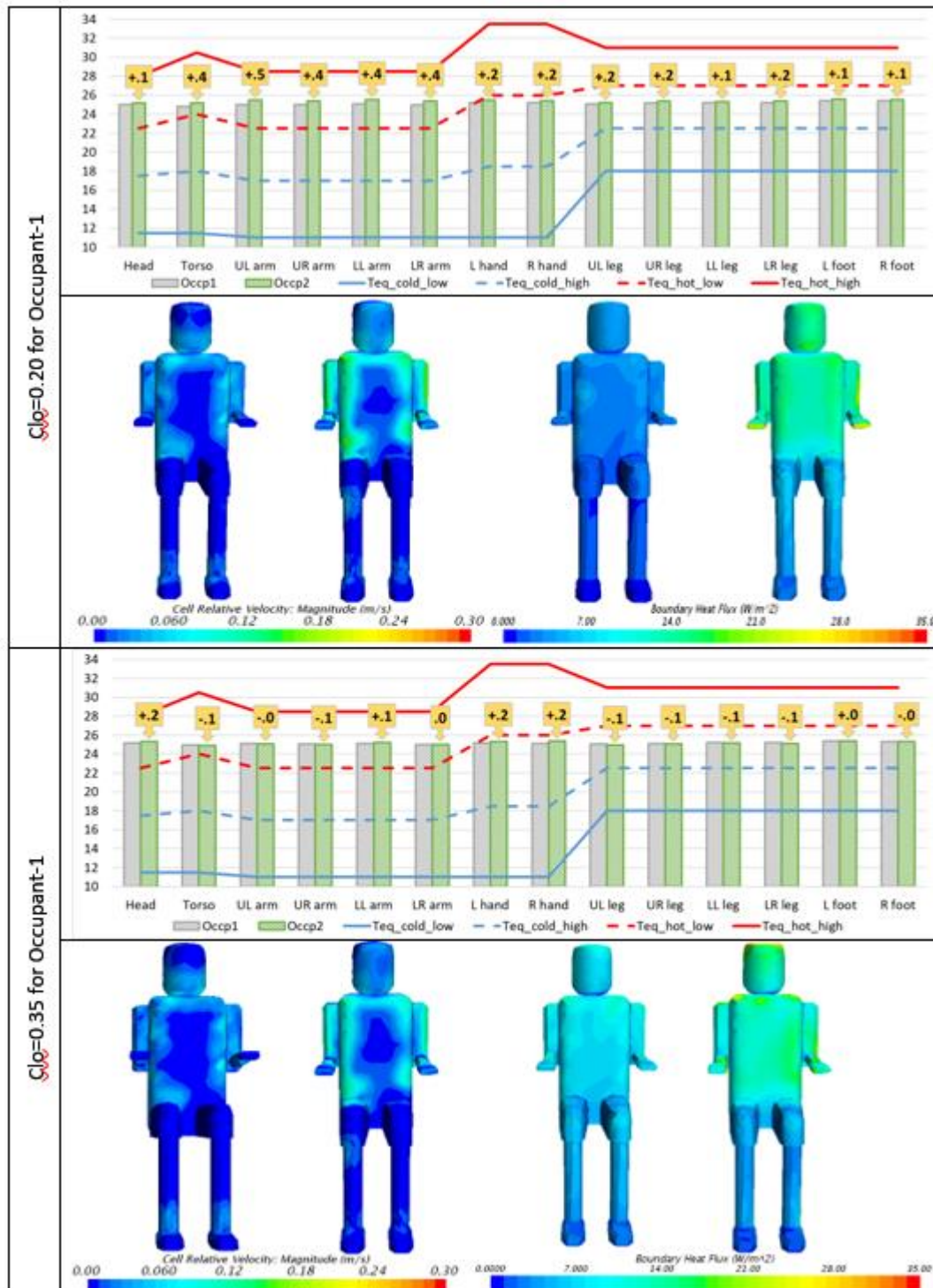


Figure 59: Comparison of equivalent temperature, air velocity on body surface and skin temperature of manikins for different clo values of manikin-1.

5.2.4 Energy Analysis

The main objective of the AVS is providing customized and localized comfort in an energy efficient way. The main source of efficiency is prevention of conditioning unnecessary parts of the rooms. These regions would be unoccupied or the occupants don't ask for change in comfort conditions. When this is realized, it would be possible to use less conditioned air (so the less energy) in order to meet comfort conditions. In modern HVAC control interfaces, it is possible to arrange the amount of air volume to be conditioned by setting fan speeds. Obviously, this results in the change of energy consumption of the HVAC machinery. Figure 60 shows the additional power of controller set level changes in terms of the rated power of the reference system of this study. As an example, when this fan-coil unit is switched from second to third controller set level, it requires additional power with the amount 13% of rated power. In other words, when it is switched from third level to second one, it saves 13% of energy usage during this operation period.

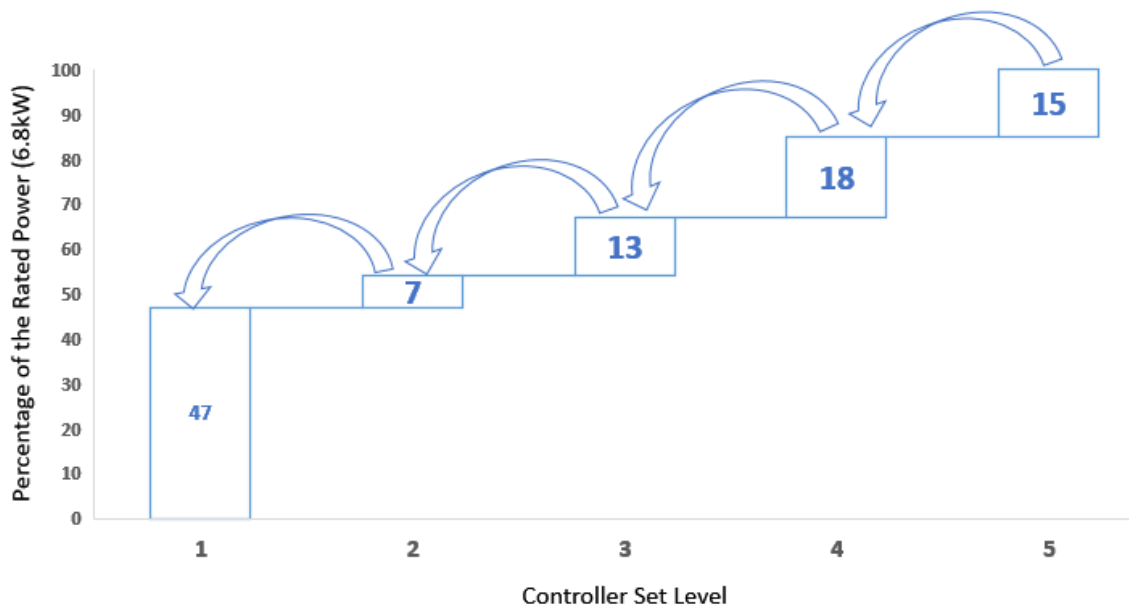


Figure 60: Percentage of the rated power (6.8 kW) of the reference fan-coil unit for different controller set levels.

The AVS aims to operate HVAC machinery at the lowest condition by meeting the desired comfort conditions in the localized parts of the room. Hence, in order to assess the energy saving potential of AVS, it is compared with conventional systems. For the south part of the room (left side in the figures), thermal comfort level of the manikin (manikin-1) is compared under two conditions: (i) a conventional system is blowing out air in all direction by working in 4th-level, and (ii) AVS is blowing towards south by working in 3rd-level. A similar comparison is also made for manikin-2 where AVS is blowing towards north in the second case. The results are shown in Figure 61. For occupant-1, AVS provide slightly less air temperature (out of hands) but steel keep occupant in warm region. For occupant-2, AVS provide almost same comfort condition. Hence, these scenarios show that AVS would save energy by keeping system (HVAC machinery) controller at the lower set levels without a sensible change in comfort conditions.

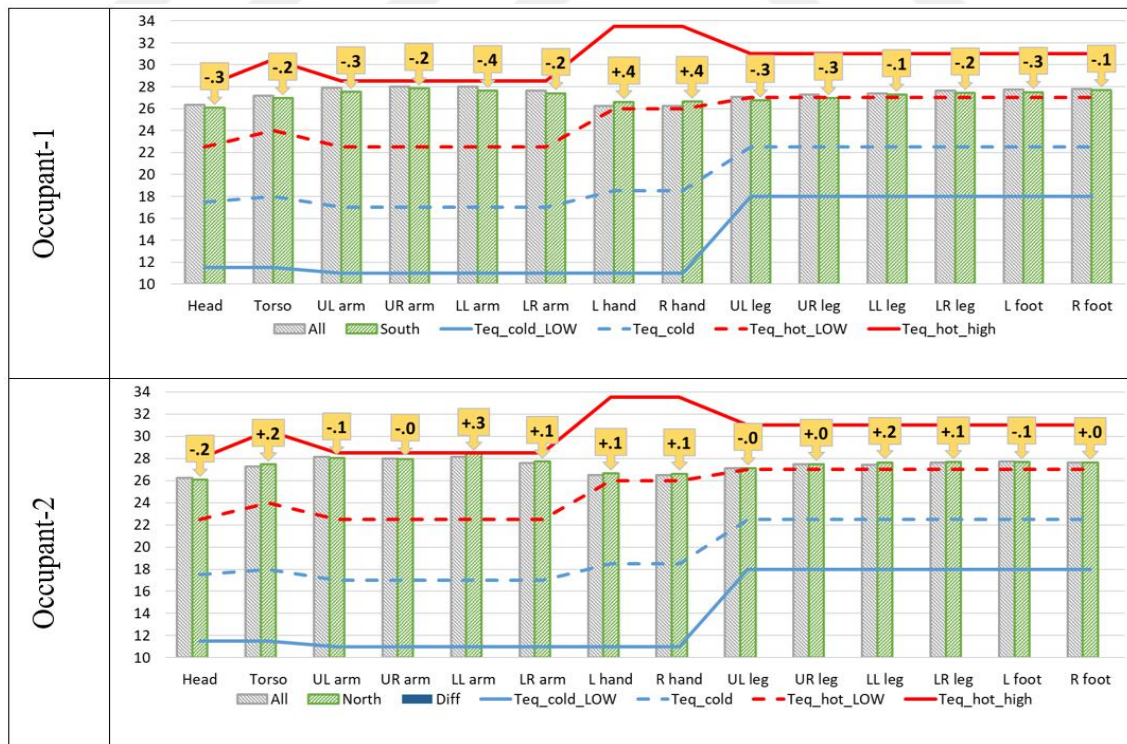


Figure 61: Comparison of comfort levels of conventional (grey) and localized (green) conditioning (Controller Set Level is 4 for conventional system and 3 for localized conditioning).

