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High-performance Building Envelope: an Energy Evaluation of Double-skin Facades Linked into the Earth

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HIGH-PERFORMANCE BUILDING ENVELOPE:

AN ENERGY EVALUATION OF DOUBLE-SKIN FACADES LINKED INTO THE EARTH

by

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ABSTRACT

HIGH-PERFORMANCE BUILDING ENVELOPE: AN ENERGY EVALUATION OF DOUBLE-SKIN FACADES LINKED INTO THE EARTH

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Good Architecture inclusively addresses all the matters that should and could be considered including but not limited to economic, social, or environmental dimensions. One might perceive ecological architecture in the same way; in reaching high-performance architecture regarding the “good,” wherein the integration of an ecological worldview should be recognized as a fundamental goal. In this domain, energy is surely a crucial concern. This dissertation’s focus is to examine ways to optimize the Load Intensity (LI) of buildings with a Double-Skin Facade (DSF) as an integrated, high-performance building envelope system. A high-performance design rooted in ecological architecture can diminish the built environments’ dependency on exhaustible energies. Instead of these, non-fossil energy sources such as sun, earth, wind and water could be employed to supply built environments’ necessities. It is, thus, critical to assimilate this approach into architectural design from early stages in order to create high-performance buildings that are formed as environmental systems rather than as standalone objects.

From social and environmental standpoints, DSFs are presumed as smart, high-performance solutions, which can improve the quality of both indoor and outdoor surroundings. Yet, DSFs’ economic performance is debated. Specifically, a DSFs’ goal to minimize building energy use in different climatic conditions is controversial, presenting it occasionally as not the most economically viable solution. In this dissertation, it is hypothesized that by linking a DSF into the earth, as the second major natural resource, the building’s energy demands would be reduced, and as result its economic performance will be also improved. This hypothesis is examined by designing a system that combines a naturally-ventilated DSF, inspired by the vernacular architectural concept of Persian wind-catchers, with the idea of “geothermal” implementing Earth-Tubes systems, inspired by the concept of Roman hypocausts. To conduct the inquiry, a simulation method is applied that employs both TRNSYS and CANTAM softwares to model and explore energy performance of potential proposed systems.

TABLE OF CONTENTS

LIST OF FIGURES

Chapter I

Chapter II

Chapter III

Chapter IV

Chapter V

Chapter VI

LIST OF TABLES

LIST OF ABBREVIATIONS

- AIVC: Air Infiltration and Ventilation Centre
- ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers
- BRI: Building-Related Illness
- Btu: British thermal units
- CFD: Computational Fluid Dynamic
- DSF: Double-Skin Façade
- EUI: Energy Utilization Intensity/Energy Use Intensity
- HVAC: Heating, Ventilation, and Air-Conditioning
- IAQ: Indoor Air Quality
- LI: Load Intensity, which is related to energy required for heating, cooling, dehumidification, and humidification
- NPL: Neutral Pressure Level
- PR: Performance Requirement
- RLF: Residential Load Factor
- SBS: Sick Building Syndrome
- SI: International System of Units
- TRNSYS: Transient Systems Simulation Program
- WHO: World Health Organization

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PREFACE

Poetics Pursues Performance

In its essence, architecture is after the creation of "good." Yet, what is or to be perceived as "good" in architecture is rather subjective with different connotations from the standpoints of various parties and stakeholders: a user, an architect, or an environmentalist, for instance. Vernacular, modern, or ecological architecture each seems to be the indirect result of distinctive definitions of the "good" by the cited audience respectively, which is also evolved over the course of centuries. From the standpoint of a user, for instance, good architecture might be assessed by its intended functions such as physical, cultural, social, or psychological aspects of a built environment. From the standpoint of an architect, as Antoniades (1992) points out, "good" or "virtuous" could be the "attitude that will generate works whose being depends on the resolution of all the parameters that affect it, be they internal, external, conceptual, technical, and of a detailed or general nature (p. 4)."[1] From the standpoint of an environmentalist, as Orr (2002) argues, to build a better world that is sustained ecologically while sustaining us spiritually, we should obtain a viewpoint that links valuable achievement of civilization with a broader view of our place in the universe. That is, "that philosophy must connect us to life, to each other, and to generations to come (p. 4)." Ironically, this viewpoint may lead to a point that even discourages any change towards the nature for sake of "good," questioning what an architect may propose itself as a design solution.[2]

Good architecture, I argue, should inclusively address all issues essential to be considered from diverse viewpoints and/or disciplines. That is, to include all concerns in achieving design components that not only are good themselves, but also contribute to the creation of good as a whole. That is, an integrated solution derived from a juxtaposition of multidimensional sub-systems shaping architecture into an autonomously complete, well-functioning "system."[3] My philosophy towards architectural design, thus, is a holistic approach that can bring to fruition what Antoniades has defined expressively as an "*inclusivist architectural poetics*."[4]

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[1] Anthony C. Antoniades, (1990). *Poetics of Architecture: Theory of Design.* Van Nostrand Reinhold Company.
[2] David W. Orr (2002). *The Nature of Design: Ecology, Culture, and Human Intention*. Oxford University Press.
Orr (2002) cites that: "In Wendell Berry's felicitous phrase, good design "solves for pattern," thereby preserving the larger patterns of place and culture and sometimes this means doing nothing at all (1981, 134-145)." (p. 28).
[3] Richard L. Crowther (1992). *Ecologic Architecture*. Butterworth-Heinemann.
Crowther (1992) emphasizes that "in ecology the architecture becomes the system," adding that "the holistic integration of systems is critical to ecological architecture." (p. 40).
[4] In Antoniades' (1992) terms, "inclusivity means the attitude of exploring ideas and the "making" of a work through many more points of contemplation (not only functional, not only formal, not only spiritual, not only as part of a historical/traditional or contemporary milieu) than the

As one who perceives architecture through the lens of sustainability and who, therefore, is interested in high-performance design, I see essential to elaborate on my perception of sustainability. In general, sustainability can have a broad spectrum of definitions, but it has been most simply defined as the conservation of the capacities and resources of the environment for future generations. A more established delineation of sustainability can be extracted from Brundtland's Report of 1987: "meeting the needs of the present without compromising the ability of future generation to meet their own needs."[5] This definition, however, is missing the other complimentary aspects of sustainability. Known with "three pillars," sustainability embraces the three realms of environment, economy, and society, thus, comes to existence where all issues associated with these three are overlapping.[6] From an ecological standpoint, sustainability could also be declared as those important things that one can relearn about "the arts of longevity" from other previous cultures and societies.[7]

Simon Guy and Graham Farmer (2001) have recognized a broader explanation by identifying six competing logics for sustainability: Eco-centric, Eco-cultural, Eco-aesthetic, Eco-technic, Eco-medical, and Eco-social.[8] These, in brief, are consecutively defined as: harmony with nature and the least footprint, locally vernacular low-tech strategies, globally reconstructed in a pragmatic and iconic manner, intelligent and energy efficient high-tech technology, naturally improved life quality, and reunion of individual and community through participation. One may legitimately argue whether focusing on any, some, or more of these logics is a necessary and sufficient condition in reaching sustainability. The elaboration on my grasp of sustainability and interpretation of its various dimensions benefit the addressing of major grounds and premises of this inquiry.

My approach towards sustainability is a proximate reflection of Antoniades' (1992) "inclusivist" method of architectural design, as stated earlier. I view this linkage as a major reason why, I argue, architecture and sustainability should not be deliberated as being distinct. Susan Maxman (1993) refers to sustainable

limited or one-sided ones of the past. In this sense the poetics of architectural inclusivity is the making of architecture through a process of genesis (creativity) in which the aesthetic argument addresses a greater range of potential aesthetic constants, while at the same time operating on totally nondoctrinaire grounds while giving the benefit of the doubt to and exploring the advantages and disadvantages of the various creative possibilities and aesthetic systems (p. 5)." To him, "poetics has been tackled thus far as "the making" of art through the thoughtful, contemplative path of what is "good," or what would be the promises or subtle differences between the various possible ways of making, with regard to the "good." (p. 3)"

[5] Brundtland, G. H. (1987). Report of the World Commission on Environment and Development:" Our Common Future." United Nations.

[6] Adams, W. M. (2006). The Future of Sustainability: Re-thinking Environment and Development in the Twenty-first Century, Report of the IUCN Renowned Thinkers Meeting, January 2006. Retrieved from: *http://cmsdata. iucn. org/downloads/iucn_future_of_sustanability. pdf*. Date Accessed: February 16, 2009.

[7] The Nature of Design: Ecology, Culture, and Human Intention by David W. Orr (2002 p. 11)

[8] Simon Guy and Graham Farmer (2001). Reinterpreting Sustainable Architecture: The Place of Technology. *Journal of Architectural Education*, *54*(3), 140-148.

architecture as "… an approach, an attitude. It shouldn't really even have a label. It should just be architecture."[9] My approach, after all, is not merely restricted to any one of the greater realms: of environment, economy, and society. Yet, it is an "integrated" one. In fact, sustainability should adopt a comprehensive worldview in order to be able to virtuously inform the decision-making process of architectural poetics as a whole. This approach must encompass and integrate all such dimensions, along with other potential aspects not cited, from the different standpoints of diverse beneficiary parties. If looked at from this perspective, sustainability forms not a new realm distinct from architecture, but "a general raising awareness of all the issues that can be considered (Cook and Golton, 1994, p. 684)."[10] To me, *sustainability itself is the poetics of architecture*.

Ensuing the statement above is an analysis of the architectural design process and creation of forms. Most primitive architectural creations in history had, in their processes, largely dealt with the issue of basic function, as primitive societies were mainly in search for simple shelters to help them overcome extreme contextual conditions. Later on, the notion of aesthetics was further considered, to also create more visually-appealing places. A manifestation of this was the paintings or carved remnants discovered on the walls of ancient dwellings. In addition, philosophical and epistemological transformations originally explored by Greeks were also among the influential aspects related to the poetics of Western architectural theory (Gelernter, 1995, p. 45).[11] Gradually, Giacomo Barozzi da Vignola's (1562) "The Five Orders of Architecture," *Tuscan, Doric, Ionic, Corinthian,* and *Composite*, became the larger influential foundation in Western cultures, seen as a common language of form.[12] In chorus, principles of abstract visual form such as *proportion*, *scale*, *rhythm*, *contrast*, *color*, and *hierarchy* also became other progressive values seen as universally applicable in the process of architectural form creations. In following periods, architectural design slowly became more context-responsive to particularly address further aspects of social, cultural, economic, and climatic conditions, while viewing earlier typical vernacular architectural solutions invaluable. Moving towards the 20th century and modern era, efficiency factors such as economy and time became more critical, conceiving a framework of the design process where architectural form was realized as a machine following its function.[13]

[9] Susan Maxman (1993). Shaking the Rafters. *Earthwatch*, *11*.
[10] Sara J. Cook & Bryn L. Golton (1994). Sustainable Development Concepts and Practice in the Built Environment—A UK perspective. *CIB TG*, 16, 6-9.
[11] Mark Gelernter (1995). *Sources of Architectural Form: A Critical History of Western Design Theory*. Manchester University Press.
[12] Giacomo Barozzi da Vignola, J. Leeke, & D. Watkin (2011). *Canon of The Five Orders of Architecture*. Courier Corporation.
[13] In 1896, American architect Louis Sullivan had coined the phrase "form follows function" in an article called: "The Tall Office Building Artistically Considered." In 1923, Le Corbusier published Toward a New Architecture, which includes the famous Le Corbusier's statements: "a house is a machine for living in" or "a curved street is a donkey track; a straight street, a road for men."

One may also view the architectural form and making process from another angle. From the time of Vitruvius and Gropius until now, at every period in the architectural practice, the process of good design and how form would be generated has been an influence of the time's concurrent epistemological and theoretical frameworks within the realms of *knowledge*, *design*, and *education*. According to Mark Gelernter (1995), the source of architectural form in its history has to some extents been shaped by five basic ideas: "intended function," "creative imagination," "the prevailing sprit of the age," "the prevailing social and economic conditions," and "universal principles of form." [14] Based on the Zeitgeist of our time today, this inquiry would pose two challenging questions: What should the design drive (source of form) be in contemporary architecture? What should design process look like to ensure the creation of an intended good design?

Each ever-evolving theory of architecture, from early times until now, has marked its impacts on architectural design and its process. These are known today within the sub-field of Architectural Programming (AP). Unfortunately, despite the current environmental challenges and many more indispensable issues to be considered in the programming and design process, architectural design today often appears to be more one-sided than before and, in many cased, still rather subjective with arbitrary results. That, I observe, as being partially due to the existence/abundance of advanced technologies coupled with a lack of profound understandings of [the poetics of] "good" in design. In Orr's (2002) terms, our understandings of technology and science have developed beyond imagined, but "our sense of proportion and depth of purpose have not kept pace with our merely technical abilities (p. 3)." In addition to our mere techno-centric outlooks, we often also have a tendency to only perceive the built environment as an artistic and statuary form of being, one that is only prettified on paper, boards, or the computer, aside from their settings.[15] Related to the domain of experiential qualities lacking in the design of spaces, one can take Galiano's (2000) proposal in "From the Eye to the Skin" as, perhaps, the journey needed to bring life back to the world of architecture (p. xi).[16]

In the past few decades mostly into the 21st century, ecological consciousness has been increasingly adding other important dimensions to the process of decision-making in architectural design, imperatively

[14] As Gelernter (1995) puts, design theories adopt from their contemporaneous theories of knowledge or epistemology. Some design theories "are nothing more than theories of knowledge in another guise," while others "are borrowed from epistemology specific conceptions of the mind and its processes." However, some consciously react against the dominant knowledge of their societies. "The relationship between theories of knowledge and theories of creation is pervasive and fundamental (pp. 2-3)."

[15] American architect and founder of TED, Richard Saul Wurman coined the term "Information Architecture" in 1976. At the time, he was the chairman of the national convention of the American Institute of Architects (AIA), devising the theme of "The Architecture of Information." He pointed out, in an interview in 1998 with Steven Heller of Eye magazine, that: "you can make something good that will also be handsome. But you cannot make something look good, different and stylish, and then hope to find your way back to making it understandable. I celebrate understanding," Retrieved from: http://www.eyemagazine.com/feature/article/form-follows-performance, Date Accessed: March 07, 2016.

