

AN INTEGRATED COMPUTATIONAL FRAMEWORK FOR NATURAL
VENTILATION AND AIRBORNE CONTAMINANT DISPERSION ANALYSIS IN
ARCHITECTURAL DESIGN

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ANALYSIS IN ARCHITECTURAL DESIGN**

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ABSTRACT

AN INTEGRATED COMPUTATIONAL FRAMEWORK FOR NATURAL VENTILATION AND AIRBORNE CONTAMINANT DISPERSION ANALYSIS IN ARCHITECTURAL DESIGN

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Over the last four decades, the negative impact of the building industry and the growing environmental crisis have led architects to develop sustainable design strategies for a better-performing built environment. Building performance tools, which are commonly used at the end of the design process, are not integrated into the design synthesis. Therefore, there is no integration between the performance parameters. In the literature, there are many studies focusing on the seamless integration of energy and daylighting analysis. In contrast, the integration of natural ventilation and indoor airborne contamination analysis is hitherto understudied. However, natural ventilation can reduce buildings' energy demand and carbon emissions. Also, natural ventilation can provide healthy environments for building occupants by reducing potential indoor airborne contamination. There is a need for an integrated approach and a digital workflow, specifically addressing effective natural ventilation and the removal of airborne contamination. This research addresses the urgent need for the integration of natural ventilation and contaminant dispersion analysis to the creative design synthesis/analysis processes and develops an integrated and hybrid analysis pipeline that couples parametric design, building performance

simulation (CFD, daylighting, energy, and contaminant transportation), and model testing (wind tunnel) methods. The developed pipeline is implemented for a case study that consists of the shading device design of an office building. Implementing the pipeline, improving indoor air quality by providing adequate natural ventilation, and reducing the airborne contaminants while keeping the thermal loads and daylighting optimized is aimed.

Keywords: Integrated Building Performance Simulation, Natural Ventilation, Contaminant Simulation, Wind Tunnel Testing, Computational Fluid Dynamics



ÖZ

MİMARİ TASARIMDA DOĞAL HAVALANDIRMA VE HAVA KAYNAKLI KONTAMİNASYON YAYILIMI İÇİN BÜTÜNLEŞİK ANALİZ ÇERÇEVESİ

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Son kırk yılda ilerleyen çevresel krizler ve inşaat sektörünün çevreye olumsuz etkileri mimarları yapıları için daha sürdürülebilir tasarım yöntemleri geliştirmeye sevk etmiştir. Çevresel problemler, bina performansı ve araçlarına olan gereksinimi ön plana çıkarmıştır. Ancak bu araçlar genellikle tasarım sürecinin sonunda kullanılmakta, bina performans parametreleri arasında entegrasyon problemlerine sebep olmakta ve araçların tasarım sürecinde etkin kullanımı sektöre ugramaktadır. Literatürde enerji ve güneşli performansı entegrasyonu odağında sayıca çok çalışma bulunmaktadır. Ancak, doğal havalandırmanın bina havalandırması-iklimlendirmesi kaynaklı enerji kullanımını, ki bu bina toplam enerji tüketiminin 40% ını oluşturmaktadır,ve karbon salımını düşürebilme ve hava kaynaklı iç mekan kontaminasyon riskini düşürerek görece sağlıklı iç mekanlar sağlayabilme potansiyeline rağmen doğal havalandırma ve kontaminasyon analizlerinin performans temelli tasarım süreçlerine entegrasyonu kısıtlıdır. COVID-19 pandemisinin de gösterdiği üzere, doğal havalandırma sağlıklı iç mekanlar sağlayabilme ve kullanıcı konforu için gereklidir ve diğer performans parametreleri ile birlikte değerlendirilmelidir. Bu da, tasarım ve analiz için bütünsel bir akış gerektirmektedir. Bu bağlamda, bu tez doğal havalandırma hava yollu taşınan kontaminasyon yayılım

analizi süreçlerini performans temelli tasarım süreçlerine entegrasyonunu çalışmakta ve mimari tasarım için hesaplamalı ve bütünleşik bir yöntem geliştirmektedir. Bu yöntem, parametrik tasarım, bina performans simülasyonu (güneş ışığı, enerji, hesaplamalı akışkanlar dinamiği ve kontaminasyon yayılım), ve fiziksel ölçüm (rüzgar tüneli) araçlarının birlikte kullanımını sağlamaktadır. Geliştirilen yöntem, örneklem çalışması kapsamında uygulanmıştır.

Anahtar Kelimeler: Bütünleşik Bina Performans Simülasyonu, Doğal Havalandırma, Kontaminasyon Analizi, Rüzgar Tüneli Testi, Hesaplamalı Akışkanlar Dinamiği





To my family, and to the peace and joy in our minds

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LIST OF ABBREVIATIONS

ABBREVIATIONS

2D	Two-dimensional
3D	Three-dimensional
ACH	Air Change Per Hour
AFN	Airflow Network
ASHRAE	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
BPE	Building Performance Evaluation
BPS	Building Performance Simulation
BR	Blockage Ratio
BREEAM	Building Research Establishment Environmental Assessment Method
CAD	Computer Aided Design
CCL	Contaminant Concentration Level
CCL_{BR}	Contaminant Concentration Level of a Breathing Zone
CCL_{total}	Total Contaminant Concentration Level
CD	Computational Domain
CDC	Centers for Disease Control and Prevention
CEN	European Committee for Standardization
CFD	Computational Fluid Dynamics
CIBSE	Chartered Institution of Building Services
CIE	Commission Internationale de l'Éclairage
C_p	Wind Pressure Coefficient
CTA	Constant Temperature Anemometry
CTBUH	Council on Tall Buildings and Urban Habitat
DGP	Daylight Glare Probability
DLA	Daylight Autonomy
EPW	EnergyPlus Weather File
GR	Contaminant Generation Rate
GUI	Graphical User Interface
HL	Ventilation Sensitive Heat Loss
HVAC	Heating, Ventilation, and Air-conditioning
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
ISO	International Organization of Standardization

LEED	Leadership in Energy and Environmental Design
MAE	Mean Absolute Error
MAPE	Mean Absolute Percent Error
P	Pressure
PAD	Performative Architectural Design
PIV	Particle Image Velocimetry
PMV	Predicted Mean Vote
PR	Perforation Ratio
PT	Pressure Tap
R_{inh}	Inhalation Rate
SC	Scenario Category
SD	Shading Depth
SDK	Software Developer's Kit
SHGC	Solar Heat Gain Coefficient
T_{dis}	Discharge Period
T_i	Indoor Air Temperature
T_{inf}	Time of Infection
T_o	Outdoor Air Temperature
UDI	Useful Daylight Illuminance
VOC	Volatile Organic Compound
VP	Virus Particles
WHO	World Health Organization
WPP	Wind Pressure Profile
Z_o	Aerodynamic Roughness
Z_{ref}	Reference Wind Speed

CHAPTER 1

INTRODUCTION

Architectural design is a complex task requiring interaction and knowledge of diverse domains to fulfill and mediate different performance expectations. The growing environmental crisis has led architects to seek performative architectural design (PAD) strategies for sustainable and healthy buildings. PAD necessitates the knowledge of various domains and integrating building performance practices (i.e., building performance simulation, experimental measurements, and analytical models) into the design synthesis.

Among the building performance practices, building performance simulation (BPS) provides practical instruments to compromise the complexity of PAD by allowing the mediation of distinct performance parameters (Clarke & Hensen, 2015). In the 1970s, computational technologies offered BPS tools, which extended the architects' decision-making capabilities (Malkawi & Augenbroe, 2003). Until the 1990s, BPS was performed at the end of the design process as an assessment tool rather than design guidance. Notably, in the 1990s, the advancements in computational technologies enabled the integration of BPS into the architectural design process at a certain level. Since then, one of the significant aims of performance-driven architectural design has been to provide professionals with BPS-integrated design processes, which require advanced, holistic, and hybrid approaches to attain multiple performance targets.

There is a vast number of studies in the literature focusing on BPS-integrated design processes. The central focus of the existing studies is the seamless integration of energy and daylighting analyses. The integration of natural ventilation and contaminant dispersion analyses is hitherto understudied, despite their potential to provide healthy indoors and reducing HVAC dependency and carbon emissions. As the recent COVID-19 outbreak revealed, there is inadequate ventilation and airborne contamination dispersion problem in shared spaces, which can cause severe health

problems for building occupants due to prolonged and dense occupancy patterns. In this respect, integrating natural ventilation and airborne contaminant dispersion analyses into PAD is particularly urgent and crucial, requiring in-depth investigation.

In respect to

- the existing ventilation and contamination problems,
- urgency in providing healthy environments to occupants,
- limited focus on natural ventilation and contaminant dispersion analyses in the literature, and
- limited integration of natural ventilation and contaminant dispersion analysis into current BPS practices,

this study develops a hybrid, computational, and integrated tool which is a pipeline to support architects' well-informed decision-making regarding ventilation and contaminant-related building performance. The developed pipeline integrates parametric 3D modeling, BPS (daylighting, energy, CFD, and contaminant dispersion simulations), and physical testing (wind tunnel). The pipeline is implemented for a case study (open office located in Ankara), where a number of shading alternatives¹ are designed and evaluated against daylighting, energy, and ventilation-related performance parameters.

1.1 Research Motivations and Problem Statement

Building performance and sustainability as the responsibility of the architect

The research is motivated by the current environmental crisis and the professional responsibility of the actors involved in architectural design practices. The building industry is one of the significant contributors to the negative impact on the environment having over one-third of the total energy consumption, which results in increased carbon emissions and the scarcity of natural resources (Pérez-Lombard,

¹ Shading device design is mainly selected due to its multi-performative characteristics and multiple roles in improving building performance by mediating between indoor and outdoor conditions.

Ortiz, & Pout, 2008). Design and construction activities are inevitable due to society's changing needs and the increase in the population. The building industry has the potential to reverse the negative impact of buildings. By improving energy efficiency, reducing the carbon footprints of buildings should be the building sector's and architects' primary responsibility. Rather than relying only on high-performance building systems, architects need to develop effective design strategies for sustainable and healthy built environments. At this stage, the responsibility of the architectural design profession lies in the development of sustainable and performative design solutions to prevent environmental damage.

There are two significant areas where BPS needs improvements to be involved further in the design process: (a) tool-related “targeting advancements of tool functionality” and (b) process-related “targeting functional integration of simulation tools in the design process” (Augenbroe, 2002). Accordingly, the developed pipeline remains a critical contribution to both tool and process-related areas.

Performative architectural design as an integrated, multi-phase process

BPS was merely analytical, which is considered a post-design evaluation tool (Oxman, 2009). The form generation precedes the performance; thus, the generation-evaluation loop is incomplete (Oxman, 2009). The need for integrating BPS in the design generation has also been addressed by Augenbroe (1994), Eastman (1999), Flemming & Mahdavi (1993), Malkawi et al. (2005), and Shea (2004).

Over the past two decades, the advent of technology provided computational design tools that couples representation, generation, evaluation, and guidance (Kalay, 2004), enabling the seamless integration of building performance simulation and design process. Although the coupling of design generation and BPS, BPS tools still have limited integration to the design tools, requiring a high level of expertise and detailed workflows since the existing simulation tools are not customized for architectural design processes (Malkawi & Augenbroe, 2003).

Performative architectural design is a multi-disciplinary and information intense process

Information has played a crucial role in design processes, particularly in PAD, due to its complex and multi-disciplinary nature. The large volumes of data from the BPS have to be managed, such as the model geometry, building elements, performance metrics and measures, and multidirectional relationships between the design components. Due to the multi-directional nature of the design process, the information should be processed, stored, and maintained in precision, efficiency, and integration. Else, the design process runs the risk of ending with fragmented or missing information.

The limited integration between generation-evaluation in PAD requires the use of different tools for each phase. Depending on the interoperability of the tools, the information transfer runs the risk of being disintegrated or fragmented. Accordingly, an integrated pipeline can respond to the problems of fragmented and missing information and tool isolation. An integrated pipeline can facilitate the architect's control over the complexity of design processes.

Integrated support for performative architectural design

The use of separate and disconnected tools also hampers the integrity and practicality of the design processes, resulting in missing and fragmented information and rudimentary results. However, integrated workflows for PAD can improve the integrity, efficiency, and effectiveness of the design process overcoming fragmented/missing information and facilitate the architects' well-informed decision-making. Parametric tools have been argued as practical supports that can increase control over design, acting both generative and analytical during design exploration (Gürsel Dino, 2012). Parametric tools for PAD have been the focus of architectural practice and research for a decade (Malkawi, 2005). Its utmost state is integrating parametric tools to the existing simulation software via the SDKs (Software Developer's Kit). An example of such integration tools is *OpenStudio* SDK. It is an open cross-platform based on a collection of tools to support building energy

modeling, allowing third-party developers to create their software, codes, and extensions regarding their targets (OpenStudio).

Natural ventilation and contaminant dispersion analysis: urgency for the shared spaces

Indoor air quality (IAQ), natural ventilation, and occupants' health in shared indoor spaces have received increasing attention since the beginning of the 2000s with infectious airborne virus risks such as SARS, MERS, and recently with coronavirus disease (COVID-19, SARS-CoV-2). These pandemic outbreaks highlighted the vulnerability of indoor spaces with inadequate ventilation and high occupancy rates to higher contamination risks. As a result, building occupants run the risk of experiencing health problems such as allergy, asthma, lung inflammation, airborne diseases and breathing problems, lung cancer from radon exposure and carbon monoxide (CO) poisoning (ASHRAE, 2009). Centers for Disease Control and Prevention (CDC) confirmed that airborne transmission is the primary means of COVID-19 spread as a result of coughing, sneezing, singing, talking, or even breathing (CDC, 2020b). Infectious diseases are spread by contact or airborne transmission via virus-laden droplets and aerosols (Pica and Bouvier, 2012). The key determinant of aerosol behavior is the particle size. Unless proper ventilation is provided, particles smaller than 5 μm can remain airborne for indefinite periods (Fennelly, 2020). When inhaled, particles such as COVID-19 deposit in the lower respiratory tract and pose severe risks for occupant health. Natural ventilation is identified in the literature as the most effective means of reducing indoor airborne contaminant exposure (Atkinson et al., 2009; Qian et al., 2010; Zhou et al., 2018). However, the studies focusing on natural ventilation effectiveness on airborne contamination dilution are somewhat limited for shared indoors.

The existing literature focuses on the seamless integration of daylighting and energy. Natural ventilation and contaminant transportation cannot be considered in isolation from other building performance metrics. Integrating natural ventilation and contaminant analysis into PAD as a standard practice is urgent in reducing infection risks in the shared spaces, requiring designerly understanding.

1.2 Objectives

This research argues that an integrated computational pipeline can increase building performance by guiding architects for healthier indoors by integrating natural ventilation and contaminant analysis and their simulation-based and physical testing-based tools into PAD.

The objectives of this research are:

- Developing an integrated computational pipeline using 3D parametric design tools, BPS tools, and physical testing tools to improve building performance data accuracy, precision, and reliability,
- Integrating natural ventilation and contaminant dispersion analysis into a pipeline with daylighting and energy analyses, and
- Improving occupants' wellbeing and building performance by integrating natural ventilation and contaminant transportation analysis into PAD.

Accordingly, within the scope of this research:

- BPS tools and practices are explored and mapped, addressing the existing studies in PAD.
- The concept of the integrated computational pipeline supporting multi-performative design is discussed.
- The components and the requirements for the integrated pipeline are identified and outlined.
- A performance framework guiding multi-performative evaluation is developed.
- The integrated pipeline is implemented for the case study.
- The validation studies are performed for the integrated pipeline based on the case study results.

This research aims not to extend knowledge in BPS or physical testing but to find ways of utilizing hybrid off-the-shelf tools and methods to support PAD.

1.3 Research Questions

The research addresses the main question: How can natural ventilation and contaminant transportation analysis be integrated into PAD?

To answer the main question, there are a number of sub-questions:

1. What is an integrated computational design workflow that can support the integrated use of parametric design, computational and physical testing tools, and methods?

Workflow is an operative sequence of a system where the work passes from the beginning towards completion. It is necessary to develop an understanding of (1) the workflows, requirements, and the components of the existing computational and physical testing tools, methods, and processes, and (2) the existing performance frameworks and parameters involved in the design processes.

2. What are the existing computational tools and methods that address PAD?

To develop an integrated pipeline, it is necessary to review the existing tools and understand their workflows, operations, and functions. Such review offers the exploration and identification of the problems, needs, and gaps in the domain towards implementing the computational and physical testing tools in PAD.

3. What are the requirements and components of an integrated computational pipeline?

A requirement refers to a condition, quality, capability, or performance to which the workflow/model/system must conform (Eeles, 2005), and a component is part of the workflow/model/system that is to encapsulate certain functionality or a set of functionalities (Wang & MacLean, 1998). Both the requirements and the component address the implementation of the pipeline.

4. To which extent does the proposed pipeline successfully support designers in PAD?

To assess the pipeline's integration and operability, first, it is necessary to implement the pipeline for a case study. The case study is regarded as an instrument for the validation of the pipeline. The validation studies have guided the improvements for the pipeline during the research and development process.

5. What are the performance metrics for the natural ventilation and contaminant transportation analysis?

Identifying the performance metrics for the natural ventilation and contaminant dispersion analysis addressing design parameters, boundary conditions, assumptions, and constraints of the PAD is necessary for the development of the pipeline.

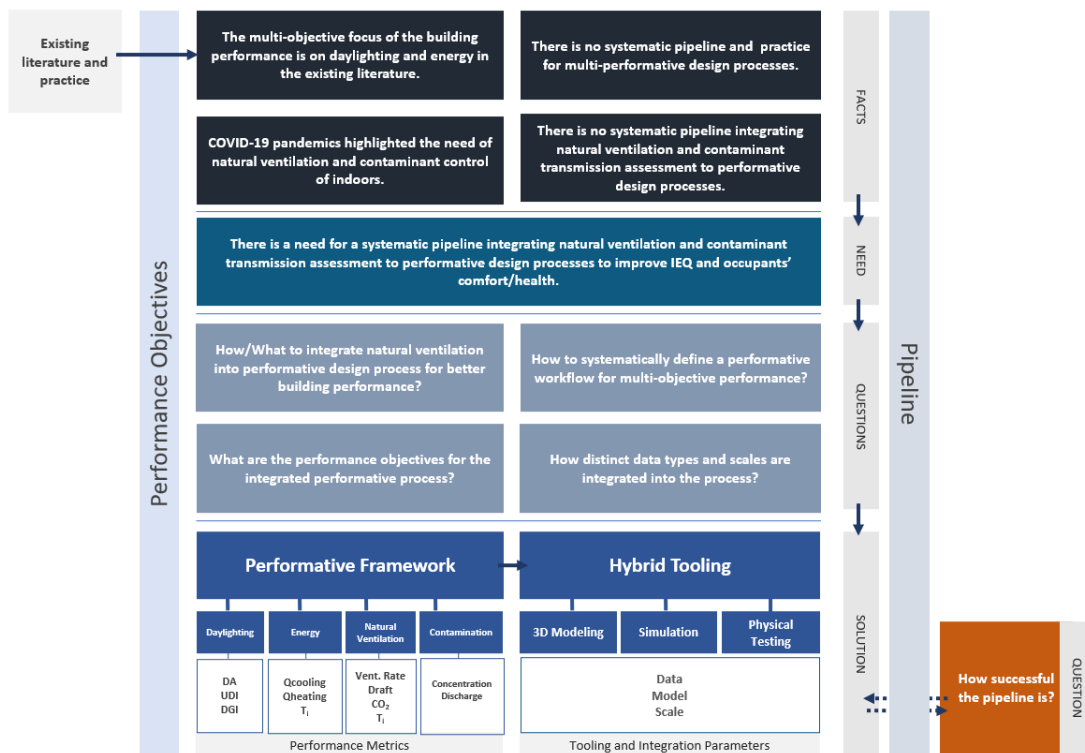


Figure 1.1. Research framework

1.4 Methodology

This research adopts a constructive research methodology, which “[i]s a form of scientific knowledge production that involves the development of innovative constructions, intended to solve problems faced in the real world, and simultaneously makes a kind of prescriptive scientific contribution.” (Dresch, Lacerda, & Antunes, 2015, p. V). According to the same source, constructive research is primarily descriptive and context-related, where the development and evaluation are essential.

Constructive research offers practical solutions called *solution concept(s)* and requires validation and assessment. *Solution concepts* are the models, and methods, which generate knowledge (Dresch et al., 2015).

Constructive research requires (1) design as artifact: a construct, model, or a method to be developed, (2) problem relevance: the development of the artifact providing a solution for the relevant problems in the domain, (3) design evaluation: the artifact to be evaluated against the utility, quality, and efficacy, (4) research contribution: the research process providing clear and verifiable grounds for the artifact, (5) research rigor: the rigorous tools and methods to be applied during the development and the evaluation of the artifact, (6) design as a research process: the available tools and methods in the domain achieving satisfying artifact, (7) communication of the research: the artifact to be presented to both technology and management-oriented audience (Hevner, March, Park, & Ram, 2004).

This research addresses an interdisciplinary approach and a problem experienced in professional and research practice. This research aims to develop and test a suitable solution, which requires the implementation and validation. This research fulfills the abovementioned mandates (Table 1.1):

Table 1.1 Constructive Research Mandates and Proposed Research (Hevner et al., 2004, p. 83)

Constructive Research Mandates	This Research
Design as artifact:	Exploratory integrated, hybrid, computational pipeline/workflow
Problem relevance:	• Integrating natural ventilation and contaminant analysis into an integrated building performance pipeline • Improving IAQ and occupants' wellbeing
Design Evaluation:	Implementation of the pipeline via a case study
Research contribution:	the design workflow that supports performative design synthesis
Research rigor:	Coupling 3D parametric design, BPS, and physical testing tools
Design as a research process:	via the development, implementation, and evaluation of the pipeline by the available tools and methods
Communication of the research:	the pipeline is applicable for both practice and research

Towards the mandates, *construction*, *justification*, and *evaluation* phases should be followed, supporting the development of the artifact by the existing knowledge of the domain (Dresch et al., 2015). This research fulfills the phases as follows (Table 1.2):

Table 1.2 Construction, justification, and evaluation phases

Constructive Research Phases	This Research
Justification	Literature review • Building performance simulation • Natural ventilation and contamination • Existing performance frameworks • BPS and PAD tools
Construction	• the development of an integrated performance framework • the development of the computational analysis pipeline
Evaluation	Validation by implementing the pipeline for a case study

1.5 Research Outputs and Significance

This research is significant for a number of aspects:

(1) This research develops a pipeline that integrates simulation-based and physical testing-based building performance evaluation (BPE) tools. Simulations are reliable and precise means to quantify the change in the system or a process over time and perform analyses for what-if scenarios (Banks, 2000). In architecture, simulations are commonly utilized to quantify a building's response to the changes occurring in its physical environment (de Wilde, 2018). Simulations are significant for natural ventilation and contaminant transmission assessment, as they can calculate the spatial variations of contaminant concentration (Megahed & Ghoneim, 2020). Though, simulation-based methods must be augmented by physical testing methods to increase the precision and accuracy of simulation results. Integrating simulation-based and physical testing-based methods requires mediation for several aspects (i.e., various data types and model scales). Accordingly, this research aims to mediate different

simulation-based and physical testing-based methods to integrate natural ventilation and contaminant transmission assessment for improved building performance.

(2) This research aims to fill the literature gap by developing a hybrid computational pipeline that quantitatively evaluates natural ventilation and indoor air contamination of spaces. Natural ventilation and contamination analysis significantly improve indoor air quality and occupants' health and comfort in indoor environments. However, integrating natural ventilation and contamination as performance metrics into PAD is somewhat limited. In this respect, this research presents an exploratory, hybrid, and integrated design pipeline using off-the-shelf BPE tools to integrate natural ventilation and contamination analysis, aiming to respond to existing problems and improve IAQ, occupants' comfort, and building performance.

1.6 Guide to Reading the Thesis

Following the introductory chapter, Chapter 2 presents an in-depth exploration and the analysis of the existing PAD research. Chapter 2 addresses the main scope and the gap in the literature. First, BPE, natural ventilation, and contamination studies are presented. Then the means and methods of PAD are reviewed.

Chapter 3 reviews the existing performance metrics and presents a performance framework for the integrated hybrid computational pipeline. Chapter 4 describes the integrated pipeline focusing on data integration, computer-based analysis, physical testing, and design integration.

Chapter 5 presents the implementation of the developed pipeline for a case study that facilitates the research's evaluation and validation. The case study scenario and the implementation procedures are discussed. The results of the case study implementation are presented in Chapter 6, presenting and discussing the main findings of Chapter 5. Finally, Chapter 7 summarizes this research's main conclusions and contributions, revisits the research questions, and discusses limitations and challenges.

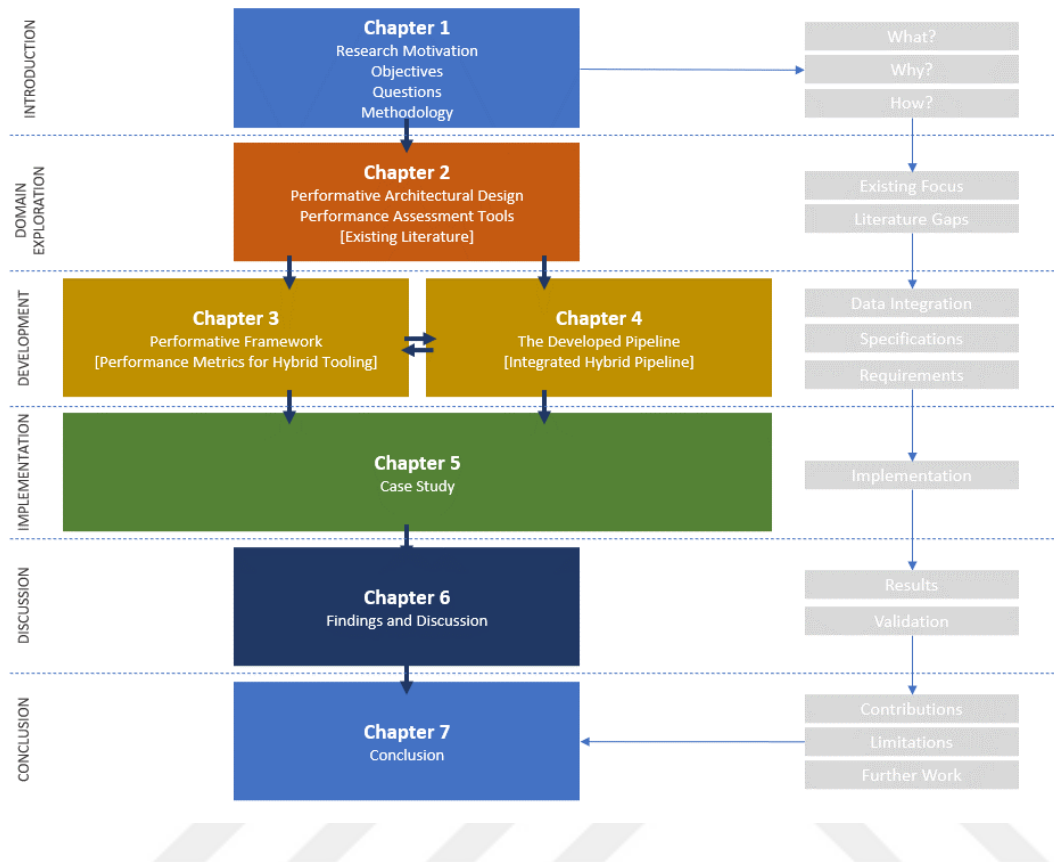


Figure 1.2. Research structure

CHAPTER 2

PERFORMATIVE ARCHITECTURAL DESIGN

This chapter presents the literature review on BPE and PAD, addressing the central focus of the existing studies. Within the scope of BPE, natural ventilation and indoor airborne contaminant studies are reviewed, while BPS tools are reviewed within the scope of PAD (Figure 2.1). The literature review indicated that (1) the central focus of integration studies is daylighting and energy analysis, and (2) parametric design tools are in the utmost state of BPE tools, enabling the integration of BPS into design processes.

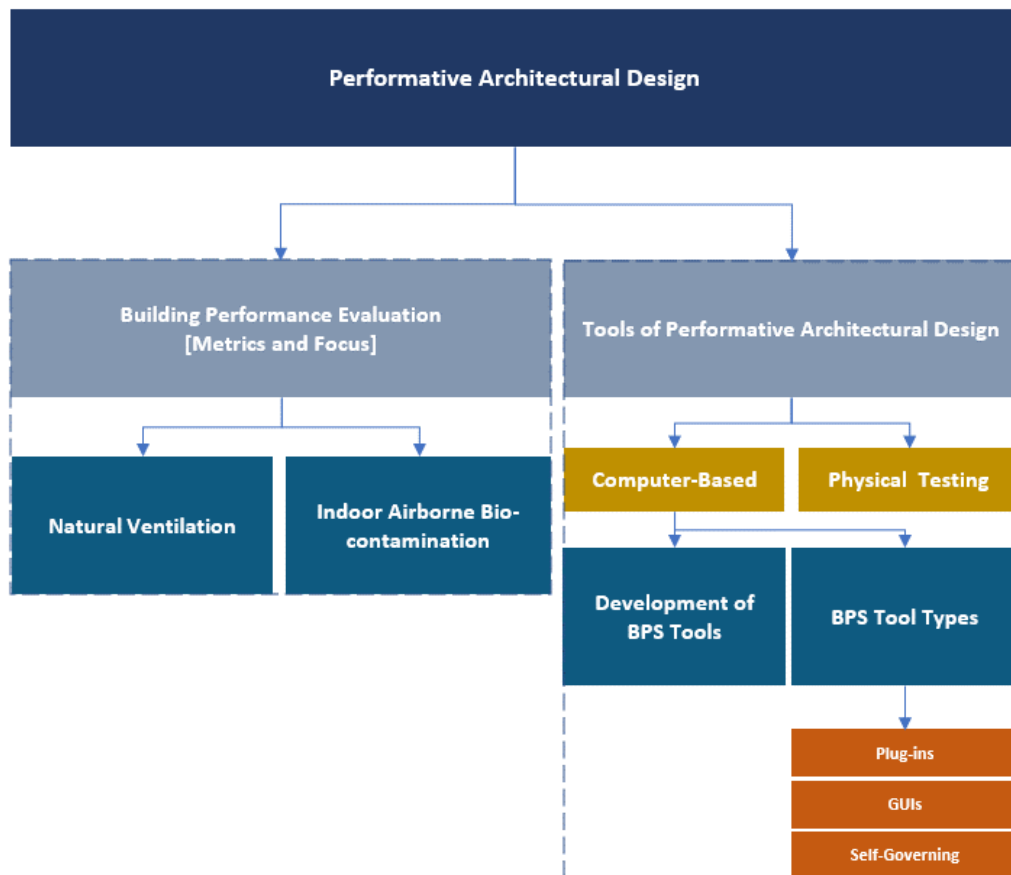


Figure 2.1. Framework for the literature review

Building performance has always been at the focus of architecture in technical and social contexts as a guiding principle of making, designing, and operating (de Wilde, 2018; Kolarevic & Malkawi, 2005). The first accounts of performance as an architectural notion are evident in the principles of Vitruvius, which are still valid today.

Performance is a broad concept due to the complexity of the design process, which ends up with several vague definitions in architecture. Performance in technical terms indicates “the action or process of performing a task or function.” (Oxford Dictionaries, 2018). Based on this definition, a number of building performance definitions are as follows:

- “building performance plays a major role in the expectations expressed by owners and occupants and their fulfillment by designers and building operators.” (Augenbroe, 2005, p. 99)
- “the whole set of basic and intrinsic aims that the end product is expected to satisfy, and the restraining general forces and environmental conditions that may inhibit the attainment of these aims.” (Becker, 1999, p. 525)
- “two kinds of understanding in the theory of architectural performance: the kind that can be exact and unfailing in its prediction of outcomes, and the kind that anticipates what is likely, given the circumstantial contingencies of built work. The first sort is technical and productive, the second contextual and projective.” (Leatherbarrow, 2005, p. 18)
- “the contribution made by a building to the functional and financial requirements of the occupiers and/or owners and the associated physical and financial characteristics of the fabric, services and finishes over time.” (Williams, 2006, p. 435)

Performance, in this research, is defined as *any entity that successfully fulfills its intended purpose*. Therefore, performative architectural design refers to the design

process guided by a set of building performance requirements to provide healthy, safe, and robust environments to the occupants.²

2.1 Building Performance Evaluation

BPE is a practice of ensuring a certain level of quality in the buildings by quantifying and benchmarking the performance measures by the performance thresholds (Becker, 1999; Preiser & Vischer, 2004). BPE is applied towards the lifecycle of the building (strategic planning, programming, design, construction, occupancy, and adaptive reuse/recycling) (Preiser & Schramm, 2005) and supports the architects' decision-making by providing feedback about the building performance.

Building performance can be evaluated by a number of measures such as daylighting, energy, and ventilation. In the literature, a vast amount of research focuses on the simulation, physical testing, and design processes separately, where the design process is not integrated into the performance simulation and testing processes. BPE is placed after the completion of the design phase. A limited amount of research focuses on developing integrated methods for improved building performance (i.e., Teeling et al., 2017; You et al., 2013, Malkawi et al., 2005; El Ahmar et al., 2019).

2.1.1 Natural Ventilation Studies

The existing literature on BPE integration into the design process indicated that the studies mainly focused on the seamless integration of daylighting and energy analysis (Appendix A). Natural ventilation and indoor contaminant analysis and metrics are remained unexplored and understudied in the literature and require urgent and in-depth

² There are a number of terms, which are used interchangeable with performative architectural design such as performance-guided design, performance-driven design and performance-based design. Within the scope of this research, the all mentioned terms refer to the design process, which are guided by a set of building performance requirements (such as thermal, acoustical, and visual comfort). As Kolarevic (2004) stated, "[...] *performance-based design can be indeed defined very broadly – its meaning spans multiple realms, from financial, spatial, social and cultural to purely technical (structural, thermal, acoustical, and so on.). If understood in those terms, performance-based design, or performative architecture, can be furthermore described as a 'metanarrative' with universal aims that are dependent on particular performance-related aspects of each project.*"

investigation. Natural ventilation must be prioritized since it is a passive cooling strategy, which replaces contaminated, stale, and warm air with fresh air and reduces indoor air temperature by wind or buoyancy. Also, natural ventilation is an effective strategy to improve indoor air and environmental quality (IAQ-IEQ) and occupants' wellbeing, which is particularly crucial for shared indoor spaces.

Natural ventilation, IAQ, and occupants' health have received growing consideration with the infectious airborne viruses (i.e., SARS, MERS, and recently COVID-19 coronavirus, SARS-CoV-2) since the beginning of the 2000s. IAQ is directly related to the occupants' health, comfort, and productivity (ASHRAE, 2009) and is determined by the existing pollutants in the indoor air (Bergman, 2012). Good indoor air quality is achieved by providing fresh and clean air to the indoor spaces and fulfilling the required thermal performance criteria (ASHRAE, 2009). Indoor air pollutants, contaminated and stale air, outdoor air pollution, dirt in mechanical ventilation systems, inadequate mechanical and natural ventilation rates (fresh air intake), and infiltration due to airtightness of the façade end up with poor IAQ (Bergman, 2012; Spengler, Samet, & McCarthy, 2001). Poor IAQ has serious consequences; building occupants face health problems such as sick building syndrome, allergy, asthma, lung inflammation, breathing problems, lung cancer from radon exposure, and carbon monoxide (CO) poisoning (ASHRAE, 2009). There are various strategies to prevent poor IAQ; the first is to install harmless and non-toxic materials (Bergman, 2012). Another strategy is the natural ventilation in support of the fresh air intake and the dilution of the airborne contaminants (Allard, 1998), which is realizable passively via operable windows, that also plays a crucial role in occupants' psychological comfort. Natural ventilation also provides thermal comfort by passively cooling the building via the wind (Hartkopf, Aziz, & Loftness, 2012). In conventional constructions, the poorly insulated buildings and the wide use of operable windows on the building façade provided fresh air through infiltration and fenestration (Bergman, 2012). However, due to the airtight insulation materials and the sealed façades of the contemporary buildings, the infiltration and fresh air intake via natural ventilation are reduced and obstructed relatively (Bergman, 2012).

Natural ventilation depends on two factors as (1) the thermal state of the building and (2) the wind characteristics (Allard, 1998); accordingly requires temperature differences between the indoors and the outdoors (buoyancy), wind, and the appropriate physical conditions for the air flow (such as a chimney, or cross-located opening) (Etheridge, 2012). It is measured by the air flow rate, which quantifies how often the air in the space is exchanged with fresh air (per hour). The performance threshold conditions are determined by the indoor environmental quality criteria (Roulet, 2005). The air flow rate through an opening is determined by the wind speed, direction, indoor-outdoor temperature difference, and the opening area (Etheridge, 2012). All such parameters impact IAQ and occupants' comfort and are interdependent. All the openings, positions, areas, operability, or non-operability directly affect the air flow rate (Etheridge, 2012). The changes in wind behavior, magnitude, direction, and flow profoundly affect natural ventilation (Etheridge, 2012). To this end, while designing the ventilation, the architects must account for the interior conditions and the wind behaviour, its unpredictability, and the occupants' behavior during the building operation. However, it can be noted that such practices involve some level of uncertainty and, in parallel, some drawbacks. Despite the profound effects of natural ventilation on IAQ, it may run the risk of being an inoperative strategy for all climates and all conditions. Natural ventilation may neither be efficient, nor healthy for the climates with very high outdoor temperature, high levels of humidity, and air pollution (Allard, 1998; ASHRAE, 2009). For such climates and air conditions, the low-energy mechanical devices can be integrated to the building to attain the requirements for good air and thermal quality (Etheridge, 2012).

Natural ventilation and Building Façade: Building façade is a significant determinant for IAQ and has multiple tasks in improving building performance by mediating indoor and outdoor conditions. Building façade is expected to fulfill the aesthetic criteria for being a visual expression in an urban context, while providing fresh air, adequate daylighting, thermal and acoustic comfort, and occupants' physical and visual access to the outdoor environment, balancing the humidity and draft, temperature, minimizing heat loss/gain, and the prevention from the water penetration (Hartkopf et al., 2012). Building façade is also required to demonstrate integrity with

other building components and the systems such as interior, structural, mechanical, electrical, lighting, and communication systems (Hartkopf et al., 2012). By satisfying the integrity and performance criteria, the building façade provides a healthy indoor environment and improves the IEQ and occupants' wellbeing (Wood & Salib, 2013).

To provide efficient environmental control, the building façades are composed of several layers. Shading devices, the outmost layer of the façade, are widely employed to control excessive solar exposure and provide adequate daylighting. To provide efficient environmental control, the building façade, together with its layers, must be considered a multi-performing system that is designed with all performative aspects.

The existing literature can be grouped based on the research focus as (1) performance of the shading device geometries and (2) natural ventilation performance parameters and frameworks for shading devices. There are also extended reviews in the literature focusing on the performance and performance parameters for the commonly used shading devices (Aflaki, Mahyuddin, Al-Cheikh Mahmoud, & Baharum, 2015; Freewan, 2016; Kirmat, Kundakci, Chatzikonstantinou, & Sarıyıldız, 2016). A large number of studies focus on the impact of (1) shading device geometry/configuration on natural ventilation performance. The studies address overhangs, egg-crates, and louvers as commonly used shading device geometries. Bayraktar and Ok (2019) performed wind tunnel experiments for four distinct louver configurations (louvers parallel to the façade with 45° and 90° slat angles and shading device perpendicular to the façade with 45° and 90° slat angles) for a generic office space. Sacht (2016) conducted wind-tunnel experiments for ventilated window sill configuration on a modular façade. Hien and Istiadji (2003) performed daylighting and CFD analysis to investigate the impact of the seven types of shading devices on daylighting and natural ventilation performance in residential buildings. Lin et al. (2017) studied the impact of shading devices on thermal comfort and ventilation by using thermal imaging, in-situ measurement, and CFD for an existing office block. Kosutova et al. (2019) performed CFD and wind tunnel experiments for cross-ventilation to investigate the impact of window openings' position with louvers on indoor airflow and air exchange. Liping and Hien (2007) investigated the optimum shading dimensions by coupled energy and CFD simulation for an existing building in a hot-humid climate for night-

time only ventilation, daytime only ventilation, full-day ventilation and no ventilation. Tablada et al. (2009) investigated the impact of louvers on indoor thermal comfort by the Predicted Mean Vote (PMV) method by performing CFD-integrated energy simulations focusing. The abovementioned studies focused on single-skin façades. There are also several studies focusing on double-skin façade. De Herde and Gratia (2007) investigated suitable placements for louvers located in the double skin cavity by employing energy simulations. Lee et al. (2015) investigated the influence of horizontal and vertical shading device configurations (slate angle configurations as 0°, 30°, 60°, and 90°) in the façade cavity on air temperature, the air velocity, and the annual energy consumption by performing CFD simulations.

Similarly, Da Silva et al. (2015) investigated the impact of movable venetian blinds on indoor air via wind tunnel tests and tracer gas methods. Lee and Chang (2015) further investigated shading devices by means of acoustic performance coupled with natural ventilation performance. Elshiwihy and Chaudhry (2019) focused on the impact of external (baseline, overhang, vertical louvres, horizontal louvres and egg-crates) and internal (vertical internal louvres, roller blinds, venetian blinds and light shelves) shading devices on daylighting factor, cooling load and total energy reduction. They performed daylighting, CFD and energy simulations.

A number of research highlight the lack of uniformity in (2) design and performance frameworks, particularly for shading devices. Bellia et al. (2014) investigated the existing shading device classification focusing on design and performance parameters. Kirmat et al. (2016) conducted a comprehensive review of existing external shading devices and the computer-based performance simulation tools. The study aimed to designate the performance aspects of the commonly used shading devices as fixed (overhangs, horizontal louvers, vertical louvers, and egg-crate) and moveable (venetian blinds, vertical blinds, roller shades, and deciduous plants). Chaudhary et al. (2019) investigated the performance of venetian blinds for fully glazed façades for visual (useful daylight illuminance- UDI) and thermal environment (annual heating, cooling, and lighting) via simulations for distinct shading control scenarios. Van Moeseke et al. (2007) investigated architectural design guidelines for overhangs and

external blinds focusing on thermal comfort and natural ventilation by shading control/management strategies.

2.1.2 Indoor Airborne Bio-Contamination Studies

Existing indoor airborne bio-contamination studies mainly focused on the aerodynamic behavior of airborne bio-contaminants through the relation between contaminant dispersion/transmission and ventilation/airflow patterns. Li et al. (2007) investigated the relationship between infection transmission and ventilation rates and underlined the strong correlation between contaminant dispersion and ventilation. Ben-David and Waring (2016) compared the performance of natural ventilation with mechanical ventilation in the dilution of indoor contaminants and its influence on energy consumption.

Previous research specifically focused on airborne infection transmission in healthcare buildings. Aliabadi et al. (2011) studied ventilation in healthcare buildings within the scope of infectious airborne transmission. Qian et al. (2010) studied cross-infection risks of airborne diseases via natural ventilation for a hospital. They found that natural ventilation has a higher capacity to reduce transmission risks than mechanical and hybrid ventilation. Zhou et al. (2014) studied the effectiveness of contaminant dilution for natural ventilation in hospital buildings and concluded that larger windows offer better ventilation and lower contamination. Despite previous studies focusing on healthcare buildings, research on contaminant dispersion in public indoor spaces is limited. Public indoor spaces require in-depth investigation since they are relatively more vulnerable to infection risks than healthcare buildings due to lower ventilation rates (Morawska et al., 2020). In healthcare buildings, since the focus is on the patients' well-being, monitoring ventilation effectiveness and IAQ is a widespread practice (Morawska and Cao, 2020).

Additionally, in healthcare buildings, ventilation effectiveness and IAQ are regulated by infection control procedures and guidelines defined by organizations such as the World Health Organization (WHO) (Atkinson et al., 2009). Also, with the widespread use of mechanical ventilation and dense occupancy patterns in public indoors,

particularly in offices, airborne contamination becomes a vital problem. In high-rise office buildings, sealed façades and mechanical ventilation are usually preferred over user-operated natural ventilation due to concerns of safety, operational difficulties of hybrid ventilation (in mixed-mode buildings), and possible conflicts regarding different comfort expectations of occupants (Wood and Salib, 2013). However, research shows that mechanical ventilation can accelerate contaminant dispersion by recirculating the indoor air and possibly increasing air humidity through the stagnant water in mechanical devices (Fink and Gilman, 2000).

Recently, the COVID-19 (SARS-CoV-2, coronavirus) outbreak placed a greater need to study contaminant-related risks in indoor spaces. Therefore, an abundant number of contamination research address COVID-19 and the built environment. Bhagat et al. (2020) explored the impact of mixing ventilation, natural and mechanical displacement ventilation, and wind-driven ventilation on the distribution, transportation, and fate of airborne contaminants. They concluded that displacement ventilation could reduce the exposure risk due to the stratification based on the indoor temperature differences (Bhagat et al., 2020). Lipinski et al. (2020) reviewed the common ventilation strategies for reducing infection transmission and confirmed that the central ventilation and recirculation systems contribute to the rapid spread of airborne infections and recommended natural ventilation to provide safer indoors. Ren et al. (2021) compared three airflow behaviors based on the various configurations of the inlets and outlets ((1) inlet-outlet on the same wall, (2) inlet-outlet on the opposite walls, (3) one inlet on the ceiling, and two outlets on the sidewalls) for a hospital ward and their impact on COVID-19 dispersion. Although their research focuses on a mechanically ventilated space, the inlets–outlets’ various positions contribute to understanding the relationship between ventilation and the built environment. Among the three inlet-outlet configurations, Ren et al. (2021) concluded that the inlet-outlet on the same wall located on the upper and the lower diagonal corners of the wall is the best performing option for contaminant removal. Abuhegazy et al. (2020) investigated aerosol transport and surface deposition in a classroom. They explored the impact of the particle size, aerosol source location, glass barriers, and opening the windows while the air conditioning runs. Although they study a mechanically ventilated room, their

recommendations and experimental setup could provide insights into the contaminant discharge by natural ventilation. They have confirmed that the air-conditioning system increased the contaminant concentration, opening windows while the air conditioning runs contribute to the particle removal, and the transmission behavior changes notably concerning the contaminant's location (Abuhegazy et al., 2020). Melikov (2020) underscored the importance of ventilation on airborne virus transmission and recommended an urgent paradigm shift in ventilation strategies. A large number of COVID-19 research focuses on the prevention strategies to reduce COVID-19 transmission. Awada et al. (2021) addressed indoor environmental quality concerning the occupants' health and presented strategies, challenges, and research opportunities for enhancing the built environment for healthy indoors. They recommended further research focusing on building and occupant-related parameters addressing heating, ventilation, and air-conditioning (HVAC) design and operations, humidity, spatial configuration, and human-building interactions (Awada et al., 2021). Coccia (2020) investigated preventive infection risk measures on an urban scale to reduce the built environments' vulnerability to the COVID-19 and future epidemics and pandemics. Megahed and Ghoneim (2020) highlighted the importance of the built environment in COVID-19 transmission. They reviewed the potential strategies such as improving ventilation, filtration, and UV-based systems to reduce indoor transmission risk. Similarly, Aghalari et al. (2021) reviewed the COVID-19 transmission and discussed preventive measures such as physical distancing, personal hygiene, ventilation, and air filtration for healthcare buildings. Melikov et al. (2020) presented intermittent occupancy and ventilation as a combined strategy to reduce viral exposure for a typical classroom and recommended continuous clean-air supply and short breaks of the occupancy every hour. Similarly, Zhang et al. (2021) proposed an occupancy-aided ventilation strategy to reduce infection risk and increase work productivity for a classroom and recommended shorter and reduced occupancy. The other foremost focus in the literature is the relationship between mechanical ventilation and COVID-19 dispersion. Borro et al. (2020) discussed the impact of air conditioning on COVID-19 transmission and proposed computational fluid dynamics (CFD)-based simulations to optimize air-conditioning. Guo et al. (2021) reviewed the HVAC operation

guidelines of different countries during COVID-19 and compared outdoor air, operation of HVAC systems, temperature and humidity setpoints, pressure differentials, filters for HVAC, air cleaning, and heat recovery equipment as the COVID-19 countermeasures. Pease et al. (2021) investigated potential aerosol transmission via central ventilation systems by two scenarios with indoor and outdoor contaminant sources to evaluate filtration, air change, and outdoor air fraction. Existing research mainly focuses on the transmission prevention strategies and the relationship between mechanical ventilation and COVID-19 airborne dispersion. There is a gap in the literature on the integration and investigation of the impact of natural ventilation and built environment on COVID-19 airborne transmission.

2.2 Tools of Performative Architectural Design

Numerous BPE methods and tools have been advancing in parallel to the improvements in computational technologies. BPE tools quantify how well a building meets its performance requirements through experimentations and measurement (de Wilde, 2018). Performance quantification can be performed through (1) physical testing and measurement, (2) calculation and simulation, (3) expert judgment, and (4) stakeholder assessment (de Wilde, 2018). Among the performance quantification methods, (1) physical testing and measurement, and (2) calculation and simulation can be performed during the design process, where there is no physical access to the building (de Wilde, 2018).

As a classical approach, physical testing and measurement can be performed for an actual building under actual conditions by the observation, a scaled building model, or a part of a building as a mock-up under the controlled conditions of a testing setup (de Wilde, 2018). On the other hand, calculation and simulation can be performed for virtual building models by employing mathematical models that describe a system's physical behavior (de Wilde, 2018). There is also a slight difference between calculation and simulation. The calculation can be performed for typical equations up to ten variables, whereas simulations can be performed beyond ten variables (de Wilde,

2018). In this respect, simulations facilitate relatively more complex physical processes as compared to calculations. Also, simulations are as reliable, practical, and less costly as physical testing and measurements.

Furthermore, with the technological developments in informatics, the application and the domain of simulation technologies have grown wider and become more integrated into the engineering and architectural design generation (Clarke & Hensen, 2015). However, simulations must be augmented by physical testing to increase precision and accuracy in performance results.

2.2.1 Development of BPS Tools

The development of computer technologies has profoundly affected PAD by offering BPS (Augenbroe, 2002). BPS refers to the simulation-based methods used to quantify the performance of the building towards performance aspects (Touloupaki & Theodosiou, 2017b) and involves diverse disciplines such as physics, mathematics, material science, and computational sciences (Clarke & Hensen, 2015). The objective of BPS is to conduct BPE to support designers with well-informed design decisions (Augenbroe, 2002). With computers, BPS facilitated BPE processes and provided a better understanding of the building performance. However, in conventional BPE processes, BPS tools are employed at the end of the design process, resulting in premature design decisions. In this respect, there is a need for BPS starting from the early design stages, where performance feedback for various aspects of the building is available for the entire design process to enhance building performance (Augenbroe, 2002; Clarke & Hensen, 2015). This integration also supports the architects' decision-making and facilitates the architects' integration in performative architectural design processes.

There is a need for interoperability and expertise for BPS-integrated design processes for multiple-criteria performance assessment, which involves various simulation tools and data transfer between the design and BPS tools (Clarke & Hensen, 2015; Garcia & Zhu, 2015; Lin & Gerber, 2014). Such integration requires seamless data transfer;

if not, there is a risk of missing or fragmented data (Garcia & Zhu, 2015). Furthermore, each BPS tool requires a tool-specific simulation model, which is also a time-consuming and tedious task that requires expertise in using the tools. In this respect, the ultimate aim of the BPS is to provide high integrity representation which is a dynamic, real-time, integrated and non-linear process, which couples the different BPS and performance criteria to perform BPE (Clarke & Hensen, 2015). To meet this need, there are diverse strategies, such as using the BPS tools of the same developer (i.e., using Revit and Green Building Studio from Autodesk Inc.) or a single platform that can integrate design and a number of BPS tools, which is regarded as an optimal solution (Garcia & Zhu, 2015). In this respect, this section reviews the earlier and current attempts to develop the BPS-integrated design process.

2.2.1.1 Early Attempts for Integration

BPE and BPS tools have been developing since the 1960s. The advancements in BPS tools are categorized as (1) R&D applied, (2) function complete, (3) interoperable, (4) code-shared, (5) design integrated, (6) web-enabled, and (7) pervasive/invisible tools (Figure 2.2) (Augenbroe, 2002). The earliest application of BPE was performed by the *calculations* in the late 1960s (Augenbroe, 2002). The computer-based BPE dates back to the development of the first computer-aided design platform by Sutherland (1963) (de Wilde, 2018). However, the maturation of the computer-based BPE dates back to the 1970s (Augenbroe, 2002). The first attempts at BPS are based on the differential-algebraic equations (DAE) derived from the laws of thermodynamics (de Wilde, 2018). Until the development of the generic simulation platforms, the simulation codes such as DOE-2, ESP-r, and TRNSYS were dominating the BPS domain (Malkawi & Augenbroe, 2003). The advancements in computation technologies, particularly object-oriented programming, offered modularity to BPS, enabled the development of code-sharing platforms (i.e., EKS, SPARK, and IDA) (Malkawi & Augenbroe, 2003). With the abundance of diverse codes, there appeared a need for *interoperability* between the tools. Responding to the need for interoperability, shared cross-application models (also known as building product models and BIM models) were

developed to integrate the tools and platforms (Eastman, 1999). COMBINE Project (Computer Models for the Building Industry in Europe) is accounted for being one of the most significant contributions aiming at the development of *intelligent integrated building design systems (IIBDS)* (Augenbroe, 1994). IIBDS enabled the evaluation of the diverse performance characteristics of a building (Augenbroe, 1994). Similarly, MODELICA, STEP, ARMILLA, and IBPM are other attempts to respond the need for the interoperability (Mahdavi et. al., 1997; Malkawi & Augenbroe, 2003). Such developments partially met the need for interoperability.