An important concern to assess the energy saving potential of an AVS is the time intervals in which occupancy states or the occupant preferences make its use reasonable for localized conditioning. When the occupants are positioned homogenously in a room and if all of them demand for change in thermal conditions, AVS will work as like conventional systems. On the other hand, if the occupants located at a certain part of the room and not demanding any extra heating or if they are absent, AVS can prevent direct heating of these parts of a room. Even if these parts will be heated (or cooled) indirectly with the secondary air flows and heat diffusion, AVS can make HVAC machinery to work in lower control levels.

Referring to Figure 60, one can calculate the potential energy savings with AVS by assuming the total time in which the localization mode is active. As an example, in a typical working day scenario in the winter time, if the localization-mode makes the HVAC machinery to work in the third level instead of the fourth level for 2 hours and to work in second level instead of third one for 1 hours, it can save 3.33 kWh during the day:

$$(6.8 \text{ kW} * 18\% * 2h) + (6.8 \text{ kW} * 13\% * 1h) = 3.33 \text{ kWh}$$

Moreover, if the designers of a building have occupancy estimations for a room in the design stage and agree on the deployment of localization for most of the time, they can decide on the installing HVAC machinery with the lower capacity to have cost and energy savings.

6. DISCUSSIONS

Existing HVAC system systems are designed and operated for providing inflexible thermal conditions (see Section 2.2). Nevertheless, due to the variations in surrounding environment, it is not always possible. The typical cases like opening a door or sun radiation exposure from a window would result in local differences in thermal conditions of a room. Furthermore, even the environmental conditions are stable, thermal sensation and preferences of the occupants may change due to variety of physiological and psychological factor. Nevertheless, the existing systems are designed to serve symmetrically to each part of the room. They cannot response to variety of expectations. On the other hand, recent developments in cyber technologies enable a better interactivity between people and digitally controlled physical instruments. The energy systems in modern buildings are a proper field to investigate the applications of this emerging field. If can be achieved effectively, this may result in both higher occupant comfort and less environmental impact. The AVS presented in this study is an attempt to reach this target.

Combining physical, technological and behavioral concerns, the AVS is intended to facilitate a better user engagement that result in energy (and monetary) savings. The key driver for this engagement is the adaptability of the proposed system. It is designed to provide localization by manipulating the indoor airflow by means of OFDs. The conventional ATUs delivers symmetric airflow to indoor environments. The only adaptation that can be achieved with them is the change of air flow rate, that is a function of HVAC machinery. However, such an action results in the change of thermal conditions of whole zone that would result in conflict among occupants. On the other, having individually operable flaps, AVS can be operated in a way that minimize these conflicts. The analysis presented in Section 5.2 for the test room shows that blowing air towards the selected region of a room result in a controllable change of the thermal conditions

without affecting the that of other regions significantly. Figure 55 shows this by comparing the conventional operation (all flaps were open) with blowing towards north and south. Furthermore, Figure 56 to Figure 58 show how flow in a direction can be controlled with flap angle, inlet air velocity (or MFR) and inlet air temperature, respectively. Hence, OFDs can provide the adaptability of personalized ventilation systems (Section 4.1) at a certain level without installing extra ducts and limiting indoor space usage. It is important to note that the air temperature difference created around the manikins is not a direct performance metric for the operation of AVS. It is intended to minimize the total conditioned (heated or cooled) air volume by decreasing the amount of air used for conditioning unnecessary parts (sub-regions that are empty or occupants are not asking for a change in thermal conditions).

Beside adaptability of the physical environment, the localized and customized conditioning of an indoor space requires an enhanced interactivity between system control unit and occupants, that is another driver for engagement. The UI of AVS provides personal monitoring and control screens to occupants (Figure 23 and Figure 24). Occupant can monitor temperature close to him/her for pre-determined time intervals (20 minutes in prototype). This is a valuable information for supporting decision making on control actions. Occupants can observe the result of actions they performed certain time ago. This kind of time dependent information (instead of instantaneous information provided by conventional systems) can help them to have a better knowledge of thermal properties of their close environment. Thus, these functionalities can also enhance the level of perceived control over the HVAC operations, that would result in better thermal sensation and productivity of occupants. Having a better understanding of system operation and thermal response of their surroundings, occupants can also identify energy saving opportunities. Beside direct energy savings, the enhanced interactivity between

occupants and the HVAC system can also augment demand flexibility (especially for cooling loads) which would result in advantages for reducing peak loads.

The functions explained above are nothing but new practices for occupants (see review of SPT in Section 2.3.1). The personalized interface provided by UI of AVS leverage perceptions and interpretation capabilities of occupants regarding to energy usage and potential savings. Moreover, additional capabilities of UI that make occupant preferences and control actions visible to other occupants (the virtual ‘doings’ and ‘sayings’) would constitute a collective approach. From the TIB perspective, supporting the ‘evaluation of outcomes’ with proper UI design can leverage attitudes and intention for energy saving behaviors. Moreover, a system that can minimize energy consumption in unoccupied regions can be considered as a ‘facilitating condition’ for behavior change. The usefulness of the system highly depends on UI design and crucial for its acceptability by the users.

The enabler and the cost of increasing interactivity between occupant and the AVS is the enhanced cyber infrastructure. Providing localized and customized thermal environments requires deployment of higher number and more kind of sensors for reliable system operation. Even the increasing demand makes temperature and humidity sensors available with reasonable prices, it is still an economical and a technical challenge to deploy higher number of sensors in built environment. Taking advantage of wireless communication may decrease installation costs but additional load on network and IT workload is a non-negligible cost. However, emerging technologies such as low power sensor (including wearables) and communication technologies (BLE, 5g, among others) would make this infrastructure economically feasible.

Another important challenge for the system administration of AVS would be the software maintenance. The emerging edge, fog and cloud technologies offer effective fleet

management tools for sensor networks and the connected actuators but their deployment on building infrastructure is not secure and cost effective enough, as of today. On the other hand, building operations require reliable control approaches for convenience and security concerns. MPC is one of them and is proper for AVS. ANN based MPC for HVAC control is a well-studied approach in literature [81]. However, its deployment in complex systems such as AVS for the daily operation requires large datasets that are difficult to establish.

Building systems are subject to environmental, technical and social factors during their operation. Thus, design and operation of them require careful consideration of factors from variety of disciplines and their interactions. Such a variety in influencing factors and the intense interaction among them make buildings and their systems complex structures. On the other hand, CPSS approach offers an effective conceptualization for the design and development of digitally controlled physical systems that are subject to high human interactivity. As explained in Section 3.1, the AVS is designed to be CPSBES. It establishes a cyber-infrastructure that links occupants with a novel physical experience. Hence, it is a challenge to model and understand system characteristics. However, the methodological framework and the modelling methodology presented in Chapter 3 and the implementation in Chapter 4 show that coupling hybrid dynamic modeling with human behavior modeling is a proper strategy for simulating dynamics of CPSBESs. It can help to link the human behavior with environmental impacts by enabling comprehensive investigation of complete system dynamics. This would pave the way for designers to innovate behavior-driven solutions.

The proposed modeling approach can provide deeper insights related to the system operation as well. Especially having a model-based understanding of mode transitions is

valuable due to the instability issues during this period. Unless being focused on a specific topic, conventional modeling approaches neglect this requirement and perform analysis only for a specific operation mode. The mode switch of an HVAC system is a good example of this shortcoming. In a regular operation of a HVAC system, the thermal response of an indoor environment can be predicted with proper formulation. Nevertheless, for a time interval after the mode change (changing inlet air velocity or temperature), it turns out to be challenging to predict it. Hence, having an approach to deal with this challenge from the very beginning is important.



7. CONCLUSIONS AND FUTURE WORKS

Developing a complex system is a challenging task since it requires involvement of variety of expertise, as well as the consensus of actors from different realms. Accordingly, impactful studies on building energy systems are seen to be either interdisciplinary or transdisciplinary. In most cases, a technical innovation (whether domain specific or multidisciplinary) is initially assessed in terms of its impact on energy efficiency and environmental sustainability. In case of successful outcomes, its individual and society level acceptance is questioned by using methods from social and economic sciences. Furthermore, legislations and incentives have a crucial role in market penetration of these systems. Since all these constitute a long, complicated and expensive procedure, researchers and developers are expected to follow rigid research strategies from the very beginning. On the other hand, advances in information technologies not only accelerate this process, but also make it continuous. Modern products and services are subject to continuous development from their early market penetration to the end of their life. Hence, the interaction among the distinct domains has to be identified at the very beginning and developed during the lifespan.

This study presents a complex HVAC ‘interface’, a novel adaptive vent system, that enables localized and customized thermal conditioning in buildings. Moreover, it is designed to be a CPSBES. The cyber components of the system are TA, CCU and UI. It involves an OFD as the physical component that is responsible of manipulating indoor airflow. The social dimension of the system is the (i) high adaptability of the system to occupant preferences and (ii) increased interactivity between HVAC system and the occupants as well as between the occupants. The system level modeling and comprehensive CFD analysis of the system is provided that characterizes system operation and presents its practical limitations. On the other hand, a methodological

framework based on novel CPSS modeling approach is presented. The modeling approach engages hybrid dynamical modeling with the behavior modeling in order to reflect three distinct realms on the system model for effective system identification. Thus, the proposed framework enables interdisciplinary studies on BES. The energy efficiency potential of the system is identified in terms of reduced volume of conditioned air. Furthermore, the AVS offers functionalities to leverage occupant interaction that can augment occupants' overall experience (beyond the physiological comfort) regarding to thermal management.

The future work on the AVS will involve three major focus areas: (i) developing a control unit for autonomous operation, (ii) conducting the performance analysis of the system in cooling mode, (iii) deploying the AVS to real-life environments. Each of these topics are explained below.

The AVS has a complex operation scheme. Currently, the flap configurations and HVAC machinery are directly controlled via UI for experiments and daily use in test room. Such a practice is not effective for real-life deployments. Hence, additional automatic control functionalities are necessary to realize systems' thermal experience and energy efficiency potential. At this point, predictive control approaches (see Section 2.1.4) offer effective control strategies. Based on the modeling approach presented in Section 3.3, a MPC based control unit for AVS can manage the temperature distribution inside the room by predicting its evaluation over a prediction horizon (typically 20-30 minutes for HVAC control). Moreover, the system can follow and predict the occupancy states of the sub-regions within the room to eliminate unnecessary conditioning. Thus, a MPC based control strategy will be developed for the effective and practical operation of AVS.