[16] Luis Fernández-Galiano (2000). Fire and Memory: On Architecture and Energy. Mit Press.

imposing the need for more sophisticated perspectives towards design and, specifically, architectural programming. That is, according to Orr (2002), “a large concept that joins science and the practical arts with ethics, politics, and economics (p. 4).” This is towards an architecture that, also according to Crowther (1992), “will have to be viewed from an entirely new perspective consistent with ecologic and societal values and equity (p. 4).” Altogether, in order to achieve an inclusivist architectural poetics avoiding any trap of one-sidedness, one must attempt to address all potential forces in shaping the form during the design process while being open to other prospective ideas. Enhancing the process, likewise, demands a new approach to architectural programming that, I maintain, should be primarily based on evaluation. This concept and significance of evaluation is extensively elaborated in the next chapter, followed by background research on other approaches in architectural programming.

The perspective, of putting evaluation at the forefront, can perpetrate drastic revisions in the process of architectural programming. In view of that, in my dissertation, I am introducing “Evaluative-Based Programming” as a dynamic, consensus-oriented, performance-driven, software-aided, and foresighted approach, being embraced within the entire course of architectural delivery. In this Evaluated-Based approach, throughout the process and from very early stages, various design options and their performances should be constantly evaluated to ensure that project goals are met, conceivably via advanced computer tools. As a result of this process, architectural poetics, and more specifically, architectural form would not follow the mere function anymore, but, as Wurman once stated, “form follows performance.”[17] Or, as I would like to put it pervasively, *Poetics Pursues Performance*.

To summarize, descriptive outlines of dissertation chapters are presented. Chapter I, “Design and Programming,” will investigate and include background understandings on various approaches to architectural programming. Chapter I will lead at the end to an argument on a practical architectural programming approach that can generate higher-performance architectural design. Chapter II and III, “Design and Energy” and “Buildings Envelope Systems and Energy,” will contain most of the literature review content of the dissertation. Chapter II, “Design and Energy,” will first discuss concepts related to thermal comfort and ventilation as the two key consumer factors of the buildings’ energy demands. Chapter II will then present analysis related to the impacts of the two factors on architectural typologies. Chapter II will at last bring in theoretical dimensions and converse about the impacts of design decisions _ relative to heating/cooling loads

[17] Richard Saul Wurman coined the phrase in 1998 in the interview with Steven Heller of Eye magazine, Retrieved from: http://www.eyemagazine.com/feature/article/form-follows-performance, Date Accessed: March 07, 2016.

and airflow_ on the Energy Use Intensity of buildings. Chapter III, “Buildings Envelope Systems and Energy,” will investigate two building systems: a Double-Skin Façade (DSF) and a geothermal component, both derived from the inclusivist ecological viewpoint of the dissertation as rendered earlier. Chapter IV, “Methodology,” will elaborate on what the main subjects of the dissertation study are, and why and how the study is conducted. Towards the ending, Chapter V, “Results and Findings,” will exhibit the outcome synthesis of a simulated DSF model linked into the earth, and the final chapter, Chapter VI, “Interpretations and Conclusions,” will wrap up the dissertation.

Chapter I: Design and Programming

1.1 Introduction

Architectural programming in its general concept has been born with architecture and explicitly design; it emerges as early as and even before architecture is initiated. The process of design and more specifically architectural programming has been directly influenced by the evolution of theoretical and philosophical frameworks in each historical period of architectural practice. In contemporary architecture, though, design has often occurred to be more subjective; it is often derived from its designer's "creative imagination." In other worlds, contemporary design is typically one-sided taking the other essentially inclusive factors for granted. This is partially due to the excessive use of advanced technologies, which sometimes even leads to a negligence of a proper architectural programming process.

Nowadays, the notion of ecological consciousness is adding new dimensions to the design and decision-making process. This addition demands an even more inclusive revision of the architectural programming process aiming at ecologically high-performance solutions. In this chapter, I will explore the relationship between architectural design and programming as well as various approaches to programming to identify an approach that generates high-performance solutions. This chapter is an effort in answering the earlier asked question of "what should design process look like to ensure the creation of an intended good design;" a design process that gives birth to *the architectural poetics pursuing its performance*.

1.2 Definitions of Architectural Programming

Programming, as Webster (1966) defines, is "a plan of procedure." William Pena, a pioneer in the area of architectural programming, believes that programming is the process of gathering necessary information to understand, explicate, and state a problem; that is called *Problem Seeking* whereas its solution through designing is *Problem Solving*. This approach necessitates a separation between programmers as opposed to designers (Figure 1.1). Architectural programming is "a process leading to the statement of an architectural problem and the requirements to be met in offering a solution. If programming is problem seeking, then design is problem solving (Pena, 1977, p.15)."

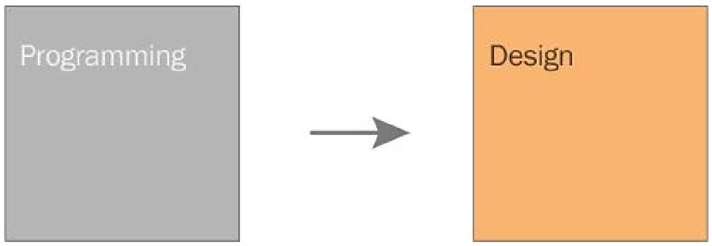


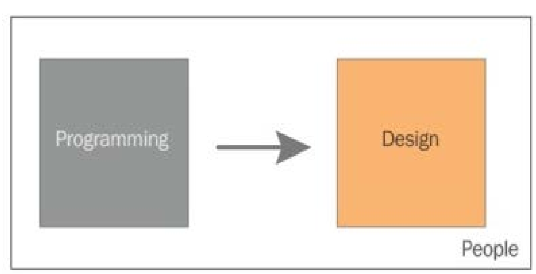
Figure 1.1
Relationship between design and programming suggested by Pena.

In Methods of Architectural Programming's foreword, Richard Dober (1977) states that "programming clearly is a way of systematically defining, ordering, and specifying goals, objectives, design intentions (p. vii)." Henry Sanoff (1977) defines program as the first sequence of built environment's design process in which a systematic forethought is desired before progressing with any action (p. 3); "it is perceived as an organizing procedure for codifying and classifying numerous bits of project information, sometimes misused, often forgotten (pp. 3-4)."

The author of the book *Architectural Programming: information management for design*, Donna Duerk (1993) defines programming as an organized investigation process which outlines the design context accompanied by successful project's criteria. Mission, goals, concepts, and performance requirements are the set of criteria that must be well-defined. This means organization of resources. "Programming is gathering, organizing, analyzing, interpreting, and presenting of the information relevant to a design project (Donna Duerk, p.9)."

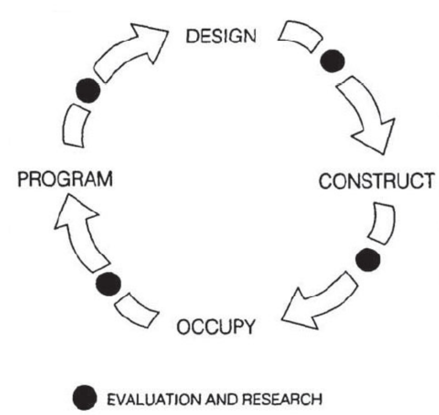
Programming outlined by Edith Cherry, one of Pena's students, is more people-oriented (Figure 1.2). Cherry sees architectural programming through the human lens of architecture while considering site and climate, and describes it in such a way that is more valuable to people. She, thus, aims to recognize occupants and clients' requirements or ideals to suggest criteria desired for a successful project. These challenges must be, finally, met via design. "Architectural programming is the research and decision-making process that defines the problem to be solved by design (Cherry, 1998, p. 3)."

Figure 1.2
Relation between programming, design, and people by Cherry.



Robert Hershberger (1999) similarly argues that programming is central in the process of architectural design; it is to understand the design problem that leads to the design solution, and is in close relation to the other stages of architecture delivery process. Evaluation and research in this approach can be just after each stage is finished (Figure 1.3). He explains that the existence of diverse design solutions is due to different programs formed by dissimilar problems. In other words, the origin of the design is the program. In his terms, “programming is the definitional stage of design-the time to discover the nature of the design problem, rather than the nature of the design solution (p. 1).” Hershberger also believes that architectural programming must respond beyond the expressed problem while generating a work of art as well as promoting architecture; it is to create a built environment which is exceptionally related to its site, climate, time along with existing and upcoming desires of users, client, architect, and society. He points out that “architectural programming is the first stage of the architectural design process in which the relevant values of the client, user, architect, and society are identified; important project goals are articulated; facts about the project are uncovered; and facility needs are made explicit (p.5).”

Figure 1.3
The process of architecture delivery by Hershberger.



Groat and Wang (2002) underscore the importance of an inclusive information gathering to create an informed design, which needs to be then evaluated. That is, “programing can be understood as an effort to maximize the amount of information about a project so that the figural concepts generated can optimally respond to those criteria (pp. 108-109).” In the following sections, different approaches towards programming by various scholars are described.

1.3 Various Approaches to Architectural Programming

Architectural programming used to be *client-based* meaning that clients were responsible to provide architects with a project's requirements and details needed for programming. This approach might be appropriate for small projects such as the design of a house, but could not include all the necessary aspects of the architectural delivery. It was the main reason that some architects such as Herbert Swinborne and Nathanial Becker started to offer architectural programming services in the late 50's (Hershberger, 1999, p.6). Harold Horowitz, in 1966, wrote an influential article, Programme and the Behavioral Sciences in which he emphasized on contribution of behavioral science and the necessity of architectural programming accomplished by architects. He believes that this method is vital to an appropriate design solution. "The quality of architect's programme is directly related to the possibility of finding a satisfactory design solution for the functional aspects of a new building. Beyond this, there are many architects who feel that the programme is the key to a satisfactory aesthetic solution because the building design must express the function (1966, p.9)." According to AIA, even today, architectural programming is a part of architect's additional services in the proposed Standard Form of Agreement[18] between client and architect.

While Pena (1977, p.15) argued that the process of programming is and should be separate from design. Yet, Julia Robinson and J. Stephen Weeks of Minnesota college of Architecture (1984) stated that the entire process of the design is a portion of programming process and understanding of a problem. They perceive programming and design neither as analysis versus synthesis nor as rational versus intuitive; it is, as they describe, verbal/numerical and formal/spatial. As they argue, before design starts, the architectural problem cannot be fully understood; therefore, problem definitions are premature until design is completed (Hershberger, 1999, p. 12-13). The Figure 1.4 illustrates their new model as opposed to Pena's model. Mainly structured based on the Hershberger's classification, the following sections will show different approaches toward architectural programming since the process of architectural design has developed.

[18] AIA DOCUMENT B141-1997, Standard Form of Agreement between Owner and Architect with Standard Form of Architect's Services.

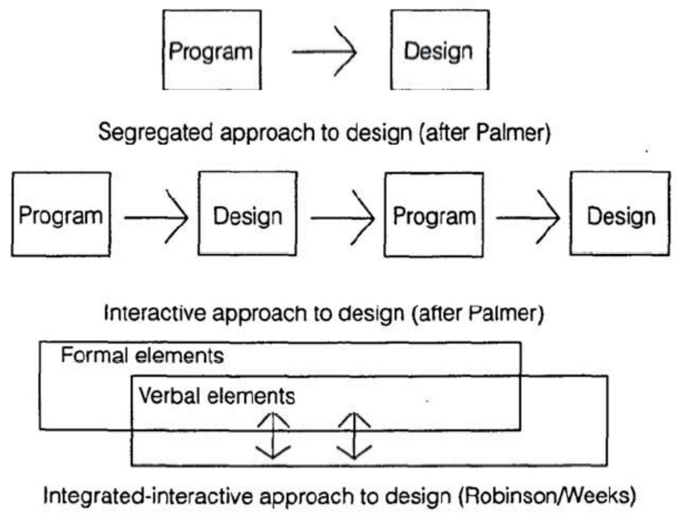


Figure 1.4
Programming approach by Robinson and Week (Source: Hershberger, 1999).

1.3.1 The Traditional Model

One of the first roman architects and the author of “De architectura” lately known as The Ten Books on Architecture, Vitruvius suggested *firmitas, utilitas, and venustas* as criteria of a successful architecture (Figure 1.5). For many years, the three main factors have been carefully considered in the process of architectural design. It simply means that any structure should be solid, useful, and beautiful, yet, could be interpreted in more profound levels of firmness, commodity, and delight. Firmness is related to structure or construction. Commodity could be about function, values, or even comfort while delight encompasses aesthetic and physical comfort. The three mentioned concepts, thus, could serve for classifying different issues relevant to a given project. As illustrated in Figure 1.5, some of these factors may overlap with one another (Duerk, 1993, p.159).”

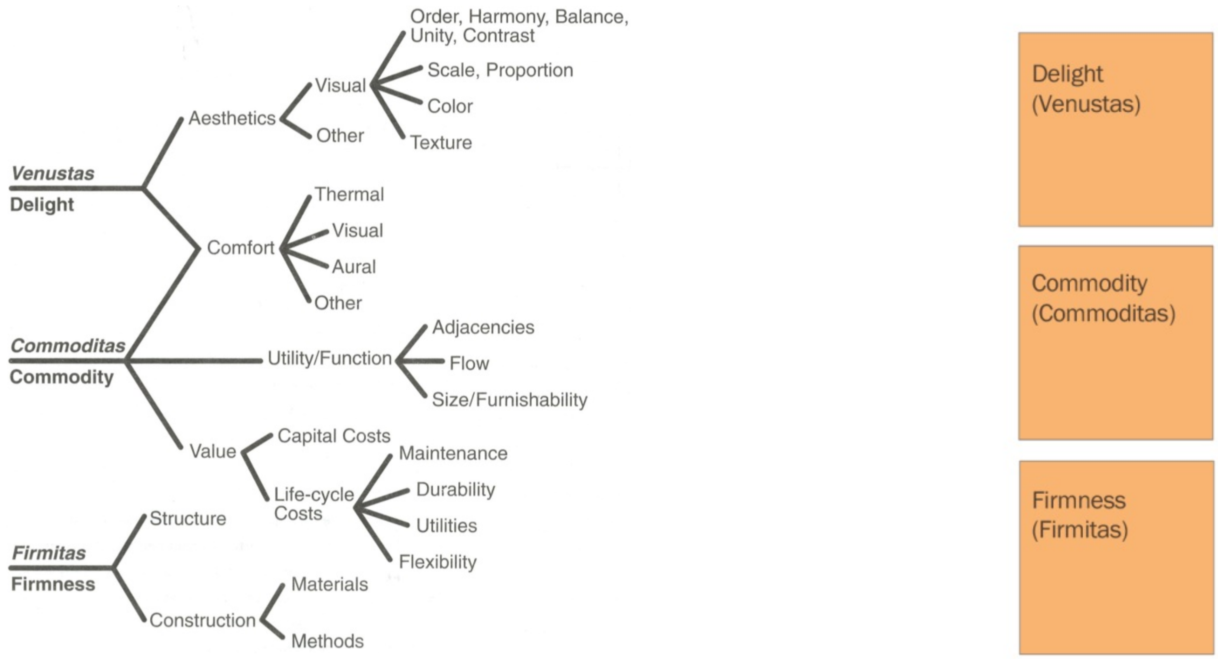


Figure 1.5
Left: Vitruvius' more comprehensive model (Source: Hershberger, 1999), Right: Vitruvius Traditional Model for a Successful Design (Source: Adapted by Author).