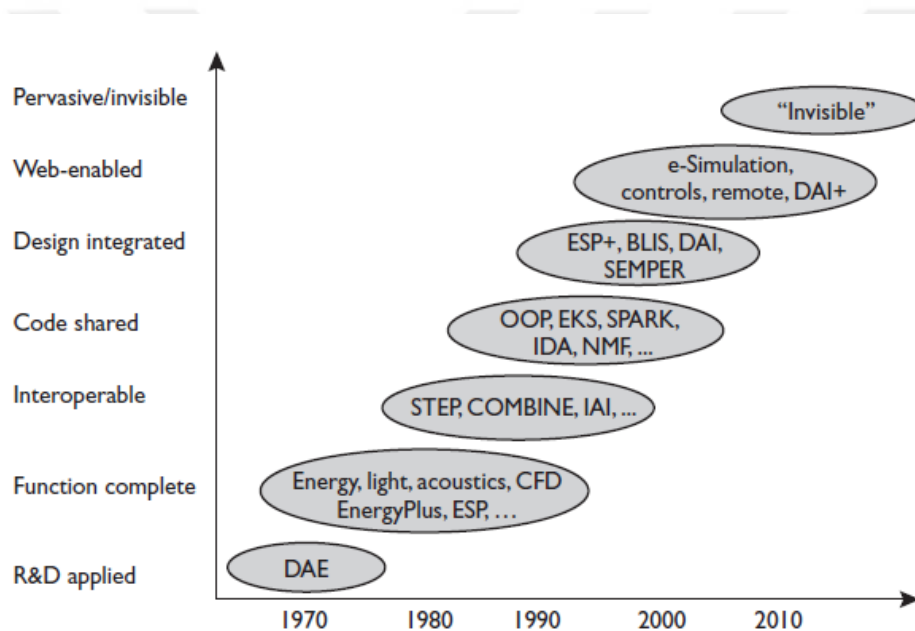


Figure 2.2. Timeline for building performance simulation (Augenbroe, 2002)

The late 1990s and the early 2000s can be regarded as a milestone for design integrated BPS, seamlessly couples BPS and design generation tools and processes. Until then, BPE was performed after the design process as an evaluation-oriented analytical rather than a design-informative practice. Becker (1999) emphasized the significance of the design generation by stating

“[t]he art of design starts with the generation of several alternative new ideas and ends with the detailed development of one of them. In

contrast to evaluation tools that rely on data from generated solutions, performance-based design tools should support the integration of suitable performance driven solutions into the first round of relevant alternatives and then into the further rounds of refinements, while the designer performs the creative tasks associated with generating the solutions. This requires the development of a comprehensive performance-integrated design platform, in difference from an evaluation shell, that can serve as the designer's working environment throughout the whole design process.” (Becker, 1999, p. 528).

There have been many tools developing in this regard; particularly, the development of SEMPER and eifForm is remarkable due to the earliest attempts to realize the performance-guided design generation. Flemming and Mahdavi (1993) addressed the limitations of the existing BPE tools, mainly due to the inadequacies and incompatibilities (lack of interoperability) of the available tools, which does not support the design process (Mahdavi et al., 1997). SEMPER is developed upon such limitations and offers the parametric analysis of the designs against the multiple performance criteria (Mahdavi et al., 1997). In this respect, SEMPER enabled the architect to dynamically interact with the design and evaluation process and observe the *bi-directional* relations and interdependencies of the design variables and performance criteria (Flemming & Mahdavi, 1993; Mahdavi et al., 1997). Exploring the bi-directional interactions potentially implies the earlier versions of the feedback cycle of the generative design processes (represent-generate-evaluate-feedback). SEMPER also provided a “seamless and dynamic communication between the simulation models and the architectural design representation” and partially responded to the integration and interoperability problems (Mahdavi et al., 1997, p. 355).

Shea (2004) proposed *eifForm* as a performance-based generative tool with similar concerns. The main objective of the *eifForm* is the generation of new forms and guiding the design process by having real-time feedback on their performance (Shea, 2004). *eifForm* is based on the structural shape grammars, aiming to converge to improved designs by the stochastic search, satisfying structural efficiency, material

use, uniformity, and form (Shea, 2004). *eiForm* also enables manipulating the form and structure in parallel, improving the initial design through the repetitive modification regarding the performance criteria (Shea, 2004). GENE_ARCH (Caldas, 2008) and EPPD (Janssen, 2009) can be regarded as two of the earliest examples of performance-driven design optimization tools performance (Lin & Gerber, 2014). Similarly, ParaGen provides a customized workflow that combines a number of tools to foster a parametric form search based on performance criteria (Von Buelow, 2012). However, they do not support rapid feedback and design flexibility (Lin & Gerber, 2014).

2.2.1.2 Performance-Driven Parametric Design Generation

Following, the advanced computation technologies in architecture have profoundly impacted the integration of BPS into the design processes by parametric design tools (Oxman, 2017a). Parametric design tools offer effective visualization (communication), analysis (evaluation), and generation (design synthesis) (Kalay, 2004), enabling the articulation of the generative logic led by algorithms (Kolarevic, 2000). The design practice has grown into dynamic exploration, transformation, and a continuous search. The design act shifted from form-making, which is a static and traditional form generation process based on the decisions of the designer, to form-finding, which is the exploration of forms directed by algorithms by generation-evaluation-feedback based on the predefined design criteria (Kolarevic, 2000; Leach, 2009; Woodbury, 1991). In this respect, parametric design tools have had a drastic impact on PAD, supported the multifaceted and integrated design process (Menges & Ahlquist, 2011).

The development and extensive use of parametric design tools are due to the developments in visual programming. Visual programming refers to the systems that enable the user to develop a code based on graphical demonstration (connecting blocks with diverse functions that define the procedure), as an alternative to textual languages (Myers, 1986). Adopting visual programming in design practices provided architects a visual coding environment for the design representation, generation, manipulation,

evaluation, and documentation of the entire design process (Jansenn & Chen, 2011; Oxman, 2017b). The component-based nature of such tools provided a higher-level description of the tasks, a rich and flexible ground to develop and customize design workflows, which supports the exploratory architectural design practice (Han, Huang, & Zhang, 2018; Jansenn & Chen, 2011). Also, visual programming provided interactive, simplified, and user-friendly design environments, increasing designers' integration into the parametric design process (Touloupaki & Theodosiou, 2017).

The flexibility of the visual programming also enabled diverse areas to be integrated into the design process. The current efforts in this field are for integrating BPS tools in design generation are due to the development of the simulation plug-ins for performative architectural design (Figure 2.3) (Oxman, 2017b; Teeling et al., 2017). Simulation plug-ins expanded the capabilities of the parametric tools, enabled the coupling of the generation, and evaluation in the architectural design synthesis, and facilitated the automation of the geometric modifications, which are informed by the optimization and iterative evaluation processes (Oxman, 2017b). To this end, visual programming and parametric design tools efficiently enabled the integration of BPS and the design process, which paved the way for performance-driven design exploration.

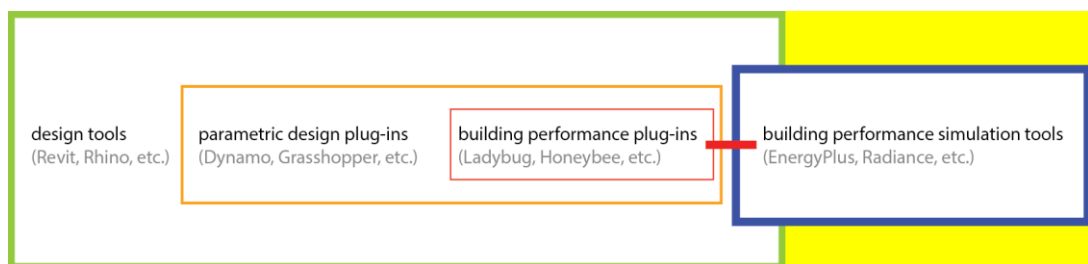


Figure 2.3. The workflow for the design tools that are coupled with parametric design and BPS simulation plug-ins

2.2.2 BPS Tool Types

In architectural design, there are **three groups of tools** as (1) design (CAD) tools (i.e., Rhino, Revit, and SketchUp), (2) simulation tools (i.e., EnergyPlus, Ansys Fluent, and Radiance), and (3) derivative tools and simulation plug-ins (i.e., Grasshopper and Dynamo) (Han et al., 2018).

In the literature, the **relationship between the BPS and design tools** are grouped as (1) design tools are coupled with outside simulation tools via simulation plug-ins (i.e., Ladybug Tools), (2) graphical user interface (GUI) for simulation engines (i.e., DesignBuilder), and (3) self-governing simulation tools (i.e., MIT Advisor) (Han et al., 2018).

There are two different **types of integration** accounted for the existing tools in the literature as (1) simulation-based design optimization, seamlessly integrates BPS tools and optimization algorithms (i.e., EnergyPlus and BeOpt coupling), and (2) performance-driven parametric design synthesis, which integrates parametric design tools and simulation tools by plug-ins (Grasshopper and Ladybug Tools) (Østergård, Jensen, & Maagaard, 2017).

In this thesis, design tools coupled with outside simulation tools via simulation plug-ins are studied for performance driven parametric architectural design.

CHAPTER 3

INTEGRATED PERFORMANCE FRAMEWORK

This chapter presents an integrated performance framework for the pipeline focusing on the natural ventilation, daylighting, and energy performance parameters. The below-mentioned performance metrics are used in the implementation phase of this research. The performance metrics are selected based on the available tools. The developed performance framework can be expanded with different tools. Similarly, additional performance measures relating to natural ventilation, energy, and daylighting can be integrated.

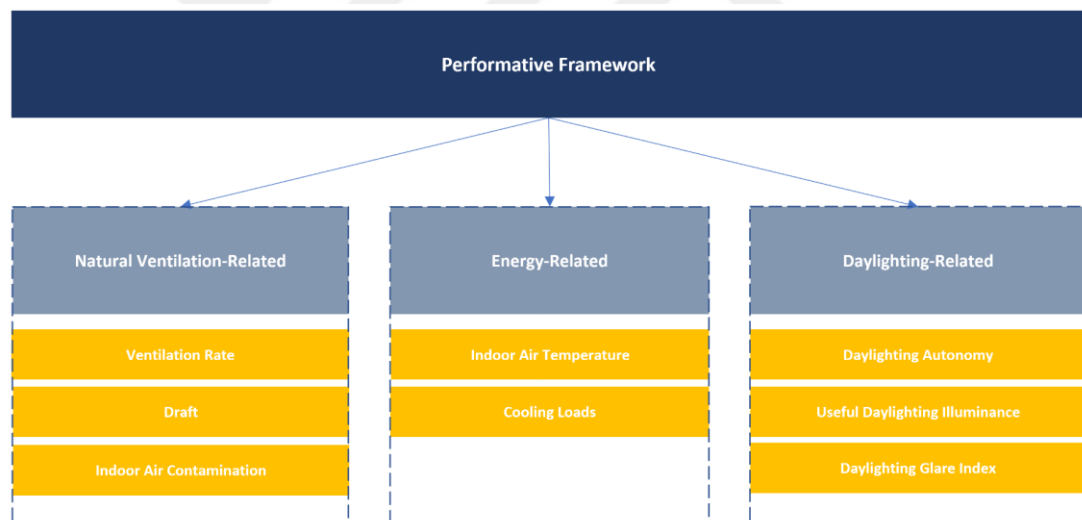


Figure 3.1. The performance framework focus

A performance framework is regarded as a guideline aiming to fulfill performance requirements used to determine how a building is functioning (de Wilde, 2018). Building performance parameters cannot be regarded in isolation. Particularly in integrated BPE, there is a need to evaluate multiple performance parameters, therefore a need for the evaluation framework for various performance aspects (Augenbroe &

Park, 2005). To meet this need, a number of conceptual frameworks, legal building codes, building certification frameworks have come into practice by NGOs, governmental and commercial bodies, such as habitability framework (Preiser & Vischer, 2004), total building performance (Hartkopf et al., 1986), Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM), The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), and International Organisation of Standards (ISO). Each framework has defined its specific performance measures and benchmarking processes. Despite the vast amount of frameworks and regulations, there is no consistent and standard set of performance metrics available for integrated building evaluation (Clarke, 2015).

Communicating multiple performance metrics is particularly crucial for indoor environmental quality (IEQ). IEQ ensures healthy, comfortable, and safe indoor environments to building occupants and directly relates to the performance metrics of air quality, lighting, and thermal conditions (USGBC, 2014). Building façade has a considerable influence on IEQ by defining air quality, lighting, and thermal conditions by acting as a mediator between indoor and outdoor. However, no established performance framework measures the impact of the building façade on the indoor environment. Accordingly, this research aims to present a performance framework focusing on the relationship between the building façade and indoor environmental quality to benchmark/quantitatively predict/assess the future performance and support the architect's decision-making process.

The performance metrics are determined based on de Wilde's (2018) summary of Hartkopf et al.'s (1986) overview of the performance criteria. The summary consists of six building performance criteria: building integrity, IAQ, visual, spatial, thermal, and acoustic performance. Among them, IAQ, thermal performance, and visual performance metrics are reviewed. IAQ is based on air, air movement, distribution, mass pollutants, energy pollutants, occupant factors, and controls. Thermal performance is based on air temperature, radiant temperature, humidity, air speed, occupant factors, and controls. Visual performance is based on ambient and task levels, contrast and brightness ratios (glare), color rendition, view/visual information,

occupant factors, and controls. Accommodating multiple performance criteria is often counterproductive and challenging, hampers the BPE process (de Wilde, 2018). In this respect, a number of performance metrics are selected among the abovementioned metrics and grouped as (1) natural ventilation-related, (2) energy-related, and (3) daylighting-related parameters (Table 3.1). de Wilde (2018) also provides strategies for each metric based on *aspect-function-performance requirement* to turn the building performance aspect into a function to fulfill the performance criteria. Based on this, a performance framework is developed following a quantify-benchmark-define strategy.

Table 3.1 Developed performance framework

Natural Ventilation-related	Aspect	Verb (function)	Performance Requirement	In this research to: Quantify-Benchmark-Define
Ventilation rate (l/s/p)	Fresh Air	Provide	Quality	Quantify: Fresh air Benchmark: with IAQ guides Define: Adequacy
Indoor Airflow Velocity-Draft (m/s)	Air Velocity	Control	Quality	Quantify: Air velocity Benchmark: with IAQ guides Define: Indoor draught state
Indoor Air CO ₂ (ppm)	Stale Air	Dispose of	Quality	Quantify: Amount of CO ₂ Benchmark: with IAQ guides Define: Ventilation rate
Indoor Air Contamination (#/m ³)	Contaminated Air	Dispose of Stop spreading of	Quality Readiness	Quantify: Amount of particles Time of discharge Benchmark: with uncontaminated room conditions Define: Concentration level
Energy-related	Aspect	Verb (function)	Performance Requirement	In this research to: Quantify-Benchmark-Define
Indoor Air Temperature (°C)	Air Temperature	Control	Quality	Quantify: Temperature Benchmark: with IEQ Define: ΔT , Cooling/Heating impact of natural ventilation
Heating-Cooling Loads	Heating Cooling	Provide	Workload capacity	Quantify: Amount of energy to heat/cool the space before (state 1) and after (state 2) the design intervention

Table 3.2 Developed performance framework (continued)

				(i.e., ventilation sensible heat loss for cooling periods) Benchmark: S1 and S2 Define: Cooling/Heating impact of natural ventilation
Daylighting-related	Aspect	Verb (function)	Performance Requirement	In this research to: Quantify-Benchmark-Define
Daylighting Autonomy	Daylight/Sunlight	Provide	Workload capacity	Quantify: percentage of the time above the illuminance threshold Benchmark: with IEQ guides Define: Adequacy
Useful Daylight Illuminance	Daylight/Sunlight	Provide	Workload capacity	Quantify: percentage of the time between 200-1000 lux Benchmark: with IEQ guides Define: Adequacy
Daylighting Glare Probability	Glare	Prevent Protect from/Limit	Quality	Quantify: Excessive daylight Benchmark: with IEQ guides Define: Glare probability

The selected performance metrics are reviewed for open offices and presented in detail based on ISO (International Organisation for Standards), CEN (European Committee for Standardization), CIBSE (Chartered Institution of Building Services Engineers), and ANSI/ASHRAE (American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers) guidelines.

3.1 Natural Ventilation-Related Parameters

Natural ventilation metrics are selected as ventilation rate, indoor air velocity/draft, and indoor air contamination levels based on the available simulation and testing outputs. The ventilation rate is calculated by the CFD or wind tunnel-integrated energy simulations. Indoor air velocity is calculated by CFD or wind tunnel testing. Indoor air contamination is calculated by CFD/wind tunnel testing and energy integrated contaminant dispersion simulations.

3.1.1 Ventilation Rate

The ventilation rate is the amount of fresh air that flows per unit time depending on the wind characteristics (wind speed, direction, wind pressure distribution) and the opening geometry for wind-induced scenarios (Etheridge, 2010). Ventilation rate is a critical parameter for occupants' well-being, indicating the adequacy of the ventilation per person (CIBSE, 2016).

Ventilation rate is calculated in terms of (1) flow rate per person (l/s/p) in occupied spaces and (2) volumetric flow rate ($\text{m}^3 \cdot \text{s}^{-1} / \text{m}^2$) in contaminated spaces (CIBSE, 2016). There are a number of ventilation standards such as *ANSI/ASHRAE 62.1-2013*, *CIBSE Guide B2-16 b* and *BS EN 15780:2011* and *EN 13779:2007* that indicate the adequate ventilation rates for acceptable IEQ (Table 3.3). In these guides, the ventilation rates are expressed as flow rate per person (l/s/p). In *ANSI/ASHRAE 62.1-2013*, the minimum ventilation rate for the office spaces is identified as 8.5 l/s/p to fulfill air class 1. In *EN 13779:2007*, the minimum ventilation rate per person for certain air classes are 20 l/s/p for high IAQ, 12.5 l/s/p for medium IAQ, 8 l/s/p for moderate IAQ and 5 l/s/p for low IAQ (CIBSE, 2016; EN 13779, 2007). In *CIBSE 2016*, the minimum ventilation rate for the office spaces is indicated as 10 l/s/p.

Table 3.3 Air classes and flow rates per person

Code	Flow rate per person (l/s/p)	Air Class/IAQ Class
ANSI/ASHRAE 62.1-2013	8.5	Air Class 1
EN 13779:2007	20	High (IDA1)
	12.5	Medium (IDA2)
	8	Moderate (IDA3)
	5	Low (IDA4)
CIBSE 2016	10	Minimum

Ventilation rate is also measured by air changes per hour (ACH), which indicates the number of times per hour that the entire air is changed (CIBSE, 2016). ACH is obtained as the ratio of the flowing fresh air volume through space in an hour divided by the volume of the space (Atkinson, Chartier, Pessoa-Silva, Jensen, & Li, 2009). The ventilation rate typically ranges from 5 to 15 ACH (CIBSE, 2016), and are calculated as in Table 3.4.

Table 3.4 Measures and equations

Measure	Equations	Notes
Flowrate (CIBSE, 2016; CoolVent, 2019)	$Q = C_d A_w V_r \sqrt{\Delta C_p}$ and $A_w^{-2} = (A_1 + A_3)^{-2} + (A_2 + A_4)^{-2}$	where C_p is the wind pressure coefficient, V_r is the upstream wind velocity, A_w is the area of the openings, C_d is the discharge coefficient (ranging from 0-1) ³
Air Change per Hour (Atkinson et al., 2009)	$n = 3600 \times Q/V$	where n is the air changes per hour (1/h) Q is the air-flow rate (m ³ /s) V is the volume of the room (m ³)
Air-change rate (Atkinson et al., 2009)	Air-change rate = [ventilation rate (l/s) x 3600 (s/hr)] x 0.001 (m ³ /s)/ [room volume (m ³)]	
Ventilation rate (Atkinson et al., 2009)	Ventilation rate (l/s) = air-change rate x room volume (m ³) x 1000 (l/m ³)/3600 (s/hr)	The air change rate is the ventilation rate in m ³ /h divided by the volume in m ³ of the enclosed space expressed in ACH (CIBSE, 2016).
Ventilation rate (Chandra, 1987)	$Q = C_a \times A_e \times V_{ref}$	where Q is the air-flow rate (m ³ /s) C_a is the air-flow coefficient ⁴ A_e is the opening area (m ²) V_{ref} is the local wind velocity (m/s)

³ “The discharge coefficient is a measure of the amount of pressure that the air loses as it goes through every opening of flow resistance. For reference, the discharge coefficient for windows is of the order of 0.65.” (CoolVent, 2019)

⁴ The air-flow coefficient is the summation of the all-positive flow values of the flow through the apertures.

3.1.2 Draft

The draft is the ‘*unwanted local cooling of the body caused by the air movement*’ (ISO 7730:2005(E)). Increasing the ventilation rate enhances IAQ; however, it can result in the draft due to the high indoor air velocity, bringing discomfort to the occupants (Mumovic, Santamouris, Chatzidiakou, Jones, & Mumovic, 2018). Discomfort can be due to mean air speed and local air temperature (CIBSE, 2006). Air speeds greater than 0.3 m/s are unacceptable for occupants’ comfort except for summer cooling (CIBSE, 2006). The airspeed is calculated as follows (CIBSE, 2006);

$$V = \frac{Q}{A}$$

where V is the airspeed (m/s), Q is the airflow (m³/s), and A is the ventilation area (m²). The relationship between air speed for sedentary office activities and indoor operative temperatures are as follows for occupants’ comfort (ASHRAE55-2010):

Table 3.5 Airspeed and operative temperatures

Upper Airspeed Limit (m/s)	Operative Temperature (°C)
0.8	$t > 25.5$
0.15	$t < 22.5$
	$22.5 < t < 25.5$

Also, the fluctuations in air speed (perceptible with discomfort between 0.3-0.6 Hz) is another prominent factor that causes discomfort (CIBSE, 2006). It is determined by the standard deviation of the airspeed or turbulence intensity and calculated as follows (CIBSE, 2006);

$$T_u = 100 (V_{SD} / v)$$

where T_u is the turbulence intensity (%), V_{SD} is the standard airspeed deviation (m/s), and v is the mean air speed (m/s).

3.1.3 Indoor Air Contamination

Indoor air pollutants have a noticeable impact on the occupants' health and well-being. The contaminant concentration levels must be simulated, measured, monitored, and controlled to provide healthy indoors. Indoor air pollutants can be gases, volatile organic compounds (VOC), odors, carbon dioxide (CO_2), and bio-contaminants (i.e., airborne viruses as SARS-CoV-1, SARS-CoV-2, influenza, and rhinovirus). In this research, CO_2 and an airborne bio-contaminant (SARS-CoV-2) are considered indoor air contaminants.

CO₂: CO_2 as a metabolic pollutant is the primary pollutant sourced by the occupants and is not regarded as harmful (CIBSE, 2006) but must be diluted or removed by the fresh air (O_2) supply for healthy indoors (de Wilde, 2018; Etheridge, 2012). CO_2 concentration depends on the occupant density and occupants' activity and can be used to measure ventilation adequacy (CIBSE, 2006). CIBSE's minimum ventilation rate for office spaces (light sedentary activities) is 10 l/s/p, which is in between the ranges of IDA2 and IDA3 classes. To provide IDA2 and IDA3, CO_2 concentration must remain between 500-800 ppm (parts per million).

Table 3.6 CO_2 Concentration (taken from CIBSE A, Section 4-3)

Classification	Rise in indoor CO_2 concentration / ppm	Default value / ppm	Range in outdoor concentration / ppm	Total indoor value* / ppm
IDA1	< 400	350	350-400	700-750
IDA2	400-600	500	350-400	850-900
IDA3	600-1000	800	350-400	1150-1200
IDA4	> 1000	1200	350-400	1550-1600

* i.e. concentration rise plus outdoor value

The CO_2 levels indicate the required fresh airflow to space (Etheridge, 2012), and regarding the required flowrate, the CO_2 levels are measured as follows;

$$C_s = C_o - N/V_o$$

where V_o is the airflow rate per person, N is the CO₂ generation rate per person, C_s is the CO₂ concentration in the space, and C_o is the CO₂ concentration of the outdoor air (Hedrick et al., 2015).

Airborne bio-contaminants: Contaminant concentration level (CCL), discharge period (T_{dis}), and time of infection (T_{inf}) are calculated based on the contaminant dispersion simulations. Contaminant dispersion simulations estimate the number of virus particles (VP) per unit volume in the room, determining the indoor contaminant concentration levels. Based on contaminant concentration levels, infection time and time of discharge can be calculated.

Infection time (T_{inf}) is the amount of time between the contaminant source's entry in the room and a selected individual's successful infection due to exposure to airborne infectious pathogens. Three parameters are considered for the calculation of T_{inf} : (1) VP_{inh} , which is the number of inhaled VP (#/m³) by an occupant during the occupancy period, (2) the air exchange (exhalation-inhalation) volume of the occupant, and (3) the infectious dose of bio-contaminant. The inhalation rate (R_{inh}) is the measure of inhaled-exhaled air volume, relying on the metabolic rate, activity level, and activity duration (U.S. EPA, 2011). The infectious dose is the number of VP required for successful infection. T_{inf} is calculated as follows:

$$VP_{inh} = \sum_{i=0}^n VP_i \cdot R_{inh} \quad (1)$$

$$T_{inf,P} = T_{CE} + t_i \quad (2)$$

where R_{inh} (m³/h) is the inhalation rate of the occupant, VP_{inh} is the number of VP (#) inhaled by the occupant, i is the timestep (hourly), VP_i is the number of VP for the

selected timestep for the selected data point, $T_{inf,p}$ is the time that occupant (located at point p) is successfully infected, T_{CE} is the time that contaminant enters the room, and t_i is the amount of time after which VP_{inh} is higher than the infectious dose.

The discharge period (T_{dis}) is the time required to discharge the room from the contaminant. T_{dis} may be influential for determining the safe re-occupancy period. T_{dis} is calculated as the time between the contaminant source leaving the room and the complete discharge of the contaminant.

3.2 Daylighting-Related Parameters

Lighting is significant for IEQ, particularly for occupants' visual comfort. The façade design is crucial to effectively use daylighting and reduce the electrical lighting demand while maintaining visual performance. To quantify daylighting performance, (1) daylighting autonomy (DA), (2) useful daylighting illuminance (UDI), and (3) daylight glare probability (DGP) are determined as performance metrics.

3.2.1 Daylighting Autonomy (DLA)

Daylighting autonomy calculates the percentage of the time during the occupancy when the test points' illuminance value is over the illuminance threshold by daylight (de Wilde, 2018). There are daylighting illuminance threshold values that vary for specific tasks and spaces. For open-plan offices, this value is recommended as 300-500 lux for screen and paper-based tasks while 500-750 lux for the deep-plan office areas (more than 6 meters away from the window walls) (Ruffles, 2005).

3.2.2 Useful Daylighting Illuminance (UDI)

Useful daylighting illuminance calculates the percentage of the time during the occupancy where the test points receive the illuminance between 100 and 2000 lux. The UDI determined the degree and the adequacy of daylighting as *little*, *enough*, and *too much* (de Wilde, 2018). Mardalevic et al. (2009) define four sub-metrics for UDI

as UDI-fell short, UDI-supplementary, UDI-autonomous, and UDI-exceeded. UDI-fell short is less than 100 lux, while UDI-exceeded is greater than 2500 lux (Mardaljevic, Heschong, & Lee, 2009). UDI-supplementary indicates the illuminance between 100 and 500 lux, which requires additional artificial lighting for the spaces. In comparison, UDI-autonomous indicates 500 to 2500 lux where the additional artificial lighting would not be needed (Mardaljevic et al., 2009).

3.2.3 Daylight Glare Probability (DGP)

Glare is the disturbance of the vision by the uncontrolled and excessive bright light, which causes visual discomfort (CIBSE, 1999). Daylighting glare probability measures discomfort through glare in daylit spaces. There are four categories in the glare scale as imperceptible glare ($DGP < 35\%$), perceptible glare ($35\% < DGP < 40\%$), disturbing glare ($40\% < DGP < 45\%$), and intolerable glare ($45\% < DGP$) (Bodart & Cauwerts, 2017). In this scale, imperceptible and perceptible glare could indicate a comfort zone, while disturbing and intolerable glare indicate discomfort.

3.3 Energy-Related Parameters

The natural ventilation and daylighting performance metrics have a profound impact on the energy performance of the buildings. The higher ventilation rates decrease the indoor air temperature and the cooling loads in the cooling season, and adequate UDI could reduce the electric light use and, therefore, the electric energy loads. To particularly measure the impact of natural ventilation performance on IEQ, heating-cooling energy loads and indoor air temperature are selected as energy performance metrics.

3.3.1 Heating-Cooling Energy Loads

Heating and cooling loads indicate the amount of energy needed/consumed to heat and cool a space during the heating and cooling period, respectively.

3.3.2 Indoor Air Temperature

Indoor air temperature is “*the temperature of the air surrounding the occupant*” (ASHRAE55-2010, 2010). The temperature of the environment consists of two measures as air temperature (T_a) and radiant temperature (T_r); and the combination of the two measures is the operative temperature (T_{op}), which is one of the critical measures for the occupants’ comfort (Nicol, 2013). Thermal comfort guidelines suggest that indoor air temperature should be set between 19°C and 23°C as upper and lower thresholds for comfortable indoors (de Wilde, 2018). In office spaces, heating is not required above 20°C and cooling below 25°C (Parsons, 2010).

CHAPTER 4

THE DEVELOPED PIPELINE

This chapter presents the pipeline focusing on methods, tool integration, systems architecture, specifications, and requirements.

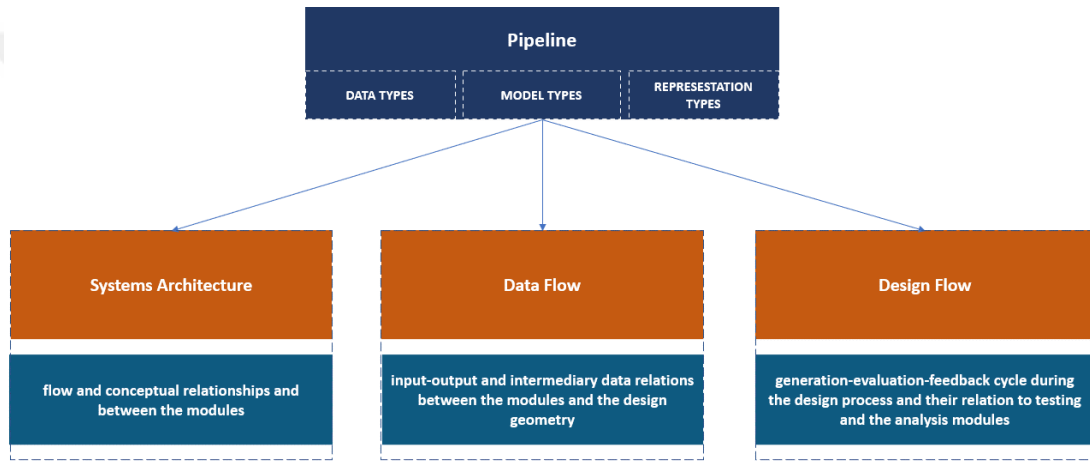


Figure 4.1. Pipeline specification framework

The developed tool adopts a ‘hybrid’ approach that integrates 3D parametric design, simulation-based, and physical testing tools. The developed tool aims at augmenting building performance, mainly focusing on occupants’ health and wellbeing, by integrating natural ventilation and contaminant dispersion analysis. The developed tool is an integrated pipeline that couples a parametric 3D design environment, daylighting, CFD, energy, contaminant transport simulations, and wind tunnel testing. The parametric 3D design environment is particularly crucial for the pipeline, enabling the seamless integration of design and BPS tools and rapid generation-simulation-evaluation of the alternative design geometries for all simulation models in the pipeline. Therefore, automated modeling and simulation can easily be performed.

Also, 3D parametric design tools provide rapid visual feedback and enhance designers' integration into the performance-driven design process.

The pipeline measures and calculates (1) the daylighting performance based on UDI, DLA, and DGP, (2) wind pressure coefficients (C_p) from CFD and wind tunnel experiments, (3) ventilation and energy performance (indoor air temperature, ventilation sensitive heat loss, CO₂ concentration, and ACH) by C_p -integrated energy simulations, and (4) indoor air contamination levels by C_p and indoor air temperature (T_i)-integrated contaminant transport simulations. Wind tunnel tests and CFD tools simulate the fluid-flow behavior (Kundu, Cohen, & Hu, 2004) and provide wind pressure coefficients (C_p). C_p values are used in both energy simulations to calculate the indoor air temperature (T_i) and contaminant transportation simulations to generate case-specific wind-pressure profiles (WPP). C_p values are non-dimensional numbers that can indicate the wind-driven pressures at particular points on the geometry relative to the freestream wind pressure (Charisi et al., 2019). In performance assessment, C_p values are used for natural ventilation performance assessment to predict indoor microclimate accurately (Charisi et al., 2019). C_p values can be obtained by full-scale measurements, wind tunnel measurements, CFD, and databases based on statistical data. Among the methods, full-scale and wind tunnel measurements are the most accurate methods to acquire C_p values (Charisi et al., 2019; Cóstola, Blocken, & Hensen, 2009) and are preferred over CFD simulations.

The integration of T_i and C_p aims to increase the precision of analysis results by calculating actual microclimatic data to contaminant transport simulations. According to the literature, environmental conditions directly impact the indoor airflow and contaminant dispersion behavior and therefore are particularly crucial for contaminant transport analyses (Carleton & Meng, 2020; Islam, Shabnam, & Erzurumluoglu, 2020; Rosario, Mutz, Bernardes, & Conte-junior, 2020; Sanchez-Lorenzo et al., 2020). In this respect, the precision of contaminant transport results is increased by integrating C_p and T_i into the pipeline. Similarly, although simulation-based methods are reliable, wind tunnel experiments are required for precision, as stressed above for C_p values. CFD can reduce the workload and expenses of wind tunnel tests; however, wind tunnel measurements are necessary to empirically provide data, where CFD cannot be precise

enough. Accordingly, CFD is used in the initial stages of the pipeline; then, wind tunnel tests are employed to improve the accuracy of airflow-related data.

Indoor contaminant assessment provides IAQ data which is crucial mainly in shared spaces. The integration of contaminant transport simulations is also another attempt to increase the accuracy of the simulation data. Alternative methods to contaminant simulations include the Wells-Riley model (Dai & Zhao, 2020; Foster & Kinzel, 2021; Pease et al., 2021; Sun & Zhai, 2020), Monte-Carlo method (Buonanno, Stabile, & Morawska, 2020; Maltezos & Georgakopoulou, 2020; Riediker & Monn, 2021; Triambak & Mahapatra, 2020; Xie, 2020), and dose-response models (Damme, Dahake, Pas, Vanham, & Assefa, 2021; Watanabe, Bartrand, Weir, Omura, & Haas, 2010; X. Zhang & Wang, 2020) in contaminant transmission assessment. However, compared to the simulation-based approaches, these methods are limited as they (a) assume contaminant concentration as constant, steady, and randomly distributed and (b) neglected spatial variations of the contaminant dispersion (Sze To & Chao, 2010). However, indoor environmental and physical conditions have a considerable impact on the distribution, transportation, dilution, and removal of the air and the contaminant, often non-uniform (Etheridge & Ford, 2008). The need to evaluate naturally-ventilated spaces under complex airflow conditions makes simulation-based contaminant transmission assessment a viable alternative to mathematical models.

4.1 Systems Architecture

Systems architecture diagram maps conceptual relationships between input, analysis, and output (Figure 4.2). The pipeline is based on three main modules as computer-based simulations I, computer-based simulations II and model testing. The pipeline starts with the initial design input, a 1:1 scale 3D parametric geometry model of design alternatives, and context input, which are weather and built environment data. Generated parametric design models can directly be used for generating daylighting, energy, and CFD models during computer-based simulation I (Figure 4.2). The initial input data is first used in daylighting simulations to calculate the daylighting performance of the previously generated design alternatives. Among the design

alternatives, the best performing options are selected and used as design input for the next step: energy and CFD simulations. CFD and energy simulation models are generated from the parametric design models, and the simulations can be performed simultaneously. Energy analysis is performed in two stages. First, the initial energy model (shown as Energy Analysis I in Figure 4.2) is built upon the parametric geometry model. Then C_p results are generated by CFD are calculated and integrated into the airflow module of the initial energy model; thus, the secondary energy models are built (shown as Energy Analysis II in Figure 4.2). The results of secondary energy analysis can give initial and rough feedback for simulated design alternatives due to the roughly calculated C_p by CFD simulations. For preliminary design stages, CFD and initial energy simulation can guide designers sufficiently to assess and then select design alternatives. Yet, wind tunnel testing is recommended for accurate and precise performance feedback (Calautit & Hughes, 2014). Therefore, the pipeline uses CFD only for preliminary design feedback and then performs wind tunnel experiments to obtain accurate C_p values.

Following the computer-based simulations I, the selected design alternatives are fabricated for wind tunnel testing. In the pipeline, pressure and particle image velocimetry (PIV) tests are performed. C_p values are obtained from wind pressure tests, while indoor flow behavior and speed are acquired from PIV tests. The calculated C_p values are integrated into the initial energy model's airflow module, and the tertiary energy model is generated (shown as Energy Analysis III in Figure 4.2). Energy analysis calculates final T_i values for design alternatives. Then, generated C_p and T_i values are used in contaminant analysis to provide feedback on indoor airborne contamination levels, time of contaminant discharge, and possible infection time of the occupants for any location in the room. As a result of this hybrid process, the final design alternative(s) is determined as relatively the best-performing option among the simulated design alternatives.

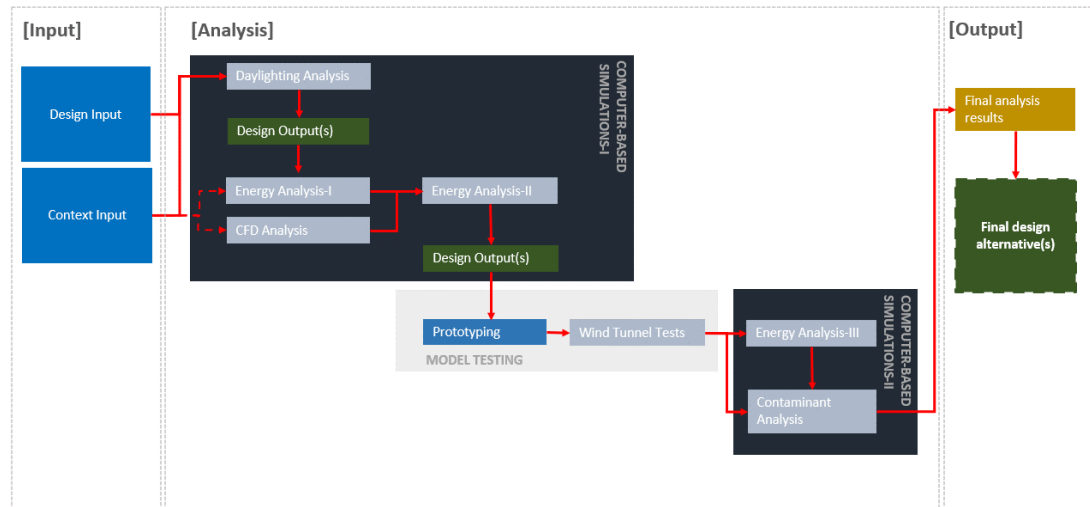


Figure 4.2. Systems architecture

Models: The pipeline utilizes (1) parametric 3D geometry models, (2) simulation models, and (3) physical models. A parametric 3D geometry model is an abstract representation of constructed relationships between design parameters which provides flexibility to rapid changes such as the geometric transformation of the design geometry (Barrios, 2005). Parametric models are made via visual programming environments, which are coupled with 3D drafting and modeling programs. Parametric geometry models are used as a base for the daylighting, energy, and CFD simulation models. For the wind tunnel measurements, the pipeline necessitates physical models. The physical models can also be directly generated based on the 3D digital geometry models by employing digital fabrication methods such as laser cutting, 3D printing, or CNC milling. Using digital geometry models for simulations and fabrication prevents potential user-made modeling mistakes. It can also save designers time and effort compared to generating separate models for each step from scratch.

Data types: The pipeline utilizes, integrates, generates, and processes (1) parametric geometry model data, (2) simulation model data, (3) analysis data, (4) context data, and (5) fabrication data. Parametric geometry model data is the digital and visual representation of the design alternatives. Simulation model data consists of the inputs that are required by the simulation tool. Analysis data consists of the generated outputs obtained from energy, daylighting, CFD, contaminant dispersion analysis, and

physical measurements. Context data is the weather and the built environment data. Weather data can be a text file that contains annual statistical weather data of a selected location, while context data can either be a digital geometry model of surrounding buildings for simulations (for daylighting and energy simulations) or can be determined as a terrain roughness parameter (for CFD simulations). The pipeline also necessitates fabrication data of the physical model of the design alternatives and their surrounding buildings (if applicable).

Data representation: The pipeline employs both the abstract and visual representation methods regarding different model and data types integrated into the pipeline. An abstract representation consists of the numeric values, while visual representation consists of the graphs (such as line charts and box whiskers), static images (such as PIV laser images and performance gradients on the simulation grid), and transient images (such as transient airflow vectors). Analysis data represented in both types support designers' well-informed decision-making. Notably, visual representations enable the designer to visually inspect the design generation process, which is crucial for designers' rapid engagement with the performance feedback and the design process.

4.2 Data Integration

The hybridity of the process is due to the coupling of various methods, tools, and different data types, necessitating a certain level of integration between them. Integration of distinct methods, tools, and data informs designers for various building performance aspects and supports well-informed decision-making utilizing multiple data. However, such hybridity results in a large amount of data to correlate and complement each other requiring structured data flow and management. Data flow diagram for the pipeline is presented in this section, which shows the input-output and intermediary relations between the tools and data.

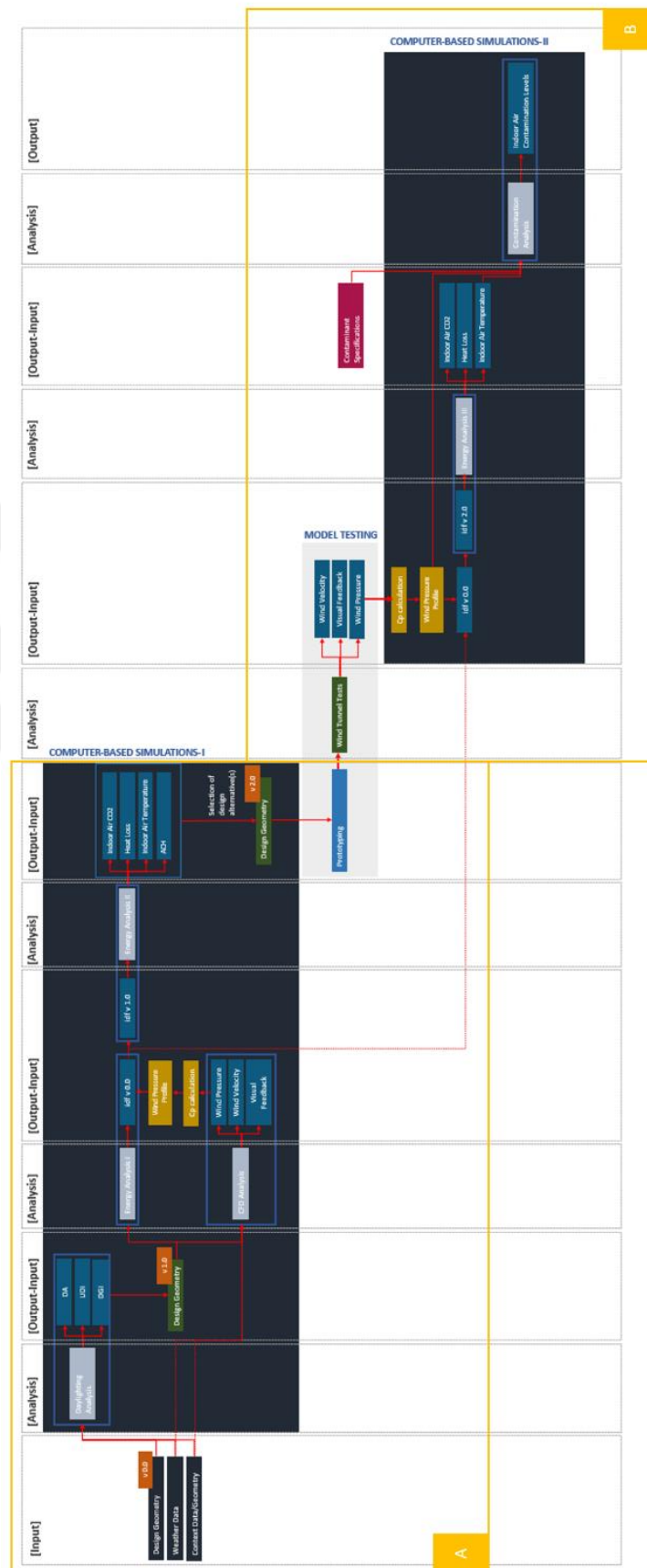


Figure 4.3. Data integration thumbnail image for Figure 4.4 and 4.5



Figure 4.4 Data integration-Part A

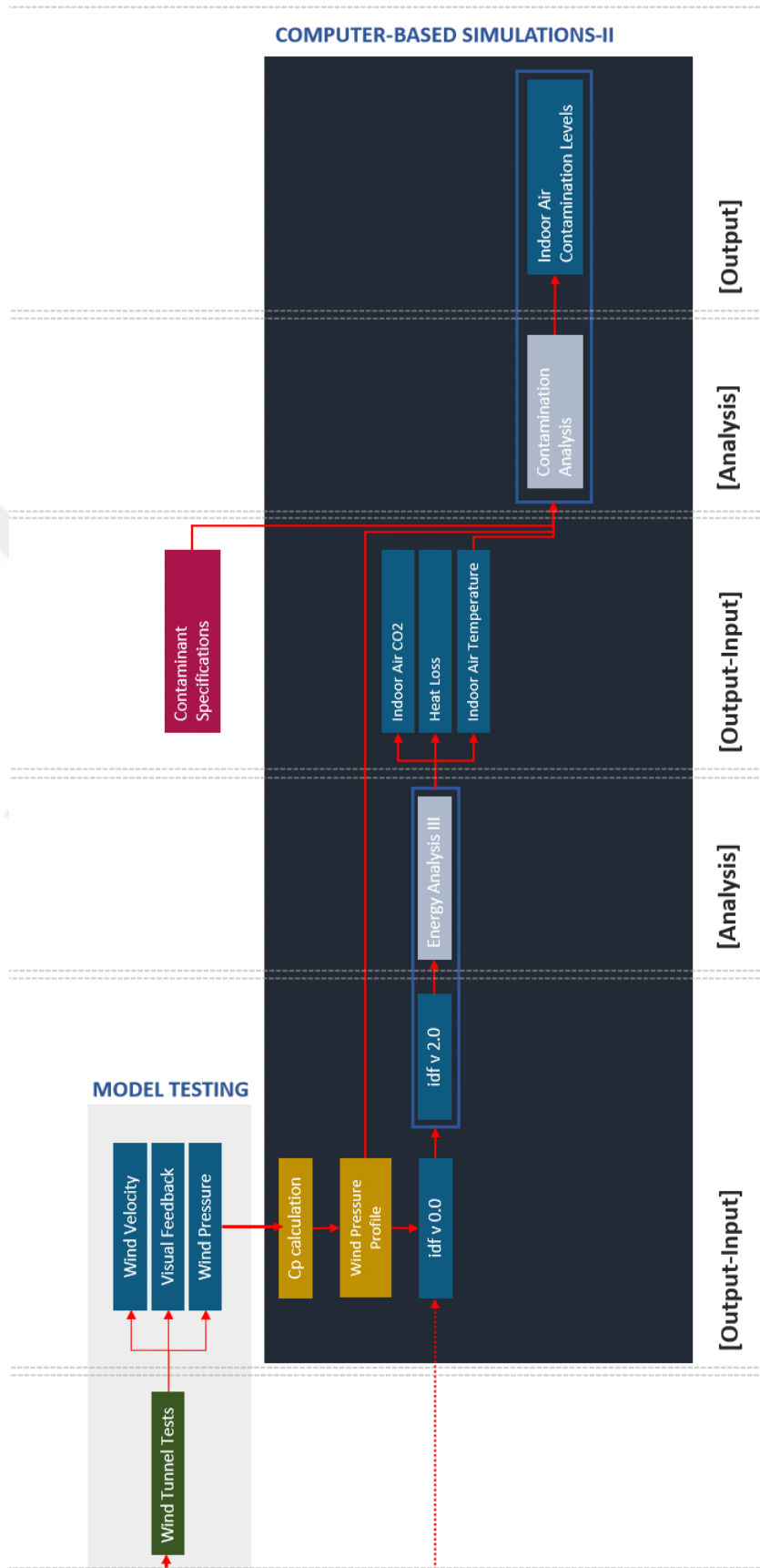


Figure 4.5. Data integration-Part B

4.2.1 Computer-Based Analysis

The pipeline necessitates simulation models for computer-based analyses. The simulation models are generated based on parametric 3D geometry models. The pipeline mainly necessitates a 3D parametric environment for computer-based analysis. BPS tools can necessitate specific requirements from the simulation model. Accordingly, this section presents typical practice and general requirements for the 3D parametric tool-coupled simulations and simulation models for the pipeline.

4.2.1.1 Daylighting Simulations

Daylighting simulations assess the daylighting adequacy and visual comfort for various daylighting performance criteria. The pipeline utilizes daylighting simulations for calculating UDI, DLA, and DGP. UDI and DLA are calculated by grid-based simulation, while DGP is calculated by image-based simulation (Figure 4.6). Grid-based simulation is based on an analysis plane split into a grid (test grid or test mesh). Each grid cell has a (computational) node placed in the center of the cell to calculate the required metrics. On the other hand, image-based simulation is based on 2D image processing to calculate required metrics. In both types of simulations, analysis results are represented as both visual and numeric values.

Daylighting models are built upon 1:1 scale 3D parametric models. First, 3D design geometry is required to be defined as a simulation geometry. Then, for the grid-based simulations, (1) the test grid on the model surfaces and the number of grid cells, and for (2) the image-based simulations, the views are identified.

Daylighting simulations also require a simulation period and a weather file generated for a specific location, containing the annual statistical weather data registered from the weather stations. The sky model, which defines sky conditions, has to be generated based on the weather file.

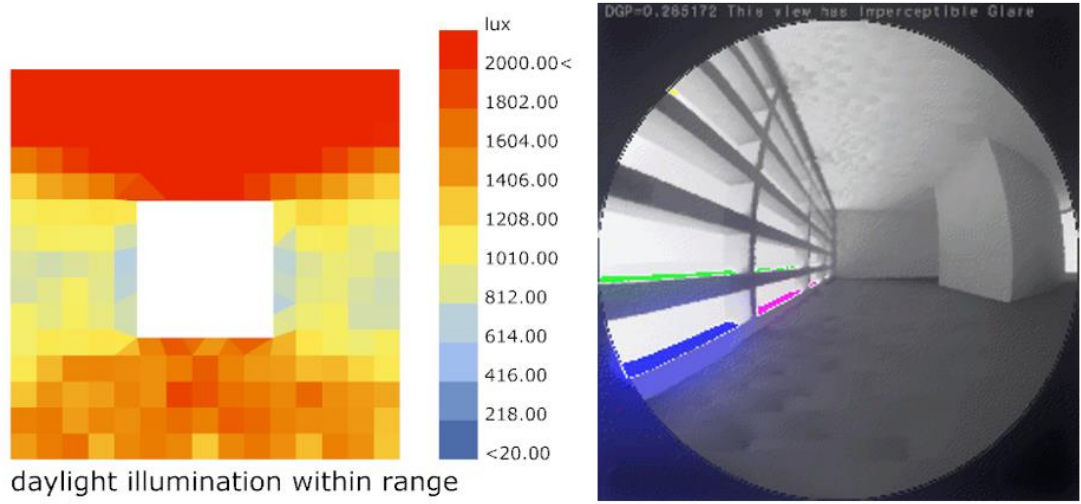


Figure 4.6. Grid-based simulation (left) and image-based simulation (right)

4.2.1.2 CFD Simulations

CFD simulations study airflow behavior and typically rely on Navier-Stokes equations (de Wilde, 2018). The most typical application for building performance in an architectural context is ventilation assessment (de Wilde, 2018). The pipeline utilizes CFD simulations to obtain wind pressure data for preliminary ventilation and energy performance assessment. Based on wind pressure data, C_p values are calculated and used to generate the wind pressure profiles (WPP) at each opening as follows (Cóstola et al., 2009):

$$C_p = \frac{P_x - P_0}{P_d} \quad ; \quad P_d = \frac{\rho \cdot U_h^2}{2} \quad (3)$$

where P_x is the pressure (Pa) derived from a test point on the building façade, P_0 is the freestream reference pressure, P_d is the dynamic pressure, ρ is the air density (kg/m^3) and U_h is the wind speed (m/s) at room altitude.

CFD models are generated based on 1:1 scale 3D parametric geometry models, and simulations require wind characteristics such as wind direction and velocity for the

selected location. CFD simulation is a complex process, where the accuracy of simulation results is based on a number of parameters such as the computational domain, quality of analysis grid (meshing and resolution), turbulence models, boundary conditions, and iterative convergence levels (Ramponi & Blocken, 2012). Computational domain (*CD*) is determined by best practice guidelines developed by Franke et al. (2011). For the vertical extension (between the building's roof and the vertical boundary of *CD*), the top of *CD* is $5H$, for the lateral extension (between the building's sidewalls and the lateral boundary of *CD*), the sides of *CD* is $5H$, for the leeward extension (the longitudinal region between the building's leeward wall and the boundary of *CD*), the distance is $15H$, and for the windward extension (the longitudinal region between the building's windward wall and the boundary of *CD*), the distance is $3H$, where H is the height of the building. Constructing an analysis grid or meshing is the division of the air volume in the/around the building geometry into the discrete computational cells (Figure 4.7) (de Wilde, 2018). The number of cell elements commonly defines the computational power and time required by CFD and the accuracy of the analysis results (de Wilde, 2018). Grid sensitivity analysis is a common practice to determine the mesh quality and accuracy of simulation results. CFD also requires boundary conditions such as inlet properties or surface roughness (de Wilde, 2018).