The current investigation of the AVS was conducted in heating mode (winter time). Accordingly, a stream of hot air enters to a medium that involves relatively colder air. In such a situation, hot air moves close to the ceiling for a distance due to buoyancy difference. On the other, in the cooling mode, cold air has higher density and air stream “drops” in a shorter distance. In other words, the airflow regime for the cooling mode has different characteristics. Hence, starting with experiments in test room in summer time, the CFD analysis presented in Chapter 5 will be repeated for cooling mode. The experimental setup in test room and the analysis tools presented here are capable of assessing the cooling mode performance of AVS. Only the empirical formulas used in Section 5.2.1 and 5.2.2 will be changed with the ones for cooling mode.

The deployment of AVS to real life environments will enable performance assessment of system for different perspectives. Initially, it will be possible to evaluate localization and customization capability and the energy savings potential of the system out of the test room. However, more importantly, it will enable the creation of a dataset to observe occupant interaction with the system. The design and development process of the AVS was included behavioral concerns to augment occupants thermal experience. However, for the objective evaluation of system performance in terms of thermal experience, it is essential to monitor occupant’s interaction with UI and quantitatively analyze it. Only such a data set can help to identify how occupants behave when the advance control options offered by AVS are delivered.

REFERENCES

- [1] “Historical Global Temperature Data by NASA” [Online]. Available: <https://climate.nasa.gov/vital-signs/global-temperature/>. [Accessed: 30-Jul-2019].
- [2] *WASTEWATER: The Untapped Resource*, 2017, The United Nations World Water Development Report Paris.
- [3] “What Is the Paris Agreement? |UNFCCC” [Online]. Available: <https://unfccc.int/process-and-meetings/the-paris-agreement/what-is-the-paris-agreement>. [Accessed: 02-Aug-2019].
- [4] *International Energy Agency Market Report Series: Energy Efficiency*, 2018.
- [5] 2016, *World Energy Council World Energy Perspectives: Energy Efficiency Policies*, London.
- [6] Kang, J. E., Ahn, K. U., Park, C. S., and Schuetze, T., 2015, “Assessment of Passive vs. Active Strategies for a School Building Design,” *Sustain.*, **7**(11), pp. 15136–15151.
- [7] “Passive Building Design - Designing Buildings Wiki” [Online]. Available: https://www.designingbuildings.co.uk/wiki/Passive_building_design. [Accessed: 14-Aug-2019].
- [8] “Design: Passive vs Active - Simplicable” [Online]. Available: <https://simplicable.com/new/passive-design-vs-active-design>. [Accessed: 14-Aug-2019].
- [9] Mardiana, A., and Riffat, S. B., 2015, “Building Energy Consumption and Carbon Dioxide Emissions: Threat to Climate Change,” *J. Earth Sci. Clim. Change*, **S3:001**, pp. 1–3.
- [10] Pérez-Lombard, L., Ortiz, J., and Pout, C., 2008, “A Review on Buildings Energy Consumption Information,” *Energy Build.*, **40**(3), pp. 394–398.
- [11] Woo, Y.-E., and Cho, G.-H., 2018, “Impact of the Surrounding Built Environment on Energy Consumption in Mixed-Use Building,” *Sustainability*, **10**, p. 832.
- [12] De Silva, M. N. K., and Sandanayake, Y. G., 2012, “Building Energy Consumption Factors: A Literature Review and Future Research Agenda,” *World Construction Conference 2012-Global Challenges in Construction Industry*, 28-30 June 2012, Sri Lanka.
- [13] Vakiloroya, V., Samali, B., Fakhar, A., and Pishghadam, K., 2014, “A Review of Different Strategies for HVAC Energy Saving,” *Energy Convers. Manag.*, **77**, pp. 738–754.
- [14] Mathews, E. H., Botha, C. P., Arndt, D. C., and Malan, A., 2001, “HVAC Control Strategies to Enhance Comfort and Minimise Energy Usage,” *Energy Build.*, **33**, pp. 853–863.
- [15] Kilkis, İ. B., 1999, “Utilization of Wind Energy in Space Heating and Cooling with Hybrid HVAC Systems and Heat Pumps,” *Energy Build.*, (30), pp. 147–153.
- [16] Chahine, K., Murr, R., Ramadan, M., Hage, H. El, and Khaled, M., 2018, “Use of Parabolic Troughs in HVAC Applications - Design Calculations and Analysis,” *Case Stud. Therm. Eng.*, **12**, pp. 285–291.
- [17] Romani, J., Pérez, G., and de Gracia, A., 2016, “Experimental Evaluation of a Cooling Radiant Wall Coupled to a Ground Heat Exchanger,” *Energy Build.*, **129**, pp. 484–490.
- [18] Yang, L., Liu, X., Qian, F., and Du, S., 2019, “Ventilation Effect on Different Position of

- Classrooms in ‘Line’ Type Teaching Building,” *J. Clean. Prod.*, **209**, pp. 886–902.
- [19] Sheth, A., 2010, “Physical-Cyber-Social Computing: An Early 21st Century Approach to Computing for Human Experience,” *IEEE Internet Comput.*, **14**(1), pp. 88–91.
 - [20] De, S., Zhou, Y., Larizgoitia Abad, I., and Moessner, K., 2017, “Cyber–Physical–Social Frameworks for Urban Big Data Systems: A Survey,” *Appl. Sci.*, **7**(10), p. 1017.
 - [21] Zeng, J., Yang, L. T., Lin, M., Ning, H., and Ma, J., 2020, “A Survey: Cyber-Physical-Social Systems and Their System-Level Design Methodology,” *Futur. Gener. Comput. Syst.*, **105**, pp. 1028–10422.
 - [22] Smirnov, A., Levashova, T., Shilov, N., and Sandkuhl, K., 2014, “Ontology for Cyber-Physical-Social Systems Self- Organisation,” *Proceeding Of The 16th Conference Of Fruct Association*, Oulu.
 - [23] Stamatescu, G., Stamatescu, I., Arghira, N., Calofir, V., and Fagarasan, I., 2016, “Building Cyber-Physical Energy Systems.”
 - [24] Jang, W. S., and Healy, W. M., 2010, “Wireless Sensor Network Performance Metrics for Building Applications,” *Energy Build.*, **42**(6), pp. 862–868.
 - [25] Dong, B., Prakash, V., Feng, F., and O’Neill, Z., 2019, “A Review of Smart Building Sensing System for Better Indoor Environment Control,” *Energy Build.*, **199**, pp. 29–46.
 - [26] O’ Donovan, A., O’ Sullivan, P. D., and Murphy, M. D., 2019, “Predicting Air Temperatures in a Naturally Ventilated Nearly Zero Energy Building: Calibration, Validation, Analysis and Approaches,” *Appl. Energy*, **250**, pp. 991–1010.
 - [27] Mylonas, A., Kazanci, O. B., Andersen, R. K., and Olesen, B. W., 2019, “Capabilities and Limitations of Wireless CO₂, Temperature and Relative Humidity Sensors,” *Build. Environ.*, **154**, pp. 362–374.
 - [28] Yoganathan, D., Kondepudi, S., Kalluri, B., and Manthapuri, S., 2018, “Optimal Sensor Placement Strategy for Office Buildings Using Clustering Algorithms,” *Energy Build.*, **158**, pp. 1206–1225.
 - [29] Pei, G., Rim, D., Schiavon, S., and Vannucci, M., “Effect of Sensor Position on the Performance of CO₂-Based Demand Controlled Ventilation,” *Energy Build.*, **In Press**.
 - [30] Wu, Z., Li, N., Wargocki, P., Peng, J., Li, J., and Cui, H., 2019, “Field Study on Thermal Comfort and Energy Saving Potential in 11 Split Air-Conditioned Office Buildings in Changsha, China,” *Energy*, **182**, pp. 471–482.
 - [31] Sayadi, S., Tsatsaronis, G., Morosuk, T., Baranski, M., Sangi, R., and Müller, D., 2019, “Exergy-Based Control Strategies for the Efficient Operation of Building Energy Systems,” *J. Clean. Prod.*, **241**, p. 118277.
 - [32] Ławryńczuk, M., and Ocłoń, P., 2019, “Model Predictive Control and Energy Optimisation in Residential Building with Electric Underfloor Heating System,” *Energy*, **182**, pp. 1028–1044.
 - [33] Wang, L., Li, H., Zou, X., and Shen, X., 2015, “Lighting System Design Based on a Sensor Network for Energy Savings in Large Industrial Buildings,” *Energy Build.*, **105**, pp. 226–235.
 - [34] Al-Masrani, S. M., and Al-Obaidi, K. M., 2019, “Dynamic Shading Systems: A Review of Design Parameters, Platforms and Evaluation Strategies,” *Autom. Constr.*, **102**, pp. 195–216.
 - [35] Ahmad, J., Larijani, H., Emmanuel, R., Mannion, M., and Javed, A., “Occupancy

Detection in Non-Residential Buildings – A Survey and Novel Privacy Preserved Occupancy Monitoring Solution,” *Appl. Comput. Informatics*, **In Press**.