1.3.2 Design-Based Architectural Programming

A method in which programming occurs at the same time that design shapes is known as design-based programming (Figure 2.6). In this approach, there is not an organized procedure of data gathering before design starts, which demands some amount of time and effort. Basically, a client and an architect would set meetings where the client knows the project requirements and the architect is ready to sketch the design. The drawings, then, will be modified through several meetings until they fully satisfy the client and the architect's desires. This approach could be efficient depending on the project scope, the client's program accuracy, or the architect proficiency as an interviewer. This methodology could be sometimes time consuming or expensive since programming is not prepared before the design process; the design would change constantly based on new information or requirements. It also can generate more potential conflicts between the architect and the client when all the aspects of design have not been defined (Hershberger, 1999, pp. 7-14).

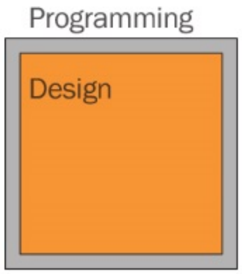


Figure 1.6
Design-based relationship between programming and design
(Source: Adapted by Author).

1.3.3 Knowledge-Based Architectural Programming

In the 1960's, architecture programming was tremendously influenced by social and behavioral sciences which at that time were brought to the area of architectural design. Accordingly, architecture started interacting more with the new interdisciplinary sciences such as environmental sociology, environmental psychology, or human ecology, considering people more as the key users of the built environment. Edward Hall (1966) and Robert Sommer (1969) researched about personal space and territoriality which was at that time vastly appreciated in architecture profession. This process of extensive research in architectural programming was even employed in practice by some architects such as Gerald Davis (1969), Jay Farbstein (1976), or Walter Moleski. This approach has been further effective in more complicated building type such as hospitals, prisons, or administrative offices. In these types of buildings, values or requirement details among different sections are not clearly explicated for which various interdisciplinary knowledge have to be achieved. Special users need research, precedent studies, user interviews, or questionnaires could be reliably informative in these types of programming procedure after they are collected, statistically evaluated, and summarized (Hershberger, 1999, p.14-17).

Evidence-Based Design, EBD, is also generated by this methodology where science indicates that certain aspects of building design can improve or worsen a user's condition. EBD, which was originated in health care area, utilizes a set of design principles that are scientifically assessed and exposed to make a positive change for users of building. Obviously, Knowledge-Based method demands extensive amount of time, money, and resources which is truly challenging for complex projects. Therefore, this method could be employed where the error cost is so high (Hershberger, 1999, pp.14-17).

1.3.4 Agreement-Based Architectural Programming

Agreement-Based architectural programming is referred to a programming process in which programmer would initially gather the existing information to meet with client's representatives, building users, or involved community as a programming committee in order to come up with a satisfactory agreement. This methodology, normally, relies on the awareness of some influential individuals on client's side who have sufficient knowledge to create programming information or can obtain reliable information on behalf of their affiliates. The programmer understanding of the designer's desires along with the committee efficiency are fundamental in this approach. Yet, other aspects such as performance specification

CRS proposed matrix[19] for defining the design problem is the best example of this method. This matrix has four main concerns, values, or issues along one side which are Function, Form, Time, and Economy. Any item relevant to the design project can be put under these categories. Environment, site, quality, or aesthetic, for instance, could be under the form while people, activity, meaning, and building purpose could be under the function classification. Pena, also, introduces five programming steps of goals, facts, concept, needs, and problem statement along the other side of the mentioned matrix. Finally, he argues that the design problem will be clearly identified if all of these twenty cells are defined (Figure 1.7). As Pena et al. (1977) put:

> It is important to search and find the whole problem. It must be identified in the areas of function, form, economy, and time. Classify information accordingly. This simplifies the problem while maintaining a comprehensive approach. A wide range of factors makes up the whole problem, but all can be classified in the four areas which serve later as design considerations (p.28).

[19] (Pena et al., 1969. 1977, 1987) In the early 1960s, William Peña, John Focke, and Bill Caudill of Caudill, Rowlett, and Scott (CRS) developed a process for organizing programming efforts. Their work was documented in Problem Seeking, the text that guided many architects and clients who sought to identify the scope of a design problem prior to beginning the design, which is intended to solve the problem.

	Goals	Facts	Concepts	Needs	Problem
Function People Activities Relationships	Mission Maximum number Individual identity Interaction/privacy Ranking of values Exercise of authority Security Progression Segregation Encounters Efficiency Information exchange	Statistical data Area parameters Manpower/workloads User characteristics Community characteristics Authority structure Value of potential loss Time-motion study Traffic analysis Behavioral patterns Space adequacy Type/intensity	Service grouping People grouping Activity grouping Priority Hierarchy Security controls Sequential flow Separated flow Mixed flow Relationships Communication	Space requirements Parking requirements Outdoor space requirements Functional alternatives	Unique and important performance requirements which will shape building design Major form considerations which will affect building design
Form Site Environment Quality	Bias on site elements Sound structure Efficient land use Physical comfort Life safety Sociality Individuality Encoded direction Direct entry Projected image Building quality level Spatial quality level Technical quality level Functional quality level	Site analysis Soil analysis F.A.R. and G.A.C. Climate analysis Code survey Surroundings Psychological implications Point of reference Entry symbols Generic nature Cost/S.F. Building efficiency Equipment costs Area per unit	Enhancement Special foundations Density Environmental controls Safety precautions Neighbors Home base Orientation Accessibility Character Quality control	Site development costs Environmental influences on costs Building cost/S.F. Building efficiency Equipment costs	
Economy Initial Budget Operating Costs Lifecycle Costs	Extent of funds Cost effectiveness Maximum return Return on investment Minimize operating costs Maintenance and operating costs Reduce life cycle costs	Cost parameters Maximum budget Time-use factors Market analysis Energy source-costs Activities and climate factors Economic data	Cost control Efficient allocation Multi-function Merchandising Energy conservation Cost control Cost control	Cost estimate analysis Energy budget (if reqd) Operating costs (if reqd) Life cycle costs (if reqd)	Attitude towards the initial budget and its influence on the fabric and geometry of the building
Time Past Present Future	Historic preservation Static/dynamic activities Change Growth Occupancy date Cost controlled growth	Significance Space parameters Activities Projections Durations Escalation factors	Adaptability Tolerance Convertibility Expansibility Linear/concurrent scheduling Phasing	Time schedule Time/cost schedule	Implications of change/growth on long-range performance

Figure 1.7
CRS Proposed Programming Matrix (Source: Duerk, 1993).

In this process, the intention is to put less emphasis on the design development information since CRS believes on the separation of architectural programming from design development, which begins after schematic design is initiated. This procedure saves time. Agreement-Based architectural programming, on the one hand, almost covers all the necessary design information for which an architect is concerned. On the other hand, there is an ultimate agreement on the design problem between client and architect prior to design initiation. It is also economically-oriented since the inefficient procedure of user's needs research is replaced by productive contribution of users or their representative in the workshop sessions, where they explicitly mention their needs. In comparison to other architectural programming approaches, the Agreement-Based architectural programming eludes the reactionary nature and misunderstandings between client and architect existing in the Design-Based architectural programming, and the high cost and time consuming nature inevitable in the Knowledge-Based architectural programming.

Being restricted just to the four values if there are some other concerns in a project is one the drawbacks in the Agreement-Based architectural programming which may cause some inadequacies in the understanding of a design problem. Anderson DeBartolo Pan added the item of “energy” as another value to cover some contemporary environmental concerns. Another drawback of this method is related to the situation in which the involved committee members are not fully representing the user needs or in any way are not capable of transferring their accurate organization information. This may happen more for complex or unknown building type (Hershberger, 1999, p.17-25). As Marans and Spreckelmeyer argue, the separation between “programmatic concepts” and “design concepts” in the CRS matrix is very problematic for individuals who do not have sufficient architecture background. In addition, the separation between these two by its nature would ignore some design detail information such as form, orientation, and furniture arrangement. This separation, however, is less highlighted in the view of the other followers of Pena’s systematic process, namely Cherry who argues that “it is sometimes an unconscious process, sometimes a conscious one, and sometimes it intertwines with the design effort (1998, p. 18).”

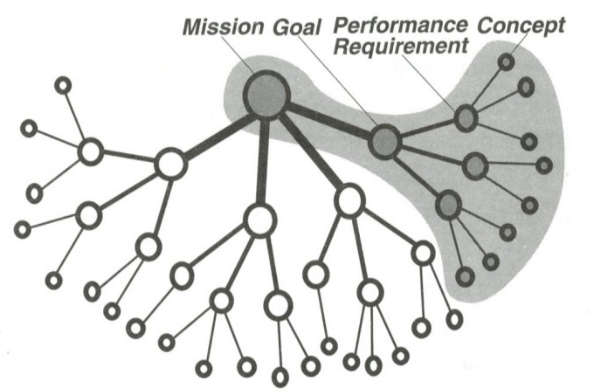


Figure 1-1 Goals, Performance Requirements, and Concepts for Each Design Issue

Figure 1.8
Mission, Goals, Performance Requirements, and Concepts for each design issue (Source: Duerk, 1993).

1.3.5 Issue-Based Architectural Programming

Donna P. Duerk (1993), the author of the book *Architectural Programming: Information Management for Design* has introduced Issue-Based architectural programming in which she divides programming into two concern areas of “Existing State” analysis and “Future State” projection. The existing state is related to the project context, and includes site or climate analysis, constraints and codes, user characteristics, and the like

which are known as Design Issues. The future state, however, is related to a set of criteria that a successful project in search for good should meet, and includes mission, goals, performance requirements, and concepts (Figure 1.8).

To understand these criteria, definition of each will be elaborated based on Duerk's definitions (1993):

> *Mission*: "the mission statement of a design project is the mega goal that sets out the purpose for the project, the reason why the project is being done at all (p.45)."
>
> *Goals*: "A goal is statement of information for the future state of a project.-what quality the project should be (p.45)."
>
> *Performance Requirements*: A performance requirement is a statement about the expected level of function for a successful design project (p.58)."
>
> *Concepts*: "A concept is a diagrammatic statement of an ideal relationship between the elements of a design (p.76)."

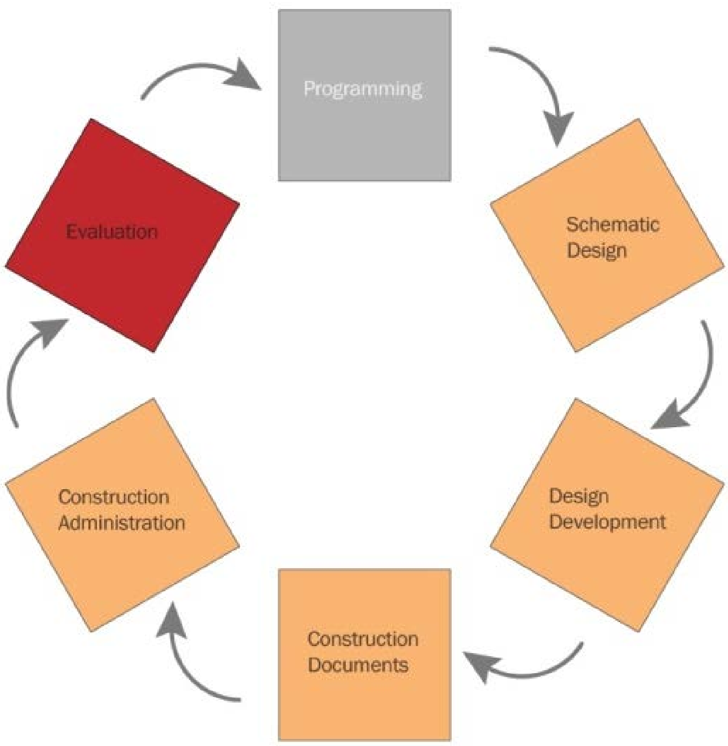


Figure 1.9
Role of evaluation in the design process proposed by Duerk (Source: Adapted by Author).

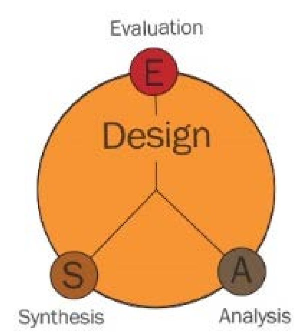


Figure 1.10
Design process consisting of analysis, synthesis, and evaluation perceived by Duerk (Source: Adapted by Author).

Unlike Pena who sees programming (as analysis) separated from design (as synthesis), Duerk believes that these two are in a constant cyclical relationship where evaluation is likewise part of this cycle; the synthesis as a function of analysis would be evaluated, and might be changed as analysis could be impacted by the evaluation. This order could be varied in the design process as the detail level is expected to be more comprehensive, but not in a linear procedure (Figure 1.9). The position of evaluation, she suggested, is after construction administration and just before programming (Figure 1.10). She also argues that a decent programming has a measure of synthesis, and analysis is portion of a proper design while the amount of analysis is more at the beginning of design process in comparison to the end of it (Figure 1.11).

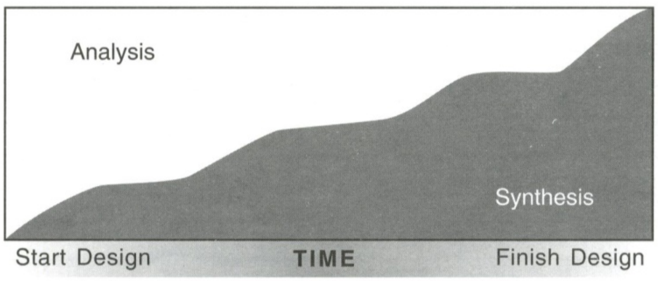


Figure 1.11
Analysis and Synthesis in Design
(Source: Duerk, 1993).

In the proposed model for architectural programming by Durek, it is central to rely on each of design issues, as the category, for establishing design information through Facts, Values, Goals, Performance Requirement, and Concepts. These issued could vary from project to project based upon the main concerns that need to be responded by the design (Figure 1.12). Therefore, for any project there are some Facts and Issues that should define Goals when evaluated by the filter of Values. Finally and as illustrated in Figure 1.13, some concepts will be generated through initiation of Performance Requirements (Duerk, 1993, pp.7-21).