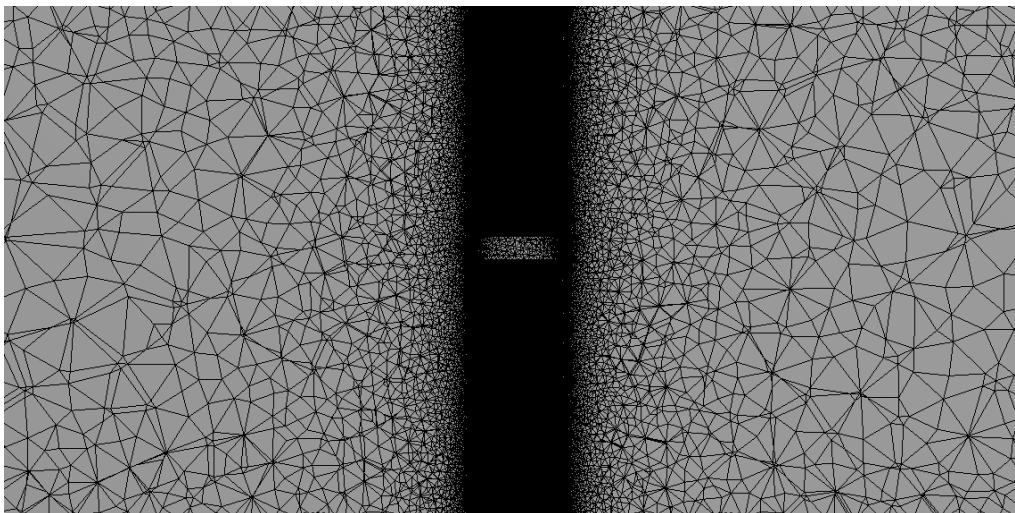


Figure 4.7. CFD meshing

There are a number of turbulence models, and selecting an appropriate turbulence model has a crucial impact on analysis results (Ramponi & Blocken, 2012). SST k- ω and RNG k- ϵ are regarded as the best performing turbulence models (Ramponi & Blocken, 2012). Iterative convergence criteria determine the convergence level of the analysis results. The convergence level for tightly converged results is determined as 1E-06 for all residuals by the best practice guidelines (Franke et al., 2011).

Building CFD models and performing CFD simulations are computationally and timewise costly and require expertise. Obtaining rough feedback during the preliminary design phases can guide designers for better-performing design alternatives. For accurate analysis results, wind tunnel tests are recommended.

4.2.1.3 Energy Simulations

Energy models are also built upon 1:1 scale 3D parametric geometry models. First, 3D parametric geometry model surfaces are decomposed and labeled based on their construction (i.e., walls, interior walls, slabs, and glazing). Material properties (i.e., thermal conductivity, SHGC, and reflectivity) are then determined for the thermal calculations. Energy simulations also require occupancy (i.e., occupant number, building operation period), heating, cooling, and lighting scenarios/schedules. Similar to daylighting simulations, energy simulations also require weather data files for a specific location and a simulation period.

4.2.1.4 Contaminant Simulations

Contaminant simulations are not coupled with 3D parametric design environments, but they can be integrated into the pipeline by data integration. First, the building geometry is required to be modeled or imported for a stand-alone contaminant analysis tool. Contaminant simulations require a specific contaminant model that contains specifications of the contaminant, such as the contaminant's molecular weight (molar mass), particle diameter, and effective density, which defines the mass and transportation behavior of the particle (Dols et al., 2020). In addition, contaminant

models necessitate contaminant generation and removal rates. Contaminant generation rate (GR) is the measure of the virus particles that are introduced into space by a contaminant source to calculate the contaminant level in the environment (Dols & Polidoro, 2015). This value is needed for the determination of the number of virus particles emitted by the contaminant source. The removal rate is the measure of the rate that the contaminant is deposited from the space (Dols & Polidoro, 2015). Similar to the energy models, contaminant simulations also require occupancy schedules, weather data, and the simulation period.

4.2.2 Wind Tunnel Tests

Wind tunnel tests are low-speed experimental procedures in performance assessment based on an airflow acting towards the scaled models (de Wilde, 2018). Wind tunnel tests can be performed for various reasons, such as determining wind loads and observing buildings' responses. In the pipeline, pressure and particle image velocimetry (PIV) tests are integrated into the workflow. Pressure tests are utilized to obtain pressure values on openings to calculate wind pressure coefficients for energy and contaminant analysis. PIV tests are used to visualize indoor airflow behavior and velocity.

The prototyping of the physical model is one of the crucial steps for wind tunnel testing. Two essential parameters can determine the prototyping process: (1) the dimensions of the wind tunnel, which determines the scale of the model (therefore blockage ratio), and (2) the type/purpose of wind tunnel testing, which determines the material of the model. Based on scale and material, the model fabrication method can be determined. In general, the model is expected to be robust and resistant to breakages and preventing air leakage. However, each test has specific model requirements, such as PIV tests, which require complete transparent material for model surfaces to capture indoor airflow behavior.

The blockage ratio is another important parameter that determines the model scale based on the wind tunnel dimensions. The buildings are located in infinite spaces; however, scaled building models are located in limited spaces such as wind tunnels.

Therefore, scaled building models are subjected to the blockage effect, which is the ratio of the front face (projected area) of the building in the flow direction to the cross-section of the wind tunnel (Franke et al., 2011). Blockage ratio (BR) is calculated as:

$$BR = \frac{A_b}{A_t} \cdot 100 \quad (4)$$

where A_b is the frontal area of the building in the flow direction, and A_t is the cross-sectional area of the wind tunnel. Typically, a blockage ratio is suggested to be < 5-10% (Choi & Kwon, 1998). For higher blockage ratios, blockage correction is recommended. Blockage correction is calculated as (W. D. Janssen, Blocken, & van Wijhe, 2017):

$$C_c = C_e \cdot \left(1 - \frac{m \cdot A_b}{A_t}\right) \quad (5)$$

where C_c is the corrected coefficient, C_e is the coefficient values calculated based on the tunnel experiments, m is the expansion factor for the wake, A_b is the frontal area of the building in the flow direction, and A_t is the cross-sectional area of the wind tunnel. Despite the improvements in wind tunnel test results, blockage correction may not be adequate to avoid overestimating results (i.e., acceleration), particularly in building or urban model tests (Blocken, 2015). Artificial acceleration of the flow may occur at the sides of the model since the lateral walls of the tunnel are close to the model (Blocken, 2015). To prevent artificial acceleration, a directional blockage ratio can be followed for blockage correction. Directional blockage ratio is the decomposition of the blockage ratio into a lateral horizontal and vertical direction, which are suggested to be $\leq 17\%$, and calculated as:

$$BR_L = \frac{L_b}{L_t} < 17\% \quad (6)$$

$$BR_H = \frac{H_b}{H_t} < 17\% \quad (7)$$

where L_b is the cross-sectional length of the building, L_t is the cross-sectional length of the tunnel, H_b is the height of the building, and H_t is the height of the tunnel (Blocken, 2015).

4.2.2.1 Pressure Tests

Pressure tests are used to measure the pressure values on the model surfaces. The experimental setup consists of flexible capillary tubes and pressure scanners to measure and register pressure values on the surfaces. The model surface is required to have holes for the assembly of capillary tubes, which are connected to pressure scanners.

4.2.2.2 Particle Image Velocimetry

Particle Image Velocimetry (PIV) is used to visualize the flow in the space, an optical flow diagnostics method based on tracing the movement of the particles by light (Westerweel, 1997). The experimental set-up consists of a continuous laser beam, high-speed camera(s), optical set-up to form a laser light sheet, and fluid with tracer particles (liquid or gaseous flows) (Alwafi, Nguyen, Hassan, & Anand, 2019). The fluid is injected into the system, and the high-speed camera(s) placed at the top or bottom of the model recording airflow behavior that is materialized by the laser rays as a section plane. Following the tests, the recoded flow behavior requires post-processing to visualize the flow behavior and calculate indoor airflow velocity.

4.3 Design Integration

Integrating 3D parametric design environments, the pipeline follows and supports the design process of generation, evaluation, and feedback cycle. Figure 4.8 shows the pipeline's design integration diagram for mapping potential design generation and decisions. The pipeline can be used for the performance-driven design process of a single design alternative to improve design decisions by obtaining performance feedback, or a number of design alternatives can be evaluated and compared/benchmarked with each other to generate/select the final design alternative(s).

The pipeline requires a 3D parametric geometry model to generate design alternatives or implement design improvements. Following the generation of initial design alternative(s) (v0.0), daylighting analyses are performed for benchmarking the performance of the design alternative(s). Based on daylighting performance, design alternatives remaining the performance threshold are eliminated. Initial energy and CFD simulations are then performed for the selected/improved design alternative(s) (v1.0). Following, the secondary energy analysis is performed with the integration of *WPP* for each design alternative. Based on the energy analysis results, design alternatives remaining below the performance threshold are again eliminated. The selected design alternative(s) (v2.0) are moved to the prototyping and wind tunnel testing phase. Wind tunnel tests are performed for the selected design alternatives (v2.0), and the analysis results are integrated into the final energy and contaminant analyses. Based on the energy and contaminant analysis, final design alternative(s) are determined.

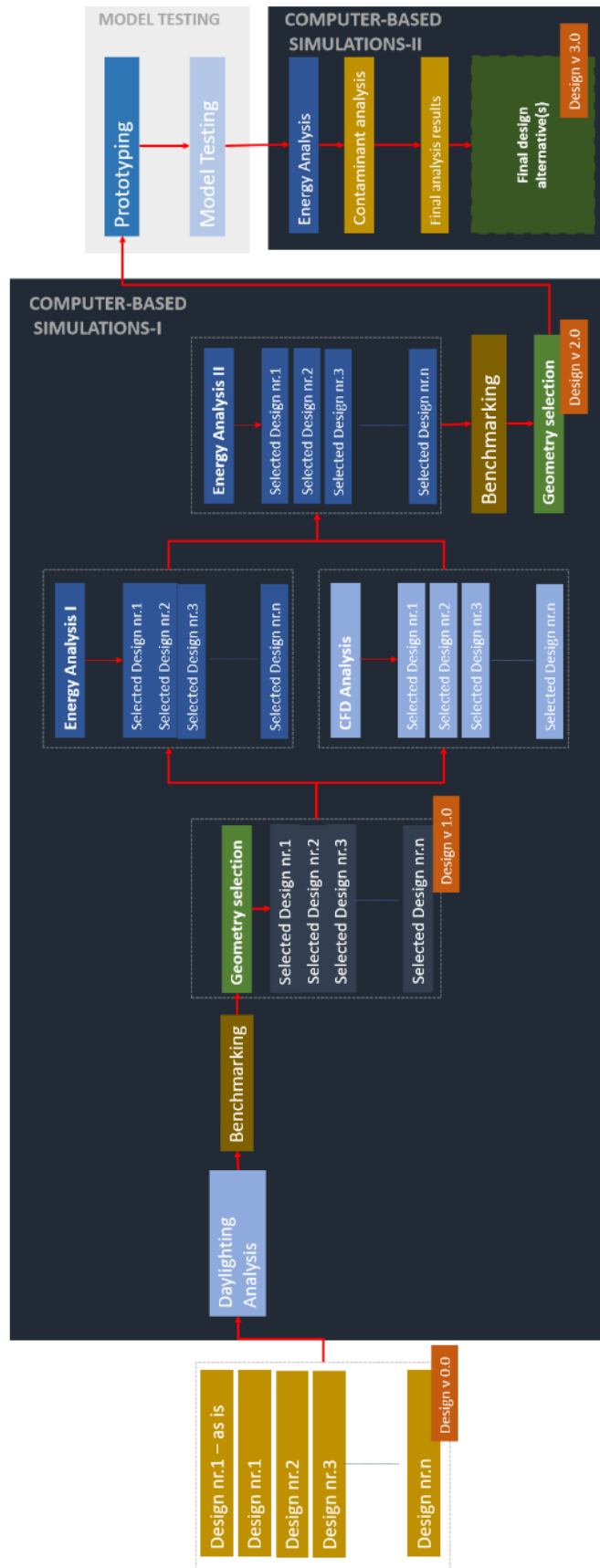


Figure 4.8 Design Integration

CHAPTER 5

PIPELINE IMPLEMENTATION

This chapter presents the implementation of the pipeline for a case study. First, a brief literature review conducted for the case study and case study design are presented. Following, the pipeline modules, simulations and experimental setups are explained in detail.

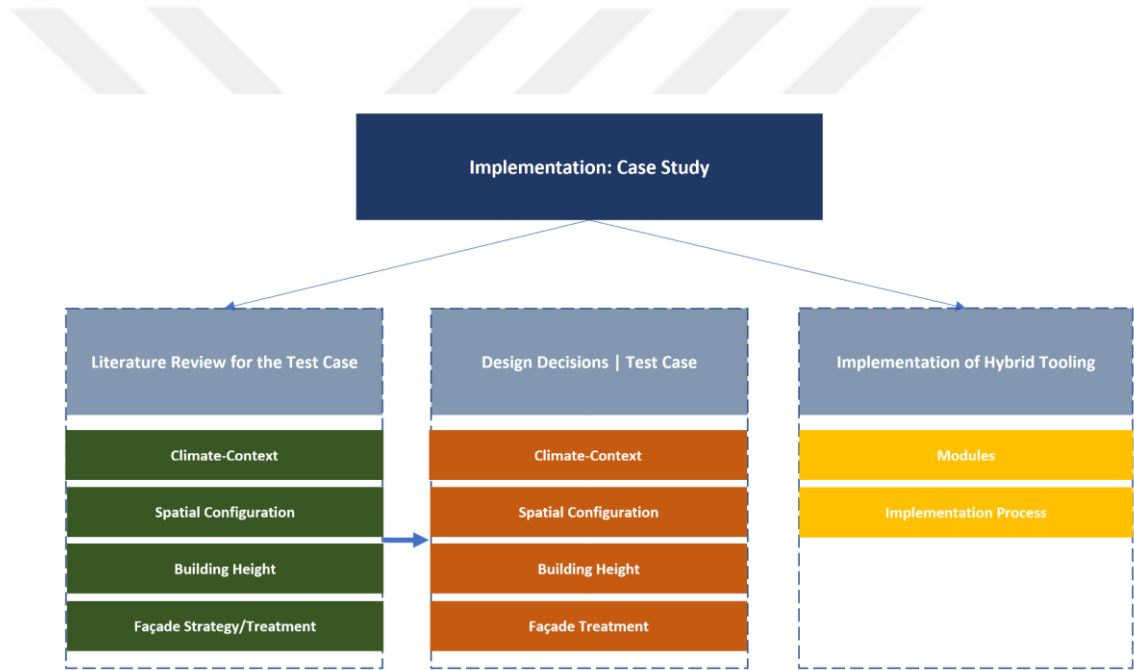


Figure 5.1. Case study structure for the pipeline implementation

5.1 Case Study

The pipeline is implemented for a case study, a naturally ventilated open office located in Ankara. Designing a naturally ventilated open office is challenging due to specific design and performance parameters such as building height, plan depth, and climate. In this respect, a literature review is performed focusing on naturally-ventilated office buildings to determine a plausible design scenario for the case study.

5.1.1 Design Parameters

Council on Tall Buildings and Urban Habitat (CTBUH) provides comprehensive research on naturally-ventilated buildings discussing the design strategies, potentials, options, and limitations (Etheridge & Ford, 2008; Wood & Salib, 2013). CTBUH mentions a number of design parameters for naturally-ventilated buildings, such as local climate and context, spatial configuration, building geometry (i.e., form and height), and façade treatment. Local climate and context have a considerable influence on a building's natural ventilation performance/effectiveness. Natural ventilation is not suitable for all climates (i.e., hot and humid climates). Spatial configuration, particularly plan depth, is essential for fresh air distribution and daylighting adequacy. Deep planned spaces may not attain daylighting and natural ventilation performance requirements. Façade treatment requires the consideration of both local climate and spatial configuration. Suitable façade treatment has the potential to improve building performance. Building height is a significant parameter for natural ventilation. Natural ventilation may not be a proper strategy for tall buildings regarding the higher wind speed, draft, and safety risks at higher altitudes.

Local Climate and Context: Temperate climates facilitate natural ventilation (Wood & Salib, 2013). On the other hand, natural ventilation is not suitable for tropical and hot-humid climates due to the high humidity rates and overheating (Wood & Salib, 2013). Diverse climate characteristics (tropical, hot-dry, temperate, cold as classified by CTBUH) require different natural ventilation strategies and bring up a number of limitations based on the building orientation, spatial configuration, site conditions, and the building façade treatments. The climate-specific strategies and limitations could be mapped as follows (Table 5.1):

Table 5.1. Diverse Climate Characteristics and Performative Design Strategies

Tropical Climate	Hot-Dry Climate	Temperate Climate	Cold Climate
-the most challenging climate for natural ventilation due to humidity -protection from solar radiation and solar heat gain -high air change rate to remove humidity -tall buildings are beneficial typologies for improving the microclimate (shade and wind movement) -night-time ventilation is beneficial -narrow flow plates for cross-ventilation -high floor height to keep the warm air away from the occupants -draft effects must be regarded -mechanical and natural ventilation zones must be separated -full natural ventilation is not possible	- protection from solar radiation and solar heat gain -east-west axis orientation with the openings on the north-west façades -natural ventilation during the day could not be possible when the external temperature is high -seasonal switchover mixed-mode strategy -night-time ventilation is beneficial -a heavy thermal mass is beneficial -evaporative cooling	-two distinct ventilation strategies for summer and winter (cooling/heating seasons) -requires adaptability in design - high thermal insulation and passive heating during the cold season -shading and higher ventilation rates during the hot season -the use of double-skin façades is a common strategy	-the conservation of heat (building form and envelope) -compact forms -curvilinear forms due to the aerodynamics -passive solar heating by orienting the glazed façades toward the intense solar radiation direction -could cause glare, adjustable shadings are beneficial

Spatial Configuration: Office spaces are required to provide healthy environments to occupants and improve well-being and productivity. Therefore they require certain

daylighting and task-lighting conditions and a certain amount of fresh airflow per person. The configuration of the interior partitions and plan depth are two main parameters that impact natural ventilation and daylight access in office buildings. The design of interior partitions may block, enable or accelerate indoor airflow, and blockage and acceleration of the airflow can cause occupants' discomfort. Similarly, both the blockage or the excess of daylighting can cause discomfort to the occupants' vision. Open plans are advantageous for office buildings to benefit from daylighting and spatial flexibility. However, the deep plan open offices can limit the access to daylighting and cause uneven distribution of the fresh air to the inner areas of the room (Etheridge, 2012). For adequate daylighting and ventilation, 1:5 floor-to-ceiling height is recommended (CIBSE, 2016). For the particular case of cross-ventilation, shallow-plans with 7-15 m in depth efficiently provide adequate and evenly distributed natural ventilation and daylighting (CIBSE, 2016).

Building Height and the Façade Strategy: The relation of the building height and wind behavior is one of the significant determinants of the façade design. Therefore, the façade strategy is discussed along with the building height.

Wood & Salib (2013) have analyzed fourteen tall buildings to discuss potential ventilation strategies concerning façade treatment. There are nine buildings with double-skin façade that ranges from 80 to 259 m (20 to 56 floors), while there are five buildings with single-skin façade that ranges from 60 to 126 m (17 to 33 floors). Only one building, Torre Cube in Guadalajara, runs entirely by natural ventilation with a single skin façade. The height of the Torre Cube is 60 m (17 floors). Wooden brise-soleils are used to control solar heat gain and regulate wind behavior. For taller buildings, the case studies show that the double-skin façades could provide flexibility by means of effective environmental control. The case studies reveal that the building height is one of the major limitations for employing natural ventilation with single skin façades. Tall buildings run the risk of being a limitation for natural ventilation due to unpredictable wind behavior, accelerated wind velocity, and wind noise at higher altitudes (Etheridge & Ford, 2008). In such cases, the natural ventilation must be supported by the façade design and alternative ventilation strategies (i.e., double-skin

façades and mixed-mode ventilation could be benefitable to control the wind speed and urban-wind noise) (Wood & Salib, 2013).

5.1.2 Case Study Design

Wind tunnel testing is also another key determinant in case study design. Building dimensions and spatial configuration are determined regarding the wind tunnel size, since the instruments of the experimentation bring some limitations (i.e., there must be an adequate room for capillary tubes). Accordingly, the case study design is finalized based on the abovementioned design parameters and the suggestions of METU Wind Center (Rüzgem) as follows:

Table 5.2. Design decisions for the test case building

Parameters	Cause of selection
Climate: Temperate Climate Simulations for a typical summer day Wind speed: 4.3 m/sec	Natural ventilation is not effective in - tropical and hot-dry climates due to excessive humidity and excessive heat, respectively - cold climates due to the need of the heat conservation.
Spatial Configuration: Interior partitions: open plan Plan depth: shallow plan	Access to daylighting and ventilation access partitions block ventilation 7-15 m depth is accepted as optimum for daylighting and ventilation access
Building Geometry: Size: 15x15x4 m Form: Rigid-Square prism 5x5x4 m core in the middle Layout aspect ratio: 1:1 (as the most common)	The major determinant is the available wind tunnel and its set-up Size: - due to the size of the wind-tunnel and the model scale. The model scale should not pose higher blockage to the tunnel Form: - Common office building geometry - Easy and rapid fabrication
Building Surfaces:	North: Glazed+Openings South: Glazed+Openings+Shading East: Blind West: Blind
Façade Treatment:	Single Skin Façade
Openings: Openings/Exterior Wall <12%	Due to the Turkish Code on the Energy Performance of Buildings https://www.mevzuat.gov.tr/mevzuat?MevzuatNo=13594&MevzuatTur=7&MevzuatTertip=5
Ventilation Type: Cross-ventilation	Effective ventilation configuration

Context: The simulations are performed for a uniform cityscape, where the terrain is covered by buildings with similar heights and open spaces.

Local Climate: The building is assumed to be located in Ankara, Turkey, with a large population and a high demand for tall office buildings. According to the updated Köppen-Geiger climate classification (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006), Ankara belongs to the Csb climate zone, which has the Mediterranean climate (climate: warm temperate, precipitation: summer dry and temperature: warm summer). Ankara has its hottest period in July and August and the coldest period in January. The temperature could reach up to 34°C during the summers and drop to -20°C in the winters. Ankara has the maximum direct illuminance and the minimum cloud cover during the summer months, which is benefitable to maximize daylighting conditions for the interiors. Ankara has maximum cloud cover during the winter months (Figure 5.2). The northern and north-north eastern winds prevail throughout the year, and western-north western winds during the warm months (from February until July) are also received. Ankara has a relatively dry climate with low humidity ratios, and wind for natural ventilation is benefitable. Regarding the bio-climatic chart, providing natural ventilation for the conditions between ~25-30°C with a 20% humidity ratio and between ~20-30°C with an 80-90% humidity ratio has the potential to expand the comfort zone.

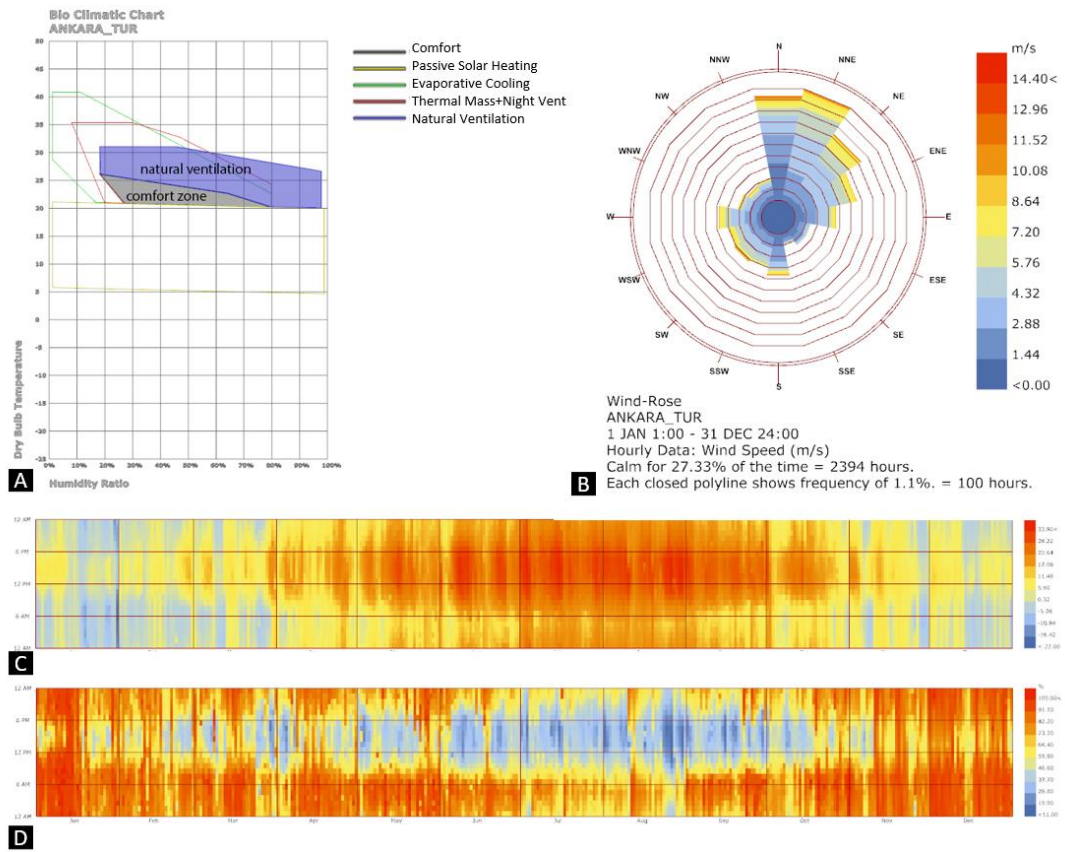


Figure 5.2. Weather graphics for Ankara (A. bioclimatic chart, B. wind-rose, C. dry bulb temperature, D. relative humidity)

Simulation Period and Weather Data: To evaluate the impact of the natural ventilation, the simulation period is selected as a summer day (August 20th) between 8:00-18:00 from a typical summer week of Ankara (August 17th –23rd, as stated in the STAT file). Specific EPW file is generated by editing the existing EPW file using *Elements* to isolate the impact of the wind and to reduce the impact of the potential temperature fluctuations on simulation results. First, the average dry bulb temperature (27.7°), relative humidity (35.3%), and wind speed (4.3 m/s) are calculated based on the existing EPW data, and the calculated average values are used in the newly-generated EPW file (Table 5.3). Four EPW files are generated for four wind directions as 0°, 90°, 180°, and 270°.

Table 5.3. Averaged weather data for the selected simulation period

	DRY BULB TEMPERATURE	WIND SPEED	RELATIVE HUMIDITY %
AUGUST			
0:01- 1:00	16.9	2.7	57
1:01- 2:00	15.8	2.5	61
2:01- 3:00	15	2.2	63
3:01- 4:00	14.3	1.9	66
4:01- 5:00	13.5	1.7	69
5:01- 6:00	15	1.9	65
6:01- 7:00	16.7	2.1	60
7:01- 8:00	18.3	2.3	57
8:01- 9:00	20.4	2.8	50
9:01-10:00	22.5	3.2	44
10:01-11:00	24.6	3.7	39
11:01-12:00	25.6	4.1	36
12:01-13:00	26.6	4.5	33
13:01-14:00	27.9	4.6	29
14:01-15:00	27.7	4.8	29
15:01-16:00	27.6	5	30
16:01-17:00	27.7	5.2	30
17:01-18:00	25.9	4.8	33
18:01-19:00	24.2	4.3	36
19:01-20:00	22.4	3.9	40
20:01-21:00	21.2	3.6	44
21:01-22:00	20.1	3.4	47
22:01-23:00	18.9	3.1	51
23:01-24:00	17.9	3	54
AVG_Selected	25.65	4.27	35.30

EPW-Ankara-average data for the occupancy period 8:00-18:00

	Dry Bulb Temperature	Wind Speed	Wind Direction	Relative Humidity
Summer	25. 7 °C	4.3 m/sec	0° 90° 180° 270°	35.30%

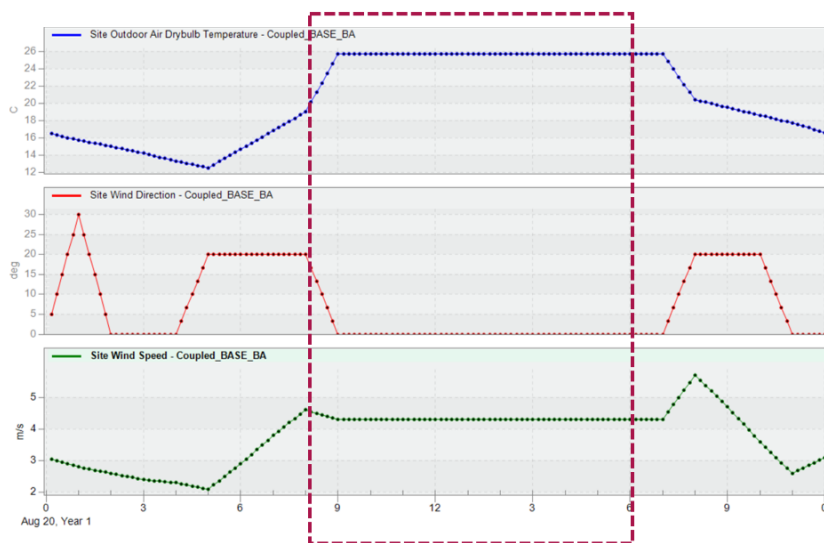


Figure 5.3. Averaged weather data for the selected simulation period

Building Geometry (Building Height, Spatial Configuration, and Material): The building dimensions are determined considering the dimensional limitations of the wind tunnel. The case study geometry is a 25-floor shallow open-plan office building (15x15x100 m dimensions, and 4m floor height) with a 5x5 m core in the middle (Figure 5.4). A particular test level is determined to focus the airflow behavior in detail. The test floor level is placed between the 48 to 52 m of the building, which represents a sample case through the atmospheric boundary layer. The geometry surfaces are two-floor slabs and four interior walls of the core that are set to adiabatic surfaces, and four exterior surfaces exposed to outdoor conditions. The U-values of the concrete walls-slabs and glazing is set to 0.90 W/m²K and 1.4 W/m²K, respectively. The glazings' solar heat gain coefficient (SHGC) is 0.55, and visual transmittance is 0.78.

Façade Strategy: North and South façades are fully glazed, and there are four operable windows on the North and South façades each. Both façades are single-skin, and the shading devices are located on the south façade. Single skin façade is based on three layers from inside to outside (1) windows (operable and fixed), (2) structural system for the shading devices, and (3) shading devices. There is a 0.40 m gap between the shading devices and the windows for the structural system.

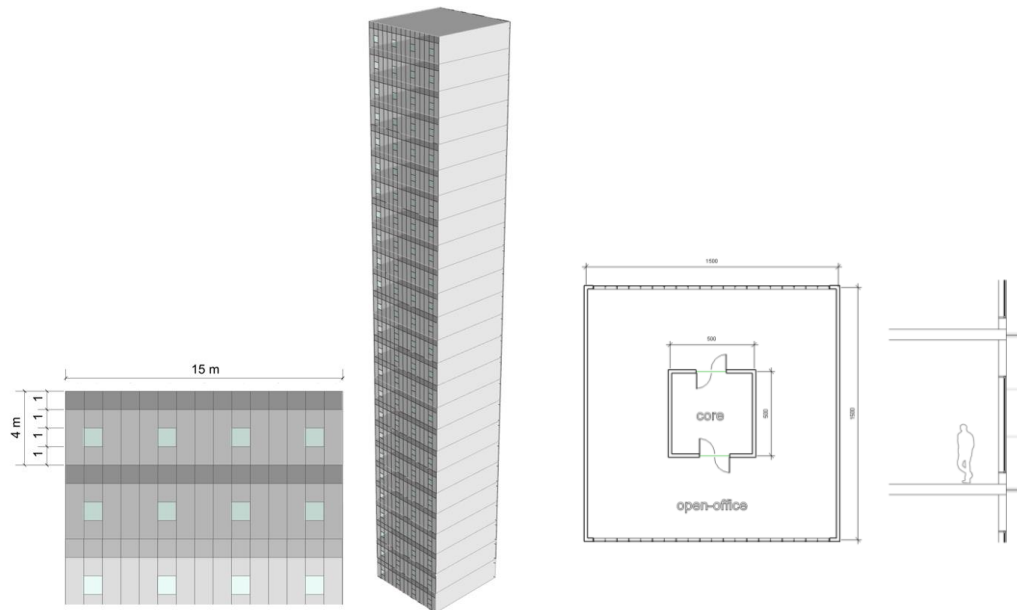


Figure 5.4. Case study geometry

Shading Devices: Six shading devices are designed for the south façade. Perforation ratio (PR) and the shading depth (SD) are determined as design parameters. Two PR values as 40% and 60% and three SD values as 40 cm, 60 cm, and 80 cm are defined for the shading devices.

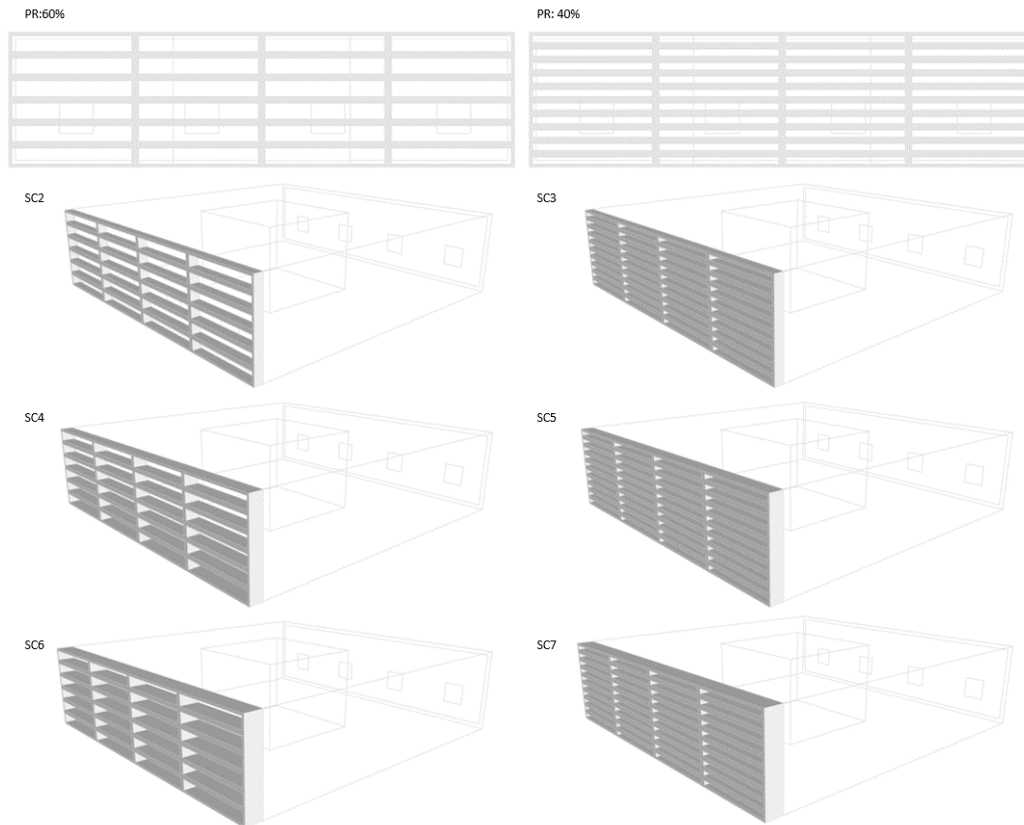


Figure 5.5. Shading device alternatives

Occupancy Scenario: The building is assumed to be occupied by 32 people between 8:00-18:00. The occupants are engaged in office activities. Occupants' activity levels are determinants of their respiratory activities and comfort levels. In this study, activity level is used to calculate (1) contaminant (virus and CO₂) generation rate and (2) virus inhalation rate. For different activity levels (resting, standing, light exercise, moderate exercise, and heavy exercise), the simulation (particularly, energy and contaminant

simulations) results can vary significantly due to metabolic rates, expiratory activities, contaminant emission, and generation rates of the occupants.

Infection Scenario: For the contamination analysis, the infected person is infected by COVID-19 and assumed to be located as in Figure 5.6. In all scenarios, the infected occupant stays in the room for an hour (9:00-10:00) during the simulation period. The height of the contaminant is set to 1.20 m for a sitting occupant. In the literature, different accounts for COVID-19 generation rate exists for different experimental setups. Also, COVID-19 generation rates vary significantly with respect to human activities (breathing, speaking, coughing, sneezing, even changing with the vocalization while speaking), the infection phase, and particle characteristics (WHO, 2020). In this research, the generation rate is taken from the study of Leung et al. (2020), which measures viral shedding rates of the patients with COVID-19, rhinovirus, and influenza.

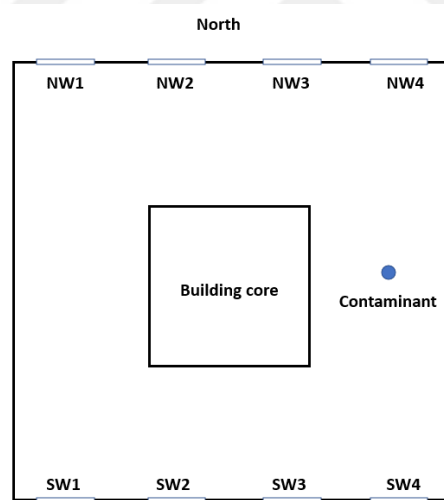


Figure 5.6. Contaminant location

Design Scenarios: The pipeline is implemented for seven scenario categories for six shading device geometries and an as-is geometry (baseline). The baseline scenario category (SC1) is established for benchmarking. Each scenario category is simulated for four wind directions (0° , 90° , 180° , and 270°) (28 scenarios and named as A-

scenarios, B-scenarios, C-scenarios, and D-scenarios referring to the wind direction) to evaluate the impact of the shading devices concerning wind direction on indoor air.

In all scenarios, the office is free-running and naturally ventilated, where no space conditioning is used. In SC1, the open office does not have shading devices. For each scenario, different geometry, energy, CFD, contaminant, and physical models are generated. For each scenario, T_i is calculated separately based on energy analysis and used in contamination simulations.

Table 5.4. Scenario categories and scenarios

Scenario Categories	Scenarios	PR	SD	Wind Direction	T_i (tunnel)	T_i (CFD)
SC-1	SC-1A	-	-	0°	25.10°C	25.36°C
	SC-1B			90°	28.39°C	27.00°C
	SC-1C			180°	25.10°C	25.36°C
	SC-1D			270°	28.39°C	27.01°C
SC-2	SC-2A	60%	40 cm	0°	24.83°C	27.46°C
	SC-2B			90°	27.17°C	27.48°C
	SC-2C			180°	24.80°C	27.45°C
	SC-2D			270°	27.16°C	27.49°C
SC-3	SC-3A	40%	40 cm	0°	24.80°C	27.32°C
	SC-3B			90°	27.03°C	27.35°C
	SC-3C			180°	24.78°C	27.31°C
	SC-3D			270°	27.03°C	27.35°C
SC-4	SC-4A	60%	60 cm	0°	24.82°C	27.41°C
	SC-4B			90°	27.12°C	27.43°C
	SC-4C			180°	24.79°C	27.39°C
	SC-4D			270°	27.11°C	27.44°C
SC-5	SC-5A	40%	60 cm	0°	24.80°C	27.30°C
	SC-5B			90°	27.00°C	27.33°C
	SC-5C			180°	24.78°C	27.28°C
	SC-5D			270°	27.1°C	27.33°C
SC-6	SC-6A	60%	80 cm	0°	24.81°C	27.37°C
	SC-6B			90°	27.08°C	27.39°C
	SC-6C			180°	24.79°C	27.35°C
	SC-6D			270°	27.07°C	27.40°C

Table 5.5. Scenario categories and scenarios (continued)

SC-7	SC-7A	40%	80 cm	0°	24.81°C	27.28°C
	SC-7B			90°	26.99°C	27.31°C
	SC-7C			180°	24.78°C	27.26°C
	SC-7D			270°	26.99°C	27.31°C

5.2 Implementation

Implementing the pipeline involves a number of tools for modeling, simulation-based analyses, and physical testing. Daylighting analyses are performed using Radiance, an open-source lighting simulation engine (Radiance, 2019). CFD simulations are performed using OpenFOAM, a piece of open-source CFD software (The OpenFOAM Foundation, 2011). Energy simulations are performed in EnergyPlus (U.S. Department of Energy's Building Technologies Office, 2001a). Contamination analyses are performed using NIST CONTAM, multi-zone IAQ and ventilation analysis software that supports the simulation of airflows, contaminant concentrations, and occupants' contaminant exposure (Dols and Polidoro, 2015). For 3D modeling of the building geometry, Rhinoceros 3D (Robert McNeel and Associates, 2020) is employed. For physical testing, pressure and PIV tests, a medium-scale suction type wind tunnel is used.

The pipeline also supports parametric modeling by employing Grasshopper 3D (Rutten, 2007), a visual programming environment that supports the algorithmic design and operates within Rhinoceros 3D. Grasshopper enables the seamless integration of daylighting, CFD and energy simulations with parametric design capabilities through various simulation tools such as Radiance, EnergyPlus, and OpenFOAM via Ladybug Tools plug-in (Honeybee, Ladybug, and Butterfly) (Roudsari and Mackey, 2012). As such, rapid geometry manipulations and the easy exploration of a wide range of parametric variations are made possible.

It is worth mentioning here that the pipeline is not limited to the tools used during the case-study implementation.

5.2.1 Study Metrics

The simulated shading designs are evaluated against the performance metrics based on the developed performance framework. The natural ventilation performance is assessed against ventilation rate (ACH), draft (m/s), CO₂ levels (ppm), CCL (#/m³), T_{inf} (HH:MM), and T_{dis} (HH:MM). Energy-related performance is evaluated against indoor air temperature (°C) and ventilation-sensitive heat loss (HL). Daylighting performance is assessed against DLA (%), UDI (%), and DGP (%).

ACH, CO₂ levels, T_i , and HL are directly acquired from energy simulations, while DLA, UDI, and DGP are obtained from daylighting simulations. However, CCL, T_{inf} , and T_{dis} require the following steps for data acquired from contamination simulations.

CONTAM calculates the number of virus particles (VP) on user-defined test points in the room. First, CCL values calculated as mass fraction format (kg/kg) by CONTAM, is converted to the number of particles per unit volume (#/m³) by following Eq.8 (W. Stuart Dols & Polidoro, 2015):

$$\# / m^3 = \frac{kg / kg}{\frac{\rho_{eff}}{\rho_{air}} \frac{1}{6} \pi D_{mean}^3} \quad (8)$$

where ρ_{air} is the density of air (kg/m³), ρ_{eff} is the effective particle density (kg/m³), D_{mean} is the mean particle diameter (m). CCL values for the test points or specific intervals are calculated by the average integration function in Tecplot 360 EX (Tecplot Inc., 2010). Average integration calculates the sum of the selected parameter of each test point over the zone or specified subset (Tecplot Inc., 2010).

CCL values are calculated for the whole room (CCL_{total}), and the selected data points as follows:

- (1) **The room (CCL_{total}):** CCL_{total} is calculated by averaging timestep CCL (CCL_t) values for the simulation period as follows:

$$CCL_{total} = \frac{\sum_{i=1}^m CCL_t}{m} \quad (9)$$

where CCL_t is the value calculated by average integration of the whole room, i is the timestep, and m is the index of the final timestep. The integration is performed for each timestep.

- (2) **Breathing zone in the room (CCL_{BR}):** CCL_{BR} is calculated for the selected data points (P) between $h=1.20$ and $h=1.80$ m-level.

$$CCL_{BR} = \frac{\sum_{i=1}^m CCL_{brt}}{m} \quad (10)$$

where CCL_{brt} is the value calculated by average integration of the breathing zone in the room, i is the timestep, and m is the index of the final timestep. The integration is performed for each timestep.

5.2.2 Computer-Based Analysis

5.2.2.1 Daylighting Simulations

Daylighting simulations are performed by Radiance to calculate UDI, DLA, and DGP, operationalized through Honeybee plug-in, which is a Python library for building energy and daylighting simulations (Mackey & Roudsari, 2018). The daylighting model is built upon the 3D design geometry of the case building modeled in Rhinoceros 3D, then defined in Grasshopper and Honeybee. The walls, ceiling, floor slabs, and openings are modeled as surfaces. Weather data for the calculations are obtained from an EPW file that contains 8760-hour annual weather data for the selected location and simulation period as determined in 5.1.2.

UDI and DLA are calculated via grid-based simulation, while DGP is calculated via image-based simulation. For grid-based simulation, an analysis grid is generated (Figure 5.7) to calculate UDI and DLA. For image-based simulation to calculate DGP, four view points are determined in the room (Figure 5.7).

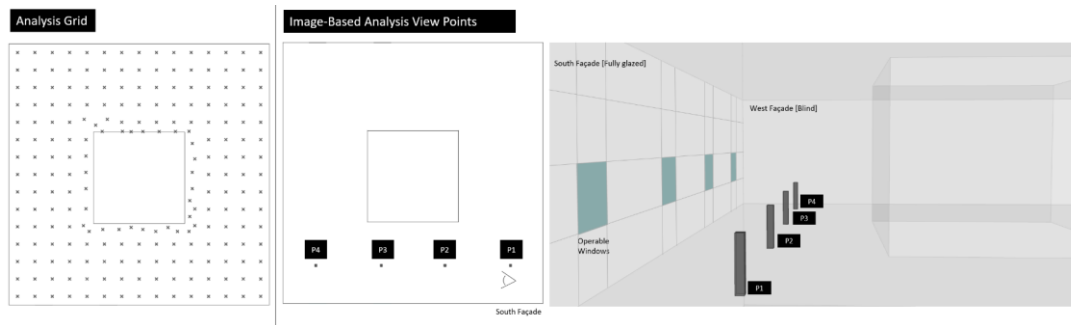


Figure 5.7. Daylighting simulation setup

The sky model, which defines sky conditions, is generated based on the EPW file as (1) climate-based sky for UDI and DLA calculations, and (2) standard CIE sky sunny with the sun for DGP analysis. The climate-based sky can model the exact sky conditions based on the EPW file for the selected location and period. In contrast, standard CIE sky is an existing sky model developed by The Commission International de l'Eclairage (CIE) by defining luminance distributions of commonly simulated sky conditions in daylighting analysis.

For UDI and DLA, a climate-based sky is preferred to simulate the conditions which are specific to the location. On the other hand, for glare analysis, a clear and luminous sky model is selected to inspect the impact of the shading devices on indoor visual comfort and glare conditions.

5.2.2.2 Energy Simulations

Energy simulations are performed to calculate T_i . To generate the energy model, the design geometry previously generated in Grasshopper is used as a base. Building

construction is based on lightweight concrete and exterior glazing (for details 5.1.2). Energy simulations are performed by EnergyPlus, operationalized through the Honeybee plug-in (Mackey & Roudsari, 2018).

Airflow Network (AFN) is a crucial component of the energy model. It simulates the performance of an air distribution system, supply/return leaks, and calculates multizone airflow induced by wind and HVAC systems (U.S. Department of Energy, 2015). In EnergyPlus, there are two possible representations for natural ventilation: ‘Wind and Stack Area’ and AFN. AFN-integrated energy simulations are more accurate, as they can incorporate actual C_p values in its calculations. Accordingly, in this research, the AFN model is used to calculate the transient thermal conditions that are affected by the airflow distribution through natural ventilation. The original modelling environment Honeybee is built upon the OpenStudio SDK (Mackey & Roudsari, 2018), in which AFN is not yet implemented (Marschall, Burry, & Tahmasebi, 2020). Therefore, the energy model is built in two consecutive stages. In the first stage, an initial model without EnergyPlus AirflowNetwork is built-in Honeybee and saved as an IDF file. Following, this IDF file is edited using the *IDF Editor* to manually add the AirflowNetwork to the room with the C_p values calculated in the previous step (Figure 5.8).



Figure 5.8. AFN integration into the energy model

From the energy simulations, hourly T_i values are obtained. Following, an average T_i value is calculated for the contaminant analysis period. This is because transient T_i values are not permitted in CONTAM.

5.2.2.3 CFD Simulations

CFD simulations are performed using OpenFOAM and operationalized through the Butterfly plug-in (Roudsari & Mackey, 2012), a Python library that performs CFD simulations (Chronis, Dubor, Cabay, & Roudsari, 2015). Butterfly is built for CFD simulations of buildings with common types of airflow simulations; therefore, the use of Butterfly is limited to architectural scale (Ladybug Tools LLC, 2017-2021.). CFD model is built upon the 3D design geometry of the case building modeled in Rhinoceros3D and defined in Grasshopper and Butterfly. The walls, ceiling, floor slabs, and openings are modeled as surfaces. The wind characteristics such as the prevailing wind direction and the average velocity are obtained from an EPW file for the selected location and simulation period as determined in Section 5.1.

CFD simulations are run for the whole building geometry, and the computational domain (CD) of the CFD model is defined with respect to the best practice guidelines of Franke et al. (2011). Accordingly, for the case study building, the vertical extension (upstream domain length) and lateral extensions are $5H = 500$ m, leeward extension (downstream domain length) is $15H = 1500$ m, and windward extension is $3H = 300$ m, where the H is the building height ($H=100$ m) (Figure 5.9).

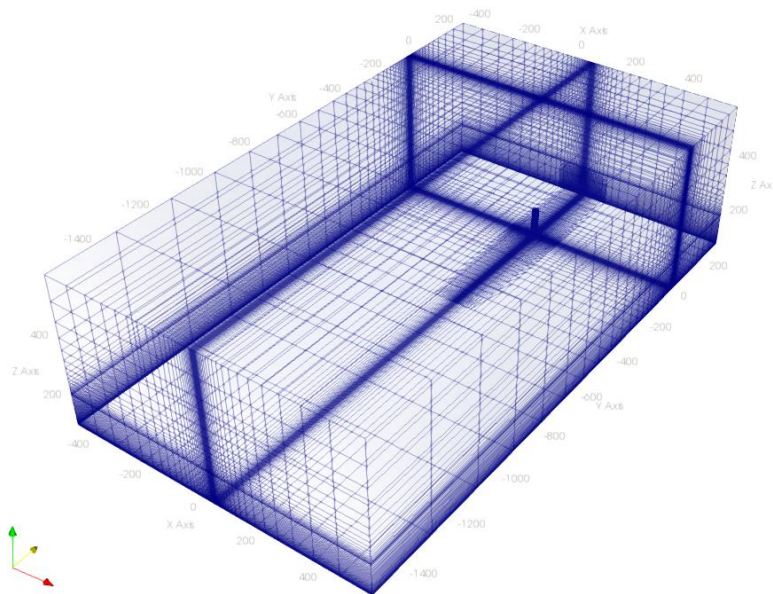


Figure 5.9. CFD computational domain

A CFD model is built for the entire building. There are two existing approaches to CFD simulations: *coupled* and *decoupled* approach (Ramponi & Blocken, 2012). In the *coupled* approach, indoor and outdoor environments are a single computational domain (*CD*), where wind interacts with both indoor and outdoor at the same time via assuming openings as voids in the CFD model (Ramponi & Blocken, 2012). In the *decoupled* approach, indoor and outdoor environments are two different *CDs* isolated from each other, where wind only interacts with the envelope of the building that the C_p are calculated for (Ramponi & Blocken, 2012). The openings are assumed to be open in the CFD model, and the *WPP* is calculated on these surfaces (Ramponi & Blocken, 2012). As a result, the boundary conditions of the contamination simulation are obtained. The coupled approach for CFD simulations is only performed to obtain C_p on the opening surfaces.

Mesh is generated by blockMesh and snappyHexMesh utilities, which are mesh generators, of Open FOAM operationalized through Butterfly plug-in. blockMesh utility constructs parametric meshes with grading and curved edges (The OpenFOAM Foundation, 2018). blockMesh decomposes the domain geometry into 3D hexahedral blocks. Similarly, snappyHexMesh constructs 3D meshes of hexahedra (hex) and split-hexahedra (split-hex) cells. snappyHexMesh enables the iterative refinement of the base mesh (The OpenFOAM Foundation, 2018). snappyHexMesh is a crucial utility to control mesh refinement levels for the accuracy of the CFD simulation results. Accordingly, first, blockMesh is generated as a base-level mesh, then the base-level mesh is re-constructed and refined by snappyHexMesh utility.

The accuracy of the simulation results is based on the quality of the mesh. A grid convergence study is a reliable method that measures the mesh quality by comparing different mesh settings based on their results. To determine the suitable mesh for CFD simulations, a grid convergence study is performed, and three different grids are constructed as (1) coarse grid (1645529 cells), (2) medium grid (2291234 cells), and (3) fine grid (2648342 cells). The grid quality is controlled by the snappyHexMesh utility's *global refinement* and *surface feature level* parameter. For each grid, *global refinement* and *surface feature levels* are altered. CFD simulations are run for the baseline case considering the north (0°) wind direction. The resulting grids are checked

by *checkMesh* utility provided by OpenFOAM. Mean Absolute Error (MAE) values are calculated for the scalar velocity and pressure values of the selected points on the geometry. For scalar velocity, MAE between the coarse and medium mesh is 0.4, whereas 0.01 between the medium and fine mesh. Similarly, for pressure MAE between the coarse and medium mesh is 6.9, whereas 0.09 between the medium and fine mesh. Residual values are also checked, and it is observed that all meshes converge as suitable to the best practice (Table 5.6). Accordingly, based on MAE results the fine mesh setup is selected for the rest of the CFD simulations.