- [36] Wang, Y., and Shao, L., 2017, “Understanding Occupancy Pattern and Improving Building Energy Efficiency through Wi-Fi Based Indoor Positioning,” *Build. Environ.*, **114**, pp. 106–117.
- [37] Naylor, S., Gillott, M., and Lau, T., 2018, “A Review of Occupant-Centric Building Control Strategies to Reduce Building Energy Use,” *Renew. Sustain. Energy Rev.*, **96**, pp. 1–10.
- [38] Labeodan, T., De Bakker, C., Rosemann, A., and Zeiler, W., 2016, “On the Application of Wireless Sensors and Actuators Network in Existing Buildings for Occupancy Detection and Occupancy-Driven Lighting Control,” *Energy Build.*, **127**, pp. 75–83.
- [39] Ouf, M. M., O’Brien, W., and Gunay, B., 2019, “On Quantifying Building Performance Adaptability to Variable Occupancy,” *Build. Environ.*, **155**, pp. 257–267.
- [40] Liu, S., Schiavon, S., Das, H. P., Jin, M., and Spanos, C. J., 2019, “Personal Thermal Comfort Models with Wearable Sensors,” *Build. Environ.*, **162**(106281), pp. 1–17.
- [41] Peng, W., Su, D., and Higginson, M., 2019, “A Novel Remote Control System for Air Conditioning in Low Carbon Emission Buildings Using Sensor Fusion and Mobile Communication Technologies,” *Build. Environ.*, **148**, pp. 701–713.
- [42] Hong, T., and Lee, S. H., 2019, “Integrating Physics-Based Models with Sensor Data: An Inverse Modeling Approach,” *Build. Environ.*, **154**(January), pp. 23–31.
- [43] Bittencourt, L., Immich, R., Sakellariou, R., Fonseca, N., Madeira, E., Curado, M., Villas, L., DaSilva, L., Lee, C., and Rana, O., 2018, “The Internet of Things, Fog and Cloud Continuum: Integration and Challenges,” *Internet of Things*, **3–4**, pp. 134–155.
- [44] Yassine, A., Singh, S., Hossain, M. S., and Muhammad, G., 2019, “IoT Big Data Analytics for Smart Homes with Fog and Cloud Computing,” *Futur. Gener. Comput. Syst.*, **91**, pp. 563–573.
- [45] Marozzo, F., and Trunfio, P., 2019, “Infrastructures for High-Performance Computing: Cloud Computing,” *Encycl. Bioinforma. Comput. Biol.*, **1**, pp. 247–251.
- [46] Liu, Q., Wang, G., Liu, X., Peng, T., and Wu, J., 2017, “Achieving Reliable and Secure Services in Cloud Computing Environments,” *Comput. Electr. Eng.*, **59**, pp. 153–164.
- [47] Chauhan, S. S., Pilli, E. S., Joshi, R. C., Singh, G., and Govil, M. C., 2019, “Brokering in Interconnected Cloud Computing Environments: A Survey,” *J. Parallel Distrib. Comput.*, **133**, pp. 193–209.
- [48] Subramanian, N., and Jeyaraj, A., 2018, “Recent Security Challenges in Cloud Computing,” *Comput. Electr. Eng.*, **71**, pp. 28–42.
- [49] Rong, H., Zhang, H., Xiao, S., Li, C., and Hu, C., 2016, “Optimizing Energy Consumption for Data Centers,” *Renew. Sustain. Energy Rev.*, **58**, pp. 674–691.
- [50] Alavi, A. H., and Buttlar, W. G., 2019, “An Overview of Smartphone Technology for Citizen-Centered, Real-Time and Scalable Civil Infrastructure Monitoring,” *Futur. Gener. Comput. Syst.*, **93**, pp. 651–672.
- [51] Yousefpour, A., Fung, C., Nguyen, T., Kadiyala, K., Jalali, F., Niakanlahiji, A., Kong, J., and Jue, J. P., 2019, “All One Needs to Know about Fog Computing and Related Edge Computing Paradigms: A Complete Survey,” *J. Syst. Archit.*, **98**, pp. 289–330.
- [52] Khan, W. Z., Ahmed, E., Hakak, S., Yaqoob, I., and Ahmed, A., 2019, “Edge Computing:

- A Survey,” *Futur. Gener. Comput. Syst.*, **97**, pp. 219–235.
- [53] Hao, F., Park, D. S., Kang, J., and Min, G., 2019, “2L-MC3: A Two-Layer Multi-Community-Cloud/Cloudlet Social Collaborative Paradigm for Mobile Edge Computing,” *IEEE Internet Things J.*, **6**(3), pp. 4764–4773.
 - [54] Lopez, P. G., Montresor, A., Epema, D., Datta, A., Higashino, T., Iamnitchi, A., Barcellos, M., Felber, P., and Riviere, E., 2015, “Edge-Centric Computing: Vision and Challenges,” *ACM SIGCOMM Comput. Commun. Rev.*, **45**(5), pp. 37–42.
 - [55] “Edge Computing and IoT - When Intelligence Moves to the Edge” [Online]. Available: <https://www.i-scoop.eu/internet-of-things-guide/edge-computing-iot/>. [Accessed: 22-Sep-2019].
 - [56] Zhan, Y., Xia, Y., and Vasilakos, A. V., 2019, “Future Directions of Networked Control Systems: A Combination of Cloud Control and Fog Control Approach,” *Comput. Networks*, **161**, pp. 235–248.
 - [57] “Optimize IoT Performance by Optimizing the IoT Edge” [Online]. Available: <https://www.embedded-computing.com/embedded-computing-design/optimize-iot-performance-by-optimizing-the-iot-edge>. [Accessed: 22-Sep-2019].
 - [58] Samie, F., Tsoutsouras, V., Masouros, D., Bauer, L., Soudris, D., and Henkel, J., 2019, “Fast Operation Mode Selection for Highly Efficient IoT Edge Devices,” *IEEE Trans. Comput. Des. Integr. Circuits Syst.*, pp. 1–13.
 - [59] An, K., Pradhan, S., Caglar, F., Patil, P., Shekhar, S., and Gokhale, A., “Cloud Computing for Cyber Physical Systems: Reliability and Security Challenges and Solutions” [Online]. Available: http://www.dre.vanderbilt.edu/~gokhale/WWW/papers/CC4CPS13_FT.pdf.
 - [60] Gill, S. S., Garraghan, P., and Buyya, R., 2019, “Fog Enabled Cloud Based Intelligent Resource Management Approach for Smart Home IoT Devices,” *J. Syst. Softw.*, **154**, pp. 125–138.
 - [61] Li, C., Sun, H., Tang, H., and Luo, Y., 2019, “Adaptive Resource Allocation Based on the Billing Granularity in Edge-Cloud Architecture,” *Comput. Commun.*, **145**, pp. 29–42.
 - [62] Forcan, M., and Maksimović, M., 2019, “Cloud-Fog-Based Approach for Smart Grid Monitoring,” *Simul. Model. Pract. Theory*, **101**(101988).
 - [63] Yaqoob, I., Hashem, I. A. T., Mehmood, Y., Gani, A., Mokhtar, S., and Guizani, S., 2017, “Enabling Communication Technologies for Smart Cities,” *IEEE Commun. Mag.*, **55**(1), pp. 112–120.
 - [64] “Wi-Fi Alliance” [Online]. Available: <https://wi-fi.org/>. [Accessed: 25-Sep-2019].
 - [65] Han, D., Jung, S. hoon, and Lee, S., 2016, “A Sensor Fusion Method for Wi-Fi-Based Indoor Positioning,” *ICT Express*, **2**, pp. 71–74.
 - [66] Wang, J., Tse, N. C. F., and Chan, J. Y. C., 2019, “Wi-Fi Based Occupancy Detection in a Complex Indoor Space under Discontinuous Wireless Communication: A Robust Filtering Based on Event-Triggered Updating,” *Build. Environ.*, **151**, pp. 228–239.
 - [67] “IEEE 802.15.1-2002 - IEEE Standard for Telecommunications and Information Exchange Between Systems - LAN/MAN - Specific Requirements - Part 15: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Wireless Personal Area Networks (WPANs)” [Online]. Available: https://standards.ieee.org/standard/802_15_1-2002.html. [Accessed: 27-Sep-2019].
 - [68] Raza, S., Misra, P., He, Z., and Voigt, T., 2017, “Building the Internet of Things with Bluetooth Smart,” *Ad Hoc Networks*, **57**, pp. 19–31.

- [69] Oosterlinck, D., Benoit, D. F., Baecke, P., and Van de Weghe, N., 2017, "Bluetooth Tracking of Humans in an Indoor Environment: An Application to Shopping Mall Visits," *Appl. Geogr.*, **78**, pp. 55–65.
- [70] "Zigbee 3.0 | Zigbee Alliance" [Online]. Available: <https://zigbee.org/zigbee-for-developers/zigbee-3-0/>. [Accessed: 27-Sep-2019].
- [71] Ghayvat, H., Mukhopadhyay, S. C., and Gui, X., 2016, "Issues and Mitigation of Interference, Attenuation and Direction of Arrival in IEEE 802.15.4/ZigBee to Wireless Sensors and Networks Based Smart Building," *Meas. J. Int. Meas. Confed.*, **86**, pp. 209–226.
- [72] Takacs, B., 2016, "Synthesis And Implementation Of Model Predictive Control," Slovak University Of Technology In Bratislava.
- [73] Raemaekers, A. J. M., 2007, "Design of a Model Predictive Controller to Control UAVs."
- [74] Chen, X., Wang, Q., and Srebric, J., 2015, "Model Predictive Control for Indoor Thermal Comfort and Energy Optimization Using Occupant Feedback," *Energy Build.*, **102**, pp. 357–369.
- [75] Killian, M., and Kozek, M., 2018, "Implementation of Cooperative Fuzzy Model Predictive Control for an Energy-Efficient Office Building," *Energy Build.*, **158**, pp. 1404–1416.
- [76] Preglej, A., Rehrl, J., Schwingshackl, D., Steiner, I., Horn, M., and Škrjanc, I., 2014, "Energy-Efficient Fuzzy Model-Based Multivariable Predictive Control of a HVAC System," *Energy Build.*, **82**, pp. 520–533.
- [77] Oldewurtel, F., Gyalistras, D., Gwerder, M., Jones, C. N., Stauch, V., Lehmann, B., Morari, M., and Division, B. T., 2012, "Use of Model Predictive Control and Weather Forecasts for Energy Efficient Building Climate Control," *Energy Build.*, **45**, pp. 15–27.
- [78] Drogna, J., Kvasnica, M., Klauco, M., and Fikar, M., 2013, "Explicit Stochastic MPC Approach to Building Temperature Control," *52nd IEEE Conference on Decision and Control*, Florence.
- [79] Tanaskovic, M., Sturzenegger, D., Smith, R., and Morari, M., 2017, "Robust Adaptive Model Predictive Building Climate Control," *IFAC-PapersOnLine*, **50**(1), pp. 1871–1876.
- [80] He, R., and Gonzalez, H., 2017, "Comfort-Aware Building Climate Control Using Distributed-Parameter Models," *arXiv:1708.08495v1*.
- [81] Afram, A., Janabi-Sharifi, F., Fung, A. S., and Raahemifar, K., 2017, "Artificial Neural Network (ANN) Based Model Predictive Control (MPC) and Optimization of HVAC Systems: A State of the Art Review and Case Study of a Residential HVAC System," *Energy Build.*, **141**(February), pp. 96–113.
- [82] Amai, H., and Novoselac, A., 2016, "Experimental Study on Air Change Effectiveness in Mixing Ventilation," *Build. Environ.*, **109**, pp. 101–111.
- [83] Loomans, M. G. L. C., 1998, "The Measurement and Simulation of Indoor Air Flow," Technische Universiteit Eindhoven.
- [84] Ahmed, A. Q., 2017, "Modelling Thermal Comfort and Energy Saving Enhancements in an Office Room Served by Stratified Air Distribution Systems," University of Leicester Engineering Department.
- [85] Tham, K. W., and Pantelic, J., 2010, "Performance Evaluation of the Coupling of a Desktop Personalized Ventilation Air Terminal Device and Desk Mounted Fans," *Build. Environ.*, **45**(9), pp. 1941–1950.