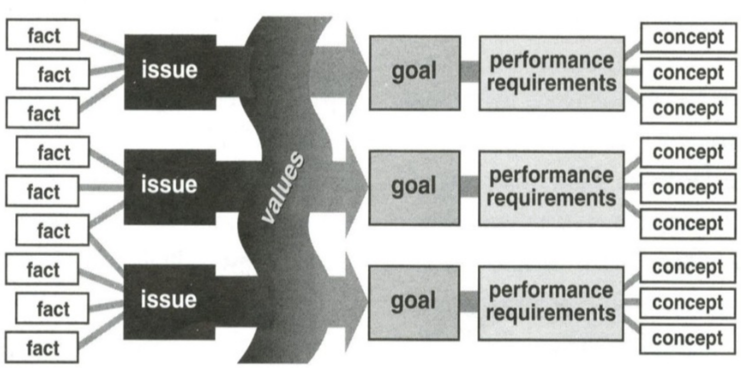


Figure 1.12
Schematic Design Programming
Recommended by Duerk
(Source: Duerk, 1993).

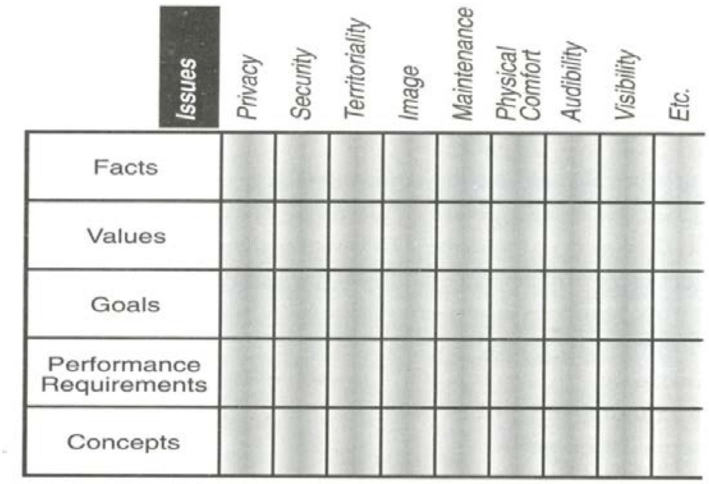


Figure 1.13
The model Suggested by Duerk
(Source: Duerk, 1993).

1.3.6 Value-Based Architectural Programming

Value-Based architectural programming attempts to combine advantages of the mentioned approaches and eliminating their disadvantages. That is, investigation of client's goals, values, and budget along with physical influences such as site, climate, or other external impacts. This could be achieved through interviews, conversation, interaction, and lifestyle experience in order to start an initial design solution which is generally acknowledged by the client, user, or community without change. Frank Lloyd Wright and Louis I. Kahn's distinctive design procedure is an appropriate example of Value-Based architectural programming. Wright is known for the dedicated time that he spent with his clients and the site to recognize their values as well as a project's goals. Kahn also was passionate to explore design problems through extensive interaction with clients, users, and site. (Hershburger, 1999, p. 25-29).

Authorizing programming process adjustment through profound study of project values, in the early stages of programming and before design is started, is a unique character that distinguishes Value-Based programming from the other approaches. In this process, community or user representatives would be also involved in the early stages of programming as seen in Agreement-Based architectural programming. As Hershberger (1999) puts it, "value-based programming makes certain that the most important design issues are addressed in the programming document (p. 31)."

The systematic process of information gathering used in Knowledge-Based architectural programming through literature review, interviews, observation, questionnaire, and the like for finding values, goals, facts,

and needs is appreciated in Value-Based architectural programming as well. Yet, it does not allocate tremendous amount of time and budget similar to what is defined in Knowledge-Based architectural programming. Doing this in the early stages would identify areas which need more emphasis and research to avoid potential future expenses as well as areas which need less emphasis to save time and budget, similar to Design-Based architectural programming. As Hershberger (1999) argues, "value-based programming uses systematic information gathering procedure to ensure that important information is not overlooked in the programming process (p. 31)."

Value-Based architectural programming is profoundly grounded in the CRS proposed matrix. Essential values and concerns are listed along left side of the matrix and goals, facts, needs, and ideas are along top of it to ultimately generate the design problem which is agreed by all involved individuals. "Value-based programming recognizes the importance of obtaining agreement with the client, users, and community in open work session environments (Hershberger, 1999, p. 32).

Hershberger, similarly, argues that programming is central in the process of architectural design; it is to understand design problem leading to design solution, and is in close relation to the other stages of the architectural delivery process. Evaluation and research in this approach can be just after each stage is finished (Figure 1.14). He explains that the existence of diverse design solutions is due to different programs formed by dissimilar problems. In other words, the origin of the design is the program. "Programming is the definitional stage of design-the time to discover the nature of the design problem, rather than the nature of the design solution (Hershberger, 1999, p. 1)." Hershberger also believes that architectural programming must respond beyond the expressed problem while generating a work of art as well as promoting architecture; it is to create a built environment which is exceptionally related to its site, climate, time along with existing and upcoming desires of users, client, architect, and society. "Architectural programming is the first stage of the architectural design process in which the relevant values of the client, user, architect, and society are identified; important project goals are articulated; facts about the project are uncovered; and facility needs are made explicit (p. 5)."[20]

[20] Robert G. Hershberger (1999). *Architectural programming and predesign manager*. New York: McGraw-Hill.

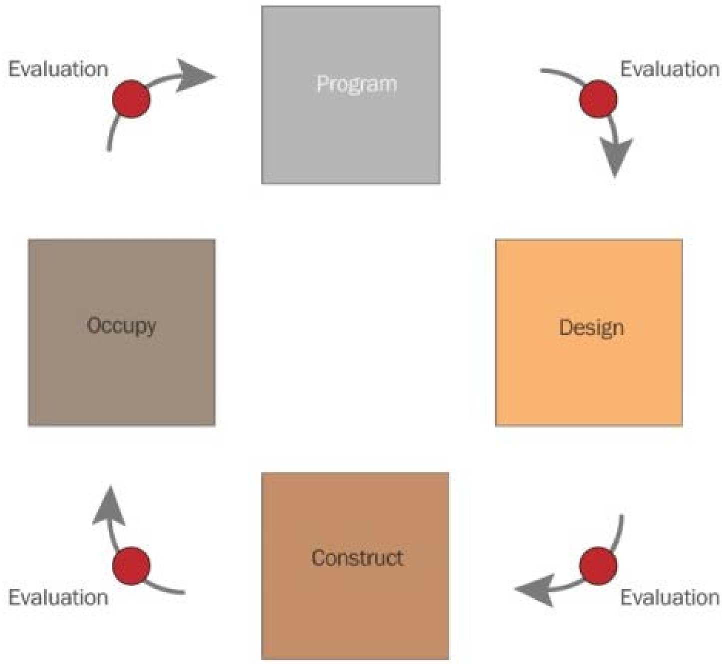


Figure 1.14
The architectural delivery process defined by Hershberger (Source: Adapted by Author).

As Hershberger outlines, there are also four key differences between Value-Based architectural programming as opposed to Agreement-Based architectural programming. First, the values are not restricted to the ones suggested by CRS (Function, Form, Time, and Economy). There would be more theoretical concerns like History, Tradition, Environment, Image, Meaning, Safety, or the like which could differ from project to project. Also, the order of the mention values could be based on their priority. Second, the top of the CRS matrix which is designated for goals, facts, needs, and concept is not exactly the same in Value-Based architectural programming. Since it is difficult to separate programmatic concepts from design concepts before the need statement, they will be specified as “ideas” so that the designer can have all the concepts and eliminate the appropriate ones after a thorough design analysis, if necessary. Third, the CRS approach supposes that the designer is a member of programming team, and develop the problem statement as the last cell of the matrix. In Value-Based architectural programming, however, this portion of programming is one of the designer responsibilities. The designer should be able to do this based on the issues and their priorities in the matrix no matter s/he is part of the programming team or not. Ultimately, the program is confirmed both by the designer and the client prior to design initiation. Finally and as the forth difference, in Value-Based architectural programming schematic design is not separate from design development accepted in Agreement-Based architectural programming. It means that all the detailed design suggestion in the process of programming can be used for designer to come up with better schematic design options.

"Complete value-based programs include design development information presented on space program sheets in order to help the designer make informed schematic design decisions (Hershberger, 1999, pp. 33-34)."

1.3.7 Pattern-Based Architectural Programming

Christopher Alexander (1977) and a couple of his students of UC Berkeley, California proposed a unique language named a pattern language, which was derived from timeless entities called patterns by the authors. A Pattern Language is a different attitude toward architectural design and planning. It has a structure of a network and, as result, a sequence going through patterns from larger to smaller; various patterns make a language through sequence. Via a sequence, thus, right decision that has to come first is figured out. A pattern language relies on contribution of the entire people in a society sharing a common and inherently evolving pattern language in order to create an alive building or town. Patterns are the elements of this language describing both design issues and their solutions' core. These core solutions can be used many times without repeating the same manner even twice. Each pattern addresses a problem clearly introduced by a consistent format. A pattern, therefore, is connected to certain larger patterns above it as well as to certain smaller patterns below it in the language as a whole. In this approach, making things does not happen solely in isolation. Rather, the domain around and within it must be also considered as a coherent whole. Solutions for each pattern are stated in such an abstract fashion allowing the adaption to various internal or external design conditions, user preferences or contextual climatic condition for instance. These solutions, thus, address inevitable essentials without imposing anything on designers. (pp. i-xliv). As Sanoff (1997) puts:

> The idea of a pattern is based on the premise that typical systems of connections exist. As an example, the relationship between an entry, receptionist, and the waiting area in offices seems to occur frequently with very slight variations. While there are many people who do not believe that typologies of solution exist, the pattern concept seeks to identify these typological situations (p. 98).

1.3.8 Computer-Based Architectural Programming

With the increasing improvement of computer technologies, lots of efforts have been put to enhance the process of architectural programming. For instance, the Social Economic Environmental Design (SEED) is a multipurpose computerized design system for architectural design's early stages. "The goal of the SEED

project is to develop a software environment that supports the early phases of building design and thus, in principle, to augment all aspects of the early design process that can benefit from such support (Flemming et al., 1993)[21]." As Omar Akin et al. (1994) argue:

> SEED-Pro is designed to take as an input a typical high level description of a building project, such as building type, capacity, site description, available budget, etc., and help the user generate a consistent architectural programming with a well-defined scope. Five components together perform this task: Specification, Generation, Evaluation, Input, and Output (p.3).

Although some programmers' method toward architectural programming, from specification to design, is a linear or systematic approach, programming and spatial design could overlap each other for other programmers. One of the advantages of SEED-Pro is allowing users to start with any method and process which is more suitable for the project. It is also a flexible environment in which varieties of computer assisted architectural programming (CAAP) modalities are supported. Another advantage is constant control of cost estimation along with budget management in the process of architectural programming. Lack of ecological analyses as well as energy management evaluation can be considered as one of this software's drawback. Figure 1.15 illustrates the architectural programming process and functionalities offered by SEED-Pro (Akin et al., 1995).

Trelligence Affinity[22] is one of the other most inclusive architectural programming software to boost the architectural design process. It allows initial planning, programming, schematic design, design validation, reporting, BIM integration, and sustainability analysis of architectural projects during its entire process. Affinity

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[21] The other members of the SEED team include Ömer Akin, Rana Sen, Magd Donia, S. Fenves, R. Coyne, J. Garrett, R. Woodbury, S. Chiou, B. Choi, H. Kiliccote, T. Chang, J. Snyder, C. Chen and N. Lopez. The development of SEED is sponsored by Battelle Pacific Northwest Laboratories, the US Army Corps of Engineers Construction Engineering Research Laboratories (USA CERL), the National Institute of Standards and Technology (NIST), the Engineering Design Research Center (EDRC - an engineering research center supported by the National Science Foundation) at Carnegie Mellon University, the National Science Foundation (grant # MSS-9114459), the Australian Research Council, and the University of Adelaide.

[22] Based on Trelligence Affinity's website (http://www.trelligence.com/affinity_overview.php):
Trelligence Affinity™ is BIM software focused on enhancing the early architectural design process with a unique programming, space planning and schematic design solution. Targeted at the worldwide architectural, engineering, construction and owner/developer (AECO) market, the Trelligence Affinity patent-pending software integrates with ArchiCAD® from Graphisoft, AECOsim Building Designer from Bentley, Revit® Architecture from Autodesk, SketchUp™ from Google, VE-Gaia and VE- Navigator for LEED® from IES, and other design tools to extend the benefits of building information modeling (BIM) - faster planning, less rework, and better team collaboration - to the early design phases of complex building projects.

can capably manage a variety of small to very complex projects and could fit for education, healthcare, and government.[23]

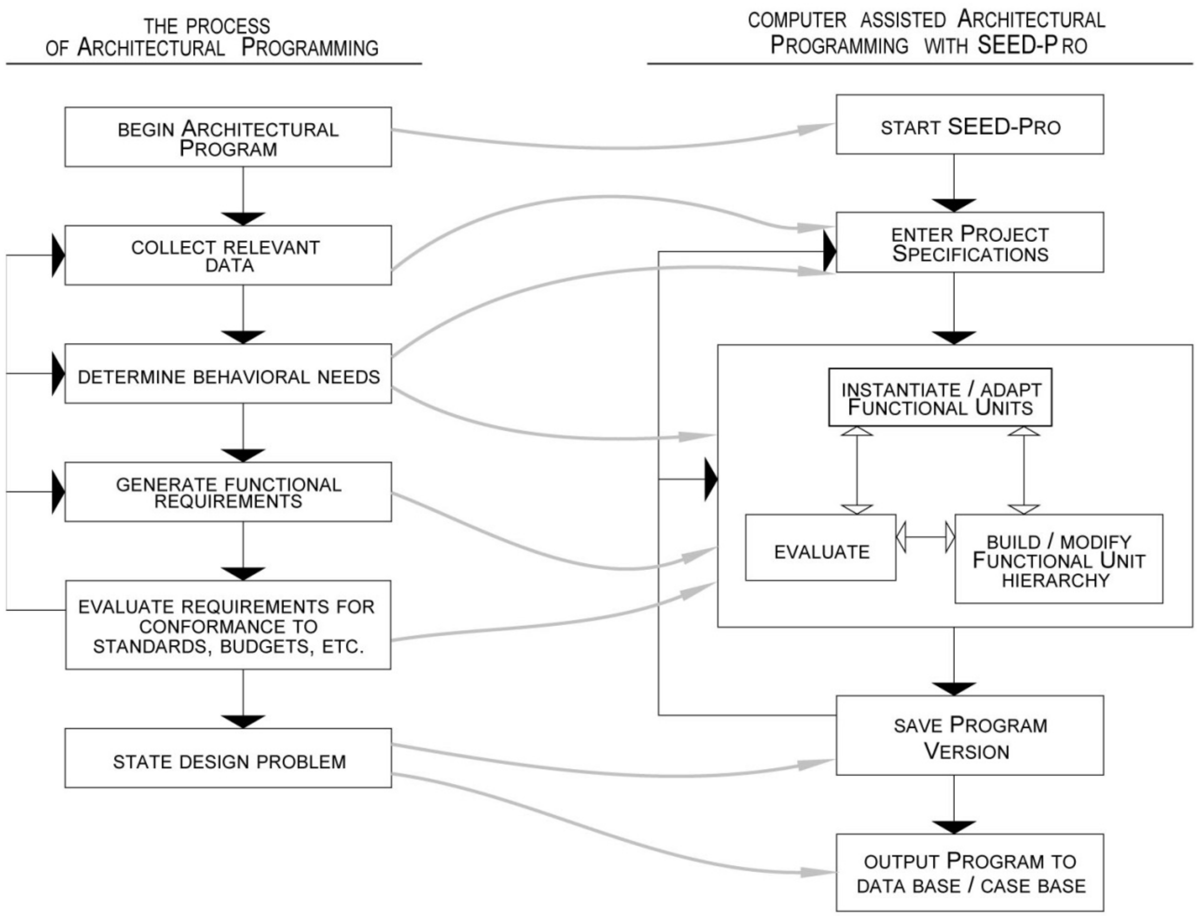

Figure 1.15
Building an architectural program and the related functionalities of SEED-Pro
(Source: Trelligence Affinity's website).