Table 5.6. Mesh convergence results

Mesh Setup	Cell Count	Residuals					
		Ux	Uy	Uz	p	epsilon	k
Coarse	1645529	5.74e-5	2.78e-6	1.72e-5	5.28e-6	1.45e-7	2.72e-5
Medium	2291234	8.36e-5	3.45e-6	2.08e-5	3.02e-6	6.92e-7	3.10e-5
Fine	2648342	8.60e-5	3.35e-6	2.38e-5	3.85e-6	4.49e-7	2.88e-5

Table 5.7. MAE results for the coarse, medium and fine meshes

Mesh Comparison	MAE	
	Scalar Velocity	Pressure
Coarse - Medium	0.4	6.9
Medium - Fine	0.01	0.09

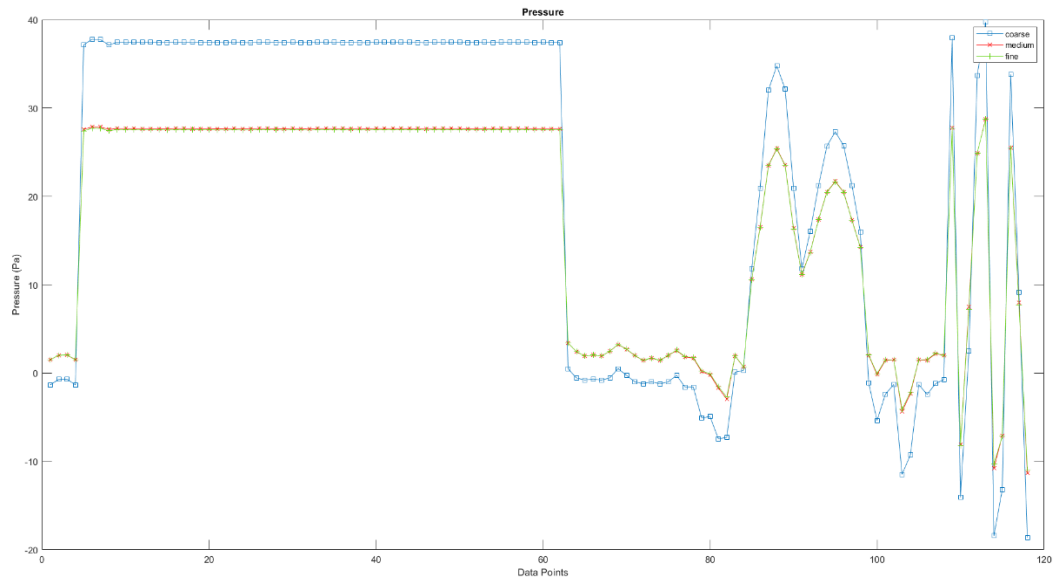


Figure 5.10. Pressure comparison graph

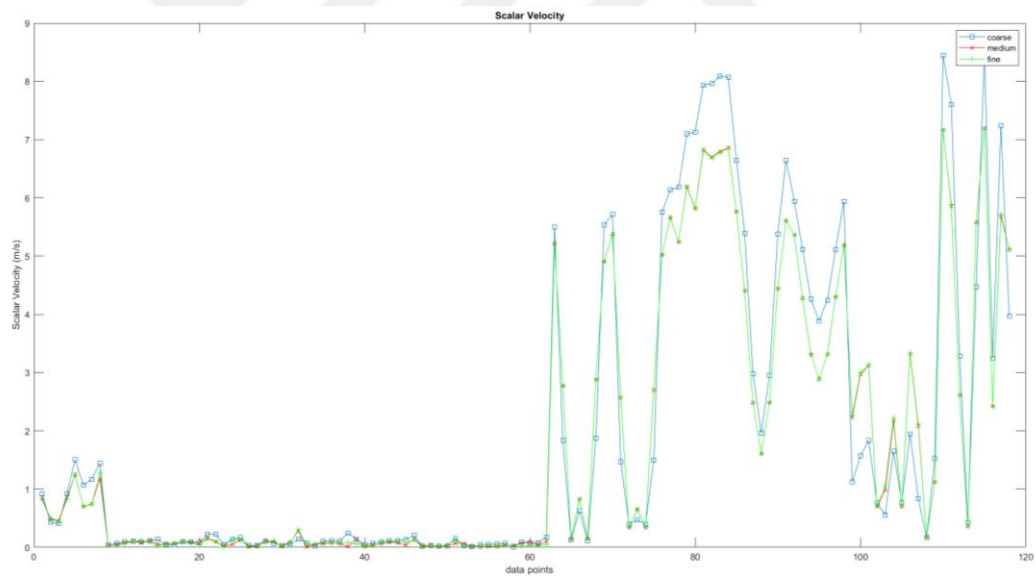


Figure 5.11. Scalar velocity comparison graph

The inlet boundary condition is set to wind vector (direction and velocity) and temperature and is calculated using the EnergyPlus weather file (EPW) that contains 8.760-hour annual weather data for the selected location. The simulations are performed for a uniform cityscape, where the terrain is covered by buildings with similar heights and open spaces. The aerodynamic roughness is defined as $z_0 = 1$ m.

The terrain characteristics automatically change the atmospheric boundary layer and adjust the wind speed acting upon the building. The reference wind speed at $z_{ref} = 50$ m is 4.3 m/s, which is Ankara's daily average wind speed for the typical summer day (August 17th - August 23rd, as indicated in the existing STAT file).

Simulations are performed with Reynolds-Averaged Navier Stokes (RANS) equations and RAS- $k\epsilon$ turbulence model for steady incompressible flows via SIMPLE (Semi-Implicit Method for Pressure Linked Equations) algorithm. The simulations are performed for four cardinal directions (as inputs to EnergyPlus AFN) and are terminated at the 1000th iteration, where the residuals reach the tightly-converged values, defined as 1E-6 in the best practice guidelines (Franke et al., 2011). To generate *WPP* from the resulting pressure values, C_p values are calculated as (The OpenFOAM Foundation, 2018):

$$C_p = \frac{p}{0.5 \rho_{air} |U_{\infty}|^2} \quad (11)$$

where p is the pressure (Pa) obtained from CFD test points on the openings, ρ_{air} is the air density (1.225 kg/m³) and U_{∞} is the freestream wind speed (4.3 m/s). Finally, C_p values for the cardinal directions are integrated into the AirflowNetwork (AFN) in EnergyPlus.

5.2.2.4 Contaminant Simulations

CONTAM is used for contaminant transport simulations. CONTAM performs CFD analyses using CFD0 as an external CFD zero-turbulence model link to calculate the indoor contaminant concentrations by predicting potential impacts of the wind pressure distributions on the building exterior (L. L. Wang, Dols, & Chen, 2010). CONTAM follows CONTAM-CFD0-CONTAM path to obtain contaminant concentration levels. CONTAM-CFD0 link offers two models of coupling as (1) coupling for building exterior simulations and outdoor contaminant concentrations, and (2) embedding a CFD zone within CONTAM AFN for the contaminant transport

simulations (L. L. Wang et al., 2010). A CFD zone is a single space in a building that the CFD simulations are performed for (Dols & Polidoro, 2015). Since the C_p values are acquired from wind tunnel tests, the second coupling model is used. The CONTAM model supports dynamic coupling between CONTAM and CFD0, based on the iterative exchange of the boundary conditions (Wang et al., 2010). Once the required data (i.e., weather data and C_p values) is provided, C_p values on the openings and flow rates are obtained for the CFD zone. CFD0 calculates airflow behaviour and provides feedback to CONTAM (Wang et al., 2010).

To perform contaminant simulations, CONTAM requires a building geometry drawn in the 2D CONTAM SketchPad environment. Also, a weather file is needed in WTH format, which can be converted from EPW files using CONTAM Weather File Creator online tool (NIST, 2010). The transient outdoor air temperature values (T_o) are extracted from the EPW-converted WTH weather file. CONTAM also requires a contaminant model that specifies the contaminant's molecular weight (molar mass), particle diameter and the effective density. COVID-19 is selected as the bio-contaminant species in this study. The molecular weight of COVID-19 is 33797.0 Da (33.79 kg/kmol) (Jin et al., 2020). The diameter of COVID-19 is set to 100 nanometers (0.1 μm), which is the average value of the diameter range (between 60-140 nanometer) (Zhu et al., 2020). The particle's effective density, which defines the mass and mobility relation of the particle, is set to 1.0 g/cm^3 (Dols et al., 2020).

CONTAM constant-coefficient contaminant model is used, which requires contaminant generation and removal rates. In this study, the generation rate for COVID-19 is used from the empirical research of Leung et al. (2020), which measures the aerosol virus shedding rates of patients with COVID-19, rhinovirus, and influenza. In their study, COVID-19 infected breath samples are analyzed during 30-min of breath sampling (Leung et al., 2020). COVID-19 is detected in 40% of the aerosol samples (4 out of 10 participants with a maximum of $10^{4.7}$ and a minimum of $10^{2.8}$ particles per 30 min). The calculated average viral shedding is 35,366 aerosol virus particles per hour. The removal rate is the measure of the rate that the contaminant is deposited from the space (Dols & Polidoro, 2015). CONTAM constant-coefficient

contaminant model calculates the removal rate (Dols & Polidoro, 2010) and does not necessitate a pre-determined removal rate.

5.2.3 Model Testing

5.2.3.1 Prototyping

Prototyping was relatively a significant phase in wind tunnel testing. Three parameters for prototyping are determined as (1) material, (2) assembly, and (3) scale of the model. Also, a number of fabrication methods were studied, including CNC milling, additive manufacturing, and laser cutting, to identify the suitable prototyping technique for the case study. Based on the test procedures and the selected wind tunnel scale, laser-cutting is adopted as a prototyping method for the case study after a detailed investigation (Table 5.8).

Material: PIV tests require transparency for flow visualization. Two options are (1) a transparent plexiglass model fabricated by laser cutting and (2) a high-quality 3D-printed transparent filament model. The laser-cut transparent plexiglass model is more feasible by requiring a shorter fabrication time and budget than high-quality 3D printing.

Assembly: Assembly can be considered in three stages as (1) the assembly of the building model, (2) shading devices, and (2) the wind tunnel instruments. Pressure tests require intense assembly work for measurement instruments such as pressure taps on and inside the model surfaces. The laser-cut model gives the flexibility to the model maker to mount pressure taps on the surfaces since the model is fabricated surface by surface. The 3D-printed model can also be fabricated piece by piece; however, 3D pieces may bring new challenges to the fabrication process due to the model-scale assembling. Custom joints can be designed to assemble 3D pieces; however, the joints also have a risk of breakage or split due to the pressure while assembling the instruments.

Scale: The scale of the model is limited by the blockage ratio (Chang-Koon Choi and Dae-Kun Kwon, 1998). To reduce the blockage effect, the building model is mounted between the top and bottom walls of the wind tunnel. The directional blockage ratio is calculated based on Eq.6 for $BR_L = 15\%$ which is $<17\%$, and does not necessitate blockage correction.

Table 5.8. Model fabrication and test parameters

Model/Test Parameters	Requirements	Fabrication Solution(s)	Implementation	In this research
Material	Transparency for the airflow visualization	Option 1: Plexiglass (laser-cutting)	Requires laser cutter, and plexiglass sheets Feasible and quicker implementation compared to high-quality 3D printing	✓
		Option 2: Transparent filament (3d printing)	Requires high precision printing with high-quality printers, time and budget	
Assembly	Robustness for the wind-speed and pressure	Option 1: Monoblock by glueing	Requires methylene chloride Provides the required robustness	✓
		Option 2: Custom-designed joints	A potential risk of vibration -regarding the splits, breakage -the decrease in the precision regarding the shaking/moving -air leakage	
Scale	Reducing the blockage effect/ratio	Option 1: Full-scale fabrication of the building model		✓
		Option 2: Fabrication of the typical floor plan of the building		

As a result, a 1:100-scale building model and six shading devices are fabricated by laser-cutting. Shading devices are assembled to the building model surfaces by double-sided tapes. Three models are built from 5mm transparent plexiglass by using a laser cutter. Pressure tests are performed separately for façade pressure measurements and interior pressure measurements. Accordingly, two models are used for pressure tests, and one model is used for the PIV tests. Indoor and façade measurements required two models since the capillary tubes mounted behind the façade run the risk of affecting the indoor measurements. The model dimension is $W \times D \times H = 16 \text{ cm} \times 16 \text{ cm} \times 100 \text{ cm}$. Shading devices are fabricated separately from 4 mm, and 6 mm transparent plexiglass and fixed to the model by double-sided tape interchangeably (Figure 5.12). In both tests, the models are exposed to 4.3 m/s freestream airflow.

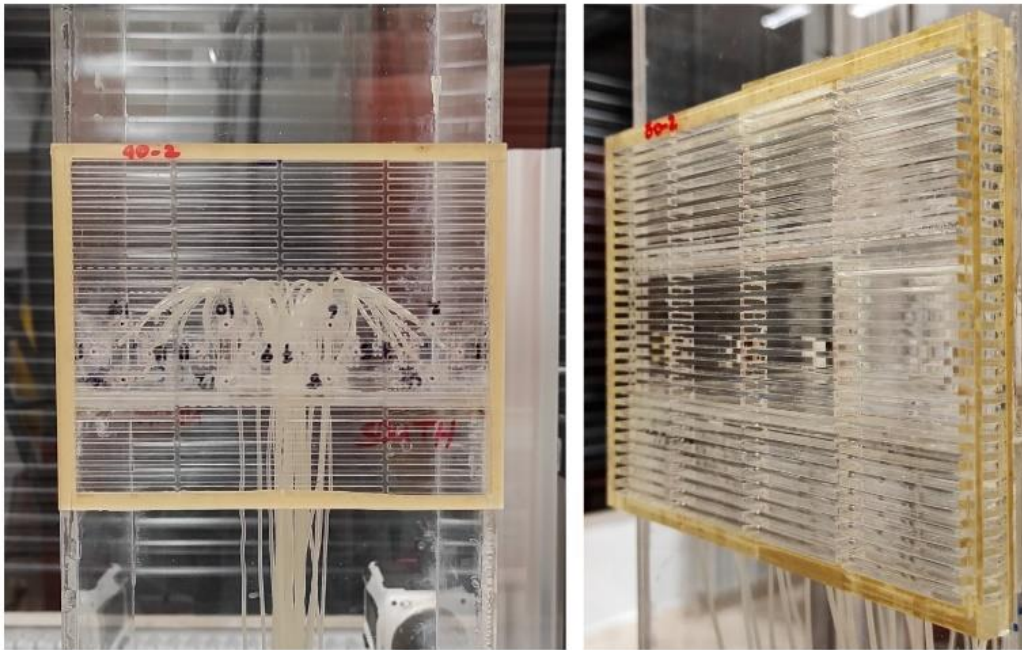


Figure 5.12. Fabricated shading devices placed in the tunnel, Rüzgem METU

5.2.3.2 Experimental Setup

Two experimental studies were performed with wind tunnel as PIV and pressure tests with 1:100 scaled transparent building models. The axial fan is driven by a 45 kW electric motor, and the tunnel has flow conditioning through honeycombs and screens

(METU Rüzgem). The tunnel is 8 m, and the test section is placed 2 m away from the tunnel outlet. The test section is 1 m x 1 m square cross-section and made of 10 mm transparent plexiglass. The airflow can accelerate up to 25 m/s with <1% turbulence intensity.

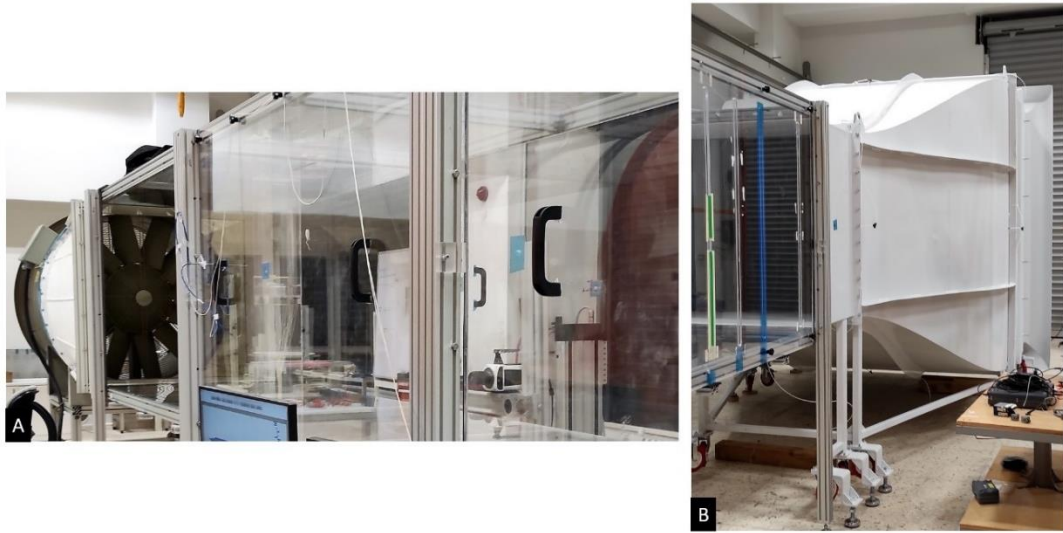


Figure 5.13. Wind tunnel, Rüzgem METU

The quality and reliability of the measurements and obtained data depend on the accuracy of the instrument in physical testing (de Wilde). Calibration and adjustments can help reducing errors and deviations in data. Therefore, prior to the actual tests, a repeatability test and error analysis are performed for the wind tunnel. First, wind from 0° angle is tested twice for each SC (SC1A to SC7A). Following, mean absolute error (MAE) and mean absolute percent error (MAPE) for two data sets of each SC are calculated. Average MAE and MAPE are calculated as 0.77 and 4.71%, respectively, which may be regarded as negligible deviations in wind tunnel test results.

Table 5.9. Repeatability test

	SC-1A	SC-2A	SC-3A	SC-4A	SC-5A	SC-6A	SC-7A	AVERAGE
MAE	1.07	0.31	0.1	0.95	1.15	1.31	0.47	0.77
MAPE	7.12%	2.04%	0.60%	5.71%	6.90%	7.78%	2.80%	4.71%

The reliability of the results also depends on test setup. In this research, atmospheric boundary layer is not simulated, and scale effects are disregarded. This research relied on the non-dimensional parameters such as wind pressure coefficients.

5.2.3.2.1 Pressure Test Setup

The pressure models require pressure taps for the measurements. The pressure taps are prepared using 16-gauge (1.63 mm) metal tubes and 1.37 mm flexible capillary tubes. The metal tubes and flexible capillary tubes are shrink-fitted. The metal tubes are attached to the holes drilled on the model surfaces (interior slab and the façades). The flexible capillary tubes are connected to a pressure scanner to register pressure values on the pressure taps (Figure 5.14). The pressure models are assembled afterward.

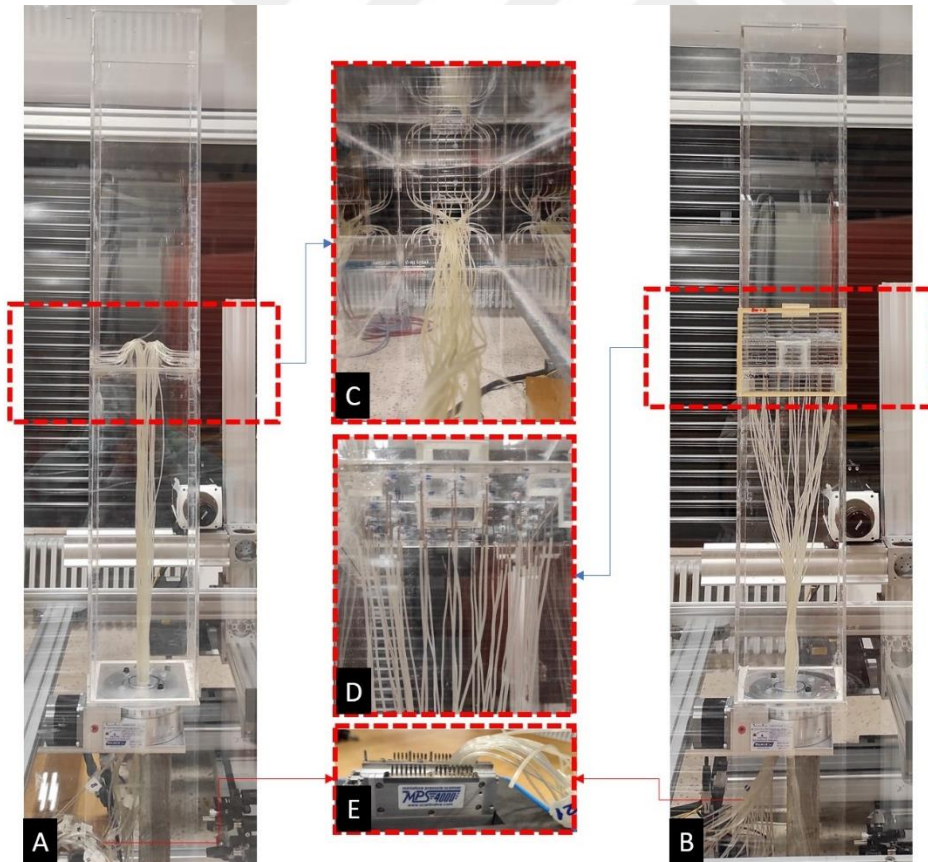


Figure 5.14. Pressure test setup, Rüzgem METU

Pressure tests are performed for the interior and the north (N) and south (S) façades of the building. 41 and 32 pressure taps are mounted on the interior ground surface and the N-S façades of the model (16 for N, 16 for S), respectively (Figure 5.15). The models are tested for eight directions for each case. A step motor, which is mounted under the wind tunnel's bottom wall, is also mounted to the ground surface of the model for rotation. Although the case study consists of four cardinal wind directions (N-S-E-W, and names as A-B-C-D-scenarios), the tests are performed for eight directions to evaluate the impact of the diagonal wind flow acting upon the building and shading device design on indoor air. Accordingly, 56 tests are performed in total.

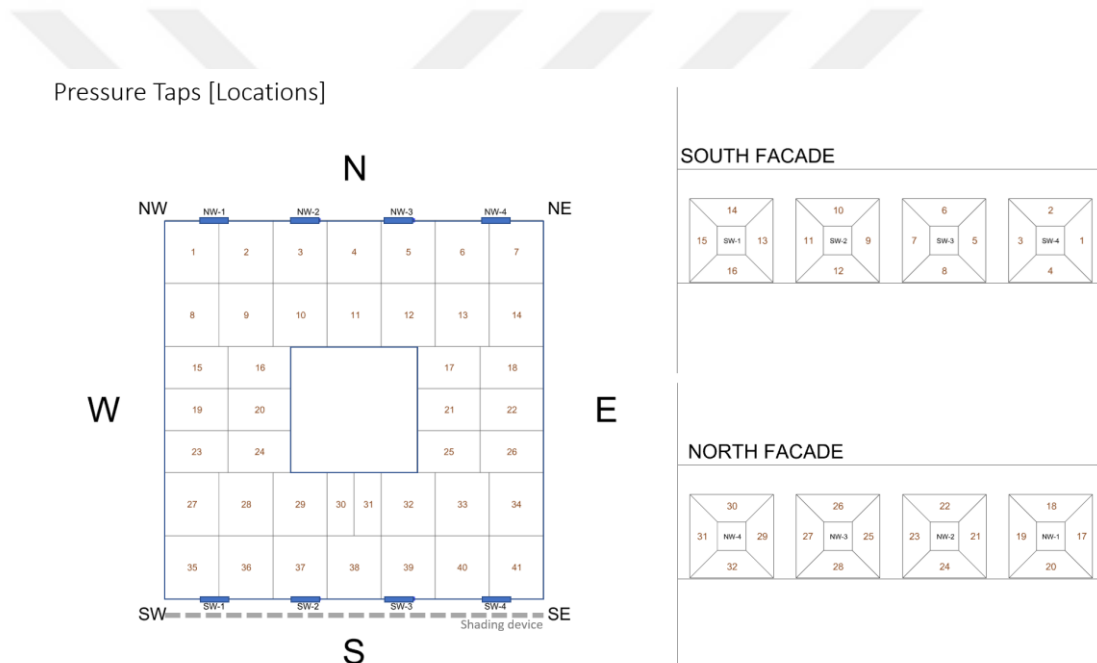


Figure 5.15 Pressure tap locations on the model (left: interior, right: façades)

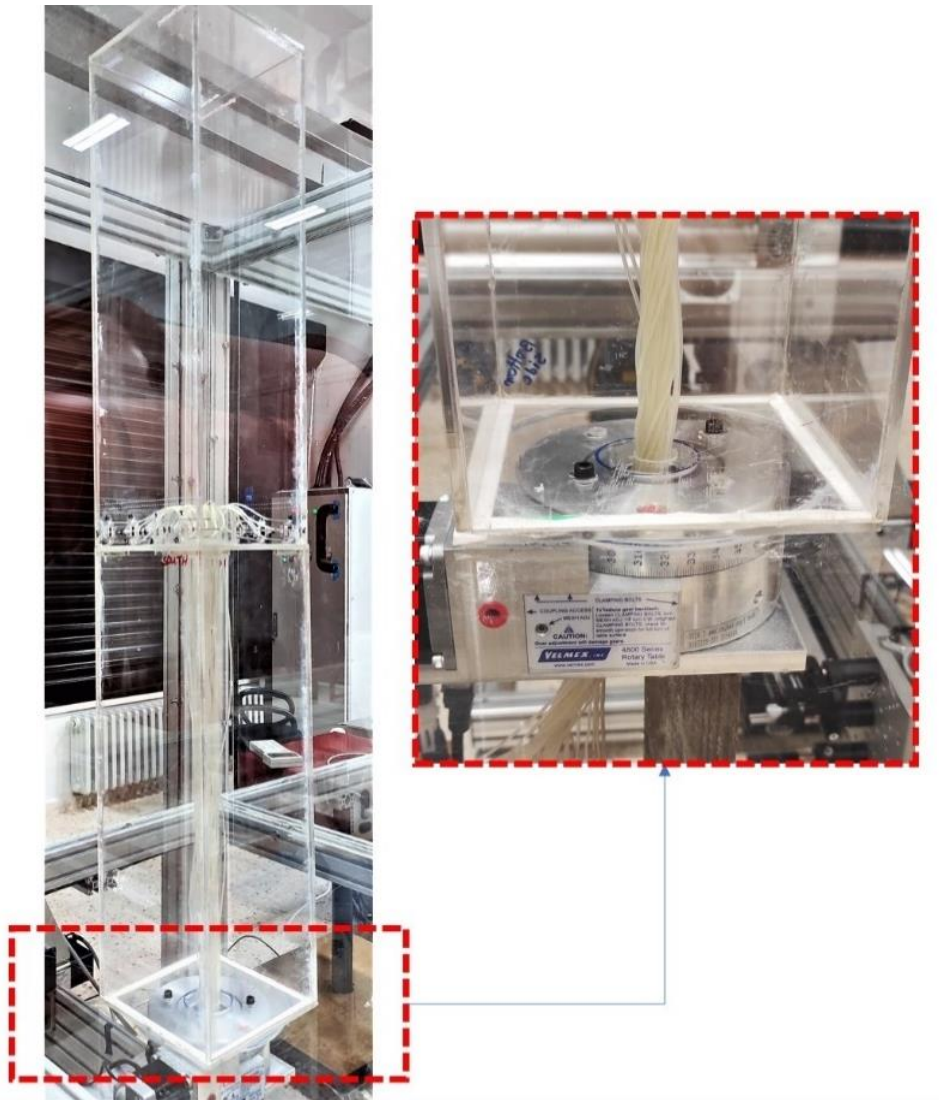


Figure 5.16. Model connection and the step motor, Rüzgem METU

5.2.3.2.2 PIV Test Setup

PIV tests are performed for all SC-A and SC-C to visualize indoor airflow behavior. Figure 5.17 shows the layout of the PIV test setup, which is based on a Phantom v641 high-speed camera with a Nikon-Nikkor 60 mm lens, a New Solo PIV Nd:YAG laser, a Dantec Dynamics timer box, and Dynamic Studio data acquisition and analysis software. The laser is placed on a 3-axis traverse, and the light beam is emitted from the laser along the horizontal section of the building model, as shown in Figure 5.17, while the camera is placed on top of the wind tunnel's top wall looking downward

through the wind tunnel test section. The incoming 4.3 m/s airflow from the tunnel inlet, as fog, is seeded with $\sim 1\ \mu\text{m}$ diameter particles. The low-pass filter method is used for the preprocessing of the captured particle/flow images to improve visual quality and to remove background noise. The test instruments and experimental parameters for PIV measurement are presented in Table 5.10.

Preliminary PIV tests showed that there was a reflection problem during the measurements due to the reflectivity of the transparent plexiglass material of the building model. To reduce the reflection, the edges and the ground surface of the test floor of the model are painted black, as shown in Figure 5.18.

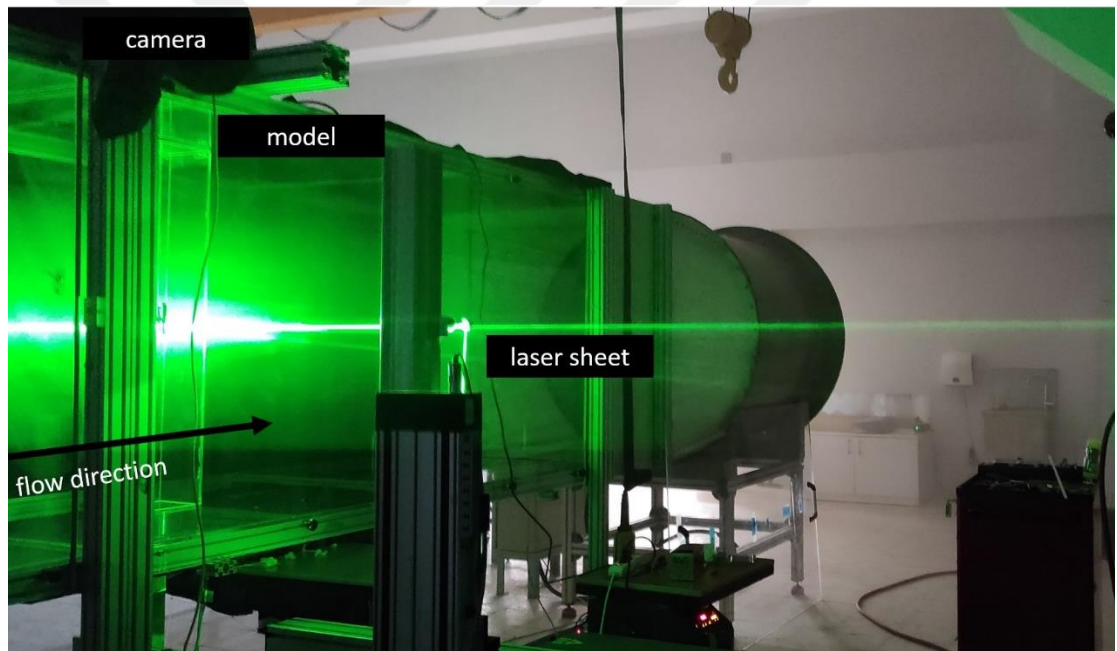


Figure 5.17. PIV test setup, Rüzgem METU

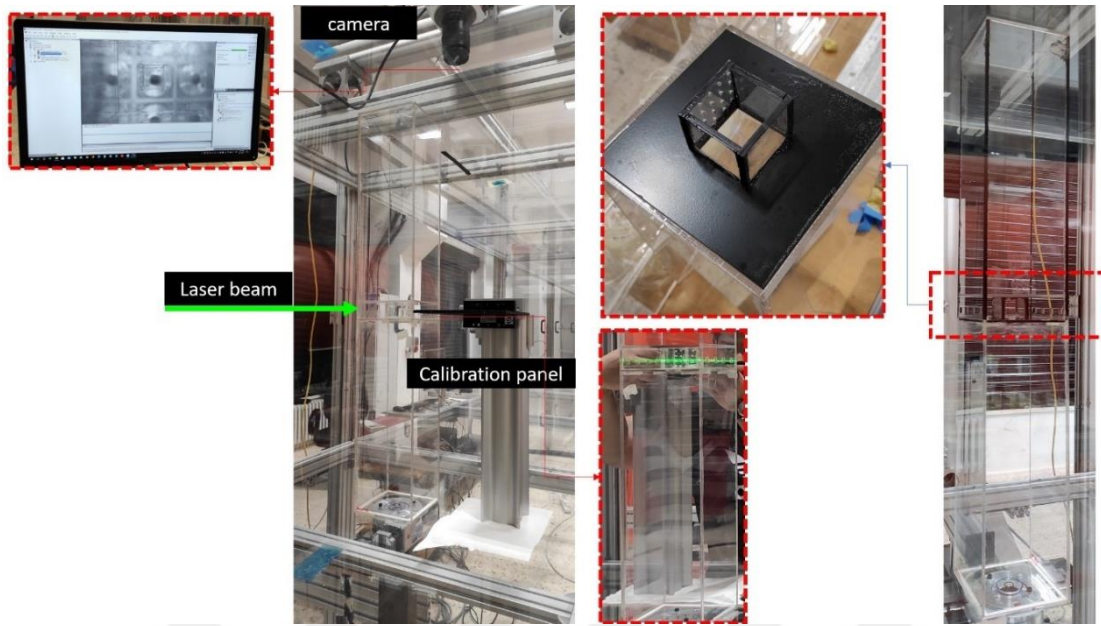


Figure 5.18. PIV test setup details, Rüzgem METU

Table 5.10. PIV test instruments

	Type	Fog
Seeding	Nominal diameter	$\approx 1\mu\text{m}$
	Seeding generator	Safex Fog generator
Laser Sheet	Laser type	Nd:YAG
	Manufacturer	New Wave Research
	Model	Solo 120XT
	Maximum Energy	120 mJ/pulse
	Wavelength	532 nm
	Thickness	$\approx 2\text{ mm}$
Optics	Mirrors	Dielectric Mirror, 532 nm
	Spherical Lens	Plano-convex, 750mm FL
	Cylindrical Lens	Plano-concave, -12.4 mm FL
Camera	Sensor type	CMOS
	Sensor resolution	2560 x 1600 pixel ²
	Sensor size	25.6 x 16.0 mm ²
	Pixel pitch (size)	10 μm
	Depth	12 bit
	Max repetition rate	1400 fps @ Full resolution 2500 fps @ 1920 × 1080
	Internal memory buffer	16 GB
	Manufacturer	Nikon
Camera Lens	Focal length	60 mm
	f# (aperture)	2.8
	Image Magnification	0.08
Imaging	Field of View (FOV)	199x320.83 mm ²
	Camera-object distance	600 mm
	Time between pulses (Δt)	80 μs
	Recording rate	10 Hz
	Pre-processing	Background intensity removal
PIV analysis	Correlation method	Adaptive-correlation
	Interrogation area (IA)	128 x 128 to 32 x 32 pixel ²
	Overlap between IAs	50% overlap
	Post-processing	Universal outlier detection With a 3 x3 kernel size
	Vector Spacing	$\approx 2.0\text{ mm}$



CHAPTER 6

ANALYSIS RESULTS AND FINDINGS

This chapter first presents the analysis results of computer-based simulations (daylighting, CFD, energy, and contaminant simulations) and wind tunnel tests (PIV and pressure). Following, the impact of shading devices on daylighting, energy, and natural ventilation-related performance metrics are discussed. In 6.1. the raw simulation and test results are presented numerically and visually. In 6.2. the analyses results are compared for each scenario. In 6.3. the findings of the implementation process is presented for shading devices and the pipeline.

6.1 Analysis Results

The analysis results are evaluated against daylighting, natural ventilation, and energy-related performance metrics as identified in 5.2.1. First, a single set of daylighting simulations is only assessed for the scenario categories since wind direction does not have an impact on the daylighting results. Then, two sets of energy simulations are performed as (1) CFD-integrated and (2) wind-tunnel integrated. The error between CFD-integrated and wind-tunnel integrated energy results are calculated. Following, contaminant simulations are investigated for each scenario separately.

6.1.1 Daylighting Analysis Results

Daylighting analysis is performed for the scenario categories. The simulation results are inspected both visually and numerically. Daylight illumination and glare within range are performed as a grid-based analysis and presented for plan views. Image-based analysis for four identified viewpoints is are presented for daylight glare probability (Figure 6.1).

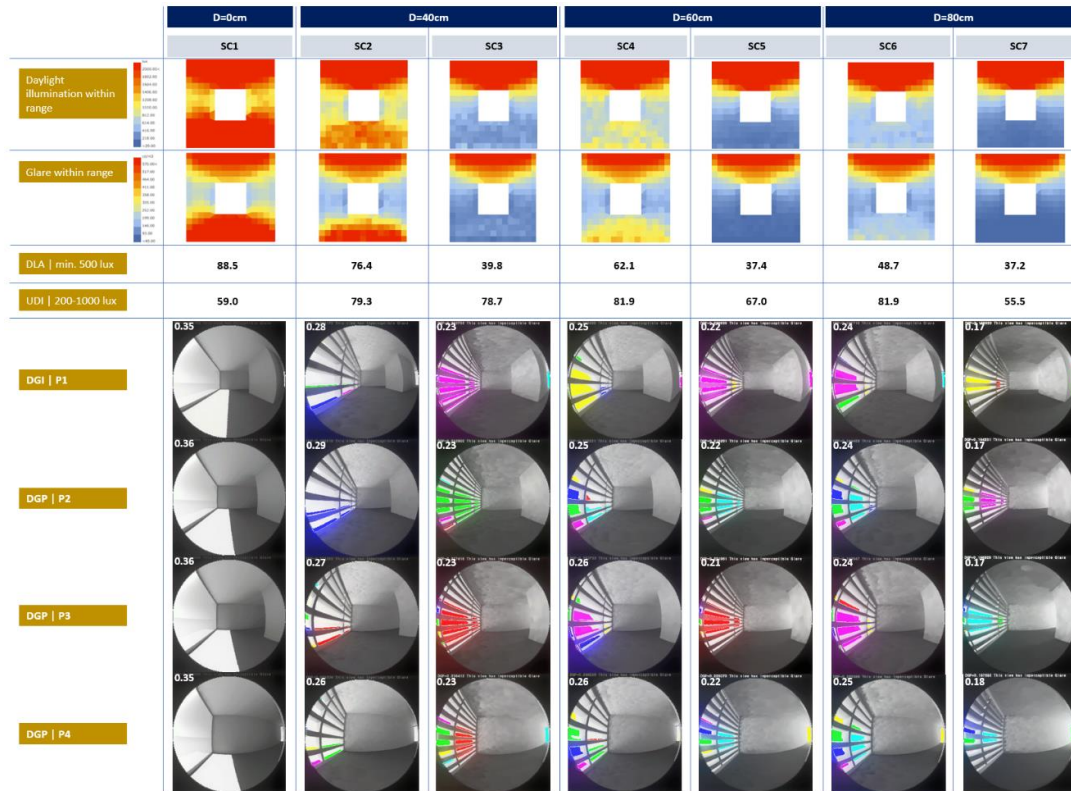


Figure 6.1. Daylighting analysis results

6.1.2 CFD Analysis Results

CFD simulations are performed for each scenario separately. Pressure and velocity values for the façade and indoor analysis grid are obtained from CFD simulations. Based on the façade pressure values, C_p values are calculated by Eq.11 and used as input in secondary energy simulations for the preliminary evaluation of design alternatives.

6.1.3 Energy Analysis Results

Two sets of energy analyses are performed as (1) CFD integrated and (2) wind tunnel integrated. C_p values are calculated for CFD simulations and wind tunnel pressure tests and integrated into EnergyPlus. Air change rate (ACH), ventilation sensitive heat loss (HL), indoor CO₂ levels, and indoor air temperature (T_i) are calculated for each

scenario. Window transmitted solar radiation rate is also calculated and presented (Figure 6.2) since shading devices have a considerable impact on transmitted solar radiation energy and increase in T_i , which may overshadow the effect of ventilation on final analysis results.

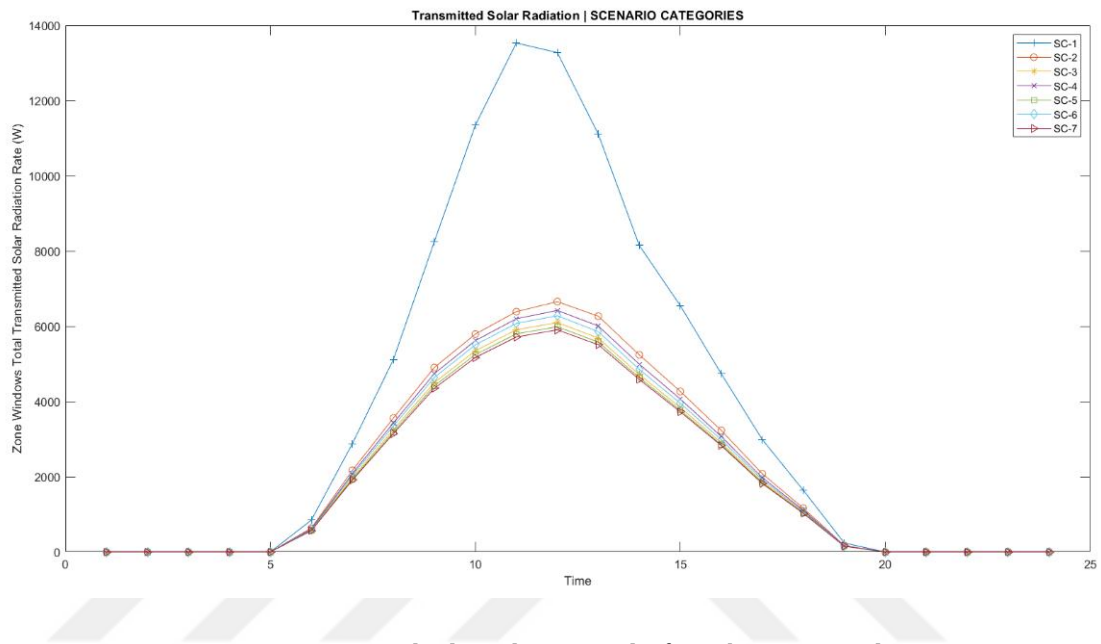


Figure 6.2. Transmitted solar radiation results from the energy analysis

6.1.3.1 CFD-integrated Energy Results

Air change rate (ACH), ventilation sensitive heat loss (HL), indoor CO₂ levels, and indoor air temperature (T_i) are calculated by energy simulations. The average (average value for 8:00-18:00) results are presented in Table 6.1.

Table 6.1. CFD-integrated energy analysis results

Scenario Categories	Scenarios	Average T_i	Average Zone Air CO ₂ Concentration (ppm)	Average Ventilation Sensible Heat Loss Energy (W)	Air Change Rate (ACH)
SC-1	SC-1A	25.36°C	324.41	5374.57	22.18
	SC-1B	27.00°C	383.15	4259.54	8.94

Table 6.2. CFD-integrated energy analysis results (continued)

	SC-1C	25.36°C	324.62	5364.75	22.07
	SC-1D	27.01°C	383.12	4271.42	9.04
SC-2	SC-2A	27.46°C	515.03	1924.29	2.17
	SC-2B	27.48°C	496.72	1973.19	2.51
	SC-2C	27.45°C	499.92	1978.75	2.52
	SC-2D	27.49°C	498.70	1974.08	2.39
SC-3	SC-3A	27.32°C	518.35	1807.85	2.12
	SC-3B	27.35°C	500.28	1853.56	2.46
	SC-3C	27.31°C	504.39	1853.81	2.48
	SC-3D	27.35°C	504.07	1851.01	2.37
SC-4	SC-4A	27.41°C	516.24	1879.24	2.15
	SC-4B	27.43°C	499.05	1924.02	2.44
	SC-4C	27.39°C	502.97	1906.60	2.43
	SC-4D	27.44°C	503.25	1922.91	2.36
SC-5	SC-5A	27.30°C	519.10	1785.28	2.11
	SC-5B	27.33°C	502.02	1835.00	2.40
	SC-5C	27.28°C	505.55	1810.00	2.40
	SC-5D	27.33°C	506.05	1826.11	2.32
SC-6	SC-6A	27.37°C	517.14	1847.51	2.14
	SC-6B	27.39°C	500.03	1891.85	2.43
	SC-6C	27.35°C	503.95	1871.73	2.40
	SC-6D	27.40°C	504.26	1890.25	2.34
SC-7	SC-7A	27.28°C	521.86	1766.30	2.09
	SC-7B	27.31°C	502.56	1818.67	2.40
	SC-7C	27.26°C	506.03	1793.52	2.39
	SC-7D	27.31°C	506.52	1809.53	2.31

6.1.3.2 Wind Tunnel- integrated Energy Results

Air change rate (ACH), ventilation sensitive heat loss (HL), indoor CO₂ levels, and indoor air temperature (T_i) are calculated by energy simulations. The average (average value for 8:00-18:00) results are presented in Table 6.3.

Table 6.3. Wind tunnel-integrated energy analysis results

Scenario Categories	Scenarios	Average T_i	Average Zone Air CO ₂ Concentration (ppm)	Average Ventilation Sensible Heat Loss Energy (W)	Air Change Rate (ACH)
SC-1	SC-1A	25.10°C	316.73	5593.32	31.49
	SC-1B	28.39°C	472.67	3222.08	6.09
	SC-1C	25.10°C	319.43	5516.45	30.90
	SC-1D	28.39°C	470.45	3261.13	6.54
SC-2	SC-2A	24.83°C	316.50	3508.95	31.96
	SC-2B	27.17°C	504.12	1897.87	5.86
	SC-2C	24.80°C	317.88	3466.15	31.99
	SC-2D	27.16°C	499.78	1908.23	6.31
SC-3	SC-3A	24.80°C	316.23	3320.45	32.49
	SC-3B	27.03°C	505.64	1774.00	5.88
	SC-3C	24.78°C	317.99	3268.79	31.88
	SC-3D	27.03°C	502.63	1785.87	6.39
SC-4	SC-4A	24.82°C	316.26	3436.94	32.43
	SC-4B	27.12°C	505.55	1850.03	5.87
	SC-4C	24.79°C	317.87	3387.77	32.11
	SC-4D	27.11°C	500.26	1862.67	6.41
SC-5	SC-5A	24.80°C	316.29	3282.01	32.38
	SC-5B	27.00°C	506.75	1751.20	5.84
	SC-5C	24.78°C	318.05	3230.83	31.91
	SC-5D	27.1°C	503.21	1763.42	6.36
SC-6	SC-6A	24.81°C	316.32	3382.67	32.31
	SC-6B	27.08°C	506.58	1818.21	5.85
	SC-6C	24.79°C	317.91	3333.97	32.09
	SC-6D	27.07°C	501.23	1824.34	6.37
SC-7	SC-7A	24.81°C	316.81	3246.01	31.28
	SC-7B	26.99°C	508.40	1732.65	5.57
	SC-7C	24.78°C	318.75	3176.85	30.79
	SC-7D	26.99°C	504.78	1744.30	6.06

6.1.4 Wind Tunnel Analysis

The scenarios are tested for eight directions during the pressure tests and two directions during the PIV tests. The analysis results are compared for the shading characteristics in terms of SD and PR and the impact of the wind direction on pressure and velocity values for each scenario. In both experiments, symmetry of the airflow, pressure distribution, and airflow velocity values are observed. This symmetry is due to the symmetric indoor and façade characteristics.

6.1.4.1 Wind Tunnel Validation Study

Validation refers to ‘*[t]he process of determining the degree to which a model is an accurate representation of the real work from the perspective of the intended uses of the model*’ (de Wilde quoted from Oberkampf and Roy: 2021: 25). Wind tunnel validation study is first planned to be performed for Butterfly CFD simulations. However, Butterfly posed challenges while simulating the reduced-scale model since it is limited to building and urban-scale applications (Ladybug Tools LLC, 2021). Accordingly, CFD analyses are performed using ANSYS Fluent, a fluid simulation software with advanced physics modeling capabilities. CFD is performed for SC1A, the baseline scenario. CFD setup, meshing, and boundary conditions are presented in details as follows:

CFD setup: In CFD simulations, the coupled approach is used, thus, the wind tunnel and the simulated building floor geometry are modeled as a single fluid domain. The analysis is performed for a tunnel-scale model, which is 1:100. The fluid domain is $W \times H \times D = 100 \text{ cm} \times 100 \text{ cm} \times 800 \text{ cm}$.

The airflow is modeled by using the $k-\Omega$ SST turbulence model regarding its superiority over the other turbulence models (Ramponi & Blocken, 2012). Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) velocity-pressure coupling is employed. Second-order upwind discretization scheme is selected for the solution as it increases the accuracy of the analysis results (Ramponi & Blocken, 2012).

Meshing: In addition to the discretization scheme, the accuracy of CFD simulation results is considerably dependent on mesh/grid quality (Ramponi & Blocken, 2012). To overcome the grid-dependency, three different grids are generated for the geometry by increasing the mesh resolution from (1) coarse (1,877,887 cells), over (2) medium (3,862,758 cells), to (3) fine (6,723,375 cells). The sizes of the mesh elements also vary in the grid, as the grid is refined around the critical areas of the model, such as the building walls and the openings. Accordingly, the mesh elements of the tunnel are modeled relatively larger as compared to the building faces and openings (Figure 6.3). The results of these three grids are compared by pressure and wind speed along the centerline of the selected openings.

The average percent change from coarse to medium grid pressure and velocity is 17.25% and 3.57%, respectively, and from medium to the fine grid are 0.90% and 3.08%, respectively. Also indicated in Figure 6.4 and Figure 6.5 there is a greater difference between coarse and medium grids and a relatively small difference between medium and fine grids. The resolution of the fine grid is selected for the simulation of SC1A.

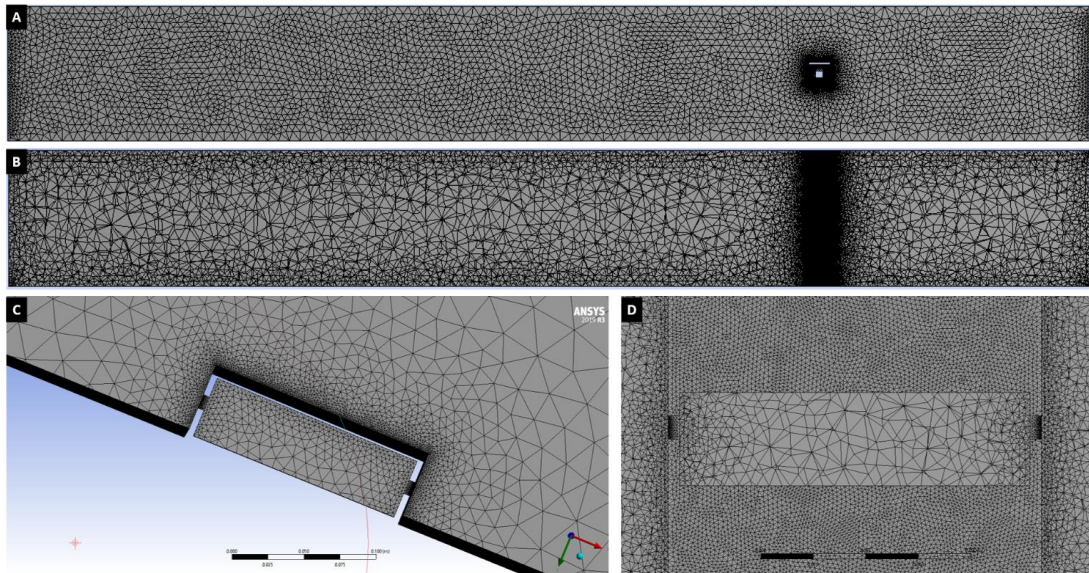


Figure 6.3. Meshing study: A. top view, B. section from a fluid domain, C. top view from the section, and D. section of the simulated room

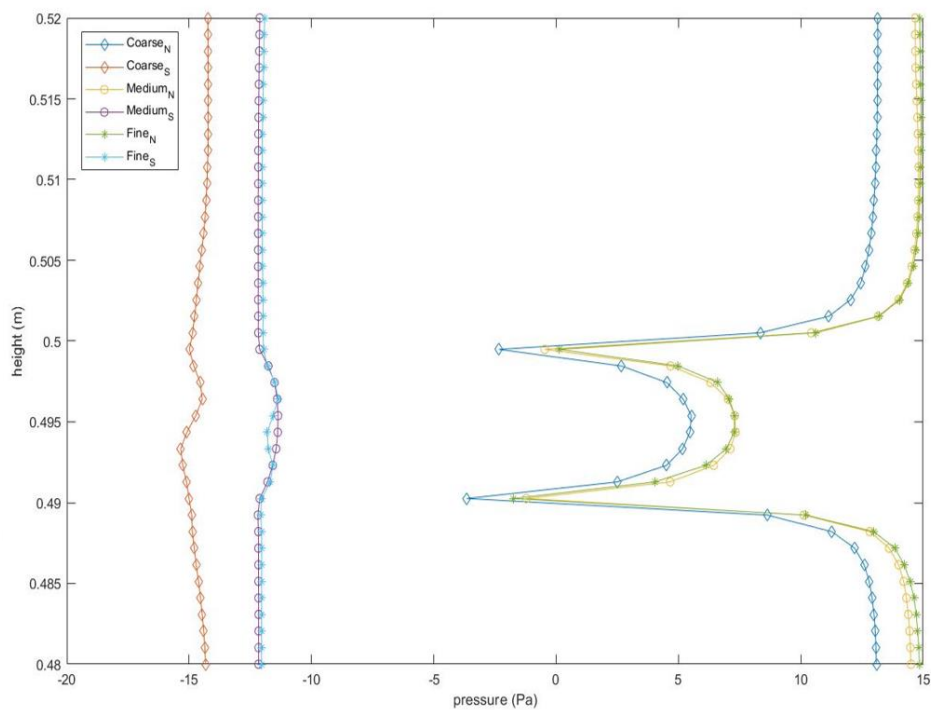


Figure 6.4. Grid convergence pressure comparison

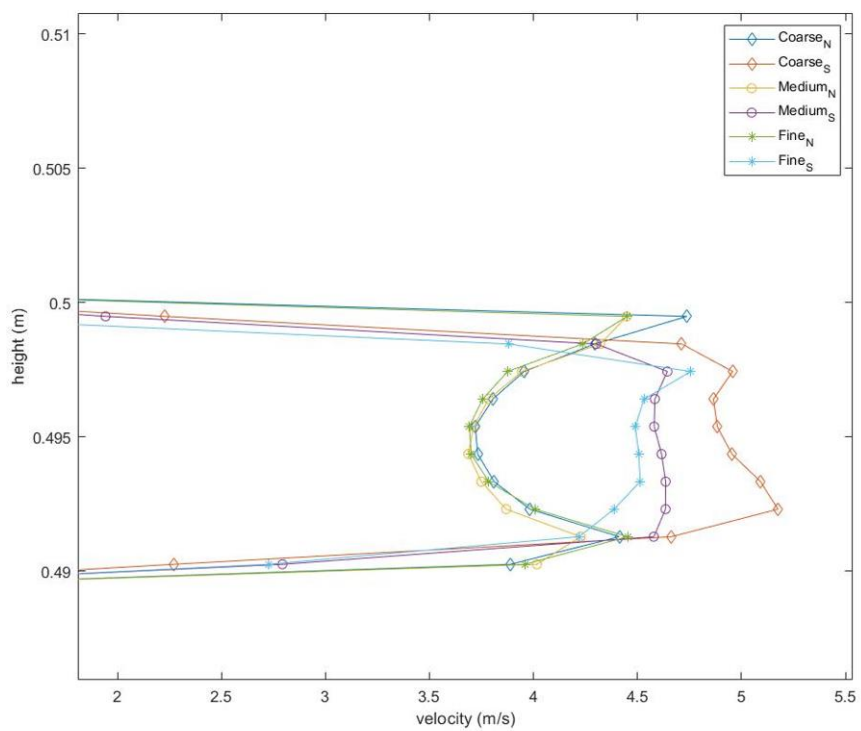


Figure 6.5. Grid convergence scalar velocity comparison

Boundary: A wall boundary condition is used to determine a boundary between the fluid domain of the tunnel and the fluid domain of the building. Wall boundary condition is defined as ‘no slip’ and assigned to the building walls. Velocity inlet is assigned to the wind tunnel’s inlet surface. Velocity inlet generates a flow field with a determined wind velocity. Wind velocity is defined as uniform and constant. The opposite surface of the tunnel is defined as a pressure outlet. The analysis is performed for steady-state conditions. The required data (wind velocity, gauge pressure, and air density) for inlet conditions are acquired from the performed wind tunnel experiments (Table 6.3).