- [86] Srebric, J., and Chen, Q., 2002, "Simplified Numerical Models for Complex Air Supply Diffusers," HVAC&R Res., **8**(3), pp. 277–294.
- [87] Tripathi, B., and Moulic, S. G., 2012, "Investigation of Air Drafting Pattern Obtained from the Variation in Outlet Positions inside a Closed Area," J. Appl. Fluid Mech., **5**(4), pp. 1–12.
- [88] Nielsen, P. V., 2007, "Analysis and Design of Room Air Distribution Systems," HVAC R Res., **13**(6), pp. 987–997.
- [89] Zou, Y., 2001, *Air Jets in Ventilation Applications*, Stockholm.
- [90] Andersen, K. K., Madsen, H., and Hansen, L. H., 2000, "Modelling the Heat Dynamics of a Building Using Stochastic Differential Equations," Energy Build., **31**, pp. 13–24.
- [91] Sørensen, D. N., and Voigt, L. K., 2003, "Modelling Flow and Heat Transfer around a Seated Human Body by Computational Fluid Dynamics," Build. Environ., **38**, pp. 753–762.
- [92] Stamou, A., and Katsiris, I., 2006, "Verification of a CFD Model for Indoor Airflow and Heat Transfer," Build. Environ., **41**(9), pp. 1171–1181.
- [93] Heng, J., and Li, Y., 2002, "Study of Indoor Air Quality Air Flow Pattern in a Room With Floor Heating," pp. 278–283.
- [94] Stavridou, A. D., and Prinos, P. E., 2017, "Unsteady CFD Simulation in a Naturally Ventilated Room with a Localized Heat Source," Procedia Environ. Sci., **38**, pp. 322–330.
- [95] Chow, W. K., and Fung, W. Y., 1996, "Numerical Studies on the Indoor Air Flow in the Occupied Zone of Ventilated and Air-Conditioned Space," Build. Environ., **31**(4), pp. 319–344.
- [96] Heist, D. K., Eisner, A. D., Mitchell, W., and Wiener, R., 2003, "Airflow around a Child-Size Manikin in a Low-Speed Wind Environment," Aerosol Sci. Technol., **37**(4), pp. 303–314.
- [97] Awbi, H. B., 2008, *Ventilation Systems: Design and Performance*, Taylor & Francis, New York.
- [98] 2009, *ASHRAE Handbook: Fundamentals*, ASHRAE, Inc., Atlanta, GA 30329.
- [99] Awbi, H. B., 1998, "Chapter 7: Ventilation," *Architecture: Comfort and Energy*, C. Gallo, M. Sala, and S. A.M.M., eds., Elsevier, Oxford.
- [100] Huo, Y., Haghighat, F., Zhang, J. S., and Shaw, C. Y., 2000, "A Systematic Approach to Describe the Air Terminal Device in CFD Simulation for Room Air Distribution Analysis," Build. Environ., **35**(6), pp. 563–576.
- [101] Burum, S., 2004, *American Cinematographer Manual*, ASC Press.
- [102] Rajaratnam, N., 1976, *Turbulent Jets*, Elsevier, Amsterdam.
- [103] Awbi, H., 2005, *Ventilation of Buildings*, Taylor & Francis, New York.
- [104] Albright, L. D., and Scottf, ; N R, 1974, "The Low-Speed Non-Isothermal Wall Jet," J. agric. Engng Res, **19**, pp. 25–34.
- [105] Katić, K., Li, R., and Zeiler, W., 2016, "Thermophysiological Models and Their Applications: A Review," Build. Environ., **106**, pp. 286–300.
- [106] Tredgold, T., 1929, *The Principles Ow Warming and Ventilating Public Buildings*, London.

- [107] Fiala, D., Psikuta, A., Jendritzky, G., Paulke, S., Nelson, D., Lichtenbelt, W. D. van M., and Frijns, A., 2010, "Physiological Modeling for Technical, Clinical and Research Applications," *Front. Biosci.*, (June 1), pp. 939–968.
- [108] Stolwijk, J. A. J., and Hardy, J. D., 1966, *Temperature Regulation in Man - A Theoretical Study*, STew Haven, Connecticut.
- [109] Stolwijk, J. A. J., 1971, *A Mathematical Model of Physiological Temperature Regulation*, Washington, DC.
- [110] Enescu, D., 2019, "Models and Indicators to Assess Thermal Sensation under Steady-State and Transient Conditions," *Energies*, **12**(5).
- [111] Van Hoof, J., 2008, "Forty Years of Fanger's Model of Thermal Comfort: Comfort for All?," *Indoor Air*, **18**(3), pp. 182–201.
- [112] Knoblauch, G., *Modeling Human Thermoregulation and Comfort*, CES Seminar.
- [113] "User Guide of Star-CCM Thermal Comfort Wizard."
- [114] Wyndham, C. H., and Atkins, A. R., 1968, "A Physiological Scheme and Mathematical Model of Temperature Regulation in Man," *Pflügers Arch. Eur. J. Physiol.*, **303**(1), pp. 14–30.
- [115] 2010, *ANSI/ASHRAE Standard 55-2010: Thermal Environmental Conditions for Human Occupancy*, Atlanta, GA 30329.
- [116] 2005, "ISO Standard 7730:2005(E) Ergonomics of the Thermal Environment — Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria."
- [117] Zapka, M. J., Tran, T., Arch, D., Maskrey, A. J., Meder, S., and Peppard, E., 2015, *Generic CFD Workflow For Comfort Assessment*, Manoa.
- [118] Toftum, J., 2002, "Human Response to Combined Indoor Environment Exposures," *Energy Build.*, **34**, pp. 601–606.
- [119] Junior, C., and Dingel, O., 2019, *Energy and Thermal Management, Air-Conditioning, and Waste Heat Utilization*, Springer Nature Switzerland, Cham.
- [120] Vincent, P. B., 2018, "CFD Modeling for Thermal Comfort in an Open Workspace," *IBPSA Canada ESim 2018*, Montreal.
- [121] International Standard, 1995, *ISO-10551:1995(E) Ergonomics of the Thermal Environment: Assessment of the Influence of the Thermal Environment Using Subjective Judgement Scales*, Geneve.
- [122] Foda, E., Almesri, I., Awbi, H. B., and Sirén, K., 2011, "Models of Human Thermoregulation and the Prediction of Local and Overall Thermal Sensations," *Build. Environ.*, **46**(10), pp. 2023–2032.
- [123] Zhang, H., Arens, E., Huizenga, C., and Han, T., 2010, "Thermal Sensation and Comfort Models for Non-Uniform and Transient Environments, Part II: Local Comfort of Individual Body Parts," *Build. Environ.*, **45**(2), pp. 389–398.
- [124] Zou, P. X. W., Xu, X., Sanjayan, J., and Wang, J., 2018, "A Mixed Methods Design for Building Occupants' Energy Behavior Research," *Energy Build.*, **166**, pp. 239–249.
- [125] Keskin, C., and Mengüç, M. P., 2018, "On Occupant Behavior and Innovation Studies towards High Performance Buildings: A Transdisciplinary Approach," *Sustainability*, **10**(10), p. 3657.

- [126] Jackson, T., 2005, "Motivating Sustainable Consumption," A Rev. Evid. Consum. Behav. Behav. Chang. A Rep. to Sustain. Dev. Res. Netw. as part ESRC Sustain. Technol. Program. Cent. Environ. Strateg. Univ. Surrey Guildf., **15**(January), pp. 1027–1051.
- [127] Shove, E., 2003, "Converging Conventions of Comfort, Cleanliness and Convenience," J. Consum. Policy, **26**(4), pp. 395–418.
- [128] Staddon, S. C., Cycil, C., Goulden, M., Leygue, C., and Spence, A., 2016, "Intervening to Change Behaviour and Save Energy in the Workplace: A Systematic Review of Available Evidence," Energy Res. Soc. Sci., **17**, pp. 30–51.
- [129] Reckwitz, A., 2002, "Toward a Theory of Social Practices: A Development in Culturalist Theorizing," Eur. J. Soc. Theory, **5**(2), pp. 243–263.
- [130] Hargreaves, T., 2011, "Practice-Ing Behaviour Change: Applying Social Practice Theory to pro-Environmental Behaviour Change," J. Consum. Cult., **11**(1), pp. 79–99.
- [131] Warde, A., 2005, "Consumption and Theories of Practice," J. Consum. Cult., **5**(2), pp. 131–153.
- [132] Klein, S. J. W., and Coffey, S., 2016, "Building a Sustainable Energy Future, One Community at a Time," Renew. Sustain. Energy Rev., **60**, pp. 867–880.
- [133] Liedtke, C., Baedeker, C., Hasselkuß, M., Rohn, H., and Grinewitschus, V., 2015, "User-Integrated Innovation in Sustainable LivingLabs: An Experimental Infrastructure for Researching and Developing Sustainable Product Service Systems," J. Clean. Prod., **97**, pp. 106–116.
- [134] "Selling Light as a Service" [Online]. Available: <https://www.ellenmacarthurfoundation.org/case-studies/selling-light-as-a-service>. [Accessed: 25-Jan-2020].
- [135] Egmond, C., and Bruel, R., 2007, "Triandis' Theory of Interpersonal Behaviour," Nothing is as practical as a good theory, Analysis of theories and a tool for developing interventions to influence energy-related behaviour.
- [136] Chatterton, T., 2011, "An Introduction to Thinking about 'energy Behaviour': A Multi-Model Approach," A Pap. Dep. Energy Clim. Chang.
- [137] Maréchal, K., 2010, "Not Irrational but Habitual: The Importance of 'Behavioural Lock-in' in Energy Consumption," Ecol. Econ., **69**(5), pp. 1104–1114.
- [138] Salonen, A. O., and Helne, T. T., 2012, "Vegetarian Diets: A Way towards a Sustainable Society," J. Sustain. Dev., **5**(6).
- [139] Zierler, R., Wehrmeyer, W., and Murphy, R., 2017, "The Energy Efficiency Behaviour of Individuals in Large Organisations: A Case Study of a Major UK Infrastructure Operator," Energy Policy, **104**(June 2016), pp. 38–49.
- [140] Karatasou, S., Laskari, M., and Santamouris, M., 2014, "Models of Behavior Change and Residential Energy Use: A Review of Research Directions and Findings for Behavior-Based Energy Efficiency," Adv. Build. Energy Res., **8**(2), pp. 137–147.
- [141] Mulville, M., Jones, K., Huebner, G., and Powell-Greig, J., 2017, "Energy-Saving Occupant Behaviours in Offices: Change Strategies," Build. Res. Inf., **45**(8), pp. 861–874.
- [142] Nielsen, J., 1993, *Usability Engineering*, Mountain View, California.
- [143] Chen, C. fei, Xu, X., and Arpan, L., 2017, "Between the Technology Acceptance Model and Sustainable Energy Technology Acceptance Model: Investigating Smart Meter Acceptance in the United States," Energy Res. Soc. Sci., **25**, pp. 93–104.