Today, achieving a high-performance built environment is not possible without the integration of environmental performance criteria into the early stages of design and form making process. Regarding performance analysis, there are also integrative computer softwares that can precisely simulate the design options and as a result enhance the efficiency of architectural design processes as a whole. Performance simulation is the imitation of some real mechanism or its process, and computer simulation offers an opportunity to increase designers' ability to manage greater complexities in a shorter time, particularly about

[23] Based on Trelligence Affinity's website: (http://www.trelligence.com/index.php)

energy, thermal and lighting subjects. Advanced simulation tools are recently improved in terms of convenience, user interface, application quality control, and better interoperability. After all, the integration of sustainable design criteria and contemporary aesthetics seems challenging without the contribution of highly developed dynamic computer technologies. The followings paragraph, which is a background study on the performance simulation, conducted by Hazem Rashed-Ali (2009)[24] can support these statements.

Markus (1996) believes that measurement and appraisal of performance is central to the design process. Clark (2001) further argues that simulation permits an evaluation of building performance that corresponds to reality and enables integrated performance assessment, while Malkawi (2005) advocates that the use of performance simulation in architectural design is increasing, and that the building industry is aware of the need for better integration of these tools into the design process. Preiser and Vischer (2005) argue, for a Building Performance Evaluation (BPE) framework for the planning design, construction and occupancy of building in which quantitative and qualitative building performance criteria are used to inform all stages of the process and contend that this framework will allow decision makers to make an informed design decision. Lerum (2008) has analyzed eight case studies of high performance building, all of which utilize performance simulation in a variety of forms (Rashed, 2009).

In sum, climate analysis, site resources analysis, form options assessment, day-lighting evaluation, building energy utilization intensity, carbon emission, and life cycle assessment can be vastly studied by using Climate Consultant, ECOTECT, TRNSYS, DAYSIM, eQUEST, EPA Target Finder, and Athena in the early stage of architectural programming and preliminary design.

1.4 A Proposed Evaluative-Based Architectural Programming

After the analysis of the existing architectural programming literature, this study concludes with my integrative approach to architectural programming. This approach has inclusive capabilities to both generate and promote high-performance built environments in regards to the "good." Primarily founded on the idea of inclusivity and evaluation, I suggest the "Evaluative-Based Architectural Programming." That is the author's complementary attitude which encompasses all the perceived advantages from the stated architectural programming approaches while eliminating their disadvantages. I introduce Evaluative-Based Programming

[24] Rashed-Ali Hazem (2009), "Integrating Environmental Performance Criteria in Architectural Design Studio," In *ARCC 2009 – Leadership in Architectural Research, between academia and the profession*, San Antonio, TX, (p.2).

as an inclusivist, dynamic, participatory, performance-driven, software-aided, and foresighted approach which embraces the entire architectural delivery.

Evaluative-Based architectural programming analyzes a client's goals and budget as well as users and allied communities values, along with physical influences such as site, climate, codes and other external impacts as the existing state, also suggested by Duerk. Basically, these are "issues" similar to what we saw earlier in the Issue-Based architectural programming, which are not limited and may vary from project to project. Recognizing these issues could be achieved through lifestyle experience, conversation, interaction, interviews, or community participation via charrettes. These issues are concurrently filtered through user, client, and community's values identified through their involvements and participation in the process, similar to Hershberger's approach. This participation allows for an inclusivist interpretation of project from various standpoints to start an initial solution which is generally acknowledged by all the stakeholders. Accordingly, a set of Performance Requirements (or *Performance Specification* mentioned by Cherry[25]) that a successful project in regards to the "good" should meet are defined. Innovative concepts, then, would be projected as the future state defined by Duerk.

Simultaneous evaluation in the entire process of architectural delivery is the essence of a concept as the performance-driven solution. This evaluation starts from the very early stages even before the design is initiated to years after it would have been used. In this approach, programming and design are not only joined, but also in a cyclical relationship influencing each other. Indeed, design as a component is a portion of the programming as a whole; the entire design process is an integral part of programming, which also includes other components such as construction, occupancy, and post-occupancy. In fact, Evaluative-Based Programming converges the three elements of design, programming, and evaluation (Figure 1.16).

The following criteria are three primary concepts that my proposed Evaluative-Based architectural programming offers:

1- Programming and design are not only joined, but also in a cyclical relationship overlapping each other, as opposed to Pena's idea. This methodology is very similar to the idea of Robinson and Weeks (1984) in which the entire process of design is a portion of programming process and understanding of a problem.

[25] In Cherry's terms, "a performance specification describes what a designed object should do rather than what it should look like or be made of. For example, at the planning scale a performance specification might state that a traffic artery must accommodate 1000 cars per hour at speeds of 35 miles per hour… In an architectural project one might encounter a performance specification stating that the lighting system must be able to deliver a certain number of foot-candles of light at desk height at any period of a 24-hour day. The resulting design recommendations might involve artificial lighting fixtures mounted in the ceiling, artificial task lighting that can move as task moves, a combination of either of these two and natural lighting during part of 24-hour period, or numerous other possibilities or combinations (1998, p.10)."

This is a type of analysis that also enhances synthesis and, at the same time, a type of synthesis that enhances analysis.

2- An inclusivist attitude in gathering relevant information throughout programming is the essence in reaching to an "inclusivist architectural poetics." It means that the same approach stated for architecture should be applied towards programming to bring a "good" built environment to fruition.

3- "Evaluation" is the most critical concept in this process which is constantly considered to analyze both programming and design in general and specifically programming, if design is accepted as a part of programming. Although evaluation was considered after each stage of the programming or design by Hershberger, in my proposed Evaluative-Based architectural programming it also has to be constantly considered during each stage of programming, and design, construction, and occupation. This approach is similar to Duerk's cyclical definition of evaluation between analysis and synthesis (Figure 1.10). The synthesis as a function of analysis would be evaluated, and might be changed as analysis could be impacted by the evaluation. This order could be different in the design process as the detail level is expected to be more comprehensive, but not in a linear procedure, as suggested by AIA (Figure 1.18).

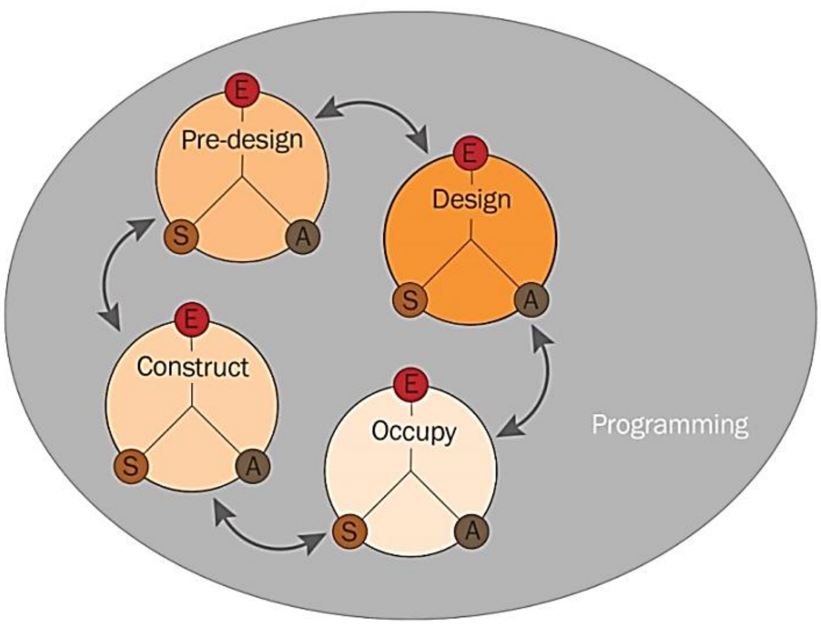

Figure 1.16
The architectural delivery process and relationship between programming and design (Source: Adapted by Author).

Issues	Environment Protection	Energy Conservation	Water Conservation	Material Conservation	Indoor Env. Quality	Life Cycle	Greenhouse gas	Visibility	Security	ETC.
Facts										
Values										
Goals										
Performance Requirements (PR)										
concepts										

Figure 1.17
My proposed architectural programming model adapted from Duerk's model (Source: Adapted by Author).

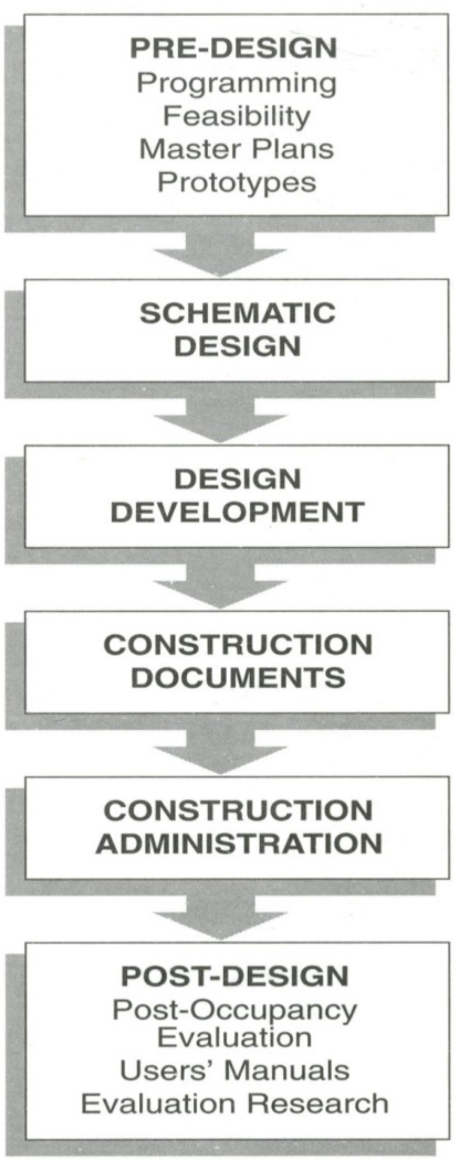

Figure 1.18
AIA Design Process
(Source: Duerk, 1993).

In my proposed model for architectural programming, the focus is on each of design issues for establishing design information through facts, values, goals, performance requirement, concepts, and evaluation (Figure 1.13). Therefore, for any project there are some facts and issues that should define goals when evaluated by the filter of values. As illustrated in the Figure 1.17, some concepts will be generated through the initiation of performance requirements. Finally, these concepts will be evaluated to ensure that all the demanded criteria are appropriately met. This could be done through simulation software or other advanced tools. As an issue, for instance, let's look at the energy utilization intensity (EUI) of a schematic design known here as the concept. This concept, which is filtered through potential design facts and values, could be assessed by using simulation softwares such as TRNSYS to check if it is in line with the energy utilization goals set for the project and more explicitly its performance criteria.

As a concrete example, the programming process for the design of a hypothetical non-residential building could be as follows: in respect to the "good," the mission is *to design, construct, and operate buildings which are environmentally cautious, socially just, and economically viable.* From an ecological point of view, this mission would address several issues including, but not limited to, environment protection, energy conservation, water conservation, material conservation, and indoor environment quality. There are clearly other substantial issues to achieve at a successful design. Focusing on energy conservation, the goal could be as follows: *the building should promote a minimum of dependency on fossil energies in order to provide human comfort*. This demands an energy utilization intensity of zero as performance requirements (PR). Then, there needs to be concepts accomplishing the defined PR. One might propose the concept of a Double-Skin Facade (DSF), as an ecological building component. Evidently, additional concepts such as a proper building orientation are required to facilitate the defined PR. From now on towards the end of the building life-span, as stated earlier, evaluation through advanced tools comes into play in order to validate the proposed concepts.

To recap, my proposed evaluative-based programming relies on the following beliefs:

- *Programming as Design:* programming and design are joined not separated.
- *Programming as Architectural Delivery:* programming encompasses all the components of architectural delivery including predesign, design, construction, occupancy, and post-occupancy.
- *Dynamic Programming:* programming's thinking process is from the whole to the detail and from detail to the whole influencing each other in a cyclical and bilateral relationship, not a linear one.
- *Inclusivist Programming:* programming attempts to address as much as information in regard to the standpoint of various stakeholders and their participation for the success of the project.

- *Performance-Driven Programming*: programming' authenticity is on evaluation.
- *Software-Aided Programming*: programming employs advanced evaluation softwares.
- *Foresighted Programming*: programming should respond beyond the expressed problem while promoting architecture.

Looking at programming from an epistemological perspective, Sanoff (1997) introduced several ways to speculate the future behavior of built environments; *Casuistics* (a search for former similar cases with matching problems), *Analogy* (correspondence establishment among two sets of activities), *Experimentation* (an isolated sub-system built to resemble a reality to some extents), *Simulation* (an abstraction of real components with high level of resemblance), *Introspection* (impact imagination of a design decision by rationally scanning the potentials), *Hindsight* (the approach that avoids prediction by explicitly manifesting and building the design to understand and resolve the issues similar to what is seen in vernacular architecture), and *Taking the Risk* (to do what seems to be reasonable) (pp. 27-28).