Table 6.4. CFD setup for tunnel validation

Transient/Steady State:	Steady State
Velocity Inlet (m/s):	4.3 m/s
Air Density:	Taken from Wind Tunnel Experiments
Gauge Pressure:	Taken from Wind Tunnel Experiments
Pressure Outlet:	Atmospheric
Wall Condition:	All walls: no slip
Residuals:	1e-06 (according to the best practice)
Number of Iterations:	1000
Turbulence Model:	k-omega SST
Turbulence Method:	Intensity and Length Scale
Turbulent Intensity:	0.5%
Turbulent Length Scale:	1 m

Result: The validation study consists of the error analysis for wind tunnel and CFD results. First, pressure results are obtained from CFD and wind tunnel pressure tests, and C_p values are calculated. The values are obtained for each opening by averaging four probes located around the edges of the openings as in the wind tunnel tests models. Following, the mean average percent error (MAPE) is calculated for the datasets. The error between wind tunnel measurements and CFD is typically around 10-20% due to the error in CFD simulations (Calautit & Hughes, 2014). The analysis results suggest a 12.8% error between the wind tunnel measurements and CFD, which is typical and acceptable. Accordingly, CFD and wind tunnel measurements agree with each other at a certain level.

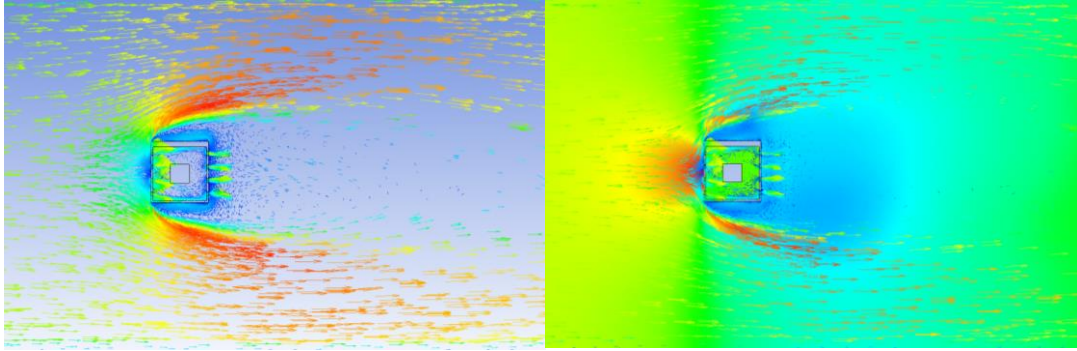


Figure 6.6. Flow vectors (left) and pressure (right) to SC1A

Impact of error between CFD and wind tunnel on performance metrics: Error analysis is also performed for the energy and contaminant simulations. C_p results obtained from CFD and wind tunnel are used as inputs for the energy and contaminant analysis. The aim is to calculate the impact of the error between CFD and wind tunnel results on energy performance and contaminant parameters. Mean absolute percent error (MAPE) is calculated for T_i , ACH, ventilation sensitive heat loss, CO_2 and CCL_{total} . T_i , CO_2 , and HL resulted in 1.0%, 2.35%, and 4.44% errors, which can be regarded as well agreement between the two datasets, while ACH and CCL_{total} showed more significant error percentage as 42.65% and 78.90%, respectively.

The error between Butterfly and Ansys CFD simulations is also calculated for SC1A based on C_p , T_i , ACH, ventilation sensitive heat loss, CO_2 , and CCL_{total} . This error analysis aims to determine the roughness of the Butterfly results. The precision can be increased by increasing test points on the building surface, which increases the need for computational power and necessitates a longer solution period, which may not be feasible to invest high computational power and period time for preliminary design stages. C_p values resulted in 13.66% error, while T_i , CO_2 , and HL resulted in 3.24%, 7.98%, and 11.41% error, which can also be regarded as a good agreement between the two datasets. In comparison, ACH and CCL_{total} showed more significant error percentages as 47.55% and 77.94%, respectively.

As a result of this validation study, this thesis agrees with the literature for using wind tunnel measurements for accurate C_p and performance analysis results. Therefore, the

pipeline utilizes CFD for the preliminary design phases for rough performance feedback but employs wind-tunnel testing for the final energy and contaminant analysis.

6.1.4.2 Pressure Results

Pressure test results are presented and compared based on P and C_p values for each scenario. Pressure distributions on the façade and the indoor ground surface are also visualized in detail and can be found in Appendix C and D.

The analysis results are investigated to explore the impact of shading devices on indoor pressure values. First, no significant pattern is found when the scenarios are compared with the baseline. Analysis results reveal that the airflow direction is considerably influential on pressure values. Airflow acting perpendicular to the façade with openings (A and C-scenarios) results in higher pressure values than the airflow from the diagonal angles. As Figure 6.7 suggests, airflow from N and S result in higher indoor surface pressures, whereas airflow from NW, SW, SE, and NE results in relatively lower indoor pressures. Also, airflow from the side angles as W and E results in the lowest indoor pressure values. When the façades with (S) and without (N) shading are compared, it is observed that the façades with shading devices exposed to the perpendicular airflow result in higher indoor pressure values.

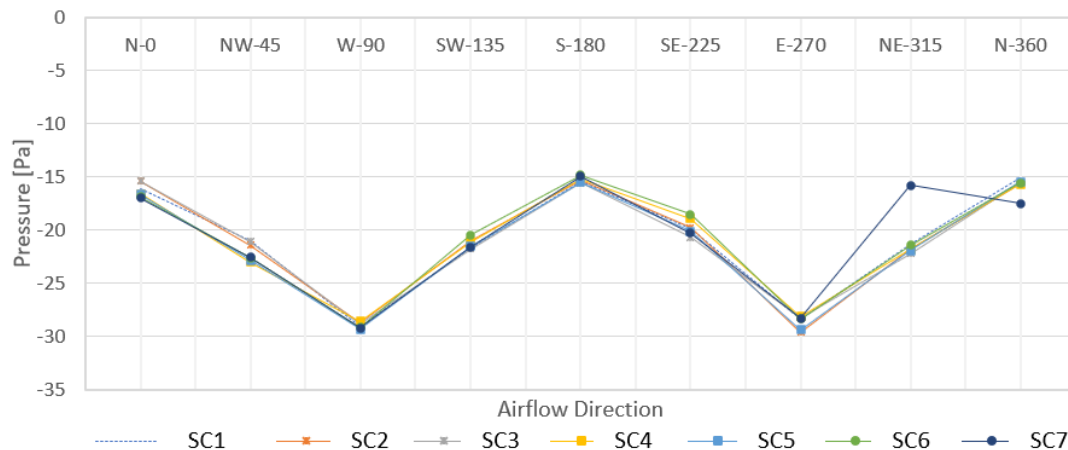


Figure 6.7. Indoor surface pressure values

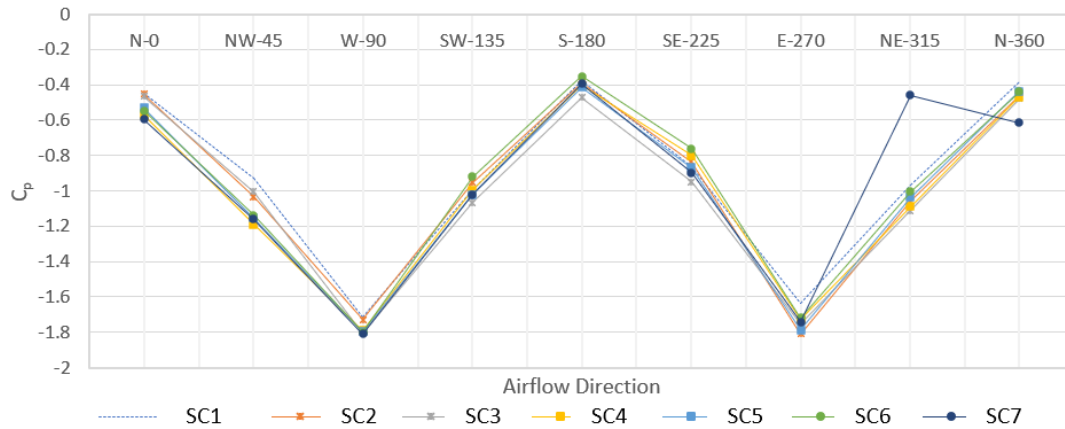


Figure 6.8. Indoor surface average C_p values

The scenarios are also compared to inspect the impact of SD and PR on indoor air pressures. The analysis results suggest that the relationship between SD and indoor air pressures is considerably dependent on the airflow direction and the direction of the façade with the shading devices. In the pressure measurements, it is observed that airflow from N (A-scenarios) ($r=-0.95$), NW ($r=-0.74$), and W (D-scenarios) ($r=-0.62$) directions lead to a strong inverse correlation between the shading depth and indoor air pressure. On the contrary, airflow from SW ($r=0.35$), S (C-scenarios) ($r=0.81$), SE ($r=0.43$), E (B-scenarios) ($r=0.43$), and NE ($r=0.61$) lead to a moderate and strong correlation between the shading depth and indoor air pressure. It can be concluded that if airflow directly acts upon the façade with shading devices, there is a moderate and strong positive correlation between the shading depth and the pressure. In contrast, if airflow acts in the opposite direction, there is a strong negative correlation between the shading depth and the indoor air pressure.

It is also crucial to define the sphere of influence of the SD on the interior. Pressure values of each pressure tap are investigated for each direction. The results suggest that airflow from N, NW, and W directions leads to a high negative correlation, and airflow from S and NE directions leads to a high positive correlation between the shading depth and pressure values on each pressure tap within a similar range (Table 6.5). It can be concluded that SD is influential almost on each part of the room for particular directions.

Table 6.5. Correlation between shading depth and indoor pressure for eight directions

	PT1	PT2	PT3	PT4	PT5	PT6	PT7	PT8	PT9	PT10	PT11	PT12
N	-0.96	-0.95	-0.94	-0.96	-0.94	-0.94	-0.94	-0.94	-0.94	-0.94	-0.94	-0.96
NW	-0.76	-0.74	-0.74	-0.75	-0.77	-0.75	-0.73	-0.72	-0.77	-0.73	-0.74	-0.73
W	-0.73	-0.63	-0.70	-0.54	-0.58	-0.55	-0.59	-0.55	-0.66	-0.62	-0.69	-0.59
SW	0.11	0.20	0.13	0.42	0.15	0.23	0.36	0.36	0.20	0.25	0.12	0.33
S	0.58	0.82	0.61	0.91	0.72	0.70	0.82	0.90	0.71	0.74	0.66	0.84
SE	0.33	0.40	0.36	0.50	0.36	0.39	0.42	0.52	0.46	0.39	0.40	0.44
E	0.35	0.45	0.34	0.50	0.35	0.41	0.44	0.48	0.41	0.44	0.41	0.42
NE	0.60	0.62	0.61	0.64	0.61	0.62	0.62	0.63	0.62	0.62	0.62	0.63
	PT13	PT14	PT15	PT16	PT17	PT18	PT19	PT20	PT21	PT22	PT23	PT24
N	-0.93	-0.96	-0.94	-0.94	-0.94	-0.95	-0.93	-0.94	-0.93	-0.94	-0.93	-0.94
NW	-0.74	-0.79	-0.72	-0.75	-0.78	-0.75	-0.70	-0.77	-0.76	-0.74	-0.70	-0.71
W	-0.56	-0.58	-0.42	-0.56	-0.56	-0.69	-0.65	-0.60	-0.58	-0.60	-0.61	-0.46
SW	0.32	0.35	0.35	0.27	0.33	0.34	0.25	0.27	0.44	0.41	0.22	0.48
S	0.79	0.83	0.83	0.85	0.68	0.79	0.81	0.80	0.64	0.77	0.77	0.84
SE	0.42	0.43	0.52	0.53	0.40	0.43	0.52	0.46	0.37	0.41	0.43	0.36
E	0.42	0.48	0.45	0.47	0.41	0.47	0.41	0.38	0.35	0.48	0.39	0.41
NE	0.61	0.65	0.63	0.63	0.63	0.61	0.60	0.62	0.61	0.62	0.62	0.61
	PT25	PT26	PT27	PT28	PT29	PT30	PT31	PT32	PT33	PT34	PT35	PT36
N	-0.94	-0.95	-0.94	-0.94	-0.95	-0.96	-0.96	-0.95	-0.95	-0.94	-0.96	-0.95
NW	-0.75	-0.76	-0.71	-0.74	-0.77	-0.76	-0.69	-0.68	-0.74	-0.70	-0.74	-0.73
W	-0.63	-0.64	-0.55	-0.63	-0.63	-0.69	-0.60	-0.34	-0.64	-0.61	-0.71	-0.70
SW	0.25	0.30	0.28	0.40	0.38	0.24	0.03	0.46	0.29	0.34	0.38	0.25
S	0.76	0.76	0.84	0.83	0.88	0.86	0.86	0.91	0.84	0.89	0.93	0.75
SE	0.37	0.43	0.50	0.43	0.45	0.41	0.45	0.46	0.47	0.48	0.37	0.34
E	0.43	0.39	0.43	0.40	0.43	0.46	0.43	0.51	0.43	0.50	0.41	0.31
NE	0.61	0.61	0.61	0.61	0.62	0.62	0.61	0.62	0.62	0.63	0.60	0.58
	PT37	PT38	PT39	PT40	PT41							
N	-0.95	-0.96	-0.96	-0.93	-0.93	SN						
NW	-0.72	-0.75	-0.73	-0.74	-0.68	SN						
W	-0.52	-0.72	-0.67	-0.65	-0.54	SN						
SW	0.47	0.23	0.34	0.28	0.32	L/MP						
S	0.91	0.78	0.82	0.68	0.84	SP						
SE	0.50	0.38	0.45	0.40	0.48	MP						
E	0.45	0.41	0.41	0.37	0.44	MP						
NE	0.62	0.60	0.61	0.60	0.62	SP						
	SN	Strong Negative										
	SP	Strong Positive										
	MN	Moderate Negative										
	MP	Moderate Positive										
	LN	Low Negative										
	LP	Low Positive										

The analysis results suggest that the relationship between PR and indoor air pressure values also depends on the airflow direction and the orientation of the façade with the shading devices. PR is particularly influential for the airflow from W ($r=0.56$), SW ($r=0.89$), SE ($r=0.89$), S ($r=0.41$), and SE ($r=0.85$). On the contrary, no correlation has been found between PR and P for N ($r=0.04$), NW ($r=-0.13$), E ($r=0.036$) and NE ($r=-0.37$). As a result, PR is mainly influential for the airflow acting directly upon the façade with the shading devices. Also, pressure values of each pressure tap are investigated for each direction for PR. No significant distinction is found for the correlation coefficients of the pressure taps for PR and P.

Table 6.6. Correlation between perforation ratio and indoor pressure for eight directions

	PT1	PT2	PT3	PT4	PT5	PT6	PT7	PT8	PT9	PT10	PT11	PT12
N	-0.01	0.04	0.04	0.00	0.08	0.06	0.04	0.01	0.06	0.08	0.04	0.05
NW	-0.15	-0.15	-0.10	-0.17	-0.07	-0.11	-0.18	-0.14	-0.10	-0.10	-0.11	-0.17
W	0.52	0.63	0.55	0.39	0.62	0.59	0.53	0.66	0.62	0.63	0.47	0.45
SW	0.93	0.92	0.93	0.86	0.96	0.93	0.88	0.87	0.89	0.93	0.94	0.89
S	0.58	0.48	0.62	0.34	0.63	0.52	0.36	0.26	0.53	0.55	0.58	0.42
SE	0.90	0.85	0.88	0.79	0.87	0.87	0.86	0.80	0.83	0.87	0.88	0.83
E	-0.03	-0.03	-0.02	-0.11	0.05	0.00	-0.04	-0.13	0.00	-0.03	0.03	-0.05
NE	-0.37	-0.38	-0.36	-0.38	-0.35	-0.36	-0.36	-0.38	-0.37	-0.36	-0.35	-0.37

	PT13	PT14	PT15	PT16	PT17	PT18	PT19	PT20	PT21	PT22	PT23	PT24
N	0.08	0.05	0.10	0.08	0.10	0.02	0.01	0.05	0.04	0.05	0.04	0.09
NW	-0.10	-0.16	-0.12	-0.11	-0.09	-0.15	-0.15	-0.10	-0.11	-0.12	-0.14	-0.14
W	0.53	0.50	0.67	0.54	0.67	0.53	0.51	0.57	0.55	0.64	0.62	0.60
SW	0.88	0.88	0.90	0.92	0.90	0.90	0.90	0.91	0.83	0.86	0.89	0.83
S	0.48	0.50	0.47	0.44	0.59	0.33	0.30	0.48	0.44	0.47	0.36	0.42
SE	0.87	0.83	0.80	0.78	0.88	0.86	0.83	0.82	0.89	0.87	0.85	0.88
E	-0.05	-0.03	0.00	-0.03	0.06	-0.10	-0.05	0.03	-0.06	0.03	-0.04	-0.02
NE	-0.37	-0.37	-0.36	-0.36	-0.35	-0.38	-0.38	-0.38	-0.37	-0.35	-0.37	-0.37

	PT25	PT26	PT27	PT28	PT29	PT30	PT31	PT32	PT33	PT34	PT35	PT36
N	0.06	0.04	0.09	0.03	0.03	0.05	-0.01	0.04	0.02	0.05	-0.03	-0.01
NW	-0.15	-0.14	-0.11	-0.13	-0.10	-0.13	-0.22	-0.17	-0.14	-0.18	-0.23	-0.17
W	0.53	0.57	0.52	0.49	0.59	0.55	0.53	0.73	0.47	0.55	0.40	0.48
SW	0.86	0.89	0.92	0.86	0.86	0.85	0.50	0.82	0.86	0.84	0.87	0.90
S	0.48	0.36	0.32	0.30	0.40	0.35	0.31	0.30	0.35	0.25	0.20	0.32
SE	0.88	0.85	0.83	0.85	0.83	0.86	0.84	0.81	0.82	0.82	0.85	0.91
E	0.03	-0.06	-0.05	-0.03	0.00	0.02	-0.03	-0.01	-0.04	-0.04	-0.18	-0.09

Table 6.7. Correlation between perforation ratio and indoor pressure for eight directions (continued)

NE	-0.37	-0.38	-0.37	-0.38	-0.37	-0.36	-0.38	-0.37	-0.39	-0.38	-0.41	-0.39
	PT37	PT38	PT39	PT40	PT41							
N	0.01	0.02	0.03	0.04	0.00		SP					
NW	-0.19	-0.17	-0.17	-0.11	-0.17		SP					
W	0.48	0.48	0.45	0.58	0.39		SP					
SW	0.78	0.87	0.87	0.88	0.85		LN					
S	0.07	0.43	0.30	0.37	0.30		MN					
SE	0.79	0.87	0.84	0.87	0.82		LN					
E	-0.12	-0.05	-0.07	0.02	-0.12		LP					
NE	-0.39	-0.39	-0.38	-0.38	-0.39		SN					
SN	Strong Negative											
SP	Strong Positive											
MN	Moderate Negative											
MP	Moderate Positive											
LN	Low Negative											
LP	Low Positive											

Pressure values of N and S façades suggest a symmetrical pressure distribution on the façades. Airflow from S and NE led to the highest and lowest N façade pressure values in all scenarios, respectively. Airflow from N and SW have led the highest and lowest S façade pressure values in all scenarios, respectively. Airflow from S, which is acting directly upon the façade with the shading devices is particularly important. All the shading devices increase façade pressure values of N and S, with airflow from S, as compared to baseline scenario.

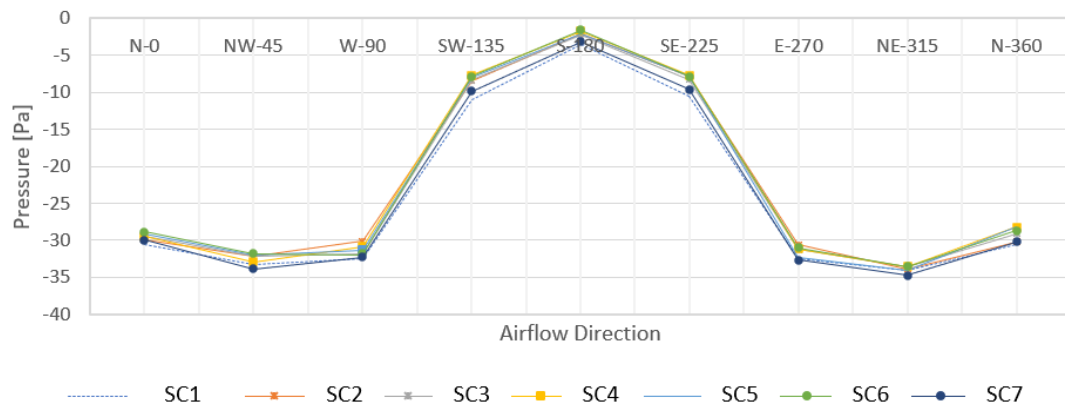


Figure 6.9. North façade surface pressure values

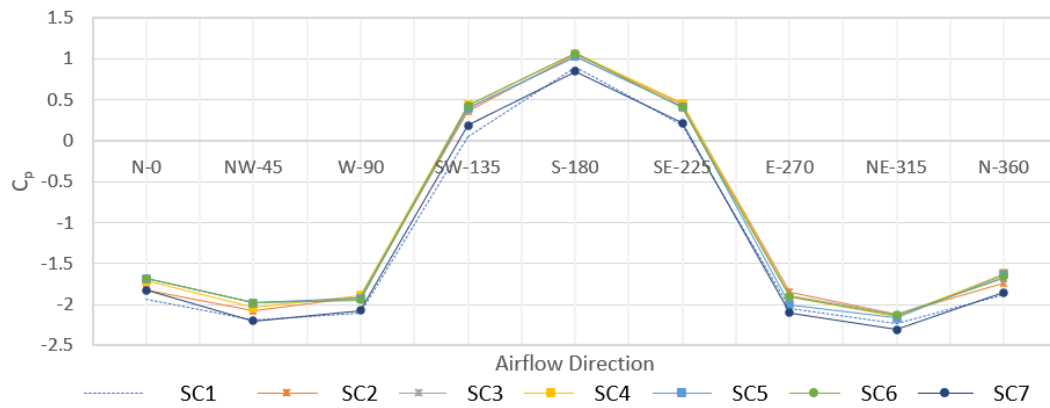


Figure 6.10. North façade surface average C_p values

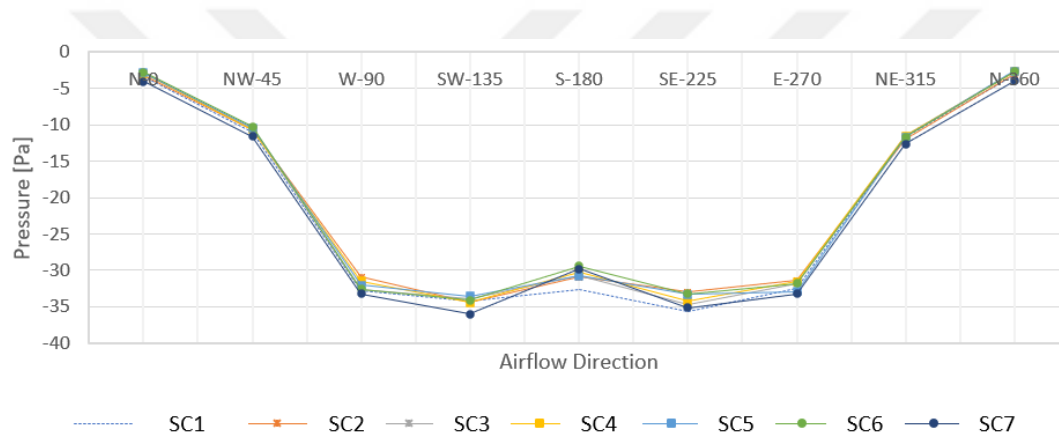


Figure 6.11. South façade surface pressure values

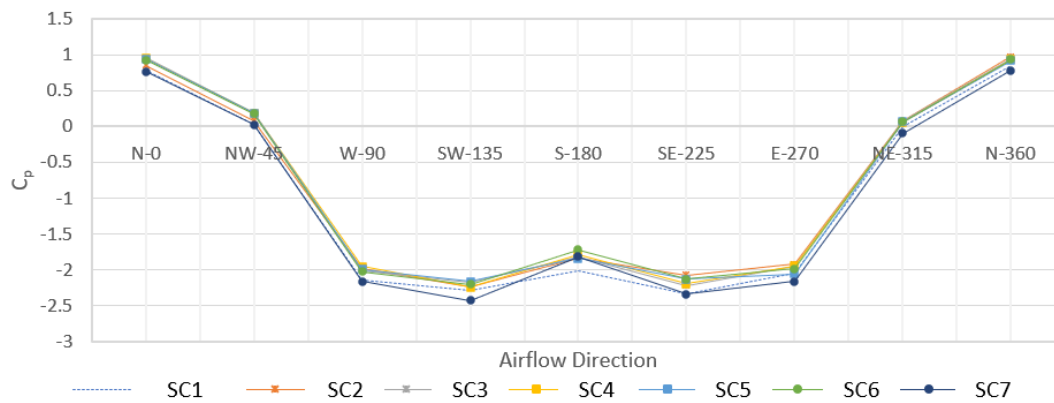


Figure 6.12. South façade surface average C_p values

The impact of PR and shading device depth on façade P values are also inspected. There is a positive correlation between the PR and P values of both N and S façade for

all directions. Contrarily, there is a negative correlation between the shading depth and P values of both N and S façade for most of the airflow directions (Table 6.8). For N façade, PR is relatively more significant as compared to depth, whereas, for the S façade, SD is particularly influential.

Table 6.8. Correlation between façade pressure values shading depth and perforation ratio

	N-0	NW-45	W-90	SW-135	S-180	SE-225	E-270	NE-315
NORTH FAÇADE								
Depth	0.21	-0.36	-0.63	-0.27	-0.17	-0.44	-0.50	-0.44
PR	0.10	0.29	0.63	0.50	0.71	0.58	0.79	0.51
SOUTH FAÇADE								
Depth	-0.34	-0.30	-0.60	-0.45	0.89	-0.18	-0.54	-0.46
PR	0.40	0.40	0.63	0.10	0.21	0.54	0.76	0.37

6.1.4.3 PIV Results

PIV tests are performed for SC-A and SC-C (N and S airflow directions) to visualize indoor airflow behavior. The results are visually inspected for airflow behavior and indoor airflow velocity. The building core is blanked since there is no observed airflow leakage. The airflow behavior in the marked region (Figure 6.13) cannot be observed due to the reflection during the experiments. In all scenarios, symmetric airflow behavior is observed due to geometrical symmetry.

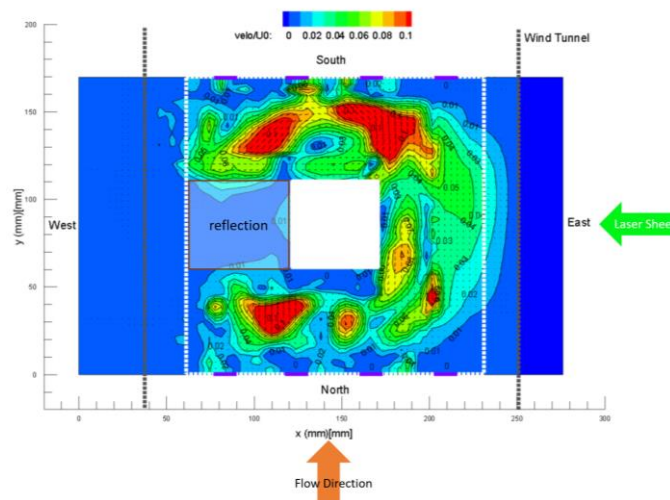


Figure 6.13. PIV sample flow visualization

Wind Direction N | Wind acting upon the façade with no shading: Experiment results suggest that, except SC6A, the shading devices reduce indoor airspeed. The highest and the lowest indoor airspeed are observed in SC6A and SC7A, respectively. Two correlations are identified among the scenarios with the same PR. There is a positive correlation for SC2A, SC4A, SC6A, whereas there is a negative correlation for SC3A, SC5A, and SC7A, between indoor airspeed and SD. Among the cases with the SD, but different PR, two different behavior is observed. Between SC2A and SC3A, indoor airspeed increases with the decrease of PR, whereas indoor airspeed increases with PR in SC4A, SC5A, SC6A, and SC7A.

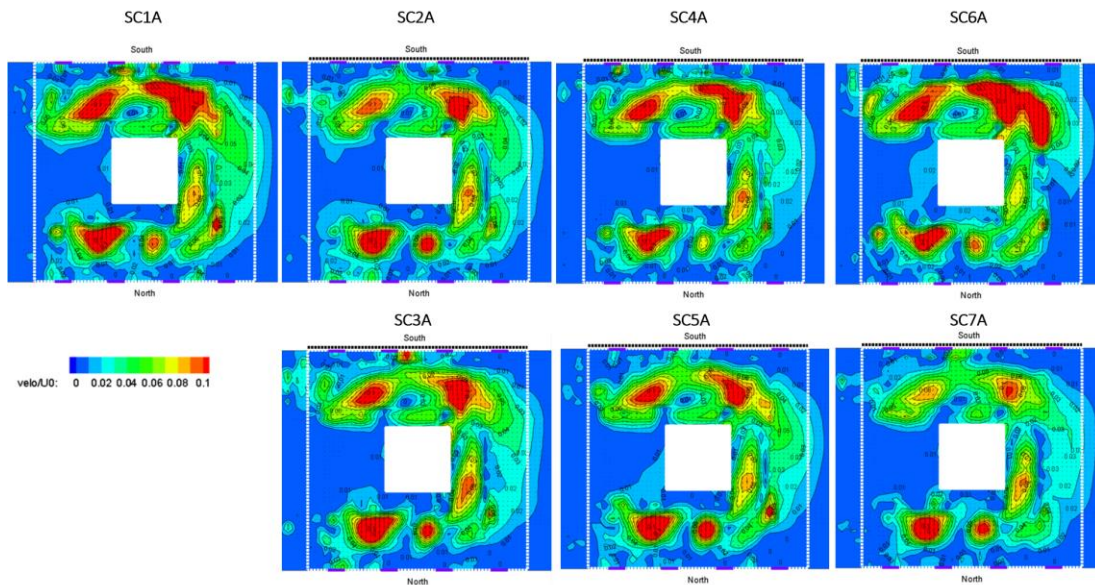


Figure 6.14. PIV flow visuals for North wind direction (A-scenarios)

Wind Direction S | Wind acting upon the façade with shading: Shading devices reduce indoor air velocity in all scenarios compared to the SC1C. SC7C and SC2C resulted in the highest and lowest indoor airspeed, respectively. Similar to the A-scenarios, for SC2C, SC4C, and SC6C, there is a positive correlation between indoor airspeed and the SD. This correlation is not evident for SC3C, SC5C, and SC7C. Among the cases with the same SD, but different PR, two different behavior is observed. Between SC2C and SC3C, indoor airspeed increase with the decrease of PR, whereas indoor airspeed increases with the increase of PR in SC4A, SC5A, SC6A, and SC7A.

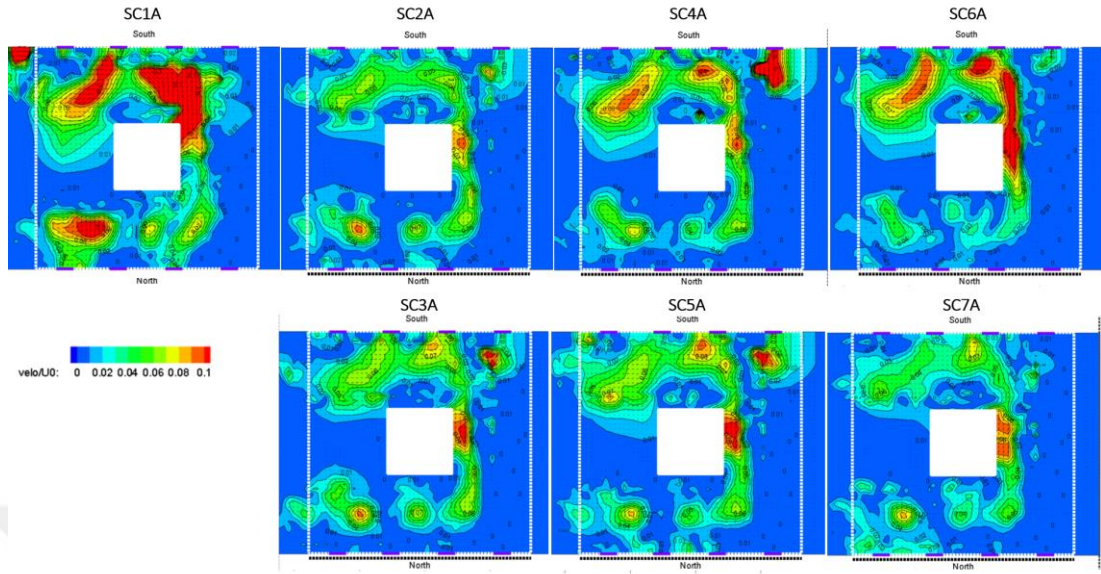


Figure 6.15. PIV flow visuals for South wind direction (C-scenarios)

6.1.5 Contaminant Analysis Results

A set of contaminant analyses is performed for each scenario by integrating wind tunnel-generated C_p and T_i values. CCL_{total} , CCL_{BR} , T_{inf} , and T_{dis} are calculated for all scenarios. T_{inf} is calculated based on CCL_{BR} since most of the respiratory activity occurs in this zone ($h=1.20-1.80$ m). T_{dis} is calculated based on CCL_{total} .

Wind tunnel-integrated contaminant numeric results and visual results for each scenario are presented in

Table 6.9 and Appendix E, respectively. Three distinct contaminant accumulation behavior for CCL_{total} is identified among the scenarios: (1) steep peak until 10:00 evident in B and D-scenarios, (2) mild peak until 10:00 as evident in A-scenarios, and (3) a horizontal stretch (plateau) as evident in C-scenarios (Figure 6.16). In all scenarios, CCL_{total} started to decrease with the contaminant's exit from the room at 10:00. Despite three distinct accumulation behaviors, there are no explicit discrepancies between SC in average CCL_{total} (Table 6.9). The simulation results suggest that contaminant is accumulated 5% higher in the breathing zone as compared

to the entire room. Among SC, SC4 result in the highest, whereas SC6 has the lowest CCL_{total} and CCL_{BR} values.

Table 6.9. Contaminant analysis results

Scenario Categories	Scenarios	PR	SD	CCL_{total} (#/m ³)	CCL_{BR} (#/m ³)	T_{dis} (HH:MM)	T_{inf} (HH:MM)
SC-1	SC-1A	-	-	85	84	11:00	9:55
	SC-1B			456	429	16:10	9:35
	SC-1C			29	48	10:15	-
	SC-1D			501	511	18:05	9:35
SC-2	SC-2A	60%	40 cm	85	85	10:55	9:55
	SC-2B			445	424	16:05	9:35
	SC-2C			31	49	10:15	-
	SC-2D			472	484	16:00	9:30
SC-3	SC-3A	40%	40 cm	82	84	10:50	9:50
	SC-3B			584	851	18:10	9:30
	SC-3C			30	48	10:15	-
	SC-3D			404	410	16:00	9:30
SC-4	SC-4A	60%	60 cm	82	84	10:50	9:50
	SC-4B			550	526	18:05	9:35
	SC-4C			33	52	10:15	-
	SC-4D			438	431	16:10	9:35
SC-5	SC-5A	40%	60 cm	82	84	10:50	9:55
	SC-5B			547	550	18:05	9:30
	SC-5C			29	47	10:50	-
	SC-5D			421	422	16:00	9:30
SC-6	SC-6A	60%	80 cm	82	84	10:50	9:50
	SC-6B			494	478	16:15	9:35
	SC-6C			34	53	10:15	-
	SC-6D			417	412	16:00	9:35
SC-7	SC-7A	40%	80 cm	89	88	11:00	9:50
	SC-7B			522	522	18:00	9:30
	SC-7C			30	49	10:15	-
	SC-7D			411	398	16:00	9:35

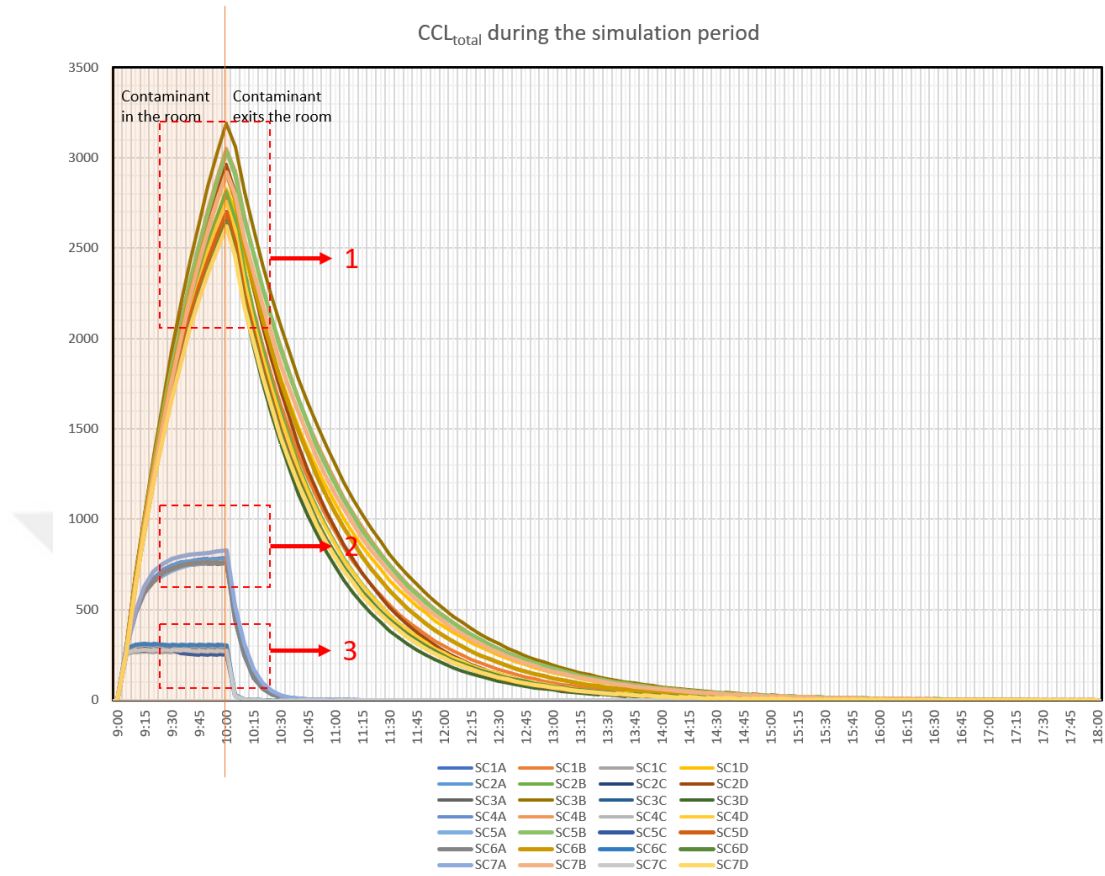


Figure 6.16. CCL_{total} of scenarios during the simulation period

Among the scenarios, C-scenarios, where the wind acts directly upon the shading device, resulting in the lowest CCL_{total} values (2.7-fold, 16.5-fold, and 14.1-fold lower as compared to A, B, D-scenarios, respectively) (Figure 6.17). C-scenarios require an average of 1H20M to complete contaminant discharge, an average of 6H30M less T_{dis} than B, D-scenarios, and an average of 0H30M less T_{dis} to A-scenarios. Analysis results indicate that C-scenarios do not result in infection risk; therefore, T_{inf} for C-scenarios is calculated as null (Table 6.7). The simulation results of A-scenarios show similarity to C-scenarios, resulting in the second lowest CCL_{total} value (64% higher than C-scenarios) and the second shortest T_{dis} (~1H55M). On the contrary to A and C-scenarios, B and D-scenarios, acting directly on the blind façades, result in the highest CCL_{total} values. The analysis result suggests that direct airflow can considerably decrease indoor air contamination.

At the same time, indirect flows increase the contaminant transport and circulate the contaminant inside the room for a longer time, posing relatively higher infection risks to occupants (Figure 6.18).



Figure 6.17. Average CCL_{total} comparison for the simulated scenarios

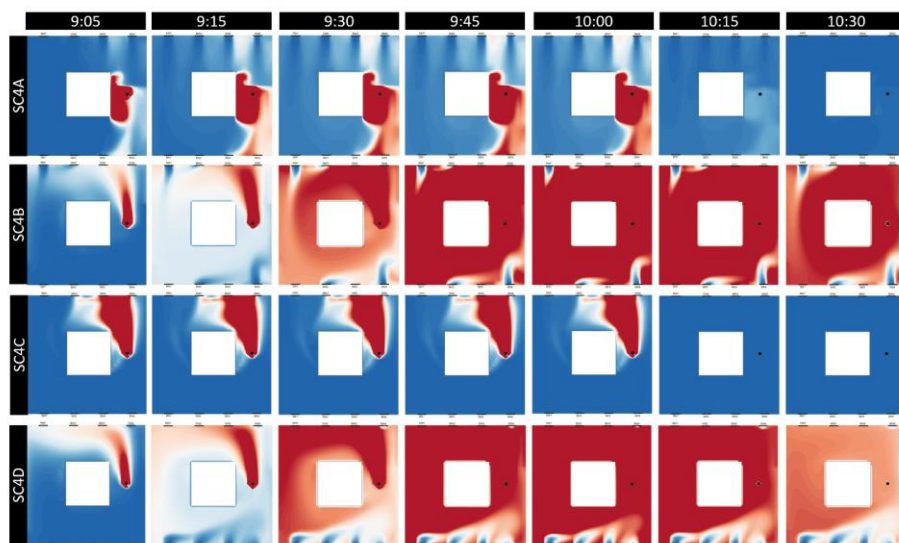


Figure 6.18. Contaminant dispersion behavior in A, B, C and D scenarios of SC4

6.2 Benchmarking

First and foremost, all the analyses are performed for all the design scenarios to generate knowledge on the impact of shading design parameters on performance metrics, despite the design selection based on benchmarking as suggested by the design integration diagram of the pipeline (in 4.3). Accordingly, in this section, all the scenarios are compared since none of them are eliminated based on their performance measures. Nevertheless, if such an elimination procedure was followed, SC3, SC5, and SC7 are the first to be eliminated due to their inadequate daylighting performance. DLA performance threshold is 50% for office tasks (300-500 lux) (Acosta, Campano, Domínguez, & Fernández-Agüera, 2019; Ruffles, 2005). However, SC3, SC5, and SC7 remained below the DLA threshold by resulting in 39.8%, 37.4%, and 37.2%, respectively. SC6 also remained below the DLA threshold but showed higher UDI values. In this respect, SC6 is not eliminated. Similarly, their UDI results remain 17.2% lower on average than UDI values of SC2, SC4, and SC6. The higher percentage means the adequacy of the daylighting conditions. In all scenario categories, DGP values are within the imperceptible glare range. SC1 is excluded from the comparison since it is a baseline case without a shading device. SC2, SC4, and SC6 are selected for the next evaluation step for their initial energy performances.

The energy analysis results of SC2, SC4, and SC6 show similar T_i , CO_2 , ventilation sensitive heat loss, and ACH values. T_i values of all three SCs resulted in similar values with only decimal changes. They remained within the comfort zone of natural ventilation regarding the bioclimatic chart for Ankara, as shown in Figure 5.2. Ventilation-related parameters are left for the tertiary energy analysis with the integration of wind-tunnel results since wind tunnel-generated C_p values are preferred over CFD-generated C_p values (Cóstola et al., 2009). As a result of wind tunnel integrated energy simulations, SC2, SC4, and SC6 also result in similar values. As compared to the secondary energy analysis, ACH values show improvement and remained far above the threshold. Following, contaminant analysis results of SC2, SC4 and SC6 are compared. SC2 and SC6 showed similar CCL_{total} , CCL_{BZ} , T_{dis} , and T_{inf} . Despite the minor discrepancies between the results, SC-2 can be selected for the final

design option due to its relatively better daylighting, ventilation sensitive heat loss and contaminant discharge performance (Table 6.7 and Appendix E). Among SC2 scenarios, SC2A and SC2C show relatively better performance. SC2C shows lower CCL_{total} and CCL_{BZ} , and requires shorter time for contaminant discharge as compared to SC2A (Table 6.10). In this respect, SC2C can be regarded as the best performing scenario.

Table 6.10. Final benchmarking table

SC	PR	SD	DLA	UDI	DGP	T _i	CO ₂	HL	ACH	CCL total	CCL BZ	T _{dis}	T _{inf}
SC2	60%	40cm	76.4	79.3	0.27	25.9	409	2695	19	258	260	13:18	0H30M
SC6	60%	80cm	48.7	81.9	0.27	25.9	410	2590	19	256	256	13:20	0H30M
SC2 scenarios													
SC2A						24.8	316	3508	31	85	85	10:55	0H55M
SC2B						27.1	504	1897	5	445	424	16:06	0H35M
SC2C						24.8	317	3466	31	31	49	10:15	0H00M
SC2D						27.1	499	1908	6	472	484	16:00	0H30M

6.2.1 The Impact of Shading Design on Daylighting Performance Metrics

Daylighting analysis results reveal that SD and PR considerably impact daylighting performance for both daylight illumination and glare (Table 6.11). There is a strong negative correlation ($p=-0.57$) between SD and glare, whereas there is a medium negative correlation between SD and DLA ($p=-0.42$), and shading depth, and UDI ($p=-0.43$). The analysis results suggest that there is a strong positive correlation between PR and glare ($p=0.77$), PR and DLA ($p=0.83$), and PR and UDI ($p=0.72$).

Table 6.11. Correlation between daylighting performance metrics and shading device design

	Glare	DLA	UDI
SD	-0.57	-0.42	-0.43
PR	0.77	0.83	0.72

6.2.2 The Impact of Shading Design on Energy Performance Metrics

Ventilation sensitive heat loss (HL): Analysis results suggest that wind acting perpendicular upon the façade with openings (SC-A and SC-C) increases HL 81.4% on average as compared to the wind acting upon parallel to the façade with openings (SC-B and SC-D). As evident in analysis results, SC-1A results in maximum HL, whereas 7B result in minimum HL. When SC-A and SC-C are compared, it is observed that wind acting upon the façade with shading devices decreases HL by 1.53%.

SC-A and SC-C scenarios result in a 40% decrease on average in HL compared to SC-1A (baseline-0°) and SC-1C (baseline-180°), respectively. In both SC, the maximum decrease is observed in SC-7A and SC-7C (42%), whereas the minimum decrease is observed in SC-2A and SC-2C (37%). Similarly, SC-B and SC-D show a 44% decrease on average compared to SC-1B (baseline-90°) and SC-1D (baseline-270°), respectively. In both SC, the maximum decrease is observed in SC-7B (46%) and SC-7D (47%), whereas the minimum decrease is observed in SC-2B (41%) and SC-2D (42%).

There is a moderate negative correlation ($p=-0.45$) between SD and HL; as SD increases, HL decreases. On the other hand, there is a strong positive correlation ($p=0.88$) between PR and HL; as PR increases, HL also increases.