- [144] Schweiker, M., and Wagner, A., 2016, "The Effect of Occupancy on Perceived Control, Neutral Temperature, and Behavioral Patterns," *Energy Build.*, **117**, pp. 246–259.
- [145] Li, D., Menassa, C. C., and Karatas, A., 2017, "Energy Use Behaviors in Buildings: Towards an Integrated Conceptual Framework," *Energy Res. Soc. Sci.*, **23**, pp. 97–112.
- [146] Yan, D., Hong, T., Dong, B., Mahdavi, A., Oca, S. D., Gaetani, I., and Feng, X., 2017, "IEA EBC Annex 66 : Definition and Simulation of Occupant Behavior in Buildings," *Energy Build.*, **156**, pp. 258–270.
- [147] Stazi, F., Naspi, F., and D'Orazio, M., 2017, "A Literature Review on Driving Factors and Contextual Events Influencing Occupants' Behaviours in Buildings," *Build. Environ.*, **118**, pp. 40–66.
- [148] Fabi, V., Andersen, R. V., Corgnati, S., and Olesen, B. W., 2012, "Occupants' Window Opening Behaviour: A Literature Review of Factors Influencing Occupant Behaviour and Models," *Build. Environ.*, **58**, pp. 188–198.
- [149] Langevin, J., Wen, J., and Gurian, P. L., 2015, "Simulating the Human-Building Interaction: Development and Validation of an Agent-Based Model of Office Occupant Behaviors," *Build. Environ.*, **88**, pp. 27–45.
- [150] Kutlar, N., and Mengüç, M. P., 2019, "Daylighting Design Process for Visual Comfort and Energy Efficiency for a Signature Building," *IOP Conf. Ser. Earth Environ. Sci.*, **290**(1).
- [151] Jia, M., Srinivasan, R. S., and Raheem, A. A., 2017, "From Occupancy to Occupant Behavior: An Analytical Survey of Data Acquisition Technologies, Modeling Methodologies and Simulation Coupling Mechanisms for Building Energy Efficiency," *Renew. Sustain. Energy Rev.*, **68**(October 2016), pp. 525–540.
- [152] Barthelmes, V. M., Becchio, C., and Corgnati, S. P., 2016, "Occupant Behavior Lifestyles in a Residential Nearly Zero Energy Building: Effect on Energy Use and Thermal Comfort," *Sci. Technol. Built Environ.*, **22**(7), pp. 960–975.
- [153] Santin, O. G., 2011, "Behavioural Patterns and User Profiles Related to Energy Consumption for Heating," *Energy Build.*, **43**(10), pp. 2662–2672.
- [154] Mahdavi, A., and Tahmasebi, F., 2015, "Predicting People's Presence in Buildings: An Empirically Based Model Performance Analysis," *Energy Build.*, **86**, pp. 349–355.
- [155] Spandagos, C., and Ng, T. L., 2018, "Fuzzy Model of Residential Energy Decision-Making Considering Behavioral Economic Concepts," *Appl. Energy*, **213**, pp. 611–625.
- [156] Hawarah, L., Ploix, S., and Jacomino, M., 2010, "User Behavior Prediction in Energy Consumption in Housing Using Bayesian Networks," *Lect. Notes Comput. Sci. (including Subser. Lect. Notes Artif. Intell. Lect. Notes Bioinformatics)*, **6113 LNAI**(PART 1), pp. 372–379.
- [157] Jensen, K. L., Toftum, J., and Friis-Hansen, P., 2009, "A Bayesian Network Approach to the Evaluation of Building Design and Its Consequences for Employee Performance and Operational Costs," *Build. Environ.*, **44**, pp. 456–462.
- [158] Erickson, V. L., Lin, Y., Kamthe, A., Brahme, R., Surana, A., Cerpa, A. E., Sohn, M. D., and Narayanan, S., 2009, "Energy Efficient Building Environment Control Strategies Using Real-Time Occupancy Measurements," *Proc. First ACM Work. Embed. Sens. Syst. Energy-Efficiency Build. - BuildSys '09*, Berkeley, Calif.
- [159] Pfafferott, J., and Herkel, S., 2007, "Statistical Simulation of User Behaviour in Low-Energy Office Buildings," *Sol. Energy*, **81**, pp. 676–682.

- [160] Page, J., Robinson, D., Morel, N., and Scartezzini, J. L., 2008, "A Generalised Stochastic Model for the Simulation of Occupant Presence," *Energy Build.*, **40**(2), pp. 83–98.
- [161] Erickson, V. L., Carreira-Perpiñán, M. Á., and Cerpa, A. E., 2014, "Occupancy Modeling and Prediction for Building Energy Management," *ACM Trans. Sens. Networks*, **10**(3).
- [162] Meng, X., Wen, Z., and Qian, Y., 2018, "Multi-Agent Based Simulation for Household Solid Waste Recycling Behavior," *Resour. Conserv. Recycl.*, **128**, pp. 535–545.
- [163] Andrews, C. J., Yi, D., Krogmann, U., Senick, J. A., and Wener, R. E., 2011, "Designing Buildings for Real Occupants: An Agent-Based Approach," *IEEE Trans. Syst. Man, Cybern. Part A Systems Humans*, **41**(6), pp. 1077–1091.
- [164] Klein, L., Kwak, J. Y., Kavulya, G., Jazizadeh, F., Becerik-Gerber, B., Varakantham, P., and Tambe, M., 2012, "Coordinating Occupant Behavior for Building Energy and Comfort Management Using Multi-Agent Systems," *Autom. Constr.*, **22**, pp. 525–536.
- [165] Yu, Z., Fung, B. C. M., Haghighat, F., Yoshino, H., and Morofsky, E., 2011, "A Systematic Procedure to Study the Influence of Occupant Behavior on Building Energy Consumption," *Energy Build.*, **43**, pp. 1409–1417.
- [166] Azar, E., and Menassa, C. C., 2014, "A Comprehensive Framework to Quantify Energy Savings Potential from Improved Operations of Commercial Building Stocks," *Energy Policy*, **67**(October), pp. 459–472.
- [167] Tunçel, E. G., 2019, "Human Body Heat Exchange Mechanism," Özyeğin University.
- [168] Halawa, E., and Van Hoof, J., 2012, "The Adaptive Approach to Thermal Comfort: A Critical Overview," *Energy Build.*, **51**, pp. 101–110.
- [169] Lam, A. H., Yuan, Y., and Wang, D., 2014, "An Occupant-Participatory Approach for Thermal Comfort Enhancement and Energy Conservation in Buildings," *Proc. 5th Int. Conf. Futur. energy Syst. - e-Energy '14*, pp. 133–143.
- [170] Jung, W., and Jazizadeh, F., 2019, "Human-in-the-Loop HVAC Operations: A Quantitative Review on Occupancy, Comfort, and Energy-Efficiency Dimensions," *Appl. Energy*, **239**, pp. 1471–1508.
- [171] Yun, G. Y., 2018, "Influences of Perceived Control on Thermal Comfort and Energy Use in Buildings," *Energy Build.*, **158**, pp. 822–830.
- [172] Humphreys, M. A., Nicol, J. F., and Raja, I. A., 2007, "Field Studies of Indoor Thermal Comfort and the Progress of the Adaptive Approach," *Adv. Build. Energy Res.*, **1**(1), pp. 55–88.
- [173] Womack, J. P., and Jones, D. T., 2000, "A Book Review : Lean Thinking by Womack and Jones," *Rev. Lit. Arts Am.*, (November), p. 5.
- [174] Keskin, C., and Mengüç, M. P., 2020, "An Adaptive Vent System for Localized and Customized Thermal Management in Buildings," *J. Heat Transfer*, **142**(5).
- [175] Bemporad, A., 2019, *Hybrid Toolbox User's Guide*, MATLAB.
- [176] Hai, L., 2014, "Hybrid Dynamical Systems: An Introduction to Control and Verification," *Found. Trends® Syst. Control*, **1**(1), pp. 1–172.
- [177] Borrelli, F., Bemporad, A., and Morari, M., 2011, *Predictive Control for Linear and Hybrid Systems*, Cambridge University Press, Cambridge.
- [178] Tolk, A., Page, E. H., and Mittal, S., 2018, "Hybrid Simulation For Cyber Physical Systems-State Of The Art And A Literature Review," *SpringSim-ANSS 2018*, Society for

Modeling and Simulation (SCS) International, Baltimore, MD, USA.

- [179] Benveniste, A., Bourke, T., Caillaud, B., and Pouzet, M., 2012, *Hybrid Systems Modeling Challenges Caused by Cyber-Physical Systems*.
- [180] Fiorentini, M., Wall, J., Ma, Z., Braslavsky, J. H., and Cooper, P., 2017, "Hybrid Model Predictive Control of a Residential HVAC System with On-Site Thermal Energy Generation and Storage," *Appl. Energy*, **187**, pp. 465–479.
- [181] Goebel, R., Sanfelice, R. G., and Teel, A. R., 2009, "Hybrid Dynamical Systems," *IEEE Internet Comput. Syst. Mag.*, pp. 28–93.
- [182] Sanfelice, R. G., 2016, "Analysis and Design of Cyber-Physical Systems: A Hybrid Control Systems Approach," *Cyber-Physical Systems: From Theory to Practice*, R. Baheti, and H. Gill, eds., CRC Press, Boca Raton, FL, pp. 3–32.
- [183] Bauman, F., and Arens, E., 1993, "Localized Comfort Control with a Desktop Task Conditioning System : Laboratory and Field Measurements," *ASHRAE Trans.*, **99**(2), pp. 733–749.
- [184] Bauman, F. S., and Arens, E. A., 1996, "Task / Ambient Conditioning Systems : Engineering and Application Guidelines," *Coord. Res. Proj. Effic. Syst. Therm. Energy Distrib. to Calif. Inst. Energy Effic. Lawrence*, **94720**(4902510).
- [185] Torrisi, F. D., and Bemporad, A., 2004, "HYSDEL - A Tool for Generating Computational Hybrid Models," *IEEE Trans. Control Syst. Technol.*, **12**(2), pp. 235–249.
- [186] "HYSDEL - Hybrid System DEscription Language" [Online]. Available: <https://people.ee.ethz.ch/~cohysys/hysdel/index.html>. [Accessed: 22-May-2019].
- [187] Sun, Y., and Smith, T. F., 2005, "Air Flow Characteristics of a Room with Square Cone Diffusers," *Build. Environ.*, **40**(5), pp. 589–600.
- [188] Yu, H., 2005, "Trajectory of a Horizontally Diffused Plane Wall Jet in a Non-Isothermal Ceiling Slot-Ventilated Enclosure," *Biosyst. Eng.*, **91**(1), pp. 99–109.
- [189] Etheridge, D., and Sandberg, M., 1996, *Building Ventilation: Theory and Measurement*, Wiley, West Sussex.
- [190] Rabani, M., Madessa, H. B., and Nord, N., 2018, "CFD Study on the Effect of Archimedes Number and Heating Rate on the Thermal Stratification of a Ventilated Office," *Proc. 59th Conf. imulation Model. (SIMS 59)*, 26-28 Sept. 2018, Oslo Metropol. Univ. Norw., **153**(November), pp. 17–23.
- [191] FG_DC-2011-0114-GB_R6-2018-05, 2018, "FLEX-GEKO Fan Coil Units Technical Data," FlaktGroup.
- [192] 2006, *ISO-14505 Ergonomics of the Thermal Environment — Evaluation of Thermal Environments in Vehicles — Part 2: Determination of Equivalent Temperature*, Geneva.
- [193] Nilsson, H. O., 2007, "Thermal Comfort Evaluation with Virtual Manikin Methods," *Build. Environ.*, **42**(12), pp. 4000–4005.