With a similar attitude, Brian Schermer (2013) suggests seven methods to identify the "design future." These include: (1) Reasoning, which highlights the necessity for an organized manner of data gathering and analysis; (2) Prediction, which emphasizes on application of the scientific method to forecast how the built environment will perform; (3) Interpretation, in which subjectivity of designers/programmers towards design/program is a valuable attitude promoting physical design, which derives from the program; (4) Enactment, where powerful clients or designers with the ability to know the future enact a process to follow a reality matching their vision and will as opposed to an systematic investigation of information to reach an informed design solution; (5) Participation, in which upcoming users and others impacted by the project are involved in the process to guarantee its acceptance; (6) Deconstruction, where voice of certain stakeholders are intentionally ignored, and there is no other solution for them to have a say in the process but via conflict and resolution; and (7) Anticipation, which demands addressing not only the current needs, but also potential future desires by understanding how the organization would look like in a short and long term. [26]

As an integrated approach addressing positive aspects of the stated former programming methodologies, my suggested approach would cover most of these solutions although the notion of deconstruction (analysis

[26] Brian Schermer (2013), Seven Ways to Know the Design Future: Epistemology and Architectural Programming, In EDRA44Providence, 2013, Providence, RI.

vs. synthesis) can be more investigated. Looking through the lens that Schermer explicitly articulated, my proposed programming could be itemized as an approach that attempts to:

- Employ already-made design decisions for somehow similar or identical problems (Casuistics or Analogy defined by Sanoff, or Prototyping, as I would like to call).
- Follow a systematic process to address all the potential information leading to an informed decision akin to that of the agreement-based by Pena (Reasoning).
- Investigate client's need, values, and budget to understand the initial design scope akin to that of the design-based (Participation).
- Involve all the beneficiary parties and stake-holders who might be influenced in the process of design so that it addresses all their concerns akin to that of the value-based of Hershberger (Participation and interpretation).
- Conduct research and examine the similar case-study to better understand the design nature akin to that of the knowledge-based (Reasoning).
- Simulate/appraise the performance of design via continuous back and forth evaluation of both process and alternative design options, as figural concepts, akin to that of the issue-based of Duerk (Prediction).
- Think beyond the scope of the existing design requirements akin to that of the value-based (Anticipation).
- Expand its process so that it is initiated before the alternative design options, and continues through the process of developing the final design, construction, occupancy, and post-occupancy as a way to constantly monitor and evaluate it throughout the building's life. (Commissioning and Monitoring as I would like to call it).
- Propose undiscovered solutions, as physical concepts, that uniquely address design issues as well as stakeholders' values (Enactment).

1.5 Summary and Transition to Chapter II

Chapter I, along with the Preface, has presented a form of dialogue about some of the key design philosophies engaged in this dissertation. The combination has offered a preferred approach towards architectural design and topics related to the characteristics of "good" architecture. That is posited as an "inclusivist" approach enabled in optimistically addressing all potential issues related to the society,

environment, and economy. The chapter has expanded upon the importance of adopting an appropriate programming attitude in order to achieve high-performance solutions in regard to the good, presented earlier in the Preface section. Due to this significance, the chapter has comprehensively examined various approaches in architectural programming. Towards the end, the “Evaluative-Based” architectural programming approach was proposed, inspired by a combination of many of the advantages of existing approaches while eliminating some of the disadvantages. The approach suggested at the end is for the most part espousing ideas from the more methodical and comprehensive “Issue-Based Programming” by Donna Duerk. A major difference: the proposed approach highlights the notion of “evaluation” in reaching high-performance built environments. Characteristics of the proposed approach are listed from both the architectural practice and theory standpoints. In the end, it is argued that this programming approach has the capacity for leading design solutions that are not only addressing functional concerns, but are also derivative of a viewpoint wherein “Form Follows Performance.”

The next chapter will discuss in-depth the relationships between architectural design and “energy,” a matter within today’s main environmental challenges, one in need for constant assessment and innovation within architectural design as well as the building industry.

Chapter II: Design and Energy

2.1 Introduction

Buildings, if left by themselves without people, would not need other complementary energy for sustaining besides the embodied energy already used in putting them together.[27] Energy, however, becomes a crucial factor in the design of buildings with people, as an important substance consumed by occupied structures and dwellings with any interrelating presence of human beings. The interface and engagement between buildings and their occupants would inflict careful energy considerations for the integrations of systems that can provide best essential comfort and healthy environments for end users. On the one hand, the essential comfort and well-being of users in building must be considered in relation to thermal, visual, and acoustic aptitudes, and, by some means, amenities using electricity. The thermal comfort would aim to bring the air temperature, humidity, radiation, and air movement within the occupants' comfort zone. The visual comfort would maintain proper quality of light for different activities, which are also, preferably, coupled with desired vistas and views. The acoustic comfort would ensure the appropriate level of sound balance in a building, while eluding any disturbing noise. Moreover, the energy used for amenities and appliances such as the computers, television equipment, refrigerators, washers, dryers, and alike bring about other mandates needed for considerations in indirectly relating to the occupants' comfort. On the other hand, in addition to the categories explained above, the essential comfort and health of users in buildings should be evaluated with regard to the fresh, purified and unpolluted air surrounding the occupants. Enhancing the indoor air quality provided by proper volumes of ventilation and the selection of clean and suitable materials can make the occupants more healthy, productive, and comfortable.

In this dissertation, on the interaction between design and energy topic, my concentration will primarily be on Heating, Ventilation, and Air-Conditioning (HVAC). The tapered subject considered is the thermal and indoor air quality factors that can impact both a building's design typology and its energy use. This chapter, thus, will further elaborate on energy, its relation to thermal comfort and healthy environments, and their impacts on design.

[27] Embodied energy is different from the operational energy and is associated with the energy required during a building's construction process. Embodied energy in general definitions is the energy utilized upfront, in the production of a specific material or product. This is including the mining and processing of natural resources, manufacturing, transport, and delivery of the final product. The operational energy, in contrast, is associated with the energy used by a building's occupants, creating for them the comfort needed and a healthy environment. See:
Nadav Malin, N. (1993). Embodied Energy-just what is it and why do we care. *Environmental Building News, 2 (3)*, *1*. Retrieved from: https://www.buildinggreen.com/feature/embodied-energy-just-what-it-and-why-do-we-care, Date Accessed: March 15, 2016.

2.2 Energy

Energy in broader, philosophical sense is a foundation of the universe, a main source of movement, development, and transformation. In Galiano's (2000) account, "energy injects life, processes, and transformations into the inanimate world of matter, and thus into the world of architecture (p. 3)." Galiano perceives the energy associated with buildings in two ways: maintenance and construction. The two respectively relate to the energy consumption of users and the energy required to organize, modify, and repair the built environment (p. 5).

Energy in science and physics is the capability of performing work. The U.S. Energy Information Administration defines energy in simple terms as "the ability to do work." Energy comes in various forms: kinetic as the energy within motion, electrical energy produced by electricity, chemical energy released when fuel burns, radiant energy as related to light, nuclear energy gained from atoms, gravitational energy caused by gravity, and thermal energy as related to heat.[28] The 2009 handbook of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) inscribes that "energy has the capacity for producing an effect and can be categorized into either stored or transient forms."[29] Looking from this perspective, energy is put in the two categories: stored which is the potential energy stored between molecules, and working which is the kinetic energy of molecules in motion.

2.2.1 Units of Energy

In addition to qualitative attributes, energy is quantifiable. In the International System of Units, the joule, going by the symbol of J, is a derived unit of energy. One Joule is a mechanical work required against a force of one newton for one meter movement of an object. Energy is also perceived as the measure of power extended over time, where one joule is equivalent to one watt released for a second. A common unit in this case is kilowatt-hour (KWh) equal to 3600000 joules. Another commonly used unit for comparing various types of energies is the British thermal units (Btu), applied primarily for measuring thermal energy while the Btu/h is used as a measure for cooling and heating power, which is equal to approximately 1055 joules.

[28] The U.S. Energy Information Administration, Energy Explained, Retrieved from: https://www.eia.gov/energyexplained/index.cfm?page=about_home, Last updated: May 30, 2017, Date Accessed: May 18, 2017.
[29] Handbook, A. F. (2009). American society of heating, refrigerating and air-conditioning engineers. *Inc.: Atlanta, GA, USA*.

2.2.2 Sources of Energy

The source of energy can fall under either the “renewable” or “nonrenewable” categories. The renewable category refers to a source of energy that can be easily replaced, for instance, solar energy. The nonrenewable category, however, includes fossil energies such as coal, oil, and natural gas. Grondzik et al (2010) outline renewable sources as those “available indefinitely but are generally diffused and arrive at a rate controlled by nature” and nonrenewable sources as those “once exhausted, cannot be replaced in a timeframe that is meaningful to the human race” (p. 29).[30] According to the U.S. Energy Information Administration, nonrenewable energy sources represent around ninety percent of all energy used. Biomass, including wood, biofuels, and biomass waste, is the largest renewable source of energy accounting for about half of all renewable energy sources, included within about five percent of the total energy consumption in the United States.

Statistics would sum up to the point that, the largest portion of America’s energy consumption still comes from nonrenewable fossil energy sources such as the petroleum products, natural gas, and coal, also coupled with nuclear energy and hydrocarbon gas liquids. (Figure 2.1 illustrates the U.S. energy consumption by energy source, 2017). In addition to electricity and hydrogen as resultant secondary energy sources, eia lists the following major, and further environmentally-friendly, renewable sources: Solar (Photovoltaics, Solar Hot Water, Sunspaces, and Double-Skin Facades); Wind (Wind Turbines and Wind-Catchers); Geothermal (Geothermal Power Plants, Earth-Tubes, and Hypocaust Systems); Hydropower (Tidal and Wave Power); Biomass (Wood and Wood-Waste); and Biofuels (Ethanol & Biodiesel).

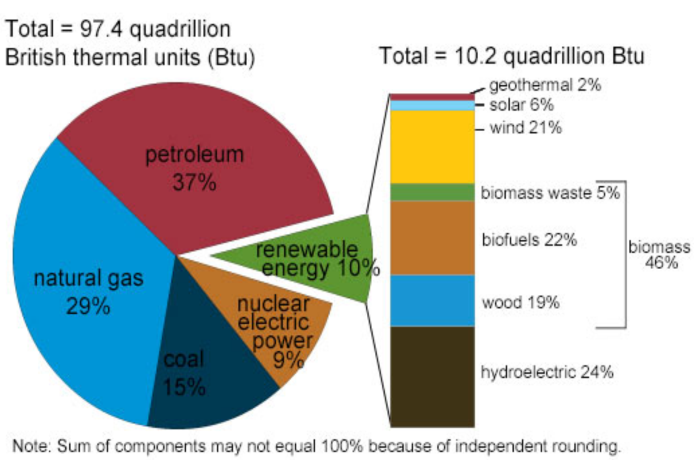

Figure 2.1

The U.S. energy consumption by energy source, 2016 (Source: U.S. Energy Information Administration (eia), *Monthly Energy Review*, Table 1.3 and 10.1, April 2017, preliminary data).

[30] Walter T Grondzik, Alison G Kwok, Benjamin Stein, and John S Reynolds (2009; originally published). Mechanical and electrical equipment for buildings, 11th ed

2.2.3 Energy Use

Today, most countries rely on nonrenewable energy resources, specifically, electricity, oil and natural gas. Listed by U.S. Energy Information Administration, energy sources are employed in various transportation, industrial, commercial, residential, and electric power sectors. Transportation needs include carrying individuals or merchandises via vehicles such as motorcycles, cars, busses, trucks, aircraft, trains, boats, and ships. Industrial necessities contain services and equipment types employed for mining, agriculture, manufacturing, and construction. Commercial requirements are used in offices, hotels, hospitals, schools, shopping centers, restaurants, warehouses, stores, and public worship/gathering places. Residential demands are used within the houses, dwellings, and apartments. Electric Power sectors use energy in facilities that generate most of the electricity consumed by the other sectors. Buildings are generally responsible for about forty percent of the world's total energy use, increasing as the population and energy utilization rate would increase. Figure 2.2 elucidates statistics related to the energy consumed by sector in 2016.

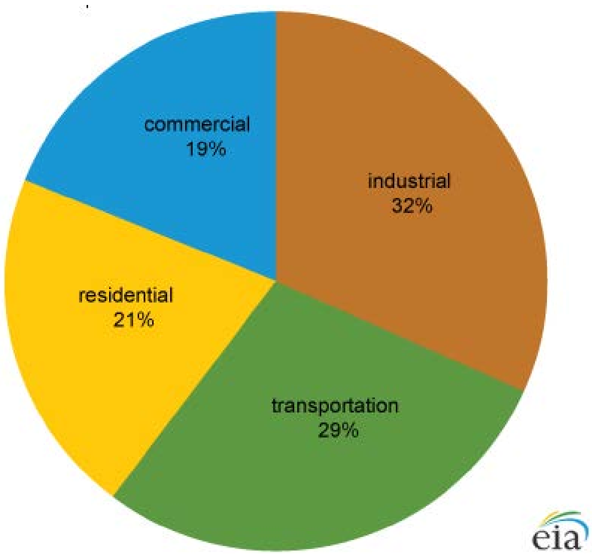

Figure 2.2

Percentages show the share of total U.S. energy consumed by end-user sector in the United States, 2016. Total number used is 97.4 quadrillion British thermal units (Source: U.S. Energy Information Administration (eia), *Monthly Energy Review*, Table 2.1, April 2017, preliminary data).

Existing data sets show the significance of considerations for the issue of energy involved in buildings. Accordingly, to be able to take appropriate approaches towards the involved energy, comprehensive energy-related understandings are essential. The occupants' comfort, as explained earlier, in relation to thermal, visual, acoustic, and indoor air quality factors as well as plug loads, should be seen as key consumers of energy in buildings. Proceeding paragraphs explicate the concepts of thermal comfort and ventilation. The

main focus includes discussions on the energy use intensity of HVAC, heating, ventilation, and air-conditioning. Figure 2.3.a demonstrates the energy use subdivisions used for homes and Figure 2.3.b displays the energy use categories used for commercial buildings.