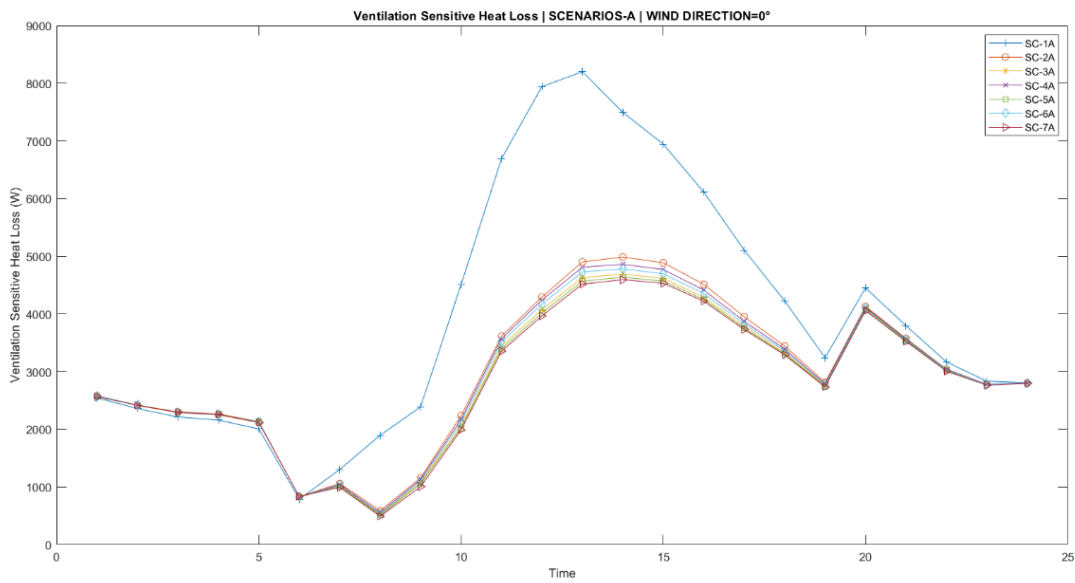


Figure 6.19. Ventilation sensitive heat loss for A-scenarios

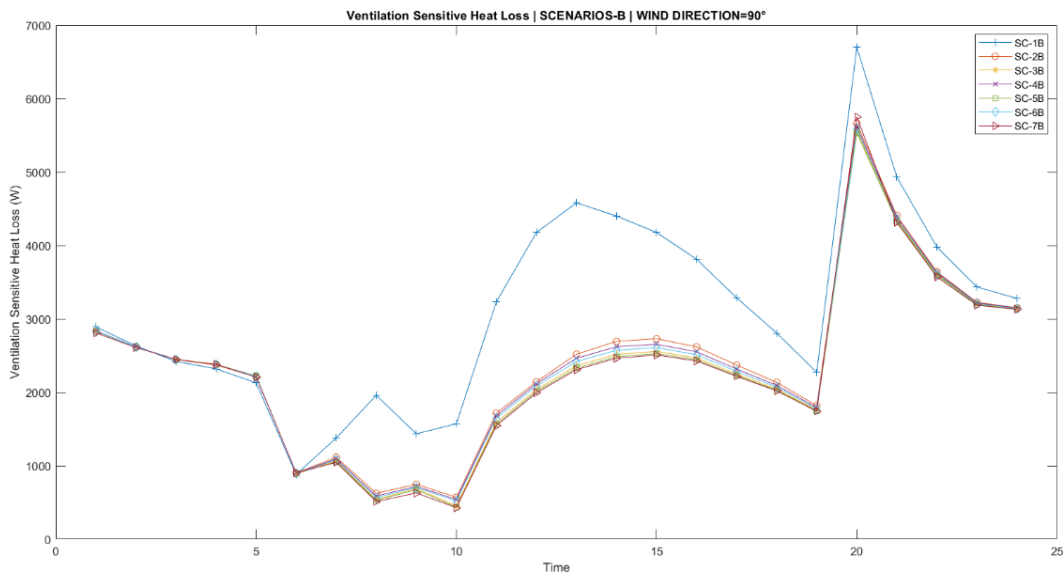


Figure 6.20. Ventilation sensitive heat loss for B-scenarios

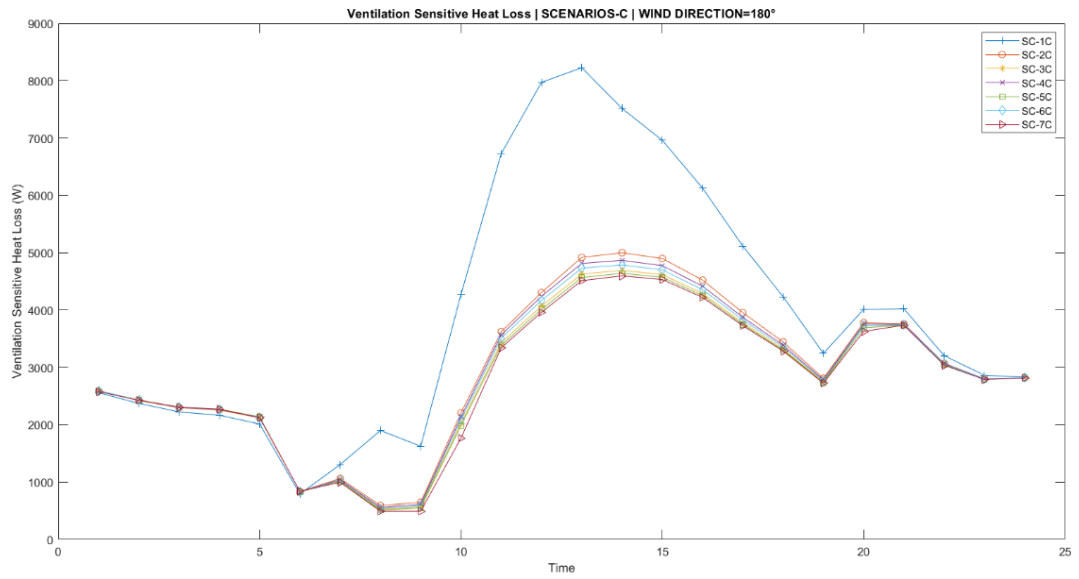


Figure 6.21. Ventilation sensitive heat loss for C-scenarios

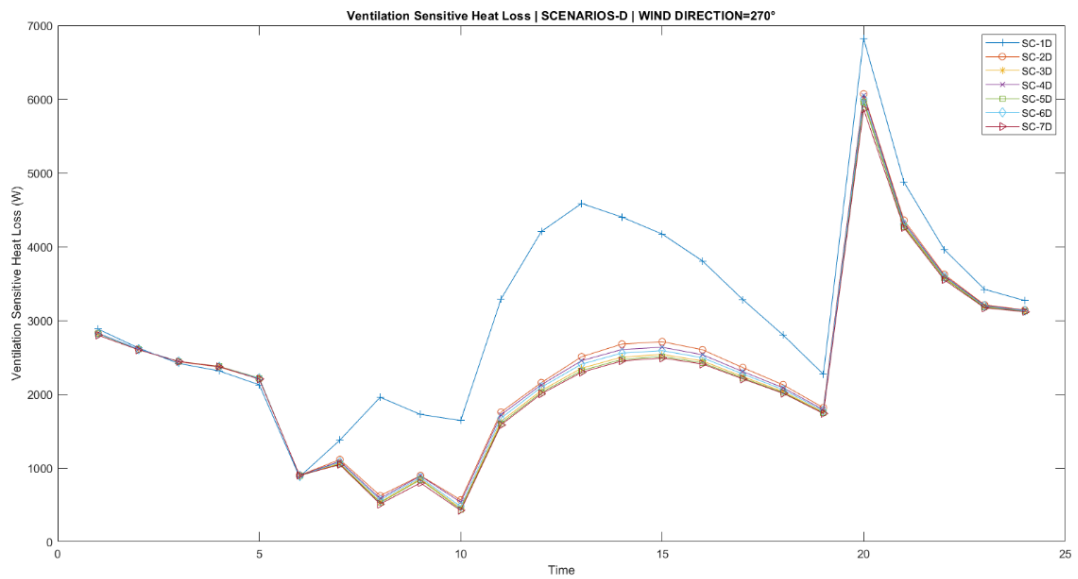


Figure 6.22. Ventilation sensitive heat loss for D-scenarios

T_i : In correlation with ACH and HL, wind acting perpendicular upon the façades (SC-A and SC-C) results in 2.5°C (9%) on average lower T_i as compared to wind acting parallel to the façades with openings (SC-B and SC-D). There is a negligible difference (0.08%) in T_i values of SC-A and SC-C scenarios, which indicates that shading devices do not have a negative impact on cooling performance. Among SCs, SC-C scenarios

result in the lowest T_i , whereas SC-D scenarios result in the highest T_i values. SC-A and SC-C scenarios result in a 1.2% decrease on average in T_i compared to SC-1A and SC-C1, respectively. On the other hand, SC-B and SC-D result in a 4.6% decrease in T_i compared to SC-1B and SC-D1, respectively. There is a moderate negative correlation ($p=-0.44$) between SD and T_i ; T_i decreases as SD increases. On the other hand, there is a strong positive correlation ($p=0.84$) between PR and T_i ; as PR increases, T_i increases in correspondence.

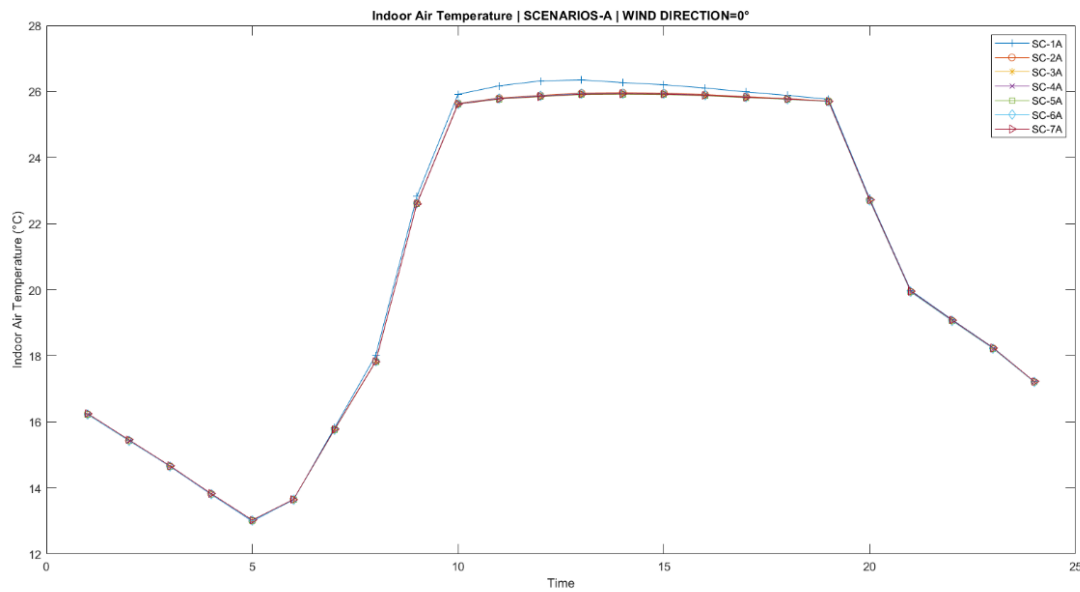


Figure 6.23. Indoor air temperatures for A-scenarios

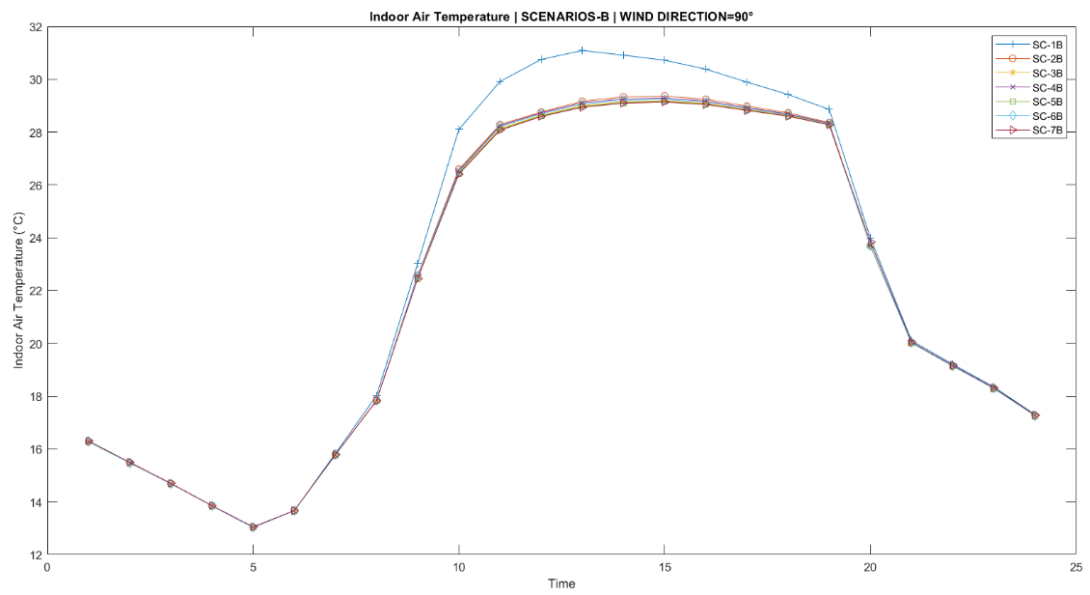


Figure 6.24. Indoor air temperatures for B-scenarios

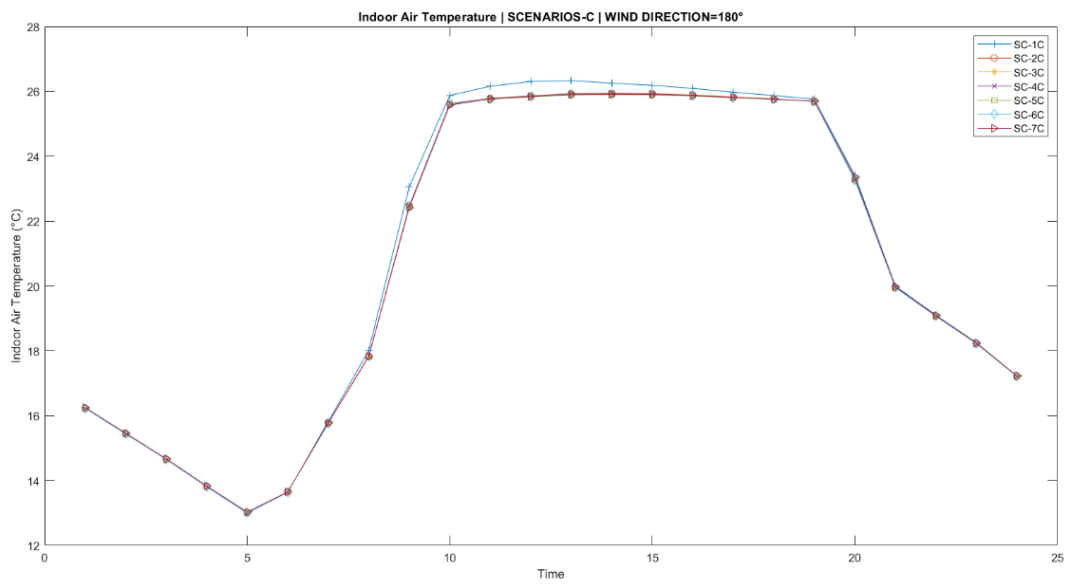


Figure 6.25. Indoor air temperatures for C-scenarios

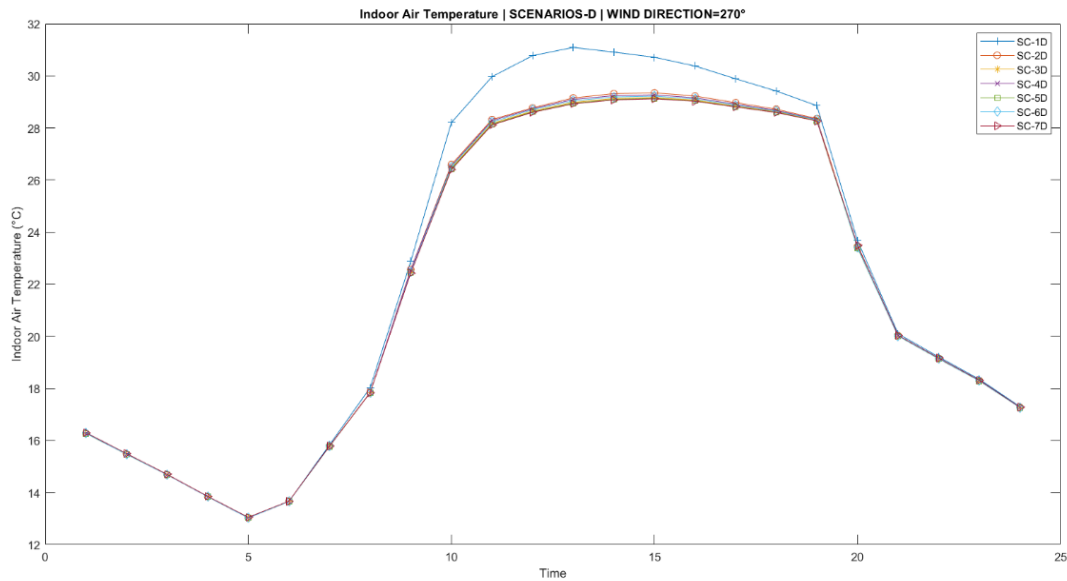


Figure 6.26. Indoor air temperatures for D-scenarios

6.2.3 The Impact of Shading Design on Natural Ventilation Performance Metrics

Air change rate (ACH): SC-3A provides the highest rate of ACH, whereas SC-7B provides the lowest ACH rate among the scenarios. Analysis results suggest that wind acting perpendicular upon the façades with openings (SC-A and SC-C) increased ACH rate 5.2-fold compared to the wind acting parallel upon the façades with openings (SC-B and SC-D). SC-C (wind acting upon the façade with shading devices) decreased ACH by 1.2% on average compared to the SC-A (wind acting upon the façade without shading devices).

SC-A and SC-C result in similar behaviors. In all SC-A except SC-7A, there is a 2% increase on average in ACH compared to SC-1A (baseline-0°). The maximum increase is evident in SC-3A (3.2%), whereas the decrease is only evident in SC-7A (0.7%) compared to SC-1A. Similarly, in all SC-C except SC-7C, there is a 2.9% increase on average in ACH compared to SC-1C (baseline-270°). The maximum increase is evident in SC-4C (4%), whereas the decrease is only evident in SC-7C (0.4%) compared to SC-1C. SC-B and SC-D also result in similar behaviors. SC-B results in

a 4.6% decrease in ACH compared to SC-1B (baseline-90°). The maximum decrease is observed in SC-7B (8.5%), whereas the minimum decrease is observed in SC-2B (3.8%). SC-D scenarios result in a 3.4% decrease on average as compared to SC-1D (baseline-270°). The maximum decrease is observed in SC-7D (7.3%), whereas the minimum decrease is observed in SC-4D (2%).

There is a moderate negative correlation ($p=-0.46$) between SD and ACH; as SD increases, the ventilation performance of the room decreases. There is a moderate positive correlation ($p=0.42$) between PR and ACH; as PR increases, natural ventilation performance increases parallel.

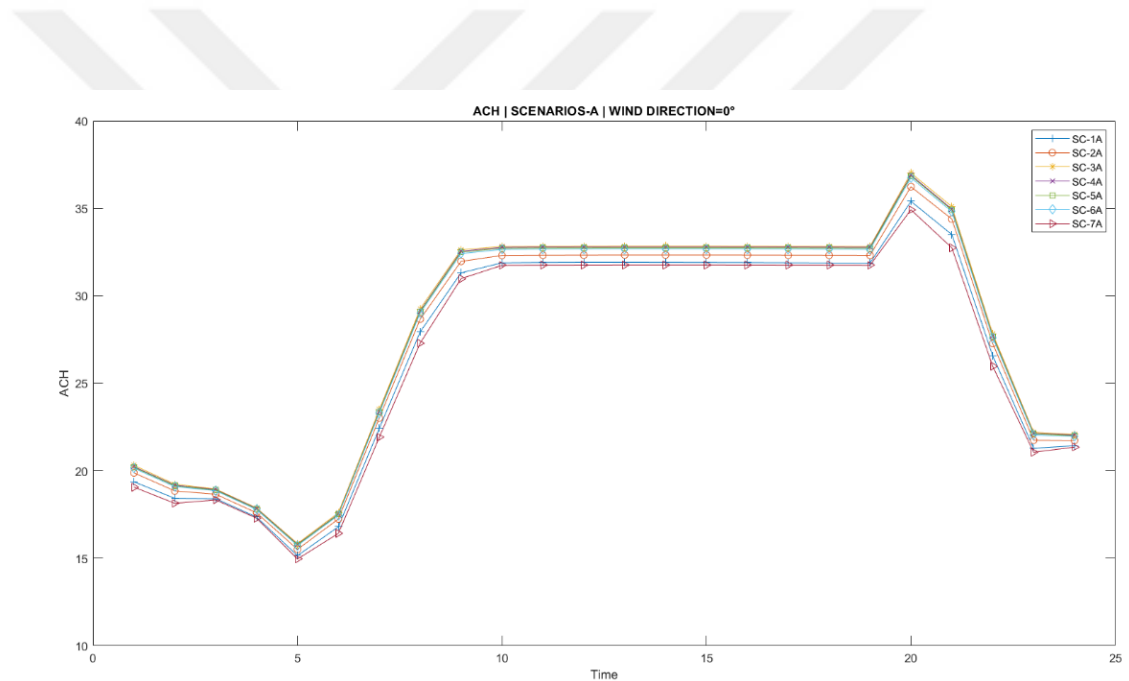


Figure 6.27. ACH for A-scenarios

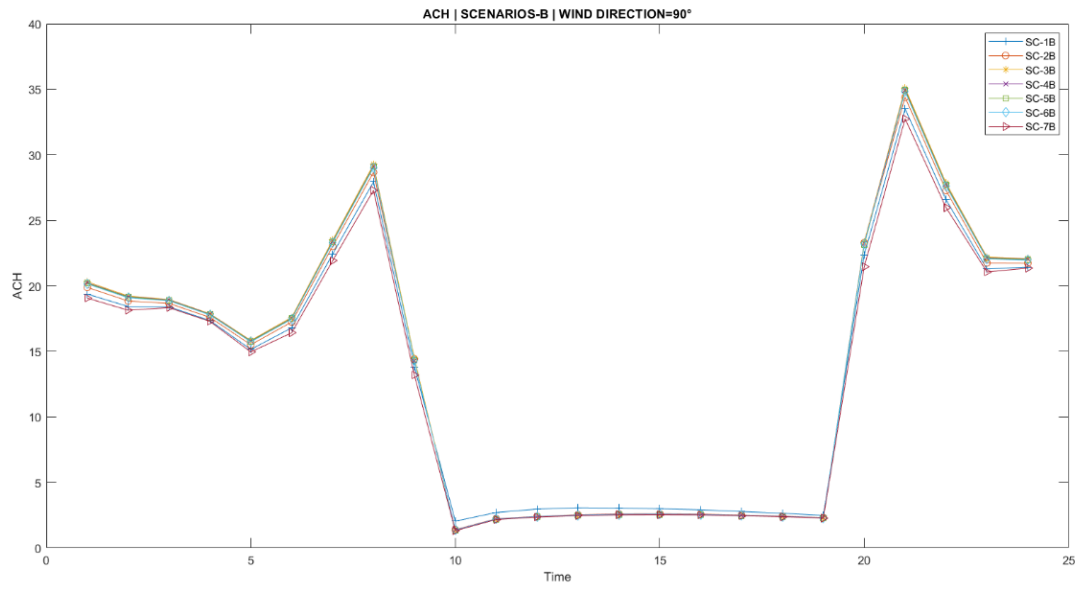


Figure 6.28. ACH for B-scenarios

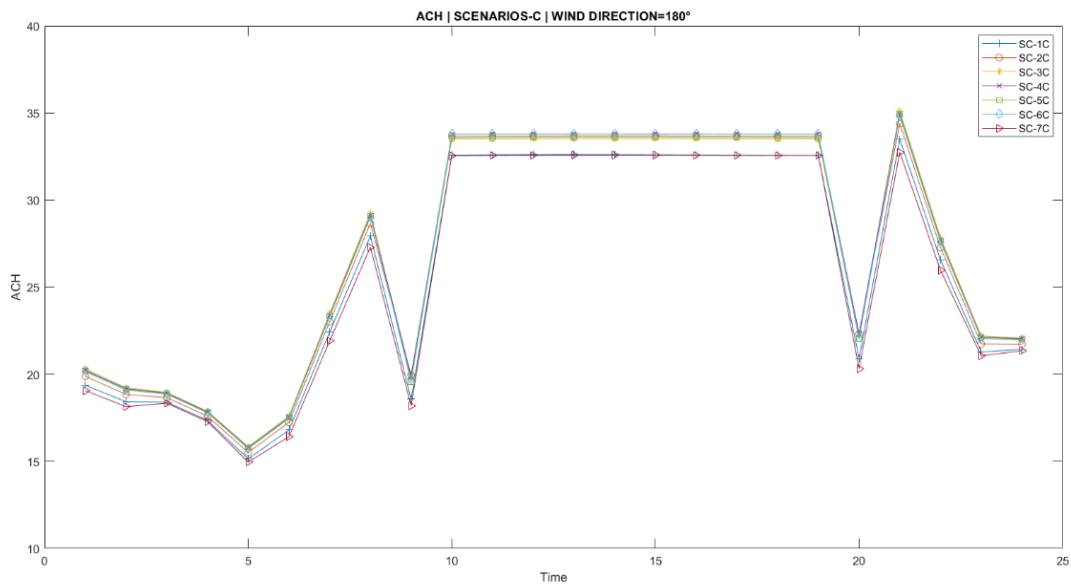


Figure 6.29. ACH for C-scenarios

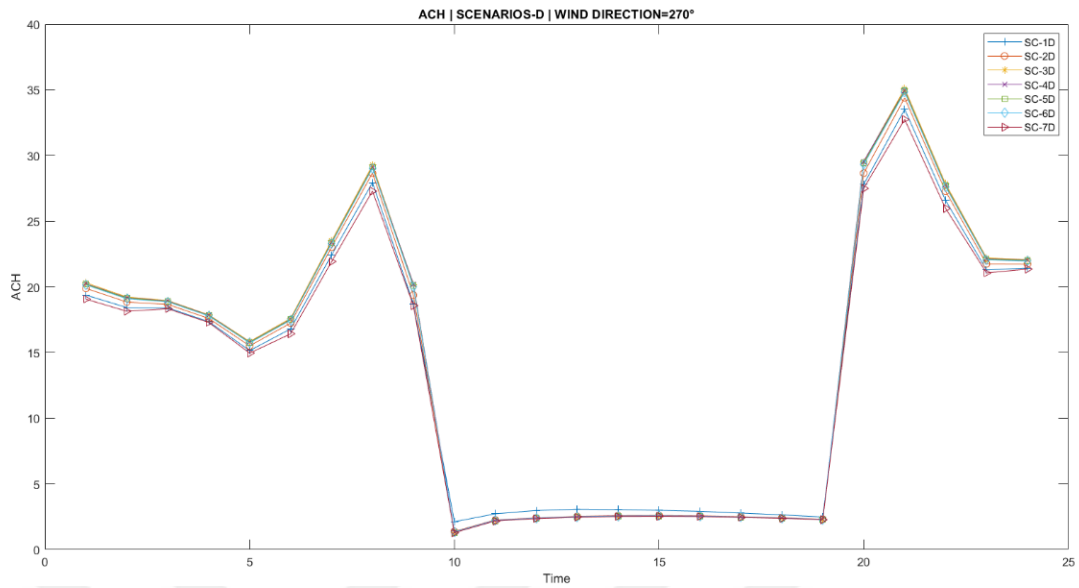


Figure 6.30. ACH for D-scenarios

CO₂: Analysis results reveal that wind acting perpendicular upon the façades with openings (SC-A and SC-C) decreases indoor CO₂ level 36.5% on average compared to the wind acting parallel to the façades with openings (SC-B and SC-D). SC-3A result in the lowest indoor CO₂ level, whereas SC-7B results in the highest indoor CO₂ level. In SC-C scenarios, indoor CO₂ levels are 0.57% higher on average as compared to SC-A due to the impact of shading devices on incoming airflow.

SC-A and SC-C scenarios result in 0.1% and 0.4% decrease on average in indoor CO₂ levels as compared to SC-1A and SC-1C, respectively, which can be regarded as negligible. The impact of shading devices (on the outlet openings of SC-A and the inlet openings of SC-C) is negligible for SC-A and SC-C. In contrast, SC-B and SC-D scenarios result in 7.09% and 6.7%, relatively higher rates, and an increase in indoor CO₂ levels compared to SC-1B and SC-1D, respectively.

There is a strong positive correlation ($p=0.61$) between SD and indoor CO₂ levels; CO₂ levels increase as SD increases. On the other hand, there is a strong negative correlation ($p=-0.76$) between PR and indoor CO₂ levels; CO₂ decreases as PR increases.

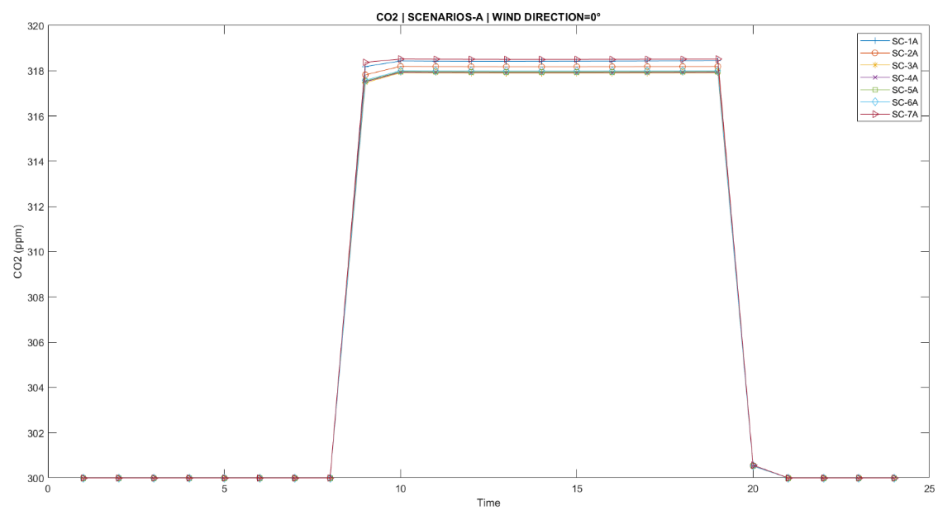


Figure 6.31. CO₂ levels for A-scenarios

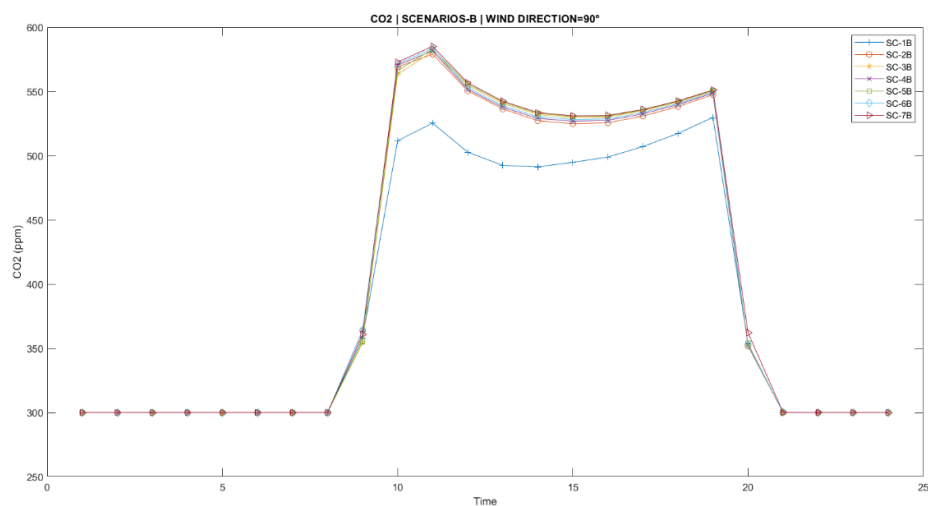


Figure 6.32. CO₂ levels for B-scenarios

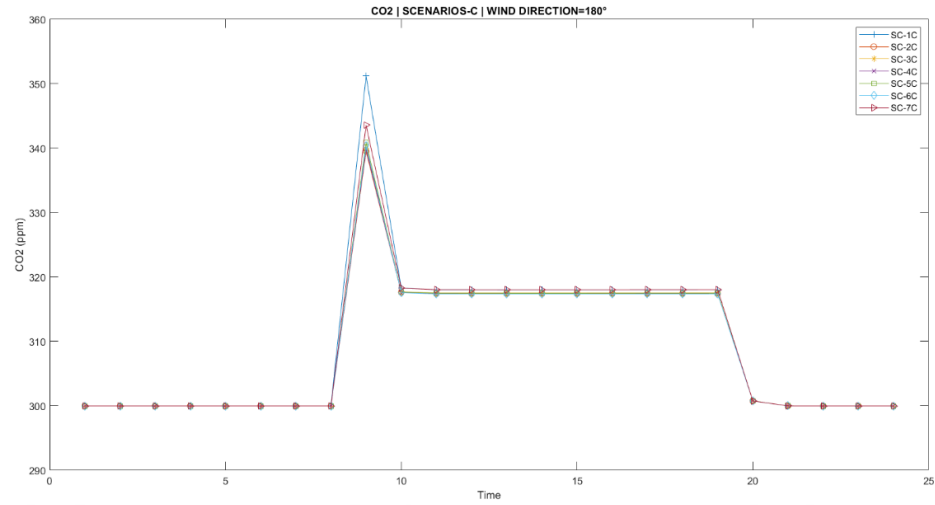


Figure 6.33. CO₂ levels for C-scenarios

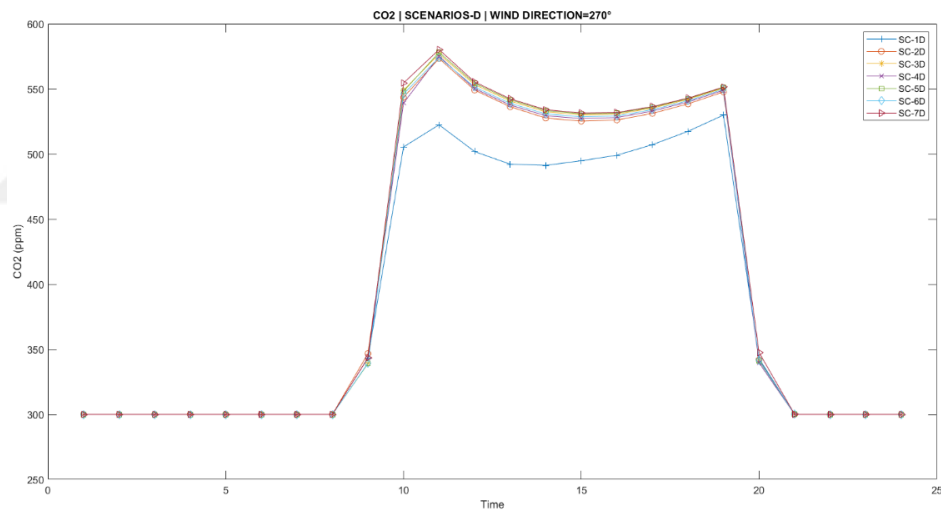


Figure 6.34. CO₂ levels for D-scenarios

Airborne Contamination: The simulation results suggest a weak negative correlation ($p=-0.25$) between PR and CCL_{total} , whereas there is a medium positive correlation ($p=0.31$) between SD and CCL_{total} . Similarly, there is a medium negative correlation ($p=-0.34$) between PR and CCL_{BR} , whereas a medium positive correlation ($p=0.42$) between SD and CCL_{BR} . The impact of SD and PR on T_{dis} and T_{inf} is also investigated. T_{dis} has a weak negative correlation ($p=-0.22$) and a weak positive correlation ($p=0.27$)

with PR and SD, respectively. No correlation has been found between T_{dis} and PR ($p=0.0$), whereas medium negative correlation ($p=-0.43$) between T_{dis} and SD.

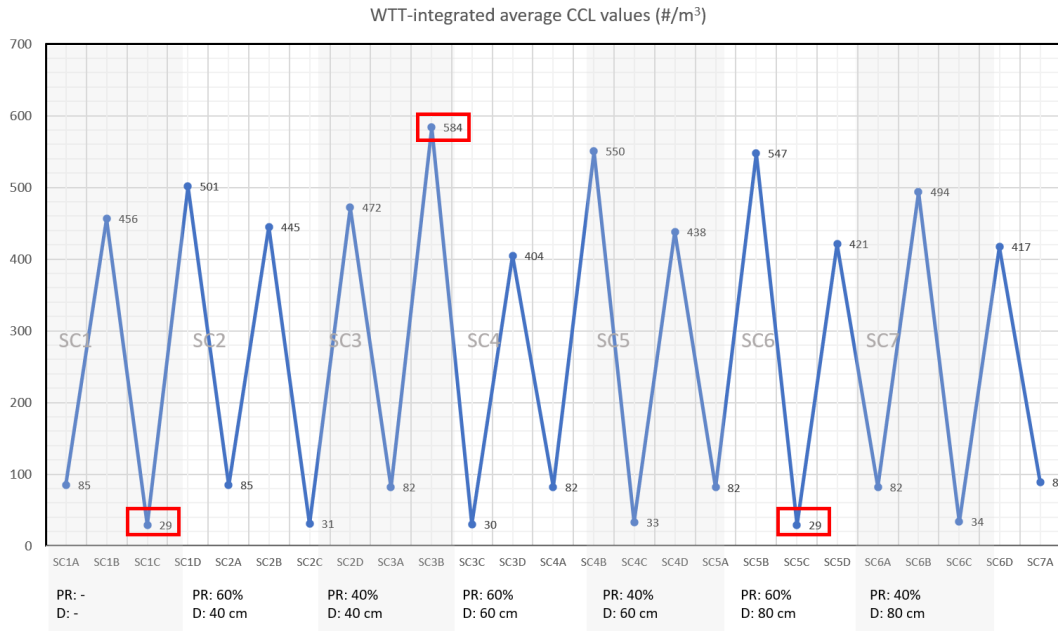


Figure 6.35. Wind tunnel-integrated average CCL_{total} results for the simulated scenarios

6.3 Findings

Developing and implementing the pipeline, this research also draws a number of conclusions for shading devices. Accordingly, the findings of this research can be discussed as (1) findings relating to the impact of shading devices on performance metrics and (2) findings relating to the pipeline.

6.3.1 Impact of Shading Devices on Performance Metrics

Shading design has a considerable impact on building performance. Therefore, the impact of shading design parameters must be calculated and assessed to attain improved building performance. As a part of the pipeline implementation, shading designs are evaluated for shading depth (SD) and perforation ratio (PR). In 6.2, all scenarios are inspected for their performance metrics based on the airflow direction

(A-B-C-D scenarios). This section investigates scenario categories for the overall relationship between PR, SD, and performance metrics. The findings are as follows (Table 6.12):

Shading depth:

- There is a negative correlation between SD and **energy performance** parameters as T_i and HL.
- For **natural ventilation performance** parameters, there is a positive correlation between SD and indoor contamination levels as CO_2 , CCL_{total} , CCL_{BR} , and T_{inf} . In contrast, there is a negative correlation between SD and ACH. No significant correlation is found between SD and T_{dis} .
- There is a negative correlation between SD and **daylighting performance** parameters as DGP, DLA, and UDI.

Perforation ratio:

- There is a positive correlation between PR and **energy performance** parameters as T_i and HL.
- For **natural ventilation performance** parameters, there is a negative correlation between PR and indoor contamination levels as CO_2 , CCL_{total} , CCL_{BR} , and, T_{dis} . In contrast, there is a positive correlation between PR and ACH. In parallel to CCL_{total} and CCL_{BR} , as expected, there is a positive correlation between PR and T_{inf} .
- There is a positive correlation between PR and **daylighting performance** parameters as DGP, DLA, and UDI.

Table 6.12. Relationship between performance parameters and shading design

	Daylighting			Energy		Ventilation					
	DGP	DLA	UDI	T_i	HL	CO_2	ACH	CCL_{total}	CCL_{BZ}	T_{dis}	T_{inf}
SD	-0.57	-0.42	-0.43	-0.44	-0.45	0.61	-0.46	-0.36	-0.57	0.02	0.27
PR	0.77	0.83	0.72	0.85	0.88	-0.76	0.42	-0.37	-0.52	-0.72	0.89

6.3.2 The Pipeline

Implementing the pipeline for a case study enabled the identification of remaining gaps, the parts that are open to further improvement, and the contributions of this research. The findings are as follows:

- The pipeline maps the data flow (input/output relations and integration) between the tools. It aims to manage complex performance-driven design processes involving multiple and hybrid tools and multi-criteria assessment.
- The pipeline improves the accuracy of the energy and contaminant analysis results by providing accurate micro-climatic data based on T_i and C_p values.
- The pipeline also improves the accuracy of the analysis results by integrating wind tunnel measurements, which is regarded as a reliable primary source to calculate C_p values.
- Accordingly, CFD tools that are integrated into 3D design environments can be used for preliminary performance feedback. However, wind tunnel testing must be performed for accurate analysis results, particularly for energy and contaminant feedback. In this respect, the computer simulation I module can be regarded as a phase that provides feedback on daylighting and energy analysis for preliminary performance assessment. Model testing and computer-simulations II can be regarded as phases providing more accurate performance feedback on energy, ventilation, and contamination-related performance metrics.
- The pipeline implementation remained within the boundaries of off-the-shelf tools and existing knowledge on performance-driven design practices. With the developments in computational technologies (i.e., improving the accuracy of CFD results within a feasible time and computational cost may displace physical measurements), the proposed workflow may necessitate revisions in the future.
- The pipeline is a framework, which can be applicable for all kinds of airborne contaminants as long as there is bio-chemical data of the contaminant.

- In the existing practice, as mentioned above, mathematical and statistical models neglect spatial variations of the contaminant dispersion and assume contaminant concentration as constant, steady, and randomly distributed. However, the pipeline provides visual feedback complementing numeric feedback that can inform design decisions about the locations vulnerable to contamination risks, guiding design decisions (i.e., plan layout, partitions, seating plan).





CHAPTER 7

CONCLUSION

This research tackles how natural ventilation and contaminant dispersion analysis can be integrated into PAD processes responding to the gap in the existing literature. Architectural design is a complex task and requires well-informed design decisions, requiring efficient use of analysis tools during the design process. The advances in computational design enabled the integration of off-the-shelf analysis tools into design synthesis but still necessitates a framework for their integrated use. There is a vast number of studies in the literature focusing on the integrated use of daylighting and energy analysis, while natural ventilation and contaminant analysis are understudied. Nevertheless, utilizing natural ventilation and contaminant analysis tools and methods during the design process must also be an essential practice of PAD. The current COVID-19 pandemics revealed their vital significance for occupants' health and wellbeing, particularly for shared and densely occupied spaces. In this respect, this research developed a hybrid computational pipeline for PAD, which is an integrated analysis framework for natural ventilation and airborne contaminant dispersion in buildings, coupling 3D parametric design, daylighting, CFD, energy and contaminant analysis and, wind tunnel testing. The pipeline can be regarded as an attempt to provide a viable workflow by investigating the data integration of the tools during a parametric design process.

7.1 Revisiting the Research Questions

The main research question addressed by this thesis is: How natural ventilation and contaminant dispersion analysis can be integrated into PAD? To answer the main question, this research focused on several sub-questions:

What is an integrated computational design workflow that can support the integrated use of parametric design, computational analysis, and physical testing methods and tools?

Workflow is an operative sequence of a system where the work passes from the beginning towards completion. Developing an understanding of how different components can work regarding data flow and data integration was crucial to elaborate the pipeline. Therefore, (1) the workflows, requirements, and components of the existing performance-driven architectural design/computational and physical testing tools, methods, and processes, and (2) the existing performance frameworks and the performance metrics involved in the design processes are investigated. Based on this exploration, the data integration and flows between the pipeline components (i.e., obtaining wind pressure coefficients from CFD or wind tunnel and integrating them into energy simulation tool) are determined and implemented within the scope of the case study.

What are the existing computational tools and methods that address PAD?

To answer this question, (1) the literature review is conducted focusing on the integrated use of design and analysis tools, and (2) the tools and methods that are utilized for PAD are investigated. The literature review revealed that the central integration studies focus on energy and daylighting analysis, while natural ventilation and contaminant studies are in a narrow focus. Exploring off-the-shelf PAD tools was particularly crucial to understanding the input-output relationships of analysis tools and their integration.

What are the requirements and components of the pipeline?

The pipeline requires a parametric 3D environment coupled with performance analysis tools: daylighting, CFD, energy and contaminant models, and wind tunnel testing and analysis.

The pipeline is based on three main modules as computer simulation I, computer simulation II, and model testing. The computer simulation I module provides feedback on daylighting and energy analysis for preliminary performance assessment. Model

testing and computer simulations II provide more accurate performance feedback on energy, ventilation, and contamination-related performance metrics.

To which extent does the pipeline successfully support designers in PAD processes?

A case study implementation, regarded as an instrument revealing the existing limitations and requirements of the pipeline, is performed to assess its viability and actual design integration. Case study implementation results indicated that natural ventilation and contaminant analysis could be integrated into and used during the design processes coupled with an energy analysis to obtain feedback on ventilation performance and probable airborne contamination/infection risks of design alternatives. Evaluating ventilation and contamination risks can inform designers about the eventual IAQ of design alternatives and allow improvements before realizing the actual building.

Also, as a result of case study implementation, using CFD during the preliminary design and wind tunnel tests for obtaining precise analysis results during the developing design stages can be a feasible strategy to manage design alternatives and the simulation workload. Due to high precision in actual measurements, integrating wind-tunnel test results into energy and contaminant simulations is recommended. In addition, the developed the pipeline can be implemented for other airborne contaminants.

What are the performance metrics for the natural ventilation and contaminant dispersion analysis?

Identifying the performance metrics for the natural ventilation and contaminant analysis was a necessary step for developing the pipeline. Existing performance frameworks were reviewed for daylighting, energy, ventilation, and contaminant metrics. However, as highlighted in the existing literature, there is no consensus on an integrated performance framework. Therefore, this thesis developed a performance framework consisting of several performance metrics for the integrated assessment of

daylighting, energy, ventilation, and contaminant. The performance framework can be extended based on the assessment criteria.

7.2 Main Research Contributions

This research investigated the integration of natural ventilation and contaminant analysis into the PAD. Responding the existing gaps in the literature and the research questions, this thesis has two main research contributions: (1) integrated performance framework and (2) the pipeline, which is the integrated analysis workflow for natural ventilation and contaminant analysis.

An integrated performance framework was necessary for the pipeline since there is no consensus on an integrated performance assessment. Integrated performance framework aimed at compiling performance assessment metrics for daylighting, energy, natural ventilation, and contamination. The performance metrics are selected based on the available tools and can be expanded with additional tools and performance measures.

The pipeline is developed as an analysis framework which

- integrates a number of distinct PAD tools,
- therefore, requires the theoretical and hands-on expertise of daylighting, energy, ventilation performance, and contamination assessment practices,
- integrates natural ventilation and contaminant assessment into PAD,
- enables multi-criteria performance assessment communicating several performance metrics,
- allows the estimation of ventilation and contamination-related performance metrics with energy and daylighting performance parameters,
- augments designers' integration to the performance analysis phased by involving both numeric and visual feedback.

7.3 Limitations and Challenges

This research has several limitations. First and foremost, none of the attempts can fulfill a complete integrated performance workflow due to a vast number of performance parameters and performance assessment practices. In this respect, a complete integrated performance workflow or framework remains beyond the scope of this thesis. This thesis is limited to its scope, tools, and research boundaries and does not claim a complete integration of all aspects of building performance and performance-driven design. This thesis only focused on a very limited part of the PAD process. Accordingly, this thesis should be regarded as an attempt to develop a hybrid computational workflow for improving IAQ and reducing airborne contamination risks while keeping daylighting and energy performance at an optimum level.

Second, the implementation of the pipeline remained within the boundaries of the integration of tools and methods. Even though the pipeline gives clues about the design integration aspect, the trade-offs between the performance parameters remained limited to explore. To deepen the exploration of the relationship between performance parameters, there is a need to implement the pipeline in professional practice.

7.4 Future Work

Integrating natural ventilation and contaminant analysis in PAD is a relatively unexplored area. In this respect, there might be a vast number of future works complementing this thesis.

First, as mentioned above, airflow-related analysis requires expertise, computational effort, and time. For the future applications of the pipeline, natural ventilation and contaminant analysis can be facilitated by the surrogate models instead of CFD simulations at preliminary design phases to reduce computational and time-wise costs.

Second, the pipeline only integrated pressure and particle image velocimetry (PIV) measurements. However, physical air pollutant measurement and testing procedures can also be integrated to develop the pipeline further.

Data and design representation aspects of the pipeline remained within the boundaries of the existing tools. However, augmented data visualization methods can enhance designers' integration to the pipeline data flow, which can support the informed decision-making process of designers.

To explore trade-offs between performance metrics, a study with professional architects can be conducted, which can also provide valuable feedback for further improvements in multi-criteria performance assessment and tool integration. However, this potential study is also limited to using 3D parametric design environments and adopting performance-driven design as a design method by professional architects and offices.

The performance-driven design practices in education can be supported and augmented by the pipeline as an exploratory computational design tool.

Last but not least, this pipeline can provide an inter/multi/paradisciplinary area in the near future which can provide a novel design service for integrated building performance. As the importance of indoor air quality has started to receive attention with COVID-19, it is plainly visible that the architectural design and construction professions need the expertise, knowledge, and communication of various disciplines. In this respect, the developed pipeline can bring the various professionals and their expertise into service.

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APPENDICES

A. Literature Review List

Table A. 1 Literature Review List

Year	Authors	Title	Focus	Metric	Tools
2018	Lobaccaro et al.	Parametric design	Methodology	Solar radiation	Grasshopper
		to minimize the	GA in a workflow	Daylighting	Galapagos
		embodied GHG	Energy performance	Embodied	Octopus
		emissions in a ZEB		carbon	Ladybug
2018	Ferrara et al.	Automated optimization for the integrated design process: the energy, thermal and visual comfort nexus	Integrated methodology Optimization	Energy demand Visual comfort	Trynsis Genopt
2017	Chi et al.	Design	Methodology	Daylighting	Grasshopper
		optimisation of perforated solar façades in order to balance daylighting and thermal		Thermal performance	Energyplus DIVA Archsim
2017	Teeling et al.	PULSE: Integrated Parametric Modeling for a Shading System From Daylight Optimization to Additive Manufacturing	Workflow Additive manufacturing Shading devices	Daylighting Structure 3D printing	Grasshopper DIVA Custom-developed GA solver
2017	Santos et al.	Automation of CAD models to BEM models for performance based goal-	A goal-oriented design methodology to automate the derivation of BEM from 3D geometry	Solar radiation Energy demand	Grasshopper Galapagos Octopus Kangaroo DIVA

		oriented design methods			EnergyPlus Ladybug
2017	Karaman et al.	Design of Rectangular Façade Modules through Computational Intelligence	To enhance indoor comfort by cost-effective façade design alternatives	Daylighting Construction cost	Grasshopper
2017	Touloupaki et al.	Optimization of Building form to Minimize Energy Consumption through Parametric Modelling	Integrated workflow	Energy demand Visual comfort	Parametric design plug-ins Evolutionary solver BPS plug-ins
2017	Camporeale et al.	Multi-objective optimisation model: A housing block retrofit in Seville	A design methodology for coupling building shape and envelope Multi-objective optimization	Energy demand Cost	Grasshopper Galapagos DIVA EnergyPlus
2017	Shadram et al.	An integrated BIM-based framework for the optimization of the trade-off between embodied and operational energy	A framework and design solution for the trade-off problem between the embodied energy and operational energy	Embodied energy Operational energy	Revit Dynamo Octopus EnergyPlus Archsim
2017	Motamedi et al.	Integrative algorithm to optimize skylights considering fully impacts of daylight on energy	An algorithm to find optimal design of skylight	Daylighting Energy demand	Grasshopper Ladybug EnergyPlus Radiance

2017	Eltaweel et al.	Controlling venetian blinds based on parametric design; via implementing Grasshopper's plugins: A case study of an office building in Cairo	A new control method for automated venetian blinds to optimize the utility of daylight	Daylighting	Grasshopper Ladybug EnergyPlus Radiance Daysim
2017	Østergård et al.	Early Building Design: Informed decision-making by exploring multidimensional design space using sensitivity analysis	A design methodology for the exploration of multidimensional design space and guide multi-actor decision making	Energy Thermal comfort Daylighting	-
2016	Kırımtat et al.	Multi-Objective Optimization for Shading Devices in Buildings By Using Evolutionary Algorithms	Multi-objective optimization	Daylighting Energy demand	Grasshopper Ladybug EnergyPlus Radiance DIVA NSGA-II
2016	Delgram et al.	Multi-objective optimization of building energy performance and indoor thermal comfort: A new method using artificial bee colony (ABC)	A simulation-based multi-objective optimization methodology	Energy demand Indoor thermal comfort	Sketchup EnergyPlus
2016	Lee et al.	Full-factorial design space exploration approach for multi-criteria decision making of the design of industrial halls	A design space exploration approach to support multi-criteria design decision making	Energy and environmental Impact Cost effectiveness	Trynsis Daysim

2016	Papadopoulos et al.	Integrating building performance simulation in agent-based modeling using regression surrogate models: A novel human-in-the-loop energy modeling approach	A modeling framework that integrates BPS in agent-based modeling	Energy demand	EnergyPlus Genopt
2016	Caldas et al.	Painting with light: An interactive evolutionary system for daylighting design	User-guided interactive evolutionary system	Daylighting	Grasshopper Radiance DIVA Galapagos Octopus
2015	Ercan et al.	Performance-based parametric design explorations: A method for generating appropriate building components	Customized workflow methodology to explore design alternatives for shading devices	Daylighting Solar heat gain	Grasshopper DIVA Galapagos
2015	Futrell et al.	Optimizing complex building design for annual daylighting performance and evaluation of optimization algorithms	A methodology to optimize building design for daylighting performance	Energy demand Daylighting	Genopt
2015	Mavromatidis	A review on hybrid optimization algorithms to coalesce computational	Review on parametric optimization tools and methods in architecture	Energy Thermal load	-

		morphogenesis with interactive energy consumption forecasting			
2015	Lin et al.	Evolutionary energy performance feedback for design: Multidisciplinary design optimization and performance boundaries for design decision support	Multidisciplinary design optimization (MDO) framework	Energy	Revit Green Building Studio HDS Beagle automation loop algorithm
2015	Negendahl et al.	Building energy optimization in the early design stages: A simplified method	A design evaluation method for the early design stages	Energy demand Capital cost Daylighting Thermal	Radiance Custom algorithm for cost Octopus
2014	Manzan	Genetic optimization of external fixed shading devices	Genetic optimization	Daylighting Energy demand	ESP-r Radiance Daysim modeFronter
2014	Jin et al.	Optimization of a free-form building shape to minimize external thermal load using genetic algorithm	Optimization proccrs	Thermal load Building form	Grasshopper GA
2014	Nembrini et al.	Parametric scripting for early design performance simulation	A simulation framework	Thermal Airflow	ANAR+ EnergyPlus Radiance BCVTB control modeling
2014	Rodrigues et al.	Automated approach for design generation	A prototype tool for the space planning	Thermal	EPSAP EnergyPlus

		and thermal assessment of alternative floor plans			
2013	Greenberg et al.	Sustain: An experimental test bed for building energy simulation	A novel test bed with an interactive graphical interface, access to simulation modules	Thermal Daylighting	Sketchup EnergyPlus Radiance
2013	Shi et al.	Performance-driven architectural design and optimization technique from a perspective of architects	A design methodology	-	Grasshopper Ecotect Radiance EnergyPlus

B. Wind Tunnel Pressure Tests' C_p Values

Table B. 1 Wind Pressure Test C_p Values

SC-1 C_p									
		NW-1	NW-2	NW-3	NW-4	SW-1	SW-2	SW-3	SW-4
0°	N	0.61	0.98	0.96	0.55	-1.90	-1.96	-1.95	-1.89
45°	NE	0.73	0.36	-0.13	-0.95	-2.06	-2.13	-2.28	-2.45
90°	E	-1.98	-2.01	-2.08	-2.10	-2.01	-2.02	-2.08	-2.07
135°	SE	-2.12	-2.23	-2.40	-2.57	0.84	0.48	0.05	-0.62
180°	S	-1.93	-2.02	-2.08	-1.99	0.66	1.10	1.09	0.74
225°	SW	-2.46	-2.31	-2.22	-2.10	-0.71	-0.07	0.31	0.68
270°	W	-2.15	-2.16	-2.15	-2.08	-2.14	-2.13	-2.10	-2.04
315°	NW	-0.68	-0.09	0.28	0.61	-2.36	-2.22	-2.14	-2.04
SC-2 C_p									
		NW-1	NW-2	NW-3	NW-4	SW-1	SW-2	SW-3	SW-4
0°	N	0.67	1.06	1.04	0.62	-1.81	-1.82	-1.84	-1.79
45°	NE	0.84	0.45	-0.06	-0.93	-2.01	-2.06	-2.17	-2.23
90°	E	-1.86	-1.89	-1.97	-1.95	-1.85	-1.83	-1.86	-1.83
135°	SE	-1.90	-1.97	-2.12	-2.26	0.93	0.62	0.27	-0.04
180°	S	-1.77	-1.82	-1.89	-1.84	0.93	1.16	1.14	0.96
225°	SW	-2.43	-2.27	-2.19	-2.07	-0.11	0.20	0.51	0.83
270°	W	-2.00	-1.99	-1.99	-1.92	-1.91	-1.87	-1.89	-1.92
315°	NW	-0.63	-0.03	0.33	0.65	-2.19	-2.09	-2.04	-1.97
SC-3 C_p									
		NW-1	NW-2	NW-3	NW-4	SW-1	SW-2	SW-3	SW-4
0°	N	0.79	1.17	1.14	0.72	-1.68	-1.68	-1.69	-1.66
45°	NE	0.82	0.45	-0.07	-0.91	-2.01	-2.05	-2.17	-2.25
90°	E	-1.89	-1.91	-2.00	-1.98	-1.90	-1.88	-1.91	-1.88
135°	SE	-2.02	-2.11	-2.28	-2.45	0.89	0.60	0.25	-0.08
180°	S	-1.74	-1.82	-1.89	-1.81	0.89	1.13	1.12	0.92
225°	SW	-2.36	-2.20	-2.12	-1.99	-0.06	0.23	0.52	0.84
270°	W	-2.03	-2.02	-2.02	-1.95	-1.92	-1.89	-1.93	-1.95
315°	NW	-0.53	0.06	0.43	0.77	-2.08	-1.99	-1.94	-1.87
SC-4 C_p									
		NW-1	NW-2	NW-3	NW-4	SW-1	SW-2	SW-3	SW-4
0°	N	0.78	1.16	1.13	0.71	-1.70	-1.71	-1.73	-1.67
45°	NE	0.80	0.44	-0.08	-0.93	-2.03	-2.08	-2.19	-2.25