APPENDIX-A: The HYSDEL Code for Modeling AVS

```
1. SYSTEM ATP_v2 {
2.
3. INTERFACE {
4.     STATE { REAL T1 [20,40];
5.             REAL T2 [20,40];
6.     }
7.     INPUT { REAL TE [10,40];
8.             BOOL occp1;
9.             BOOL occp2;
10.    }
11.    OUTPUT {REAL y1;
12.            REAL y2;}
13.    PARAMETER {
14.        REAL Ts, C1, C2, Rh1, Rh2, Rc1, Rc2;
15.        REAL Tset1, Tset2, Tact, Tpas;
16.    }
17. }
18. IMPLEMENTATION {
19.     AUX { REAL Th1, Th2;
20.           BOOL Cond1, Cond2;
21.     }
22.     AD { Cond1 = T1<=Tset1;
23.          Cond2 = T2<=Tset2;
24.     }
25.     DA { Th1 = {IF (Cond1 & occp1) THEN Tact ELSE
26.                 Tpas};
27.          Th2 = {IF (Cond2 & occp2) THEN Tact ELSE
28.                 Tpas};
29.     }
30.     CONTINUOUS { T1 = T1+Ts*(((1/(C1*Rc1))* (TE-
31.                            T1))+((1/(C1*Rh1))* (Th1-T1)));
32.                  T2 = T2+Ts*(((1/(C2*Rc2))* (TE-
33.                            T2))+((1/(C2*Rh2))* (Th2-T2)));
34.     }
35. }
```

APPENDIX-B: Validation Tables

Table 4: Comparison of experimental and simulation (CFD) data for sensors on head level

Time	Head1_Exp	Head1_sim	Error (%)	Head2_Exp	Head2_sim	Error (%)	Head3_Exp	Head3_sim	Error (%)
0	23.12	23.05	0,3%	23.31	23.05	1.1%	23.12	23.05	0.3%
60	23.19	23.12	0,3%	23.38	23.21	0.7%	23.12	23.08	0.2%
120	23.25	23.37	-0,5%	23.38	23.45	-0.3%	23.12	23.33	-0.9%
180	23.31	23.59	-1,2%	23.44	23.62	-0.7%	23.19	23.62	-1.9%
240	23.19	23.82	-2,7%	23.44	23.95	-2.2%	23.25	23.67	-1.8%
300	23.31	23.97	-2,8%	23.50	24.06	-2.4%	23.19	23.82	-2.7%
360	23.31	24.08	-3,3%	23.50	24.15	-2.7%	23.19	23.92	-3.2%
420	23.31	24.17	-3,7%	23.56	24.20	-2.7%	23.19	23.99	-3.4%
480	23.31	24.23	-4,0%	23.50	24.25	-3.2%	23.19	24.05	-3.7%
540	23.38	24.28	-3,9%	23.50	24.30	-3.4%	23.25	24.09	-3.6%
600	23.38	24.32	-4,0%	23.56	24.35	-3.4%	23.25	24.13	-3.8%
660	23.38	24.36	-4,2%	23.56	24.39	-3.5%	23.25	24.16	-3.9%
720	23.38	24.38	-4,3%	23.56	24.41	-3.6%	23.25	24.19	-4.0%
780	23.38	24.40	-4,4%	23.56	24.44	-3.7%	23.25	24.20	-4.1%
840	23.44	24.42	-4,2%	23.56	24.45	-3.8%	23.25	24.22	-4.2%
900	23.38	24.43	-4,5%	23.56	24.47	-3.9%	23.25	24.23	-4.2%
		MAPE=	3.01%		MAPE=	2.58%		MAPE=	2.87%

Table 5: Comparison of experimental and simulation (CFD) data for sensors on desks

Time	Desk1_Exp	Desk1_CFD	Error(%)	Desk2_Exp	Desk2_CFD	Error(%)	Desk3_Exp	Desk3_CFD	Error(%)	Desk4_Exp	Desk4_CFD	Error(%)
0	23.06	23.04	0.1%	22.81	23.05	-1.1%	23.19	23.05	0.6%	22.94	23.05	-0.5%
60	23.12	23.06	0.3%	22.87	23.05	-0.8%	23.19	23.05	0.6%	22.94	23.05	-0.5%
120	23.12	23.25	-0.6%	22.87	23.18	-1.4%	23.19	23.07	0.5%	23.06	23.08	-0.1%
180	23.12	23.1	0.1%	22.87	23.22	-1.6%	23.31	23.09	0.9%	23.06	23.16	-0.4%
240	23.12	23.25	-0.5%	22.87	23.22	-1.5%	23.31	23.09	0.9%	23.06	23.17	-0.5%
300	23.12	23.31	-0.8%	22.94	23.27	-1.5%	23.31	23.12	0.8%	23.06	23.17	-0.5%
360	23.19	23.37	-0.8%	22.87	23.20	-1.4%	23.38	23.13	1.1%	23.12	23.22	-0.4%
420	23.19	23.37	-0.8%	22.94	23.26	-1.4%	23.25	23.18	0.3%	23.12	23.26	-0.6%
480	23.12	23.39	-1.2%	22.94	23.30	-1.6%	23.31	23.22	0.4%	23.12	23.30	-0.8%
540	23.12	23.43	-1.3%	22.94	23.35	-1.8%	23.31	23.25	0.3%	23.12	23.35	-1.0%
600	23.12	23.46	-1.5%	22.87	23.39	-2.3%	23.38	23.28	0.4%	23.12	23.39	-1.2%
660	23.12	23.48	-1.5%	22.94	23.42	-2.1%	23.38	23.30	0.3%	23.19	23.42	-1.0%
720	23.12	23.50	-1.6%	23.00	23.44	-1.9%	23.38	23.33	0.2%	23.19	23.45	-1.1%
780	23.19	23.52	-1.4%	22.94	23.45	-2.2%	23.44	23.36	0.4%	23.25	23.48	-1.0%
840	23.19	23.54	-1.5%	23.00	23.46	-2.0%	23.38	23.38	0.0%	23.19	23.51	-1.4%
900	23.19	23.55	-1.6%	23.00	23.47	-2.1%	23.44	23.40	0.2%	23.25	23.53	-1.2%
MAPE=			0.96%	MAPE=			1.65%	MAPE=			0.50%	MAPE= 0.76%

Time	Desk5_Exp	Desk5_CFD	Error(%)	Desk6_Exp	Desk6_CFD	Error(%)	Desk7_Exp	Desk7_CFD	Error(%)	Desk8_Exp	Desk8_CFD	Error(%)
0	22.94	23.05	-0.5%	22.81	23.05	-1.1%	23.03	23.06	-0.1%	22.50	23.05	-2.4%
60	22.94	23.05	-0.5%	22.81	23.05	-1.1%	23.12	23.86	-3.2%	22.56	23.07	-2.3%
120	23.00	23.06	-0.2%	22.81	23.08	-1.2%	23.44	24.15	-3.0%	22.56	23.05	-2.2%
180	23.00	23.10	-0.4%	22.87	23.12	-1.1%	23.62	24.49	-3.7%	22.56	23.05	-2.2%
240	23.00	23.09	-0.4%	22.87	23.11	-1.1%	23.69	24.56	-3.7%	22.56	23.07	-2.3%
300	23.00	23.16	-0.7%	22.94	23.12	-0.8%	23.81	24.64	-3.5%	22.62	23.07	-2.0%
360	23.06	23.21	-0.6%	22.94	23.14	-0.9%	23.81	24.70	-3.7%	22.62	23.10	-2.1%
420	23.06	23.24	-0.8%	22.94	23.22	-1.2%	23.81	24.75	-4.0%	22.56	23.15	-2.6%
480	23.12	23.27	-0.6%	23.00	23.27	-1.2%	23.87	24.79	-3.8%	22.56	23.19	-2.8%
540	23.12	23.28	-0.7%	23.00	23.31	-1.3%	23.94	24.81	-3.7%	22.62	23.21	-2.6%
600	23.12	23.30	-0.8%	23.00	23.33	-1.5%	23.92	24.84	-3.8%	22.56	23.25	-3.0%
660	23.12	23.33	-0.9%	23.06	23.36	-1.3%	23.95	24.86	-3.8%	22.62	23.28	-2.9%
720	23.12	23.35	-1.0%	23.00	23.38	-1.7%	24.10	24.87	-3.2%	22.62	23.30	-3.0%
780	23.12	23.38	-1.1%	23.06	23.40	-1.5%	24.10	24.89	-3.3%	22.62	23.32	-3.1%
840	23.12	23.40	-1.2%	23.06	23.41	-1.5%	24.14	24.90	-3.1%	22.62	23.34	-3.2%
900	23.19	23.42	-1.0%	23.12	23.42	-1.3%	24.10	24.91	-3.3%	22.62	23.36	-3.3%
MAPE=			0.72%	MAPE=			1.23%	MAPE=			3.31%	MAPE= 2.62%

Table 6: Comparison of experimental and simulation (CFD) data for sensors on ceiling level