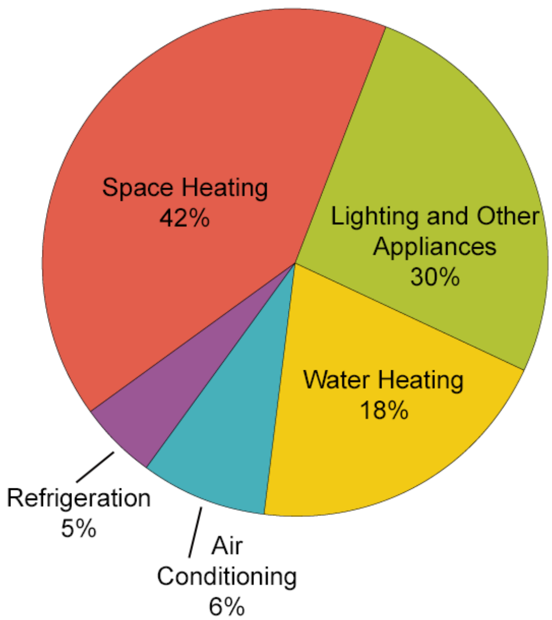

Figure 2.3. a

This 2009 statistics shows how energy is used at homes. [2009 is the most recent year for which data are available.] (Source: U.S. Energy Information Administration, *Residential Energy Consumption Survey (RECS) 2009*).

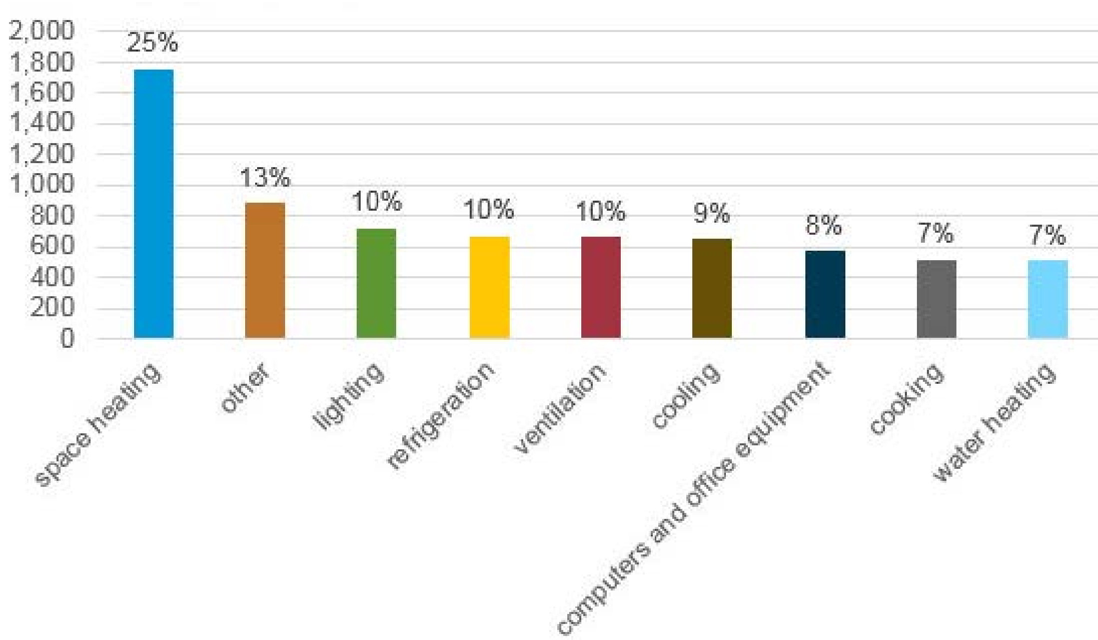

Figure 2.3. b

This 2012 statistics shows the energy use in U.S. for commercial buildings by major end-uses. Total number is trillion British thermal units. (Source: U.S. Energy Information Administration, *2012 Commercial Buildings Energy Consumption Survey: Energy Usage Summary,* Table 5, (March 2016).

Today, more than ever, the building industry is on the call-out to rely further on renewable energy sources such as sun, earth, wind, and water, as opposed to nonrenewable sources, which are considered actions destructive in our environments. Curiously, while going back in time, the modern movement in its beginnings had been in ways after the increase of efficiency in buildings. Albeit at the end, instead of relying on natural resources, some mechanical equipment features pushed in and became the energy monsters up until today. An indication to the statement is Le Corbusier's solar cycle, a perfect diagram on how energy from the sun and earth can be employed in a twenty-four-hour cycle of a single day (Figure 2.4).[31] In search for a response to address Grondzik et al's (2010) original question of: "is solar energy adequate for our energy needs (pp. 32-33)," the following list (Figure 2.5) resonates in its implied synthesis.

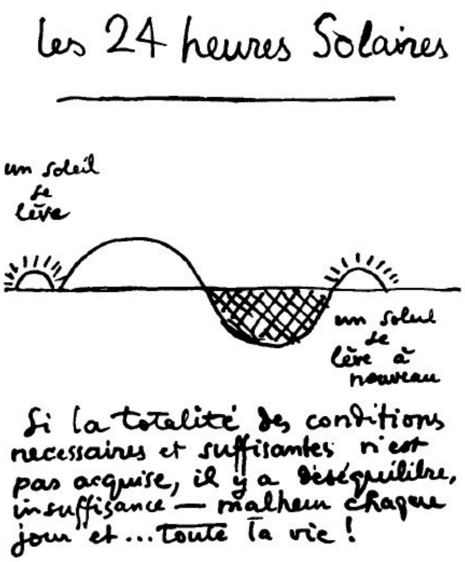

Figure 2.4
Solar Cycle sketch by Le Corbusier, 1946. "Le Corbusier under the empire of the orbits: the sun designs architecture, which is subjected to the logic of the cardinal points and the inexorable law of astral movement" (Source: Galiano, 2000, p. 26).

Figure 2.5
Earth's Daily Arrival of Solar Energy. The list indicates the earth's daily arrival of solar energy, paralleled to quantities from other sources (Source: Grondzik et al (2010, p. 37); Reprinted by permission from Lowry, W. 1988. Atmospheric Ecology for Designers and Planners. Peavine Publications, McMinnville, OR)

Solar energy received each day	1
Melting of an average winter's snow during the spring	1/10
A monsoon circulation between ocean and continent	1/100
Use of energy by all mankind in a year	1/100
A mid-latitude cyclone	1/1,000
A tropical cyclone	1/10,000
Kinetic energy of motion in earth's general circulation	1/100,000
The first H bomb	1/100,000
A squall line containing thunderstorms and perhaps tornados	1/100,000
A thunderstorm	1/1,000,000
The first A bomb	1/100,000,000
The daily output of Boulder Dam	1/100,000,000
A typical local rain shower	1/10,000,000,000
A tornado	1/100,000,000,000
Lighting New York City for one night	1/100,000,000,000

[31] Luis Fernández-Galiano (2000). Fire and Memory: On Architecture and Energy. Mit Press., p.26.

2.3 Thermal Comfort

Thermal comfort can be distinguished in two distinct ways: qualitative and quantitative. The latter is tangible, hence, measurable, while the former is intangible, therefore, more challenging to measure. The qualitative part is mainly associated with people/users and their physiological dimensions, which is something more challenging to measure. The quantitative part, however, is linked to the physical conditions and attributes of the environment surrounding the people. Merriam-Webster defines thermal as: “of, relating to, or caused by heat” and comfort as: “to ease the grief or trouble of.”[32] Basically put, the concept of thermal comfort help ease the discontents resulting from heat and temperature in buildings. ASHRAE Standard 55 (2013) refers to thermal comfort as “that condition of mind that expresses satisfaction with the thermal environment.”[33] Thermal comfort, in theory, deals with another duo area, of non-environmental and environmental. The former includes individuals’ activity and clothing factors while the latter takes account of the notions of temperature, humidity, radiation, and air movement.

In a framework, thermal comfort is, on the one hand, dependent upon individual choices and personal characteristics, of one’s body and preferences including the choice of one’s garments, for instance. It is, on the other hand, related to existing and created environmental conditions. In reality, however, thermal comfort is a lot more complex and embeds other factors beyond the stated elements. Intangible, psychological factors such as light, texture, color, sound, and scent are some of the other non-measurable factors that can play a substantial role in providing comfort. To design successful built environments that works towards the concept of “good” architecture, long elaborated in the dissertation’s preface, an inclusive perspective is needed that can consider all and beyond key psychological and intangible components. In the seminal book, *Thermal Delight in Architecture*, Lisa Heschong (1979) specifies thermal qualities linked to the attributes of “warm, cool, humid, airy, radiant, and cozy” as important elements in how spaces are experienced. Examples are the comfort experienced in a hot and arid climate garden as a cool “oasis” in a “desert” and a fireplace as the “hearth” in a “cold world” (illustrated in Figure 2.6). She describes:

> Thermal qualities might also be included in the architect’s initial conception and could influence all phases of design. Instead, thermal conditions are commonly standardized with the use of modern mechanical systems that can be specified, installed, and left to function independently of the overall design concept. Indeed, environmental control systems tend to be treated rather like the Cinderella of architecture; given

[32] Thermal. (n.d.). Retrieved July 25, 2017, from https://www.merriam-webster.com/dictionary/thermal; and Comfort. (n.d.). Retrieved July 25, 2017, from https://www.merriam-webster.com/dictionary/comfort.
[33] ASHRAE Standard 55 (2013). "Thermal Environmental Conditions for Human Occupancy".

only the plainest cloths to wear, they are regulated to a back room to do the drudgery that maintains the elegant life-style of the other sisters: light, form, structure, and so forth (p. vii).[34]

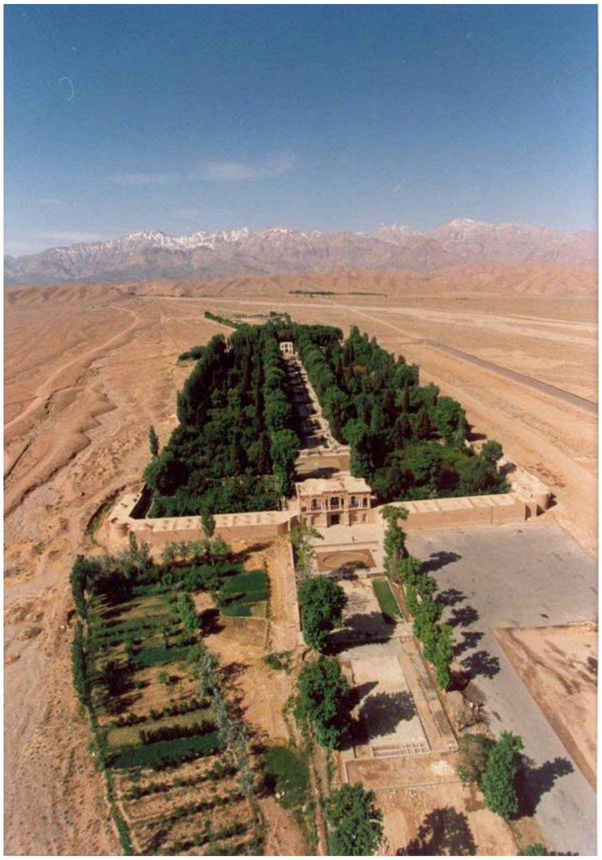

Figure 2.6

Left: Garden as a Cool "Oasis." Shazdeh Garden (*Bāgh-e Shāzdeh*: Persian) is located in the hot and arid climate of the city of Mahan, in the Kerman Province, Iran. This image represents an exceptional example of a historical Persian Garden appearing as an emerald oasis in the sand-color desert. Built originally for kings and noblemen, the retreat quality is buttressed by complex, vernacular systems of irrigation such as qanats, the underground irrigation canals made between an aquifer and the garden on the arid plain. (Image Source: Courtesy of the architect and photographer Afsaneh Mirfendereski.)[35]

Right: Fireplace as the "Hearth" in a "Cold World." The exposed fire of the fireplace gives away a spirit of warmness. This is a perception that is experienced despite that, in reality, large amounts of hot air are constantly being retired from the chimney stack. The notion of warmth as an item of perception is heightened by other senses, of sight, sound, touch, and smell. (Image Source: Courtesy of the architect and photographer Edward Allen; Originally Published in: Grondzik et al, 2010, p. 93)[36]

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[34] Lisa Heschong (1979). *Thermal Delight in Architecture*. MIT press.

[35] Retrieved from: http://www.afsaneharchitecture.com/architectural-photography/, Date Accessed: June 15, 2017.

[36] Grondzik et al (2010) similarly write: "Consider the courtyard in a hot, dry climate. Its fountain suggests coolness in the color and texture of its water; running water provides splashing sounds and sparkles of light and may generate some air motion. Vines provide shade, and their leaves sway in the slightest breeze, evidence of at least some air motion. Blossoms of flowering plants yield a cool fragrance that blends with the aroma of moistened surfaces in hot, dry surroundings. The measured coolness of such a courtyard may be but a slight improvement over the environment beyond, but it seems cool. Then consider a fireplace in a cold climate. The fire's color is intensely

The sophisticated outlooks presented extend the ways in which broader delineations of comfort can be provided, to say, intentionally and by proper design, leading to higher performance buildings. The illustration (Figure 2.7) is an interpretation of the statement, representing a means and concepts for providing thermal comfort with systems that are better integrated with the buildings themselves, instead of added-on mechanical equipment. There is no doubt that qualitative aspects, such as the ones stated, all play significant roles in the occupants' level of comfort in buildings. However, despite the importance, the elaboration of qualitative dimensions is beyond the scope of this dissertation. To narrow the scope, the following sections in the chapter would mainly focus on quantitative dimensions, numerical details related to non-environmental elements as well as roles that environmental elements can/should play in architectural design. From this discussion, parts of the assumptions of the research are extracted, refined for the following chapters and eventually used as major premises in the final energy model and simulation analysis of a Double Skin Façade (DSF) system.