90°	E	-1.89	-1.91	-1.99	-1.98	-1.92	-1.89	-1.93	-1.87
135°	SE	-1.99	-2.07	-2.25	-2.44	0.95	0.64	0.28	-0.05
180°	S	-1.73	-1.78	-1.83	-1.77	0.95	1.16	1.14	0.99
225°	SW	-2.44	-2.27	-2.18	-2.05	-0.05	0.29	0.58	0.90
270°	W	-1.96	-1.96	-1.96	-1.90	-1.88	-1.86	-1.88	-1.90
315°	NW	-0.54	0.06	0.44	0.77	-2.15	-2.05	-2.00	-1.93
SC-5 Cp									
		NW-1	NW-2	NW-3	NW-4	SW-1	SW-2	SW-3	SW-4
0°	N	0.76	1.15	1.13	0.70	-1.68	-1.68	-1.70	-1.65
45°	NE	0.82	0.45	-0.08	-0.94	-2.05	-2.10	-2.22	-2.28
90°	E	-2.00	-2.02	-2.11	-2.09	-2.01	-2.00	-2.02	-1.95
135°	SE	-1.95	-2.02	-2.18	-2.34	0.87	0.60	0.26	-0.07
180°	S	-1.76	-1.84	-1.90	-1.82	0.92	1.14	1.12	0.93
225°	SW	-2.35	-2.19	-2.11	-1.98	-0.04	0.27	0.54	0.83
270°	W	-2.01	-2.00	-2.00	-1.94	-1.89	-1.87	-1.96	-1.97
315°	NW	-0.54	0.06	0.44	0.76	-2.07	-1.98	-1.95	-1.90
SC-6 Cp									
		NW-1	NW-2	NW-3	NW-4	SW-1	SW-2	SW-3	SW-4
0°	N	0.75	1.14	1.11	0.69	-1.67	-1.68	-1.70	-1.65
45°	NE	0.81	0.45	-0.08	-0.93	-2.03	-2.07	-2.18	-2.23
90°	E	-1.93	-1.95	-2.03	-2.00	-1.94	-1.89	-1.93	-1.85
135°	SE	-1.95	-2.02	-2.18	-2.35	0.85	0.62	0.27	-0.13
180°	S	-1.67	-1.72	-1.77	-1.70	0.97	1.16	1.14	0.98
225°	SW	-2.39	-2.22	-2.14	-2.03	-0.07	0.31	0.59	0.86
270°	W	-2.04	-2.03	-2.03	-1.97	-1.93	-1.92	-1.95	-1.97
315°	NW	-0.53	0.06	0.43	0.75	-2.08	-1.98	-1.95	-1.88
SC-7 Cp									
		NW-1	NW-2	NW-3	NW-4	SW-1	SW-2	SW-3	SW-4
0°	N	0.60	0.97	0.97	0.52	-1.79	-1.84	-1.85	-1.80
45°	NE	0.65	0.26	-0.21	-1.09	-2.20	-2.26	-2.36	-2.39
90°	E	-2.10	-2.14	-2.19	-2.20	-2.11	-2.10	-2.13	-2.06
135°	SE	-2.15	-2.24	-2.38	-2.57	0.69	0.38	0.03	-0.25
180°	S	-1.76	-1.82	-1.85	-1.80	0.76	0.93	0.92	0.76
225°	SW	-2.65	-2.48	-2.33	-2.23	-0.21	0.01	0.33	0.62
270°	W	-2.17	-2.19	-2.15	-2.12	-2.02	-2.05	-2.08	-2.11
315°	NW	-0.69	-0.10	0.29	0.59	-2.28	-2.23	-2.17	-2.12