Time	North_Exp	North_CFD	Error(%)	NorthWest_Exp	NorthWest_CFD	Error(%)	NorthEast_Exp	NorthEast_CFD	Error(%)	Middle_Exp	Middle_CFD	Error(%)	
0	23.69	23.05	2,7%	23.12	23.05	0.3%	24.75	23.05	6.9%	24.31	23.05	5.2%	
60	23.69	24.07	-1,6%	23.31	23.51	-0.9%	24.87	23.74	4.5%	24.31	23.05	5.2%	
120	23.75	24.15	-1,7%	23.44	24.18	-3.2%	24.94	23.93	4.0%	24.37	23.08	5.3%	
180	23.81	24.48	-2,8%	23.50	24.36	-3.7%	24.81	24.18	2.5%	24.31	23.16	4.7%	
240	23.81	24.64	-3,5%	23.56	24.46	-3.8%	25.12	24.28	3.4%	24.37	23.17	4.9%	
300	23.87	24.73	-3,6%	23.69	24.56	-3.7%	25.06	24.35	2.8%	24.50	23.17	5.4%	
360	23.81	24.79	-4,1%	23.69	24.63	-4.0%	25.06	24.41	2.6%	24.56	23.22	5.4%	
420	23.81	24.84	-4,3%	23.69	24.68	-4.2%	24.94	24.47	1.9%	24.56	23.26	5.3%	
480	23.81	24.88	-4,5%	23.75	24.72	-4.1%	24.94	24.51	1.7%	24.69	23.30	5.6%	
540	23.87	24.92	-4,4%	23.87	24.76	-3.7%	25.00	24.54	1.8%	24.75	23.35	5.7%	
600	23.81	24.94	-4,7%	23.94	24.78	-3.5%	25.00	24.57	1.7%	24.75	23.39	5.5%	
660	23.81	24.96	-4,8%	23.94	24.81	-3.6%	25.19	24.59	2.4%	24.62	23.42	4.9%	
720	23.94	24.97	-4,3%	23.94	24.82	-3.7%	25.19	24.61	2.3%	24.75	23.45	5.2%	
780	23.87	24.99	-4,7%	24.00	24.84	-3.5%	25.25	24.62	2.5%	24.75	23.48	5.1%	
840	23.87	25.00	-4,7%	24.00	24.85	-3.5%	25.19	24.64	2.2%	24.69	23.51	4.8%	
900	23.94	25.00	-4,4%	24.00	24.86	-3.6%	25.25	24.64	2.4%	24.75	23.53	4.9%	
Mape=			3.81%	Mape=			3.31%	Mape=			2.85%	Mape=	5.20%

Time	South_Exp	South_CFD	Error(%)	SouthWest_Exp	SouthWest_CFD	Error(%)	SouthEast_Exp	SouthEast_CFD	Error(%)		
0	24.63	23.05	6,4%	25.44	23.05	9.4%	25.88	23.05	10.9%		
60	24.75	23.44	5,3%	25.62	23.28	9.1%	26.00	23.69	8.9%		
120	24.81	23.83	4,0%	25.62	24.17	5.7%	26.12	24.11	7.7%		
180	24.87	23.95	3,7%	25.62	24.24	5.4%	26.06	24.21	7.1%		
240	24.81	24.19	2,5%	25.75	24.36	5.4%	26.12	24.28	7.1%		
300	24.81	24.32	2,0%	25.69	24.45	4.8%	26.12	24.38	6.7%		
360	24.81	24.37	1,8%	25.69	24.51	4.6%	26.12	24.46	6.4%		
420	24.87	24.42	1,8%	25.75	24.58	4.5%	26.19	24.51	6.4%		
480	24.87	24.46	1,6%	25.69	24.62	4.2%	26.25	24.56	6.4%		
540	24.81	24.50	1,2%	25.75	24.66	4.2%	26.25	24.60	6.3%		
600	24.81	24.53	1,1%	25.88	24.68	4.6%	26.25	24.62	6.2%		
660	24.87	24.55	1,3%	25.75	24.70	4.1%	26.31	24.64	6.3%		
720	24.87	24.58	1,2%	25.81	24.72	4.2%	26.37	24.66	6.5%		
780	24.87	24.59	1,1%	25.94	24.73	4.7%	26.44	24.67	6.7%		
840	24.94	24.61	1,3%	25.88	24.74	4.4%	26.50	24.69	6.8%		
900	25.00	24.62	1,5%	25.88	24.75	4.4%	26.44	24.69	6.6%		
Mape=			2.36%	Mape=			5.23%	Mape=			7.06%

Table 7: Comparison of experimental and simulation (CFD) data for sensors on floor level

Time	Flr1-Exp	Flr1-CFD	Error(%)	Flr2-Exp	Flr2-CFD	Error(%)	Flr3-Exp	Flr3-CFD	Error(%)	Flr4-Exp	Flr4-CFD	Error(%)			
0	22.31	23.05	-3,3%	21.56	23.05	-6.9%	22.37	23.05	-3.0%	22.00	23.05	-4.8%			
60	22.31	23.06	-3,4%	21.56	22.71	-5.3%	22.37	23.05	-3.1%	22.06	22.68	-2.8%			
120	22.31	22.84	-2,4%	21.62	22.84	-5.7%	22.31	22.85	-2.4%	22.06	22.80	-3.3%			
180	22.31	22.93	-2,8%	21.62	22.93	-6.1%	22.37	22.92	-2.4%	22.13	22.85	-3.3%			
240	22.31	22.94	-2,8%	21.62	22.93	-6.0%	22.37	22.90	-2.4%	22.06	22.86	-3.6%			
300	22.44	22.93	-2,2%	21.62	22.94	-6.1%	22.37	22.91	-2.4%	22.06	22.92	-3.9%			
360	22.37	22.96	-2,6%	21.62	22.97	-6.3%	22.37	22.96	-2.6%	22.13	22.95	-3.7%			
420	22.37	22.98	-2,7%	21.62	22.99	-6.4%	22.31	22.98	-3.0%	22.06	22.97	-4.1%			
480	22.44	23.00	-2,5%	21.62	23.01	-6.4%	22.37	23.00	-2.8%	22.06	23.00	-4.3%			
540	22.37	23.03	-3,0%	21.69	23.04	-6.2%	22.31	23.02	-3.2%	22.06	23.02	-4.3%			
600	22.44	23.06	-2,8%	21.62	23.06	-6.7%	22.37	23.04	-3.0%	22.06	23.03	-4.4%			
660	22.37	23.08	-3,2%	21.62	23.08	-6.8%	22.31	23.06	-3.4%	22.06	23.06	-4.5%			
720	22.44	23.11	-3,0%	21.69	23.10	-6.5%	22.37	23.09	-3.2%	22.13	23.08	-4.3%			
780	22.50	23.13	-2,8%	21.69	23.13	-6.6%	22.37	23.11	-3.3%	22.13	23.11	-4.4%			
840	22.44	23.16	-3,2%	21.62	23.15	-7.1%	22.37	23.13	-3.4%	22.13	23.13	-4.5%			
900	22.56	23.18	-2,7%	21.69	23.17	-6.8%	22.44	23.16	-3.2%	22.13	23.15	-4.6%			
		MAPE= 2.83%				MAPE= 6.36%				MAPE= 2.93%				MAPE= 4.06%	

Time	Flr5-Exp	Flr5-CFD	Error(%)	Flr6-Exp	Flr6-CFD	Error(%)	Flr7-Exp	Flr7-CFD	Error(%)	Flr8-Exp	Flr8-CFD	Error(%)			
0	22.00	23.05	-4,8%	22.06	23.05	-4.5%	22.06	23.05	-4.5%	21.87	23.05	-5.4%			
60	22.00	23.05	-4,8%	22.00	22.83	-3.8%	22.00	23.05	-4.8%	21.87	22.87	-4.6%			
120	22.00	22.95	-4,3%	22.00	22.86	-3.9%	22.06	22.88	-3.7%	21.81	22.80	-4.6%			
180	22.00	22.91	-4,1%	22.00	22.81	-3.7%	22.00	22.87	-4.0%	21.87	22.80	-4.2%			
240	21.94	22.91	-4,4%	22.06	22.88	-3.7%	22.00	22.89	-4.1%	21.81	22.86	-4.8%			
300	22.00	22.94	-4,3%	22.06	22.90	-3.8%	22.06	22.91	-3.8%	21.81	22.88	-4.9%			
360	22.00	22.96	-4,4%	22.13	22.92	-3.6%	22.00	22.93	-4.2%	21.87	22.89	-4.7%			
420	22.00	22.97	-4,4%	22.00	22.95	-4.3%	22.06	22.94	-4.0%	21.81	22.92	-5.1%			
480	22.00	22.99	-4,5%	22.00	22.97	-4.4%	22.06	22.96	-4.1%	21.81	22.95	-5.2%			
540	22.00	23.01	-4,6%	22.00	22.99	-4.5%	22.00	22.98	-4.4%	21.87	22.97	-5.0%			
600	22.00	23.04	-4,7%	22.00	23.01	-4.6%	22.00	23.00	-4.5%	21.81	22.99	-5.4%			
660	22.00	23.06	-4,8%	22.06	23.04	-4.4%	22.06	23.02	-4.3%	21.87	23.02	-5.2%			
720	22.00	23.09	-4,9%	22.06	23.06	-4.5%	22.06	23.03	-4.4%	21.87	23.04	-5.4%			
780	22.00	23.11	-5,0%	22.06	23.08	-4.6%	22.06	23.05	-4.5%	21.81	23.06	-5.7%			
840	22.00	23.13	-5,1%	22.00	23.10	-5.0%	22.06	23.07	-4.6%	21.81	23.08	-5.8%			
900	22.00	23.15	-5,2%	22.06	23.12	-4.8%	22.00	23.09	-5.0%	21.81	23.10	-5.9%			
		MAPE= 4.66%				MAPE= 4.26%				MAPE= 4.31%				MAPE= 5.13%	

Time	Flr9-Exp	Flr9-CFD	Error(%)	Flr10-Exp	Flr10-CFD	Error(%)	Flr11-Exp	Flr11-CFD	Error(%)
0	21.81	23.05	-5,7%	21.94	23.05	-5.1%	21.44	23.05	-7.5%
60	21.87	22.76	-4,1%	21.94	22.94	-4.6%	21.44	23.07	-7.6%
120	21.81	22.78	-4,4%	21.94	22.80	-3.9%	21.50	22.83	-6.2%
180	21.81	22.82	-4,6%	22.00	22.80	-3.6%	21.50	22.81	-6.1%
240	21.87	22.85	-4,5%	22.00	22.81	-3.7%	21.44	22.84	-6.5%
300	21.87	22.87	-4,6%	21.94	22.83	-4.1%	21.37	22.86	-7.0%
360	21.87	22.87	-4,6%	22.00	22.85	-3.8%	21.44	22.85	-6.6%
420	21.87	22.88	-4,6%	21.94	22.86	-4.2%	21.37	22.86	-7.0%
480	21.94	22.90	-4,4%	22.00	22.88	-4.0%	21.44	22.86	-6.6%
540	21.87	22.92	-4,8%	22.00	22.89	-4.1%	21.37	22.88	-7.1%
600	21.87	22.95	-4,9%	21.94	22.91	-4.4%	21.44	22.90	-6.8%
660	21.87	22.97	-5,0%	21.94	22.93	-4.5%	21.37	22.91	-7.2%
720	21.87	22.99	-5,1%	21.94	22.94	-4.6%	21.37	22.93	-7.3%
780	21.94	23.00	-4,8%	21.94	22.95	-4.6%	21.37	22.94	-7.3%
840	21.87	23.01	-5,2%	21.94	22.97	-4.7%	21.37	22.95	-7.4%
900	21.87	23.03	-5,3%	21.94	22.98	-4.7%	21.44	22.97	-7.1%
		MAPE=	4.79%		MAPE=	4.28%		MAPE=	6.96%