C. Pressure Distribution for Scenario Categories

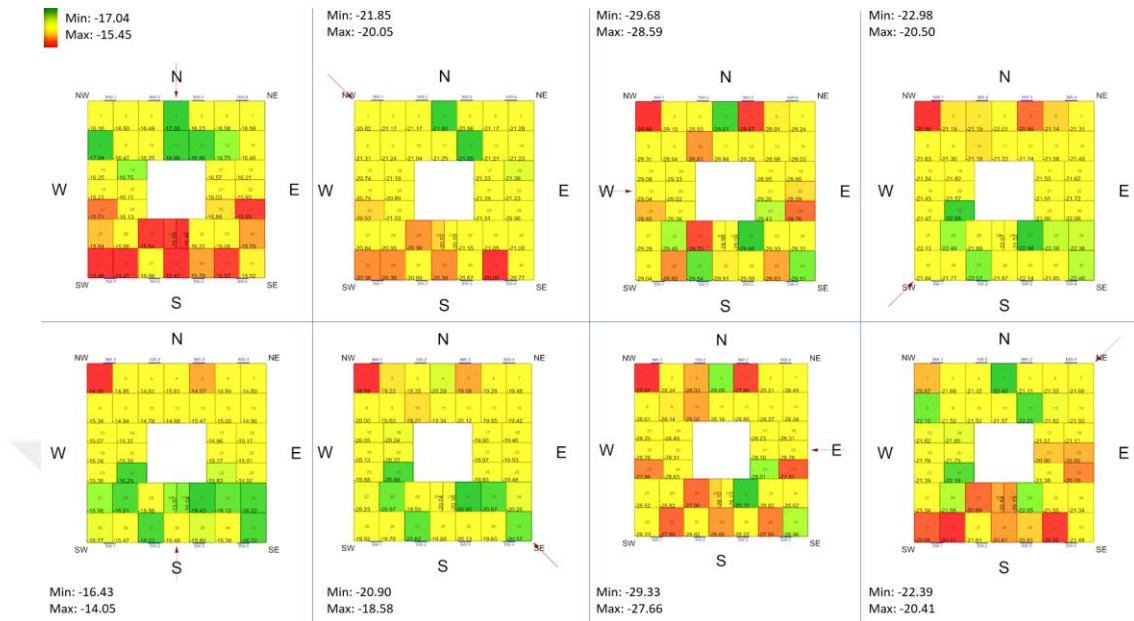


Figure C. 1 Indoor Pressures for SC1

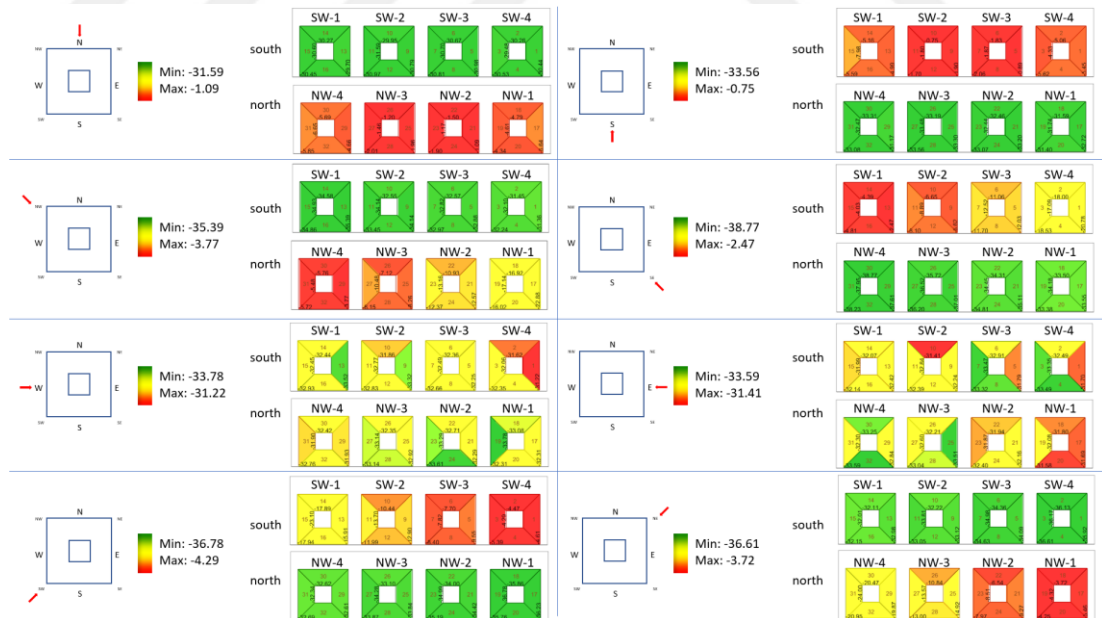


Figure C. 2 Façade Pressures for SC1

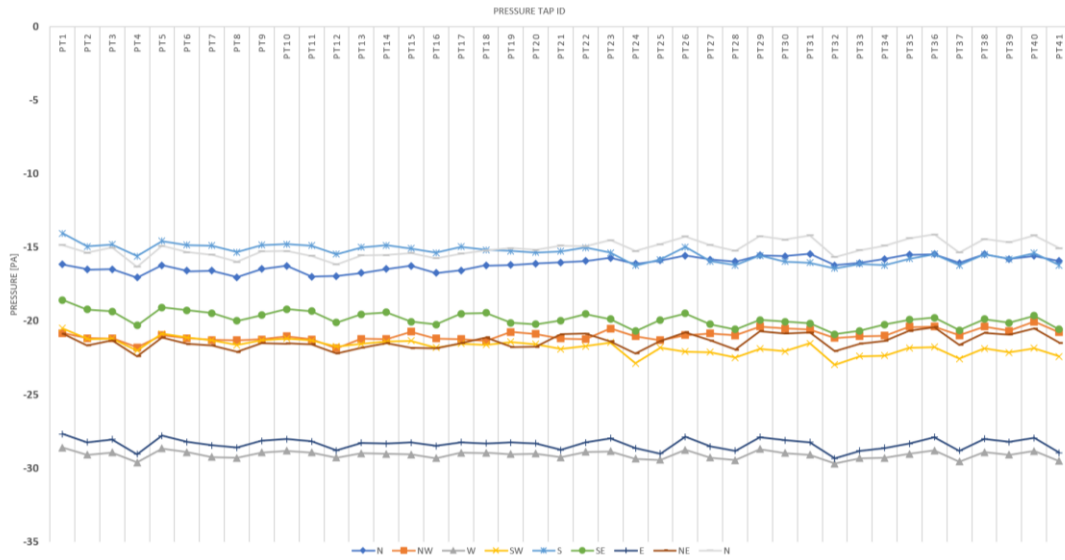


Figure C. 3 Pressure Distribution per Pressure Tap on Indoor Plane for SC1

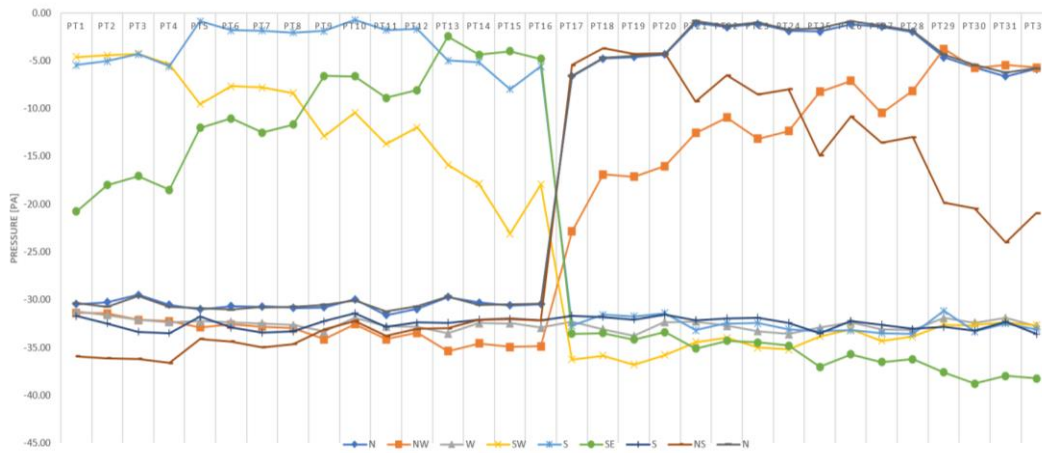


Figure C. 4 Pressure Distribution per Pressure Tap on Façades for SC1

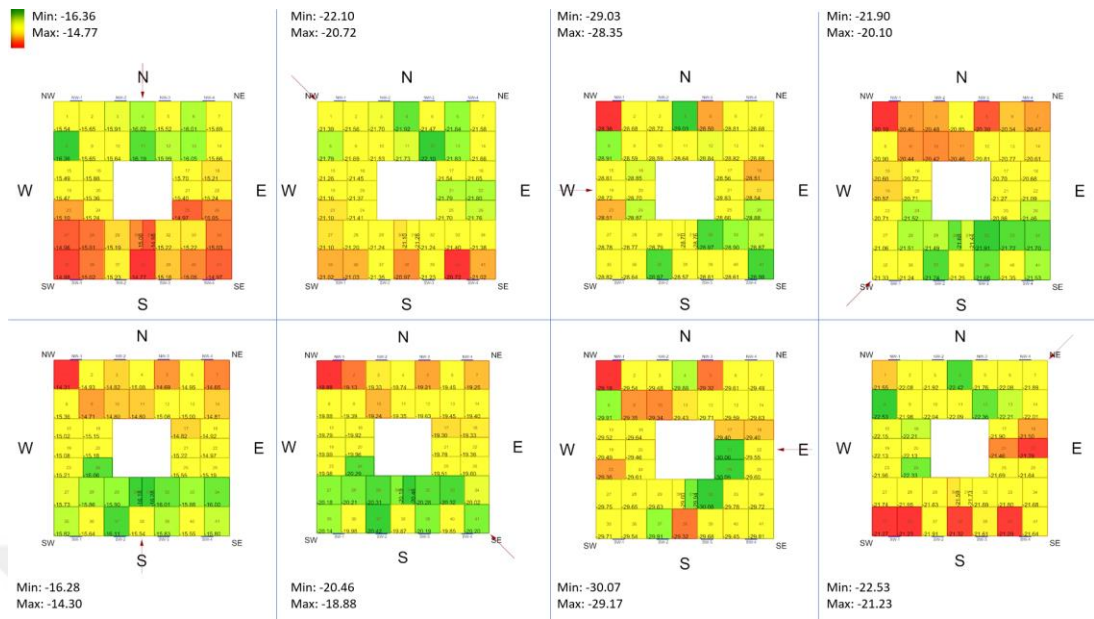


Figure C. 5 Indoor Pressures for SC2

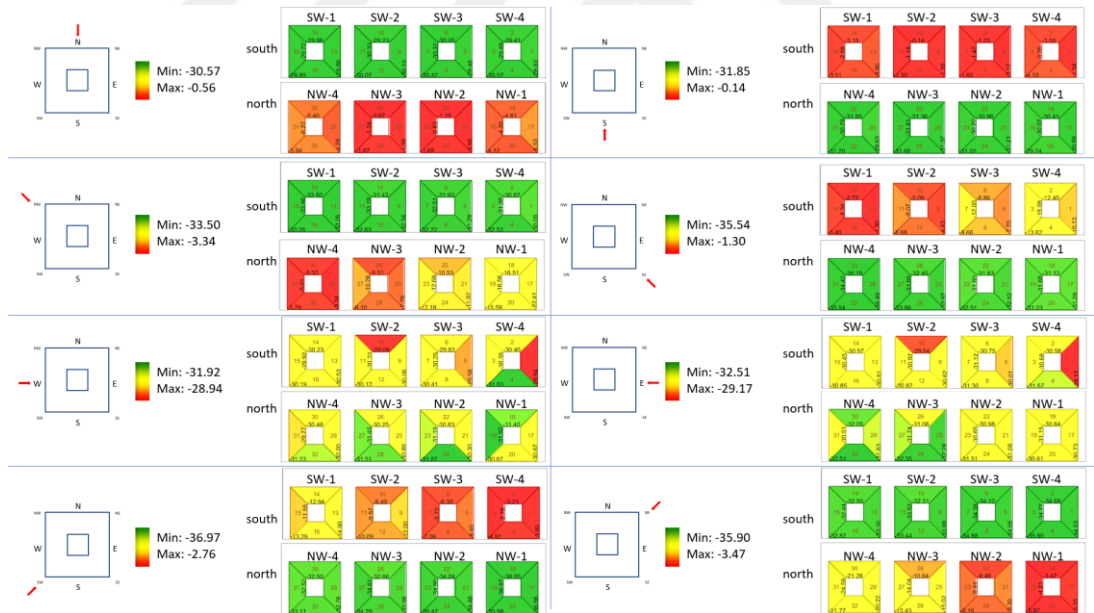


Figure C. 6 Façade Pressures for SC2

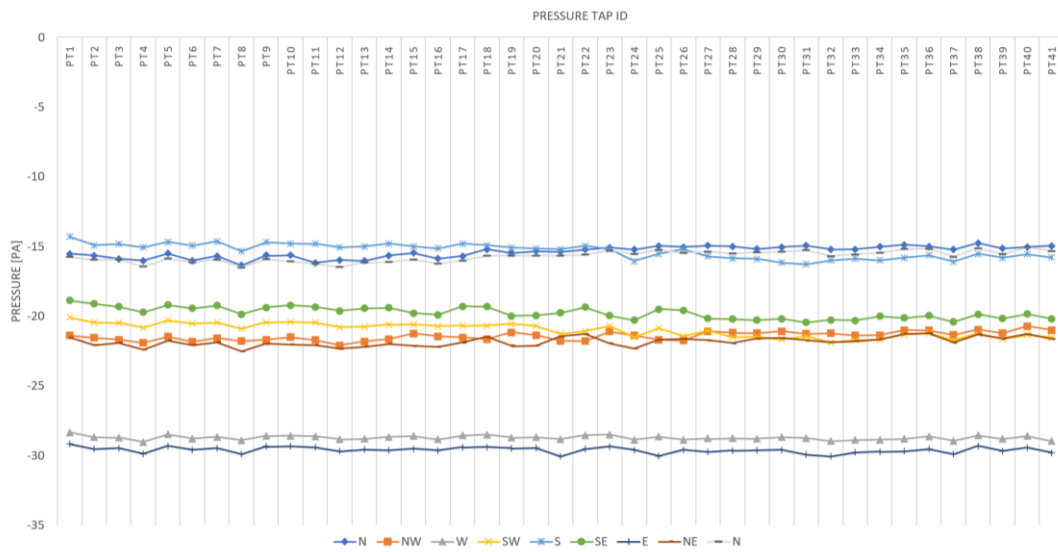


Figure C. 7 Pressure Distribution per Pressure Tap on Indoor Plane for SC2

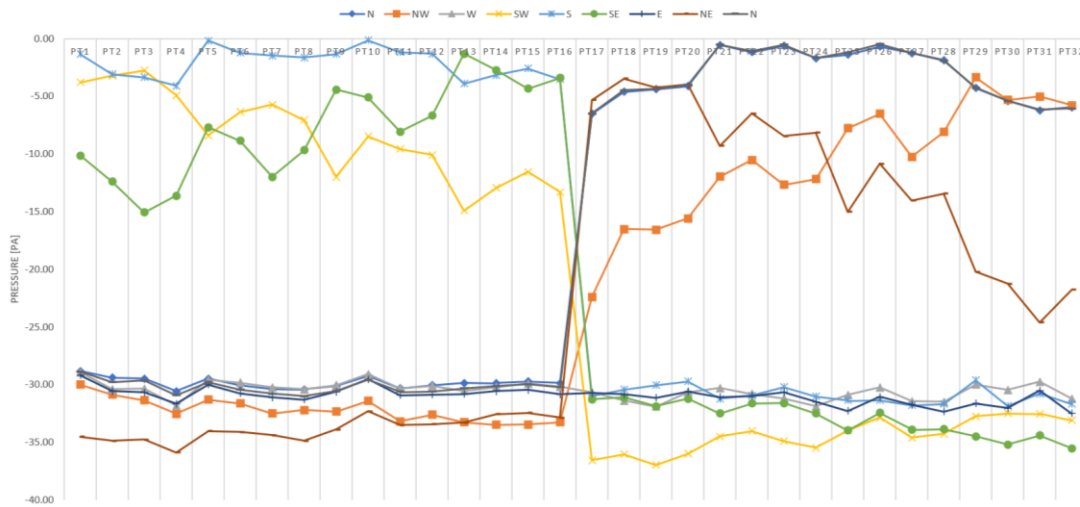


Figure C. 8 Pressure Distribution per Pressure Tap on Façades for SC2

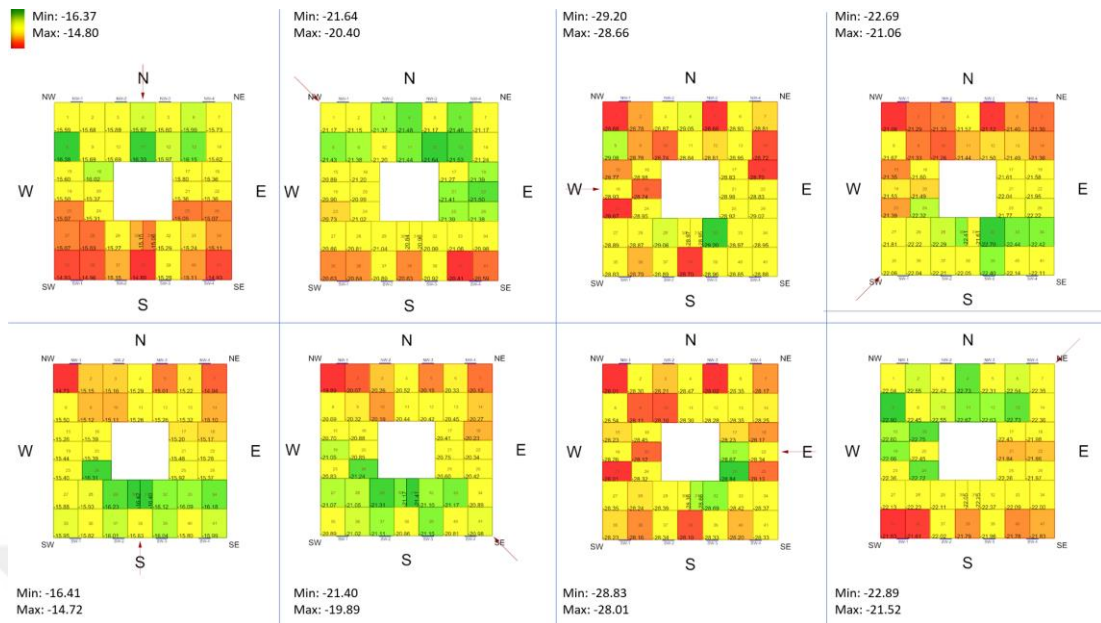


Figure C. 9 Indoor Pressures for SC3

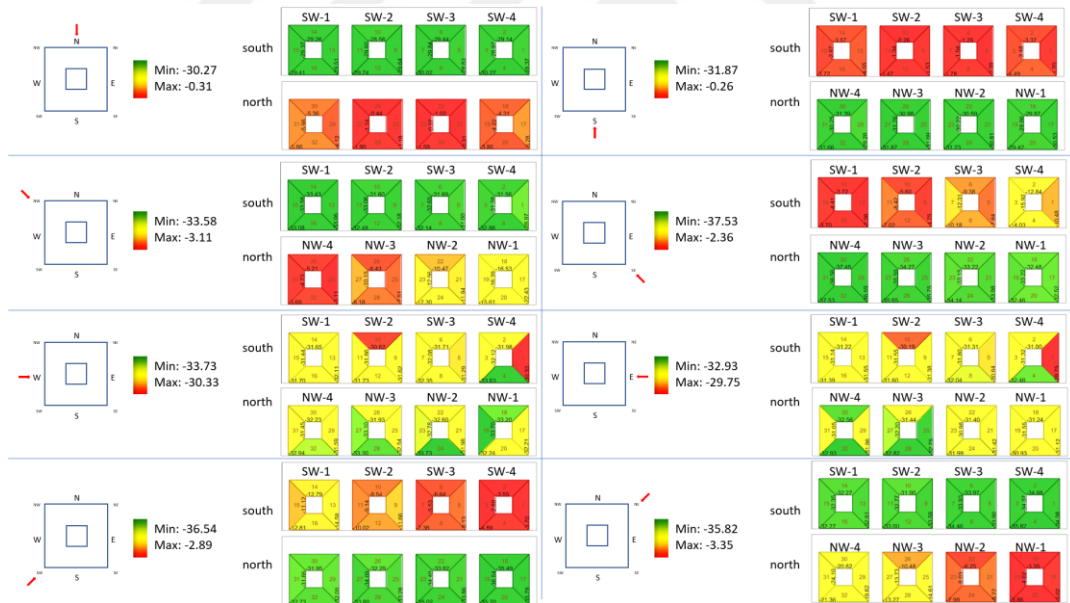


Figure C. 10 Façade Pressures for SC3

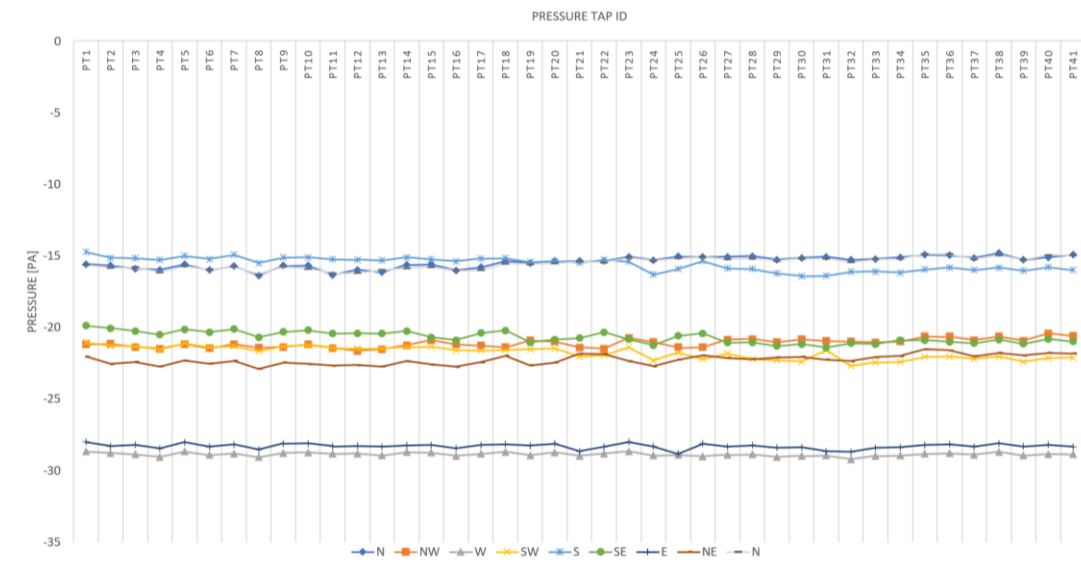


Figure C. 11 Pressure Distribution per Pressure Tap on Indoor Plane for SC3

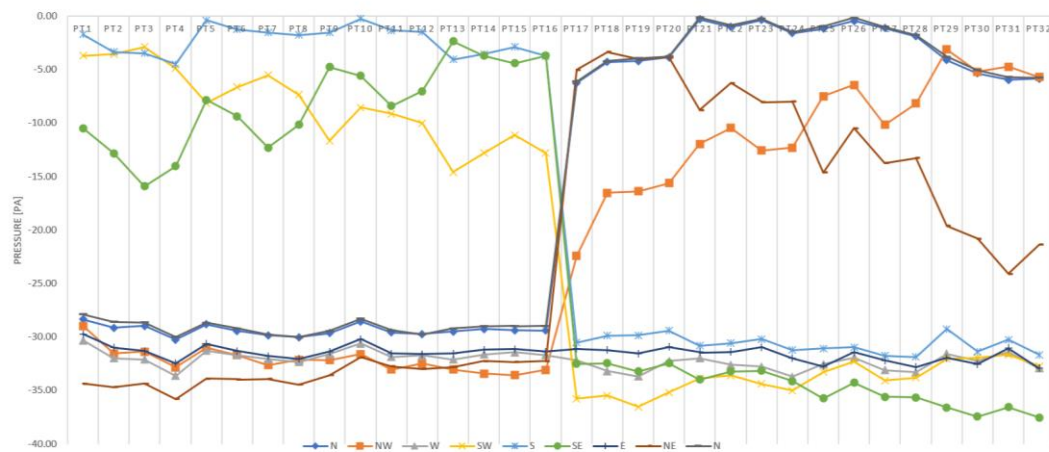


Figure C. 12 Pressure Distribution per Pressure Tap on Façades for SC3

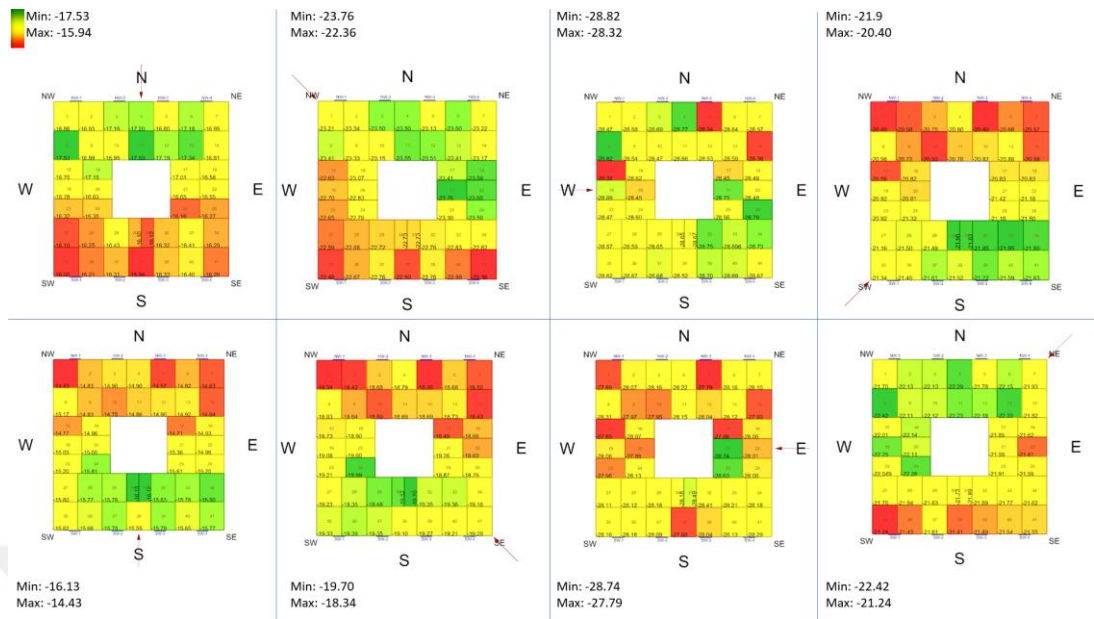


Figure C. 13 Indoor Pressures for SC4

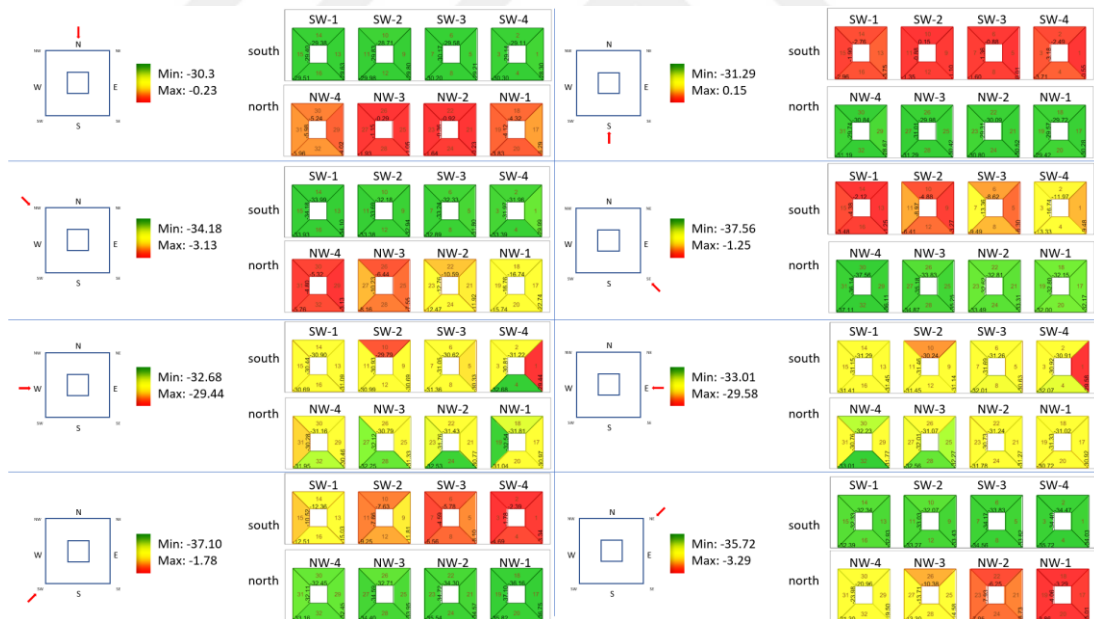


Figure C. 14 Façade Pressures for SC4

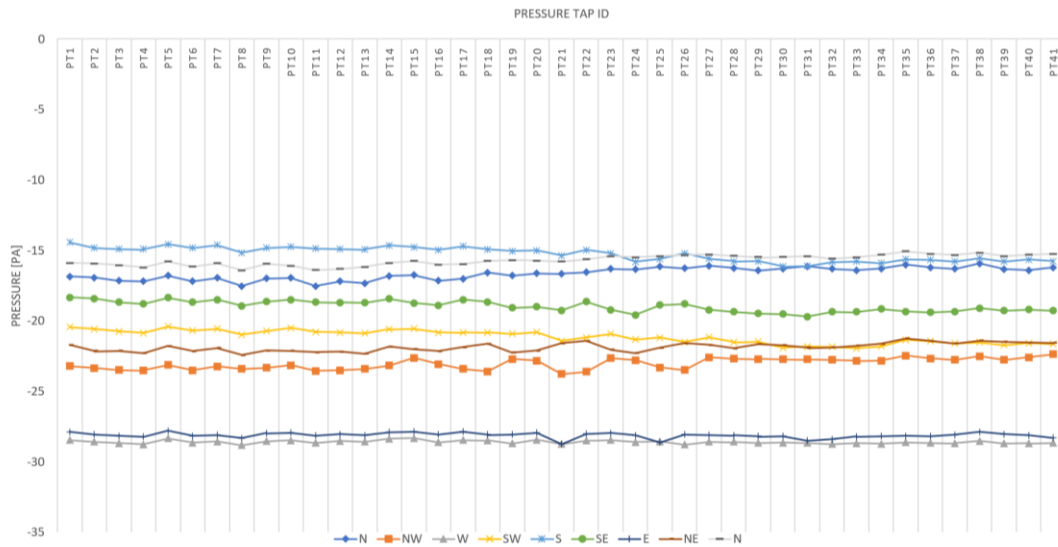


Figure C. 15 Pressure Distribution per Pressure Tap on Indoor Plane for SC4

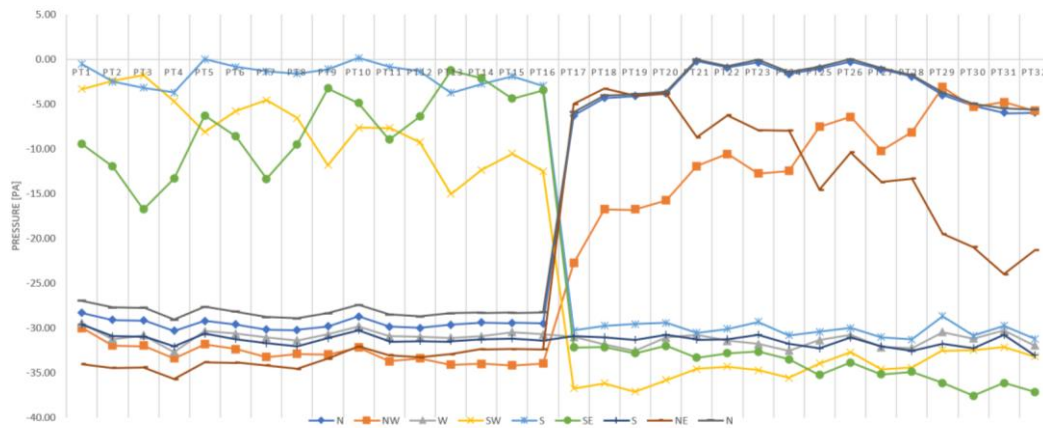


Figure C. 16 Pressure Distribution per Pressure Tap on Façades for SC4

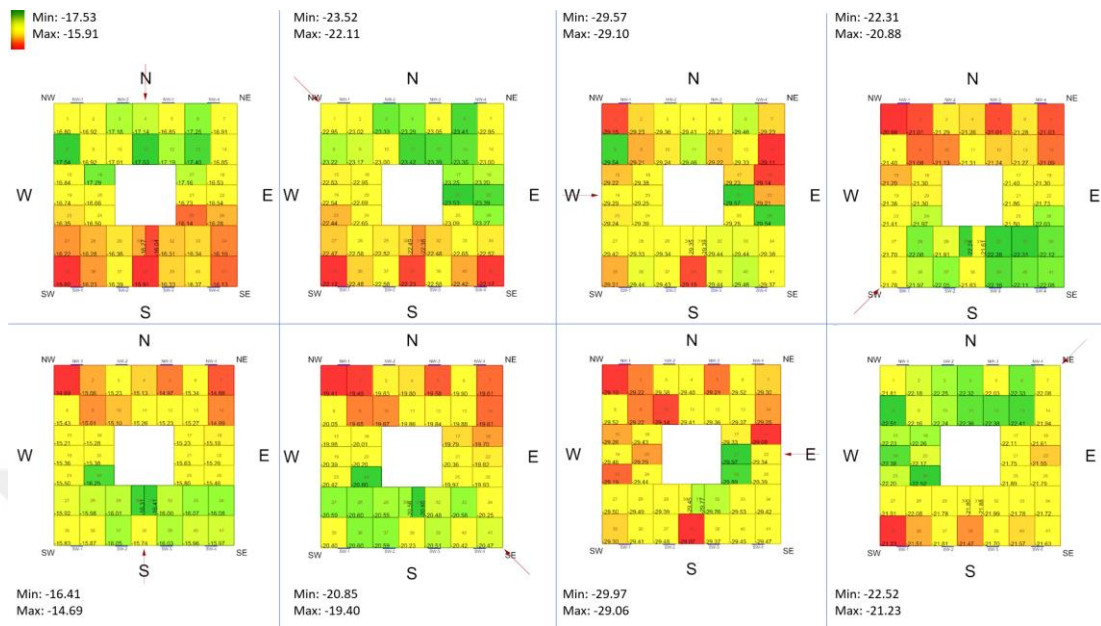


Figure C. 17 Indoor Pressures for SC5

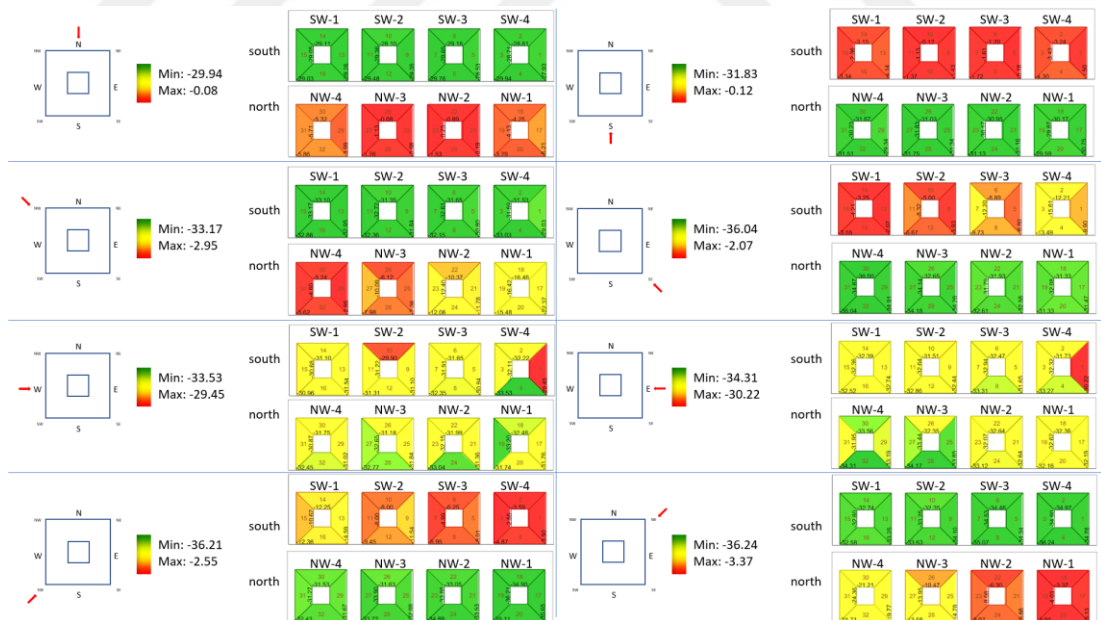


Figure C. 18 Façade Pressures for SC5

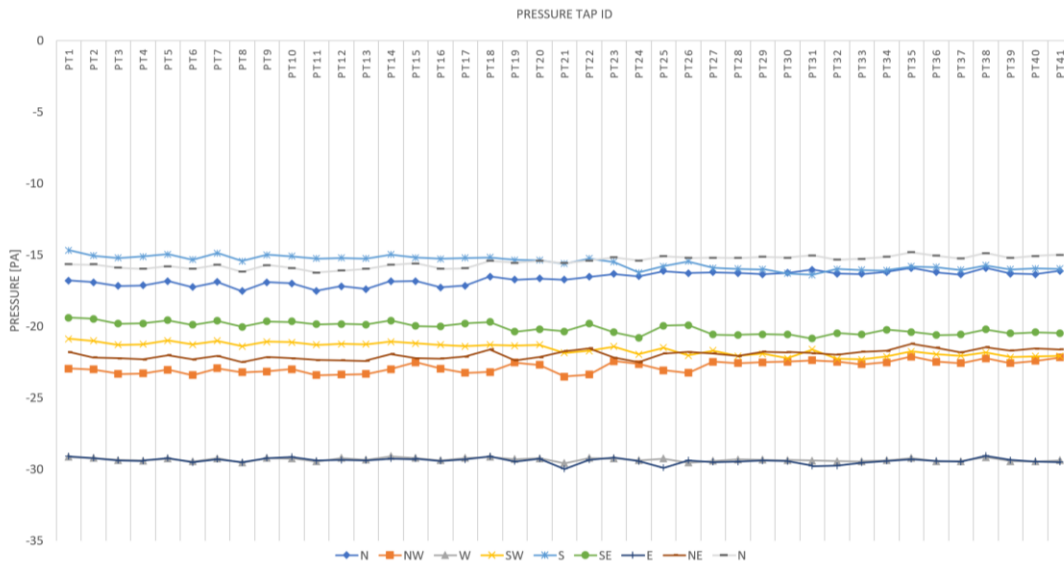


Figure C. 19 Pressure Distribution per Pressure Tap on Indoor Plane for SC5

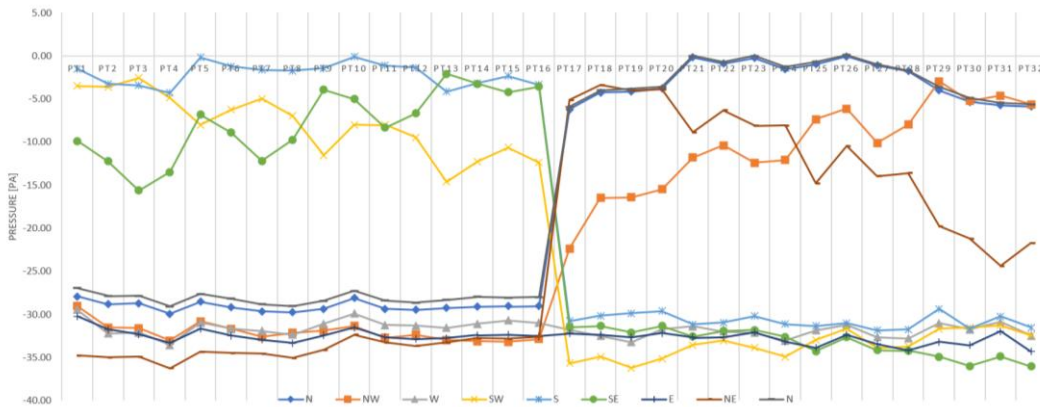


Figure C. 20 Pressure Distribution per Pressure Tap on Façades for SC5

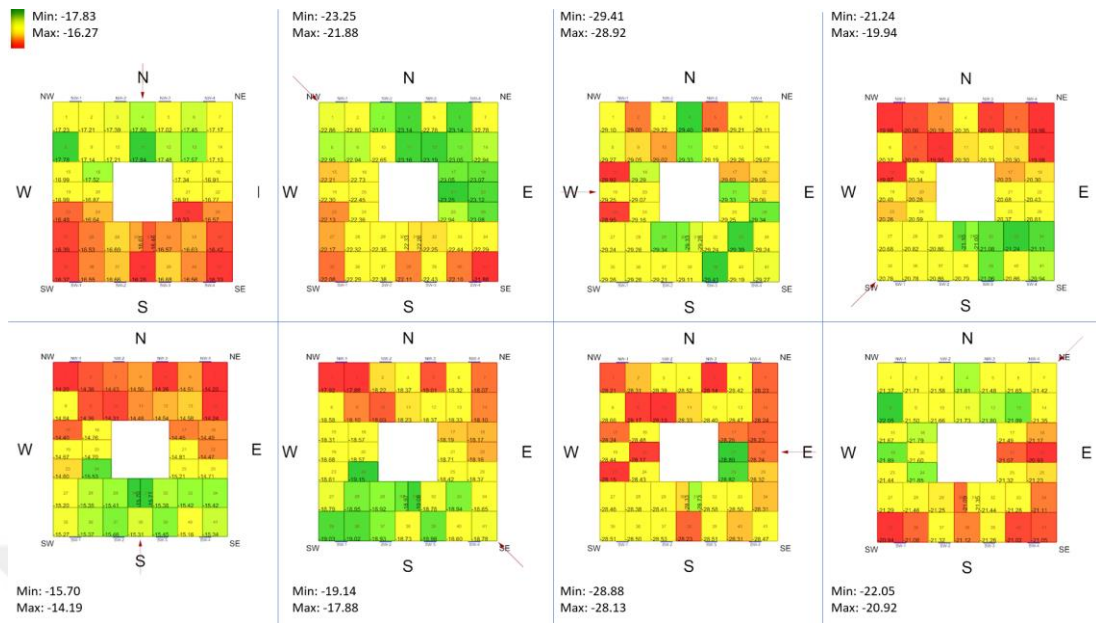


Figure C. 21 Indoor Pressures for SC6

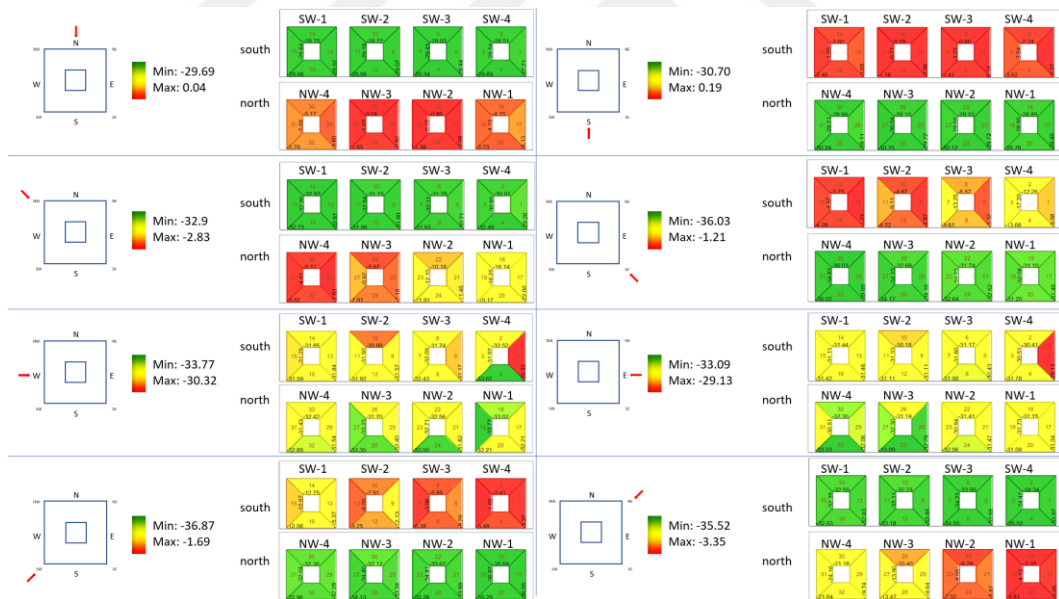


Figure C. 22 Façade Pressures for SC6

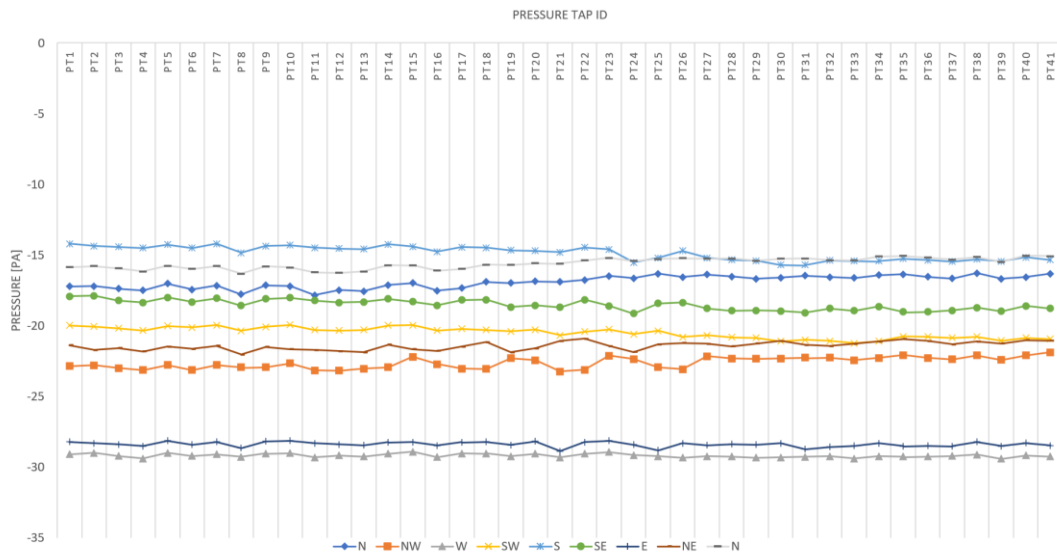


Figure C. 23 Pressure Distribution per Pressure Tap on Indoor Plane for SC6

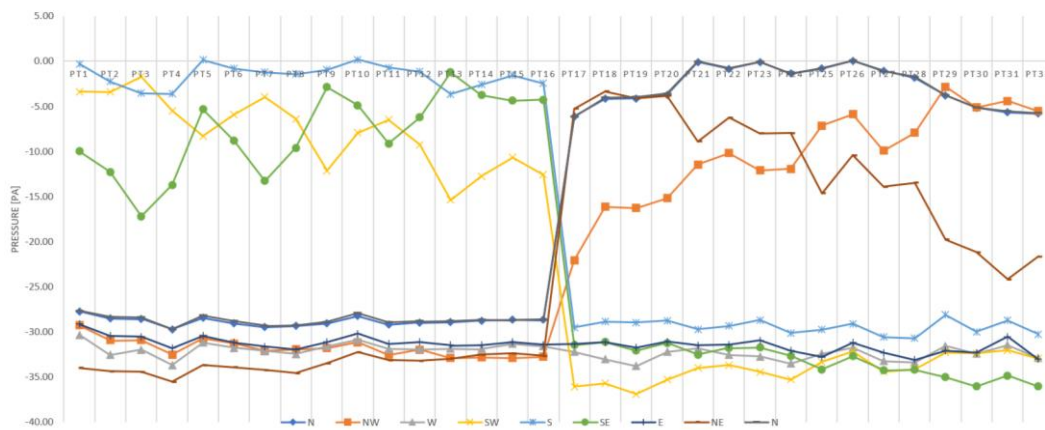


Figure C. 24 Pressure Distribution per Pressure Tap on Façades for SC6

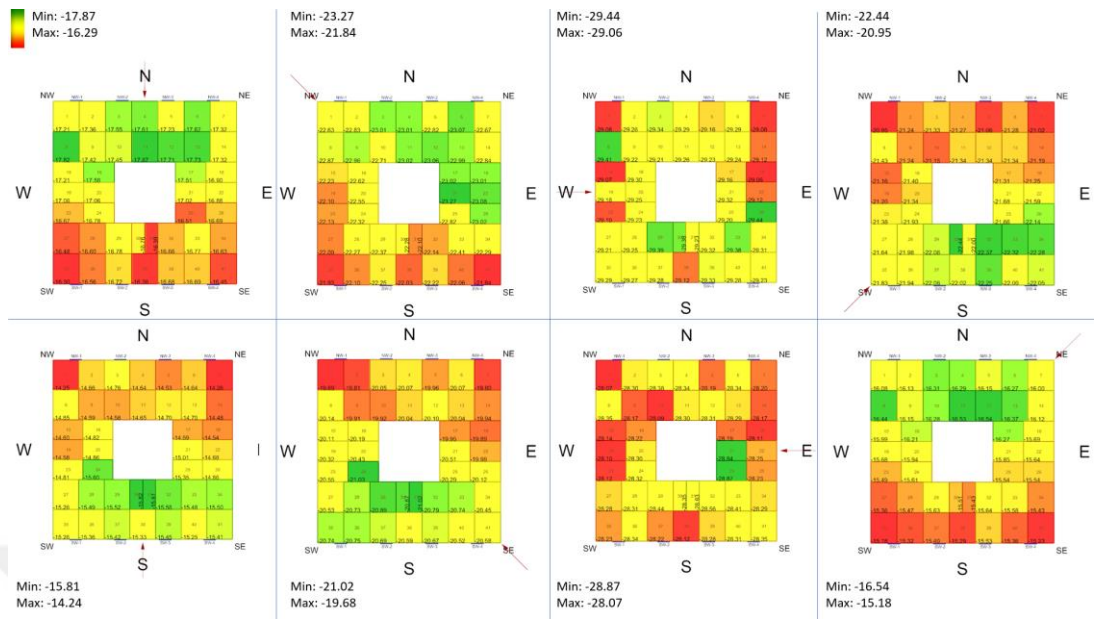


Figure C. 25 Indoor Pressures for SC7



Figure C. 26 Façade Pressures for SC7

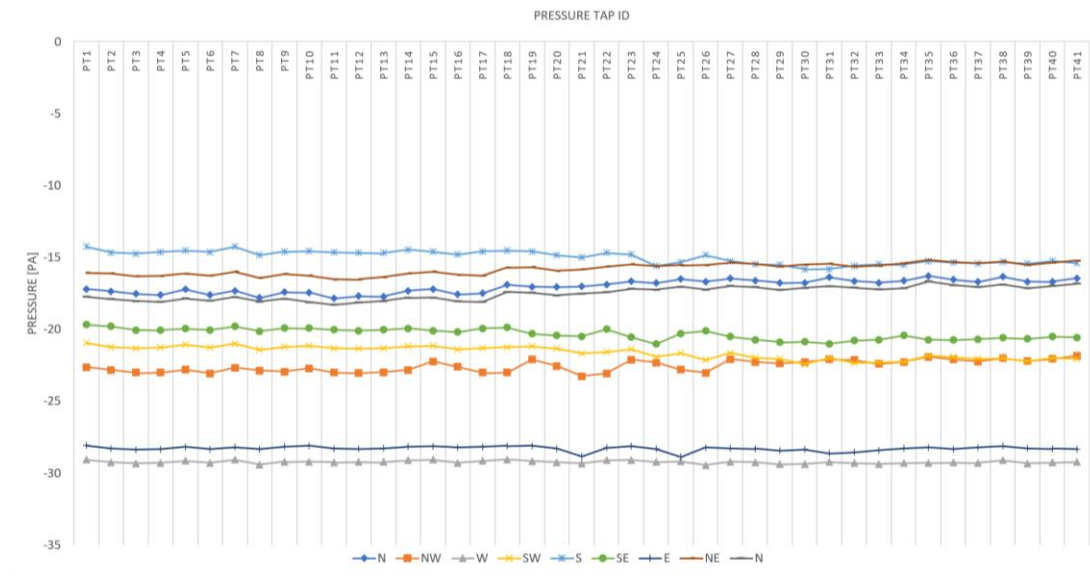


Figure C. 27 Pressure Distribution per Pressure Tap on Indoor Plane for SC7

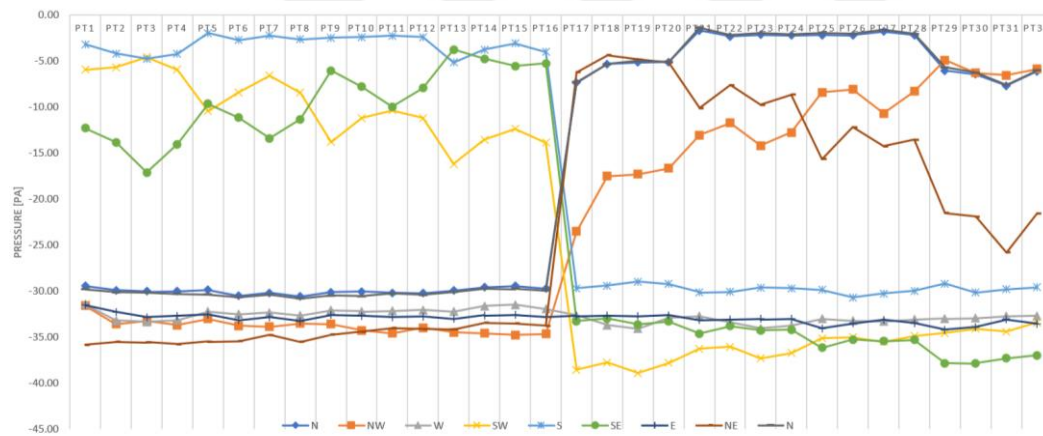


Figure C. 28 Pressure Distribution per Pressure Tap on Façades for SC7

D. Pressure Distributions for Wind Directions

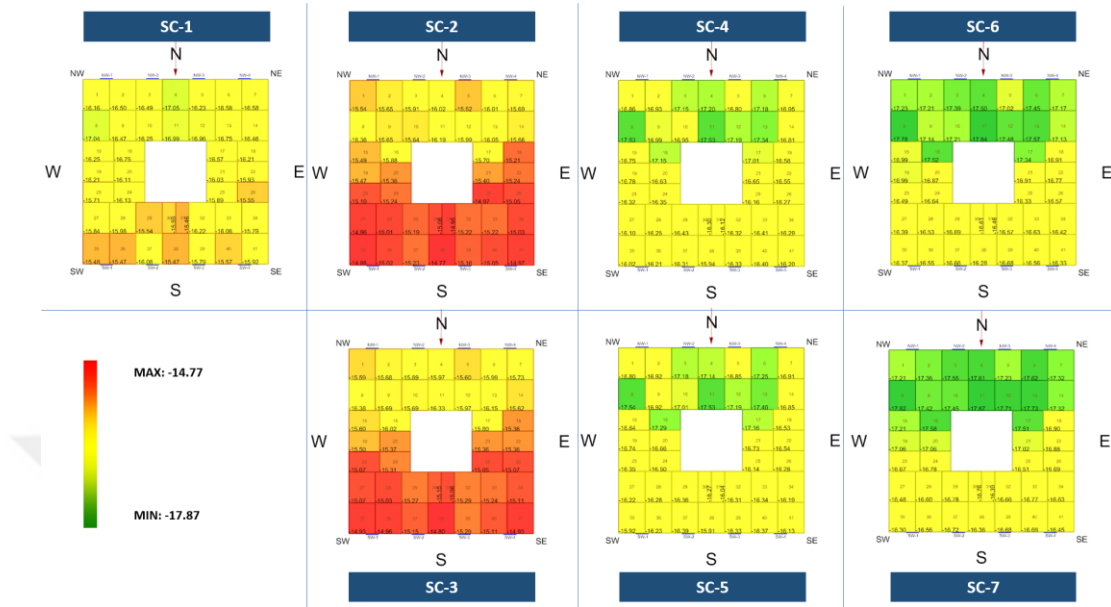


Figure D. 1 Indoor Pressures for Wind Direction 0°



Figure D. 2 Façade Pressures for Wind Direction 0°

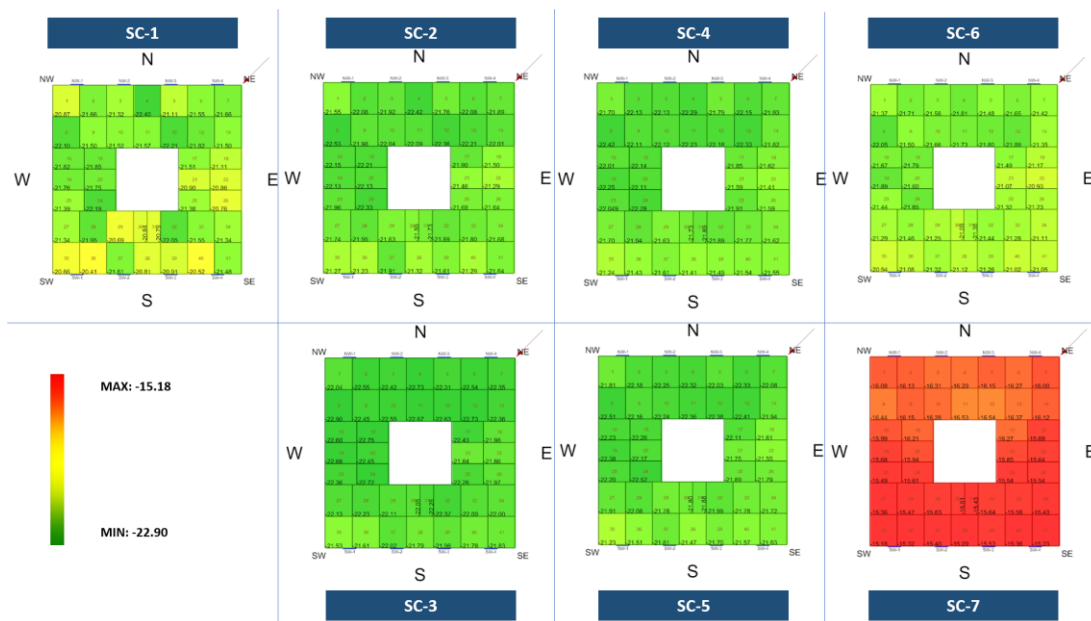


Figure D. 3 Indoor Pressures for Wind Direction 45°



Figure D. 4 Façade Pressures for Wind Direction 45°

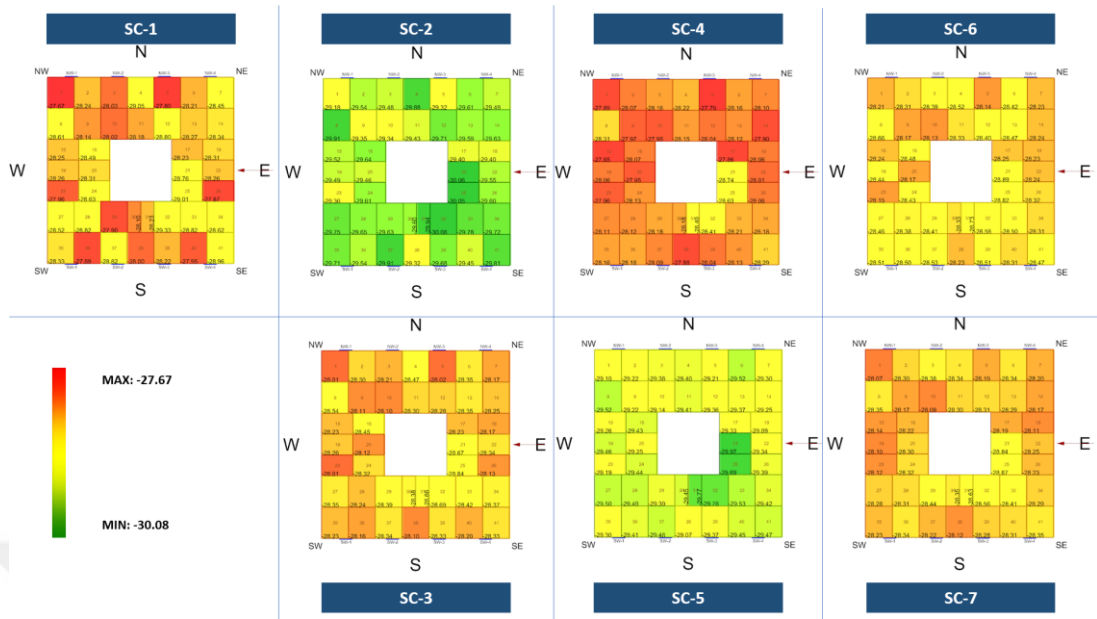


Figure D. 5 Indoor Pressures for Wind Direction 90°

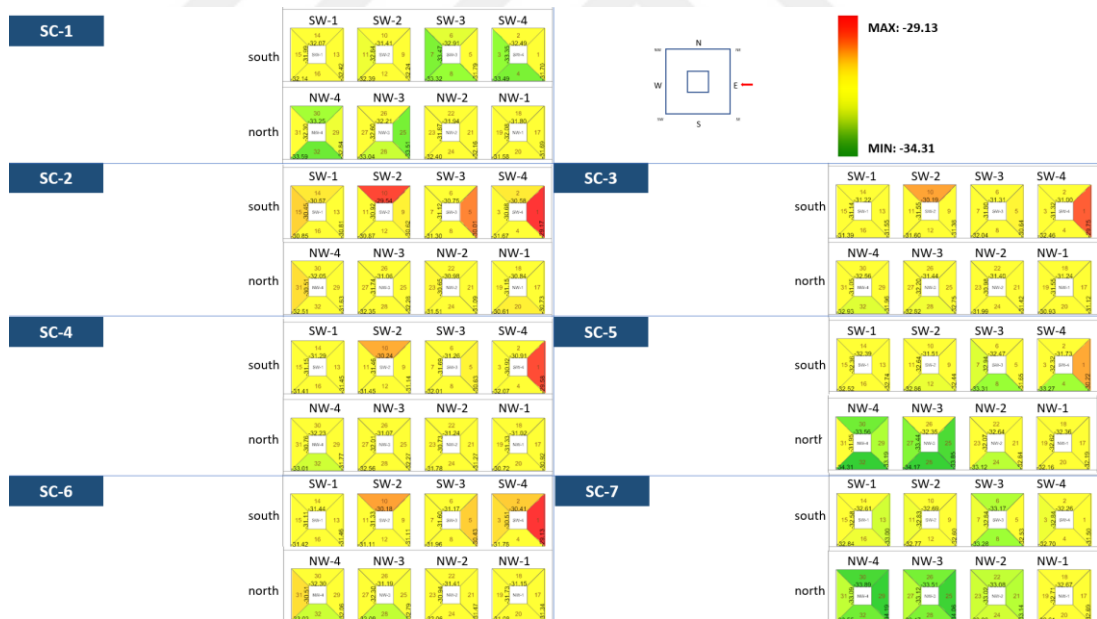


Figure D. 6 Façade Pressures for Wind Direction 90°

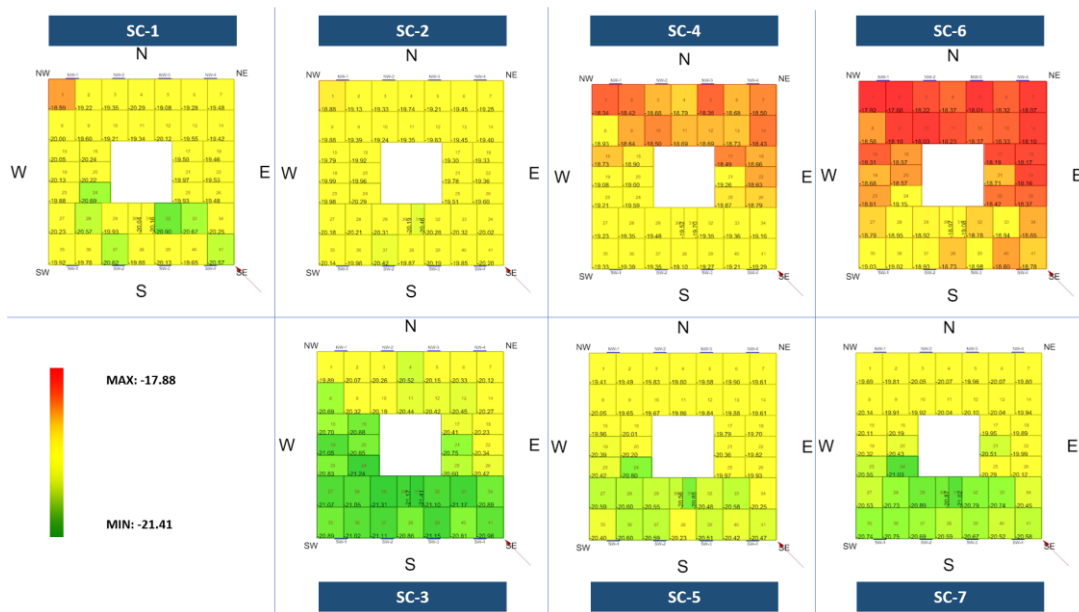


Figure D. 7 Indoor Pressures for Wind Direction 135°



Figure D. 8 Façade Pressures for Wind Direction 135°

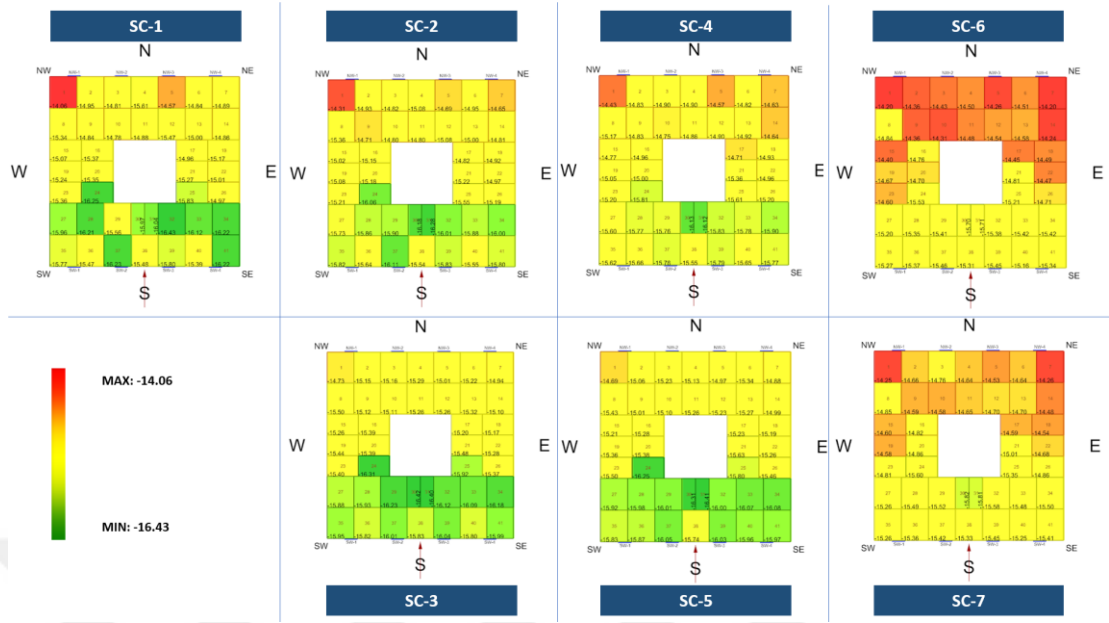


Figure D. 9 Indoor Pressures for Wind Direction 180°



Figure D. 10 Façade Pressures for Wind Direction 180°

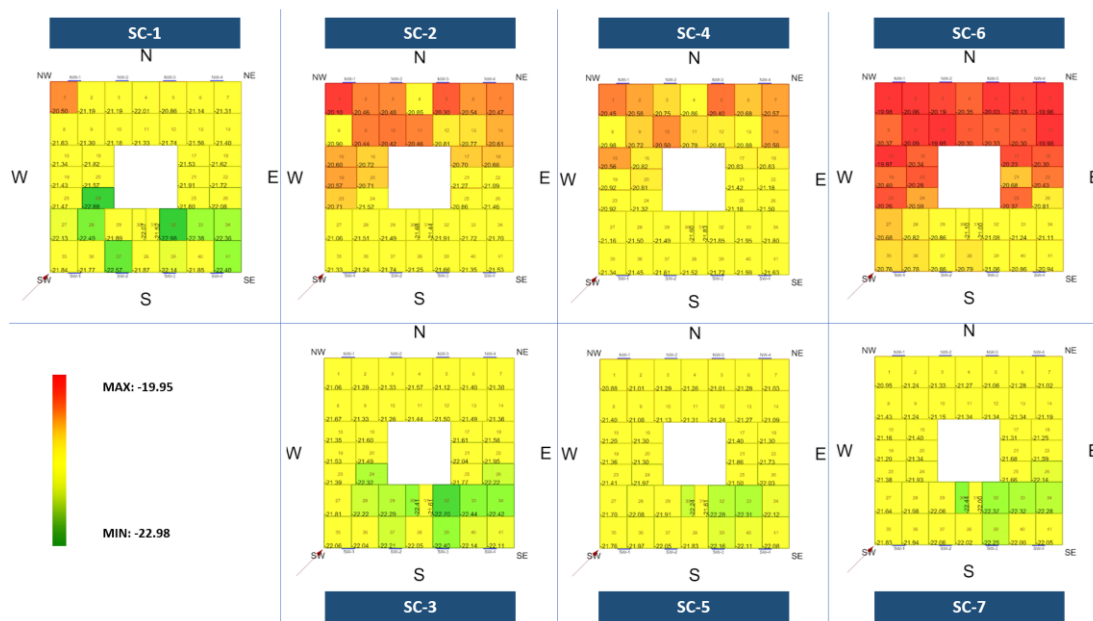


Figure D. 11 Indoor Pressures for Wind Direction 215°



Figure D. 12 Façade Pressures for Wind Direction 215°

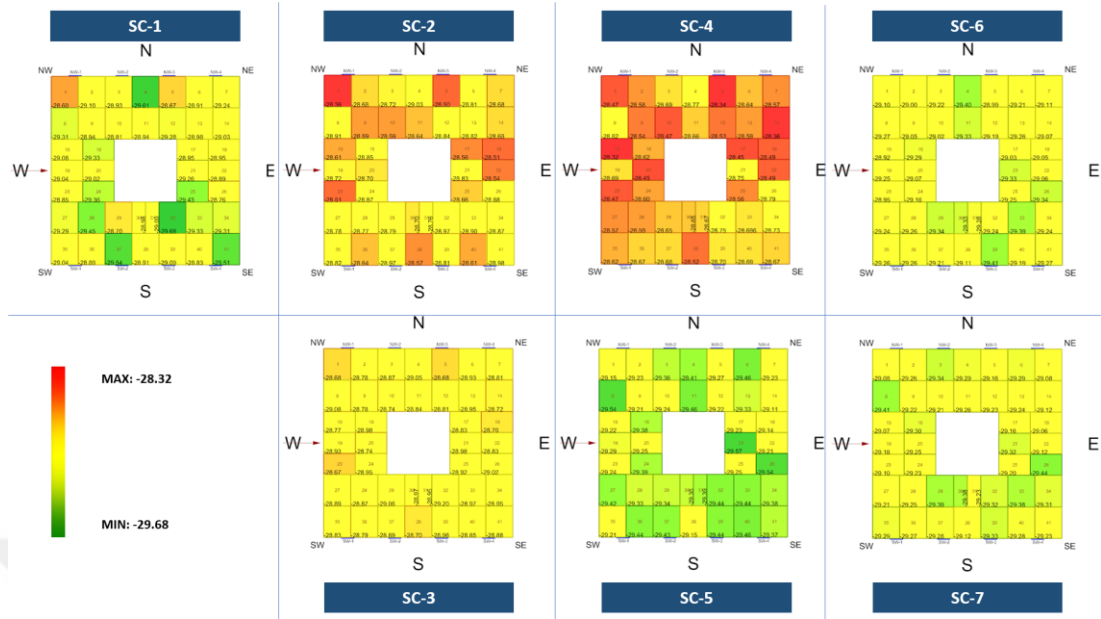


Figure D. 13 Indoor Pressures for Wind Direction 270°

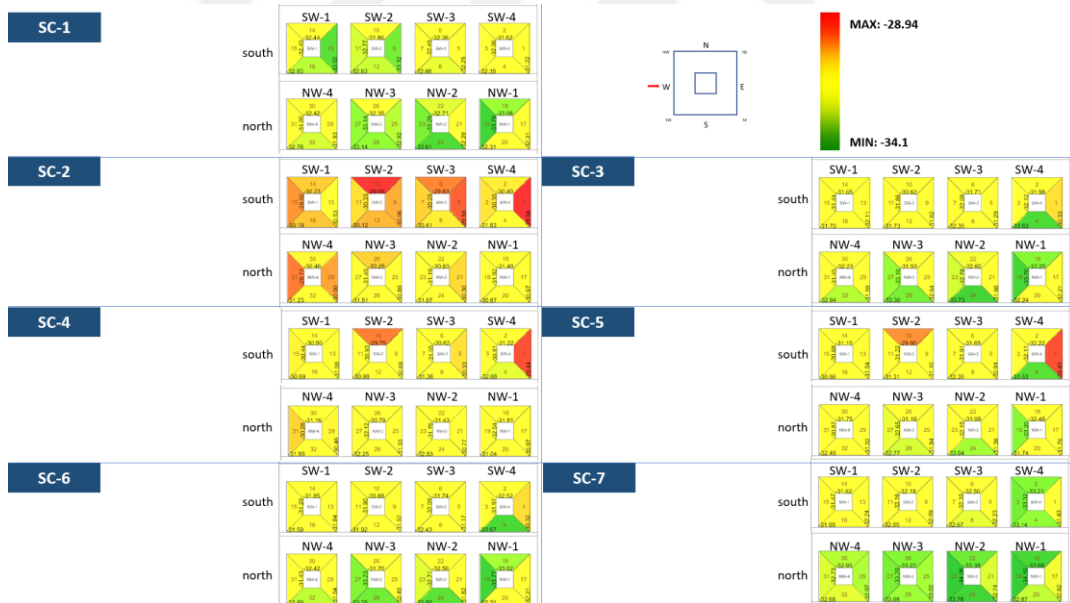


Figure D. 14 açade Pressures for Wind Direction 270°

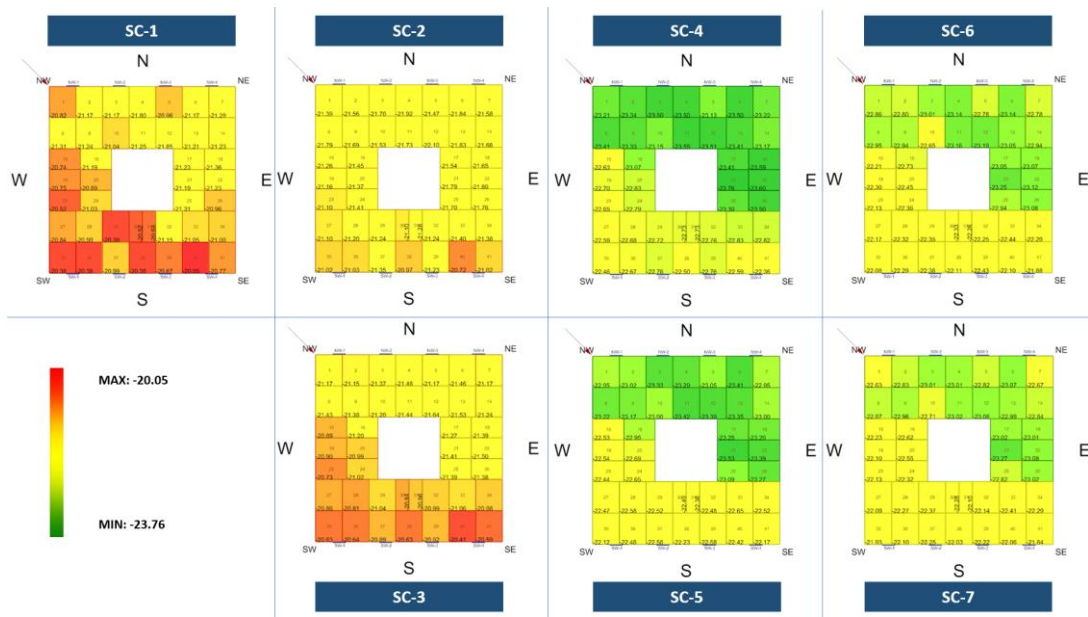


Figure D. 15 Indoor Pressures for Wind Direction 315°



Figure D. 16 Façade Pressures for Wind Direction 315°

E. Wind Tunnel-Integrated Contaminant Results

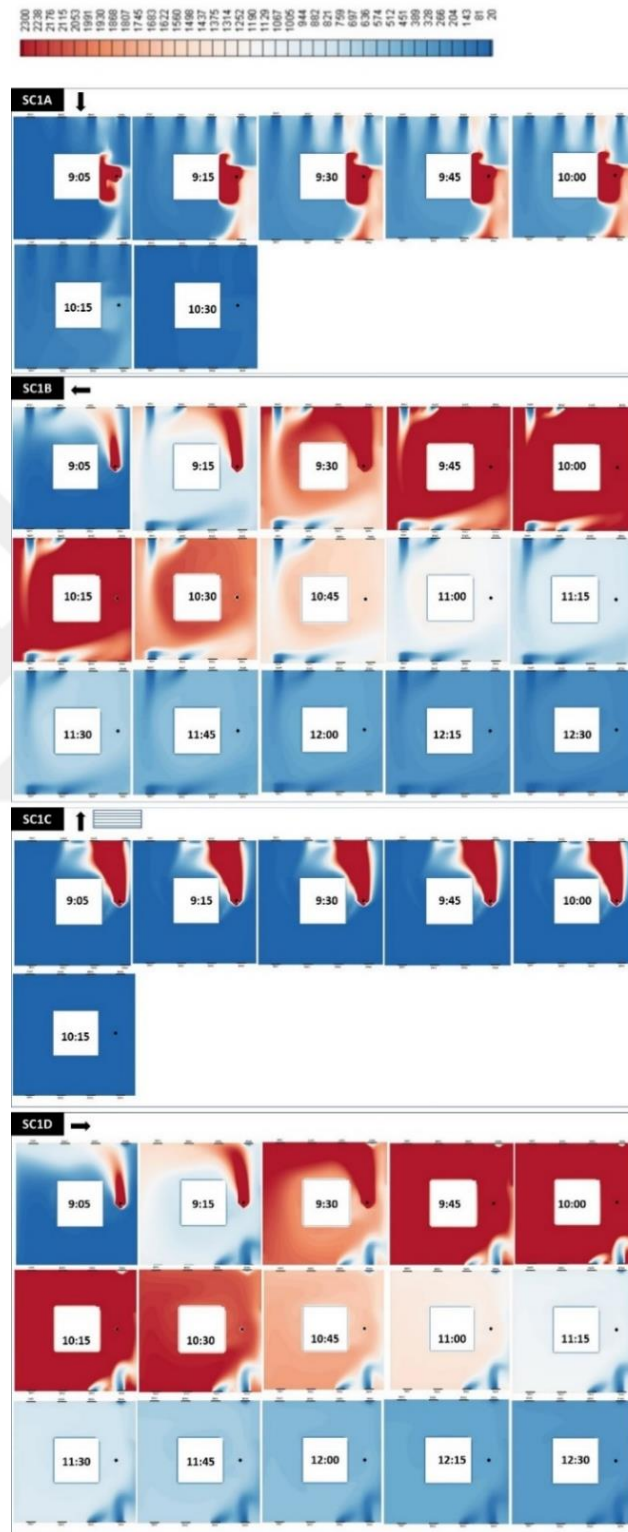


Figure E. 1 Indoor Air Contamination Behavior for SC1

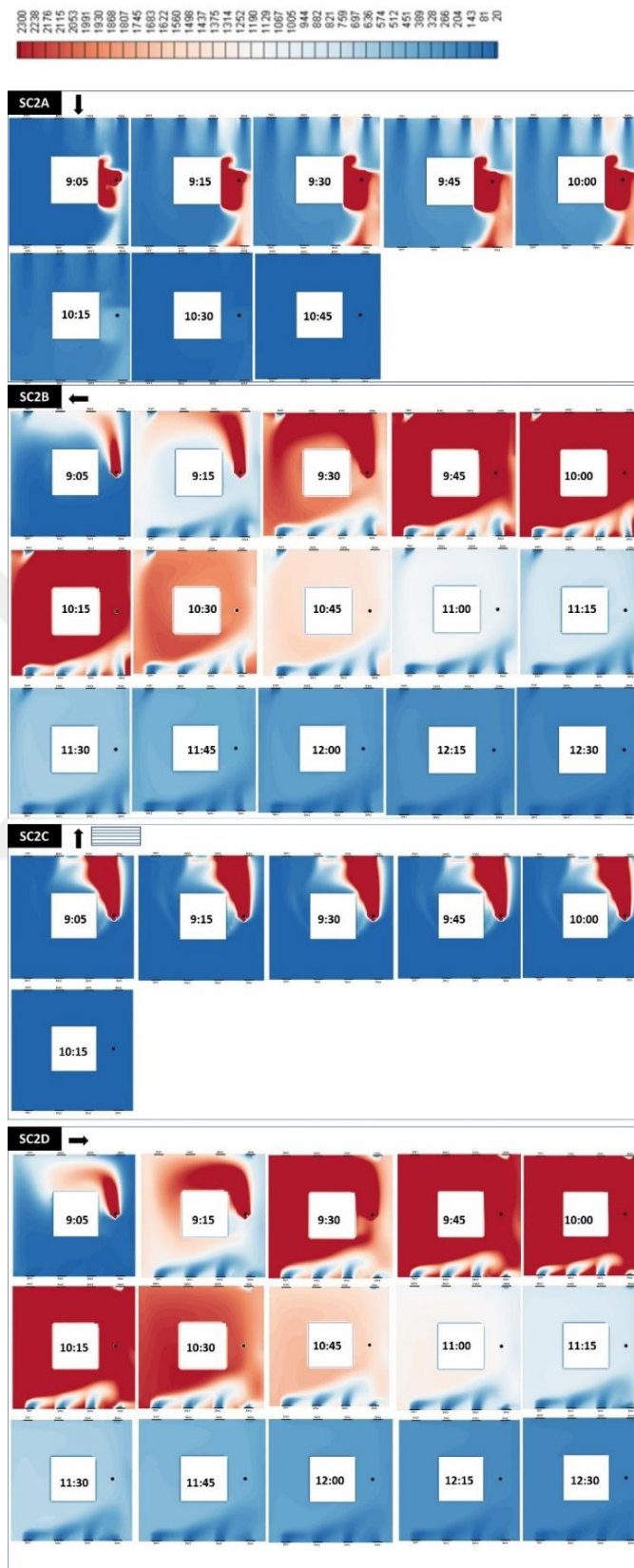


Figure E. 2 Indoor Air Contamination Behavior for SC2

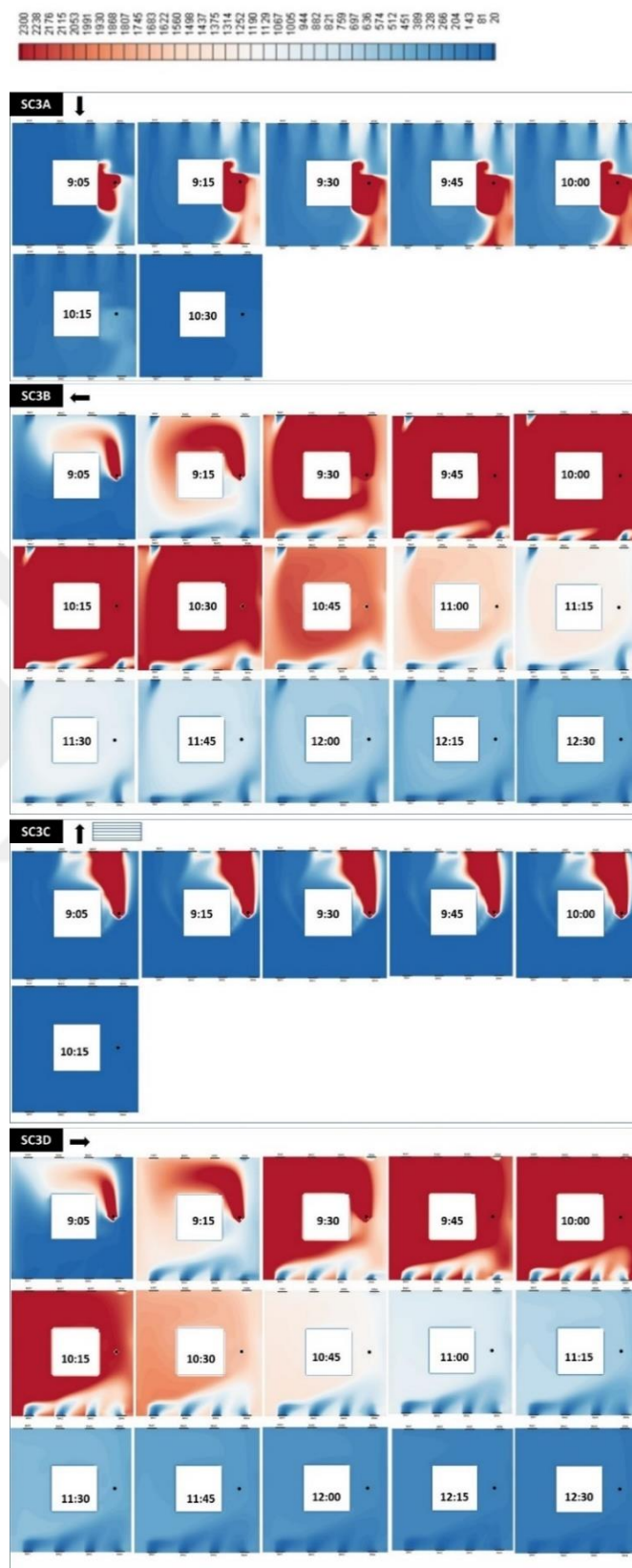


Figure E. 3 Indoor Air Contamination Behavior for SC3

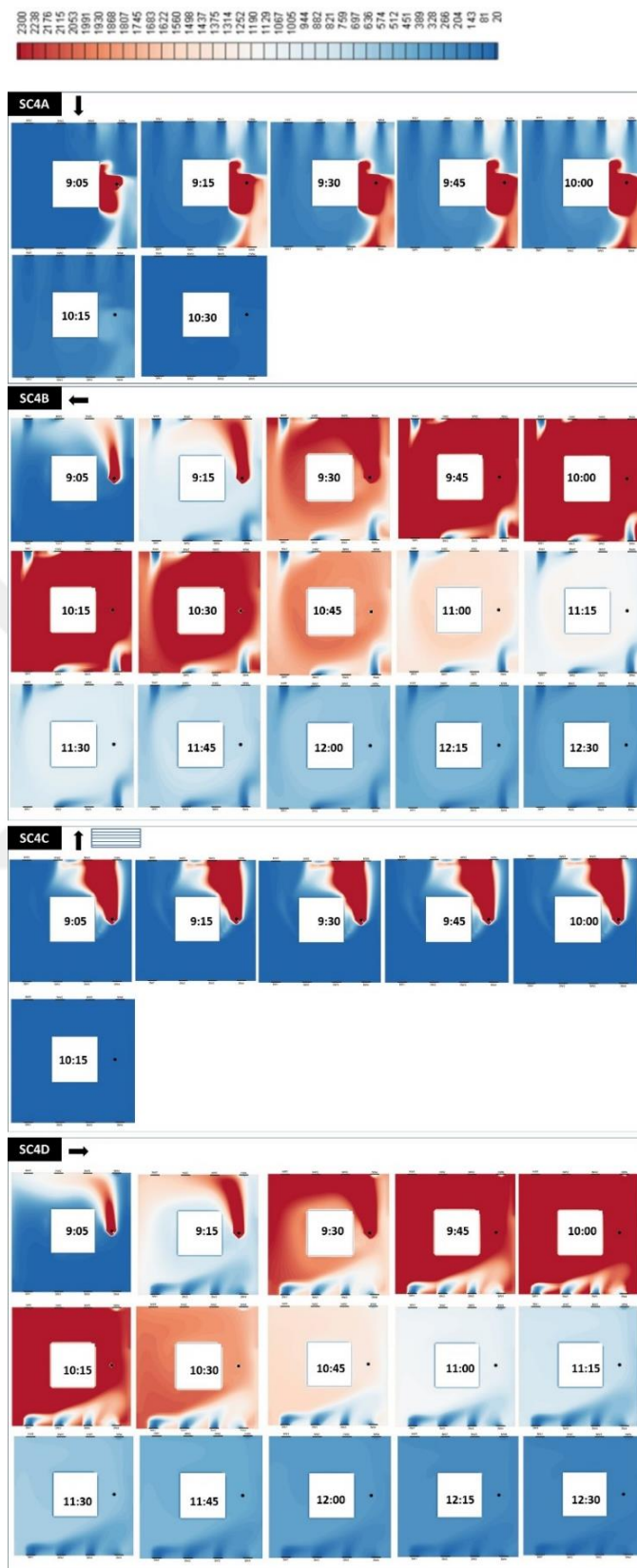


Figure E. 4 Indoor Air Contamination Behavior for SC4

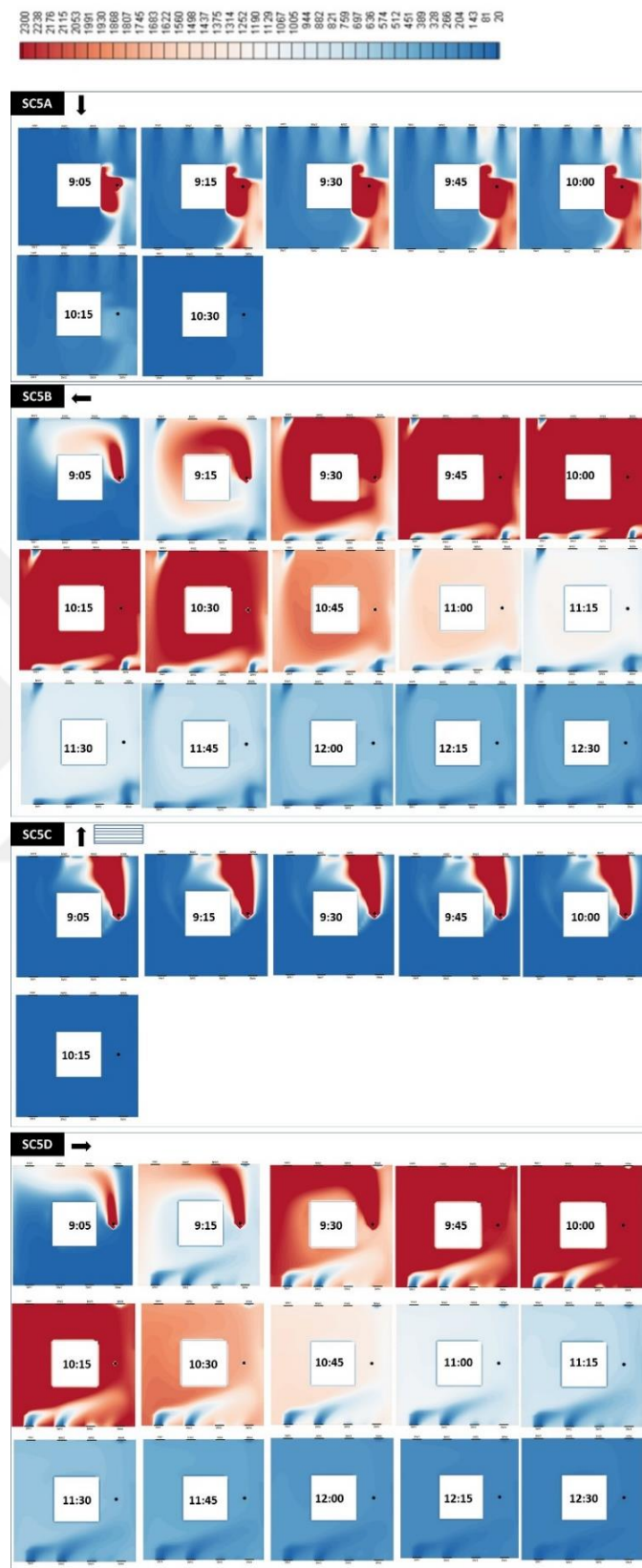


Figure E. 5 Indoor Air Contamination Behavior for SC5

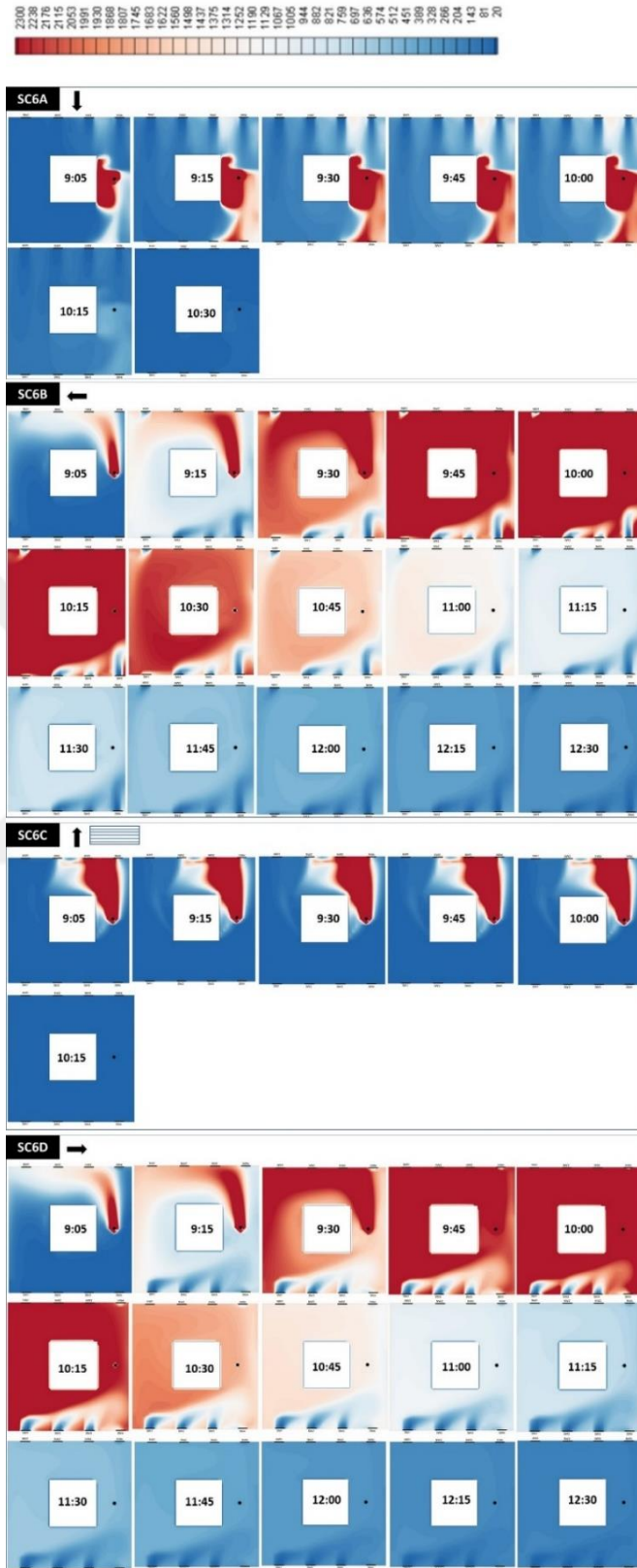


Figure E. 6 Indoor Air Contamination Behavior for SC6

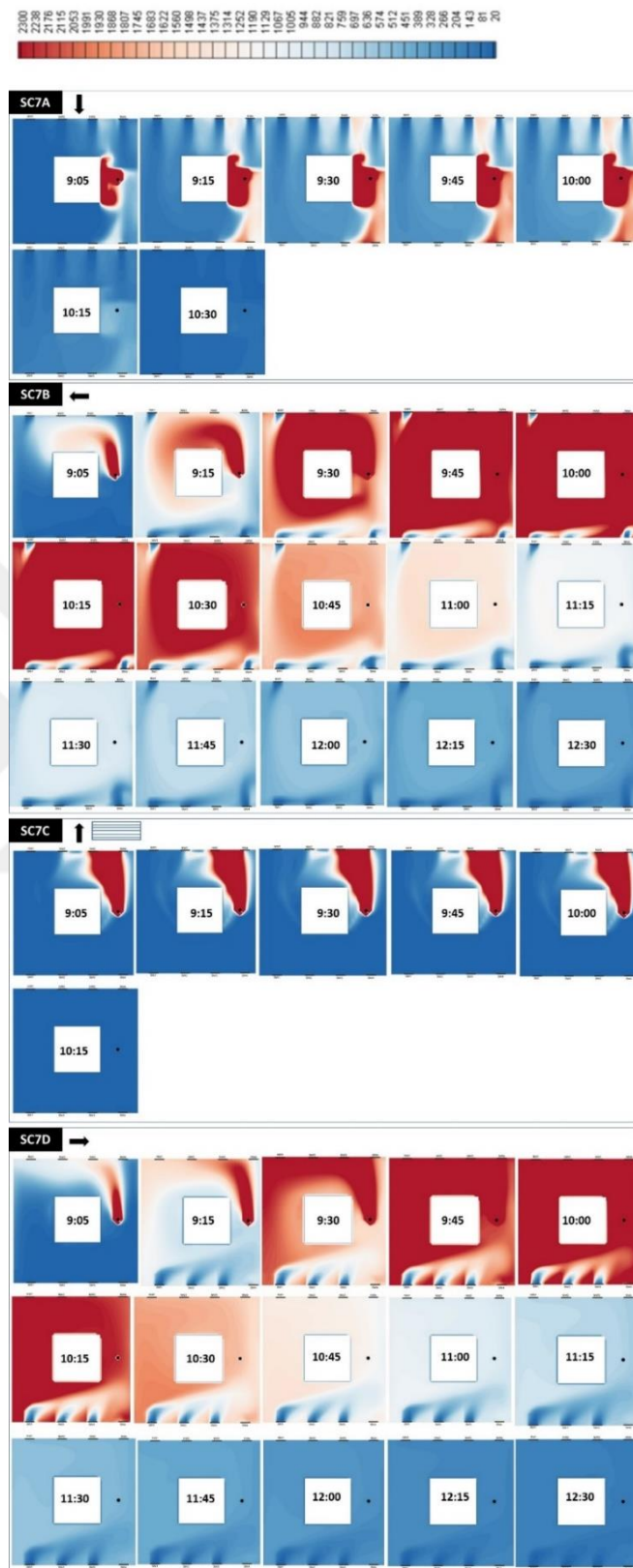


Figure E. 7 Indoor Air Contamination Behavior for SC7

F. Pipeline Specifications

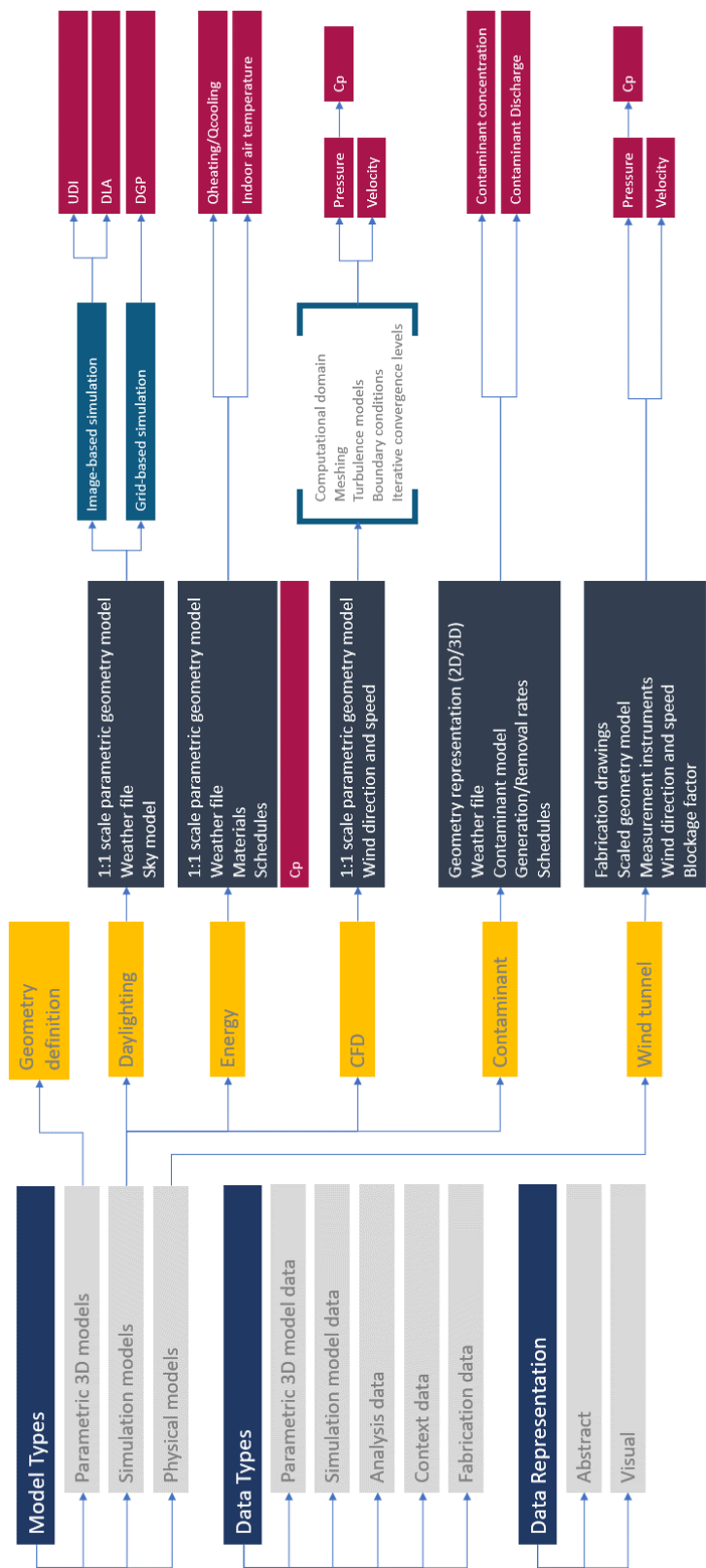


Figure F. 1 Pipeline Specifications

CURRICULUM VITAE