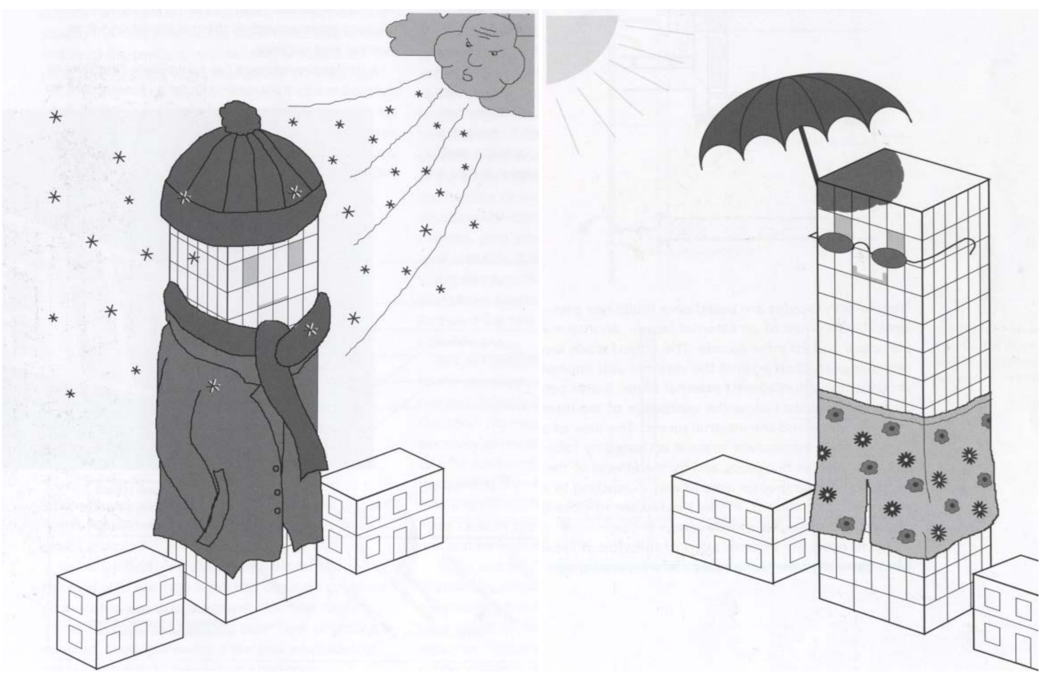

Figure 2.7
Thermal Comfort via Passive Integrated System. Taking buildings as living organisms, these anthropomorphist illustrations signify the importance of a multi-layered and complex attitude to architectural design. (Source: Lawrence, 2007)[37]

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warm, and it dances and casts a flickering light; it crackles, and it yields a smoky aroma (not appreciated by all). Few textures seem hotter than that of glowing coals. Yet a fireplace might add but slightly to the overall warmth of a room, because it draws in cold air to replace the air that passes up the chimney. We seek a place near the fire for the real radiant warmth, but also for the psychological comfort the fire offers (p. 92)."

[37] Tyson Lawrence (2007). Double-Skin Facades. ASHRAE Journal, 49(10), 70.

2.3.1 Non-Environmental Effects

To stay alive and properly function, human body maintains a specific range of temperature within itself via heat loss. This heat loss is mainly influenced by the type of activity performed and garment worn by an individual. Human body releases heat due to its metabolism, which is around 100 W of heat for a resting adult. This core temperature, generally, increases with the level of an individual's activity. Since the heat loss is happening by means of the skin, it could also be specified by the heat loss per unit area of skin, which is equivalent to 58 W/m², assumed to be 1 Met. According to ASHRAE (2009), an attentive ruling of body temperature is critical to human health and comfort. The temperature regularity center in the brain is about 36.8 °C at rest in comfort, increasing to about 37.4 °C in walking and to 37.9 °C in jogging. "An internal temperature less than about 28 °C can lead to serious cardiac arrhythmia and death, and a temperature greater than 46 °C can cause irreversible brain damage (p. 9.1)." Figure 2.8 shows the relationship between metabolic heat and human activities.

The choice of clothing is another non-environmental factor that can enhance or decrease an individual's thermal comfort. Clothing functions as insulation for the body against the various means of heat transfer, happening through convection, conduction, and radiation. Simply put, a thick-knitted blouse in a cold day, for example, can help a lot in protecting the skin from the exposure to wind, cold air, or excessive heat loss. In contrast, a light shirt can be more desirable in a hot day, allowing exposure to air movement coupled with supporting proper amounts of heat loss through the skin. Alongside, in the hot day, it is likewise important to protect the skin from any solar radiation. An appropriate garment in this case can also function as a shading device. Clothing's insulation value is normally measured in CLO units where one CLO is equal to a typical 1941 men's business suite. It is, thus, 0.155 m2 K/W in SI or 0.88 ft² h °F/Btu in Imperial system. The total CLO of a garment could be specified using specific values, illustrated in the Figure 2.9. "To regulate our body's heat loss," as Grondzik et al (2010) specify:

> We have available three common layers between our body cores and the environment: a first skin, which is our own; a second skin, our clothing; and a third skin, a building (p. 89).

Metabolic Rates for Typical Tasks

Activity	Met Units	Metabolic Rate W/m^2	(Btu/h·ft^2)
Resting			
Sleeping	0.7	40	(13)
Reclining	0.8	45	(15)
Seated, quiet	1.0	60	(18)
Standing, relaxed	1.2	70	(22)
Walking (on level surface)			
0.9 m/s, 3.2 km/h, 2.0 mph	2.0	115	(37)
1.2 m/s, 4.3 km/h, 2.7 mph	2.6	150	(48)
1.8 m/s, 6.8 km/h, 4.2 mph	3.8	220	(70)
Office Activities			
Seated, reading, or writing	1.0	60	(18)
Typing	1.1	65	(20)
Filing, seated	1.2	70	(22)
Filing, standing	1.4	80	(26)
Walking about	1.7	100	(31)
Lifting/packing	2.1	120	(39)
Driving/Flying			
Automobile	1.0-2.0	60-115	(18-37)
Aircraft, routine	1.2	70	(22)
Aircraft, instrument landing	1.8	105	(33)
Aircraft, combat	2.4	140	(44)
Heavy vehicle	3.2	185	(59)
Miscellaneous Occupational Activities			
Cooking	1.6-2.0	95-115	(29-37)
House cleaning	2.0-3.4	115-200	(37-63)
Seated, heavy limb movement	2.2	130	(41)
Machine work			
sawing (table saw)	1.8	105	(33)
light (electrical industry)	2.0-2.4	115-140	(37-44)
heavy	4.0	235	(74)
Handling 50 kg (100 lb) bags	4.0	235	(74)
Pick and shovel work	4.0-4.8	235-280	(74-88)
Miscellaneous Leisure Activities			
Dancing, social	2.4-4.4	140-255	(44-81)
Calisthenics/exercise	3.0-4.0	175-235	(55-74)
Tennis, single	3.6-4.0	210-270	(66-74)
Basketball	5.0-7.6	290-440	(92-140)
Wrestling, competitive	7.0-8.7	410-505	(129-160)

Figure 2.8
The table taken from ASHRAE indicates the typical metabolic heat generation for several human activities (Source: ASHRAE, 2009, p. 9.1).

Clothing Insulation Values for Typical Ensembles[a]

Clothing Description	Garments Included[b]	I_{cl} (clo)
Trousers	1) Trousers, short-sleeve shirt	0.57
	2) Trousers, long-sleeve shirt	0.61
	3) #2 plus suit jacket	0.96
	4) #2 plus suit jacket, vest, T-shirt	1.14
	5) #2 plus long-sleeve sweater, T-shirt	1.01
	6) #5 plus suit jacket, long underwear bottoms	1.30
Skirts/Dresses	7) Knee-length skirt, short-sleeve shirt (sandals)	0.54
	8) Knee-length skirt, long-sleeve shirt, full slip	0.67
	9) Knee-length skirt, long-sleeve shirt, half slip, long-sleeve sweater	1.10
	10) Knee-length skirt, long-sleeve shirt, half slip, suit jacket	1.04
	11) Ankle-length skirt, long-sleeve shirt, suit jacket	1.10
Shorts	12) Walking shorts, short-sleeve shirt	0.36
Overalls/Coveralls	13) Long-sleeve coveralls, T-shirt	0.72
	14) Overalls, long-sleeve shirt, T-shirt	0.89
	15) Insulated coveralls, long-sleeve thermal underwear tops and bottoms	1.37
Athletic	16) Sweat pants, long-sleeve sweatshirt	0.74
Sleepwear	17) Long-sleeve pajama tops, long pajama trousers, short 3/4 length robe (slippers, no socks)	0.96

[a] Data are from Chapter 8 in the *2001 ASHRAE Handbook—Fundamentals*.
[b] All clothing ensembles, except where otherwise indicated in parentheses, include shoes, socks, and briefs or panties. All skirt/dress clothing ensembles include pantyhose and no additional socks.

Figure 2.9
The table specifies Typical Clothing Insulation Values. (Source: Grondzik et al, 2010, p. 89).

2.3.2 Environmental Effects

Besides the personal factors specified earlier, thermal comfort is greatly influenced by the environmental criteria such as temperature, relative humidity, radiation, and air movement. Although each can play into the notion of comfort, the combination of all should be seen as a more important indicator. For instance, a high temperature of 26 °C (78.8 °F) could be perceived either as comfortable or not comfortable depending on the percentage of relative humidity, amount of solar radiation, and air movement. Proper levels of air movement, thus, can also make it more pleasant, on condition that one is located in a shaded area where relative humidity is not more than around 50%. With the same concept, a low temperature of 18 °C (64.6 °F) could feel more comfortable if one is exposed to sunrays. As also argued earlier, the type of the activity and metabolism one is engaged in can also have influences, either bringing a condition within or pushing it outside of one’s comfort zone (Figure 2.10).

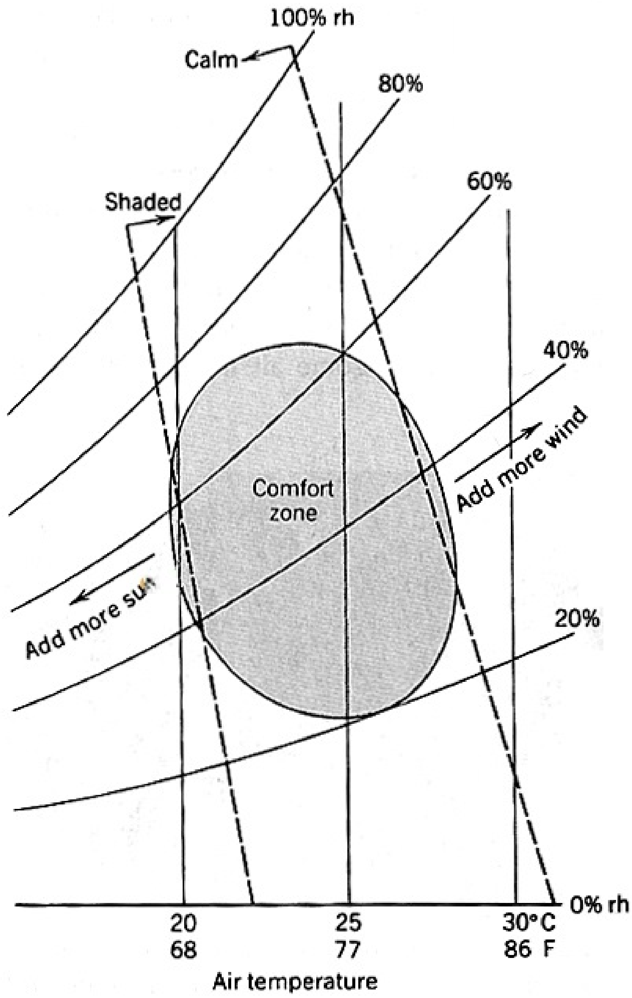


Figure 2.10
Comfort zone diagram based on air temperature and relative humidity (Source: Grondzik et al, 2010, p. 93).

Thermal comfort can be accurately diagrammed considering the operative temperature, which additionally includes radiation and air movement, humidity ratio, person's activity of 1-1.3 Met, and clothing value of 0.5 or 1 CLO in a specific air speed not greater than 0.20 m/s (40 ft/min). The result is valid for 80% occupant acceptability of healthy adults at atmospheric pressure up to 3000 m (10,000 ft) for a timeframe not less than 15 minutes. To understand this adaptive model, in accordance with ASHRAE's Section 5.2, it is textually supportive to start with a closer look at related concept definitions. According to BSR/ASHRAE Addendum d to ANSI/ASHRAE Standard 55-2004, Thermal Environmental Conditions for Human Occupancy, the following concepts are described:

Adaptive Model: a model that relates indoor design temperatures or acceptable temperature ranges to outdoor meteorological or climatological parameters.

Air Speed: the rate of air movement at a point, without regard to direction.

CLO: a unit used to express the thermal insulation provided by garments and clothing ensembles, where 1 CLO= 0.155 m2 °C/W (0.88 ft2 ·h·°F/Btu).

Comfort, Thermal: that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation.

Environment, Thermal: the characteristics of the environment that affect a person's heat loss.

Environment, Acceptable Thermal: an environment that a substantial majority of the occupants would find thermally acceptable.

Garment: a single piece of clothing.

Humidity Limit: Systems designed to control humidity shall be able to maintain a humidity ratio at or below 0.012, which corresponds to a water vapor pressure of 1.910 kPa (0.277 psi) at standard pressure or a dew-point temperature of 16.8 °C (62.2 °F).

Humidity Ratio: the ratio of the mass of water vapor to the mass of dry air in a given volume.

Humidity, Relative (RH): the ratio of the partial pressure (or density) of the water vapor in the air to the saturation pressure (or density) of water vapor at the same temperature and the same total pressure.

Insulation, Clothing/Ensemble (LCL): the resistance to sensible heat transfer provided by a clothing ensemble expressed in CLO units. Note: The definition of clothing insulation relates to heat transfer from the whole body and, thus, also includes the uncovered parts of the body, such as head and hands.

Insulation, Garment (LCLU): the increased resistance to sensible heat transfer obtained from adding an individual garment over the nude body expressed in CLO units.

Met: a unit used to describe the energy generated inside the body due to metabolic activity, defined as 58.2 W/m2 (18.4 Btu/h· ft^2), which is equal to the energy produced per unit surface area of an average person, seated at rest. The surface area of an average person is 1.8 m2 (19 ft^2).

Metabolic Rate (M): the rate of transformation of chemical energy into heat and mechanical work by metabolic activities within an organism, usually expressed in terms of unit area of the total body surface. In this standard, this rate is expressed in met units.

Percent Dissatisfied (PD): percentage of people predicted to be dissatisfied due to local discomfort.

Predicted Mean Vote (PMV): an index that predicts the mean value of the votes of a large group of persons on the seven-point thermal sensation scale.

Radiant Temperature Asymmetry: the difference between the plane radiant temperature of the two opposite sides of a small plane element.

Temperature, Air (ta): the temperature of the air surrounding the occupant.

Temperature, Dew Point (tdp): the temperature at which moist air becomes saturated (100% relative humidity) with water vapor (psdp = pa) when cooled at constant pressure.

Temperature, Mean Monthly Outdoor Air (ta(out)): this temperature is based on the arithmetic average of the mean daily minimum and mean daily maximum outdoor (dry-bulb) temperatures for the month in question.

Temperature, Mean Radiant (tr): the uniform surface temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual non-uniform space.

Temperature, Operative (to): the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non-uniform environment.

Temperature, Plane Radiant (tpr): the uniform temperature of an enclosure in which the incident radiant flux on one side of a small plane element is the same as in the existing environment.

Temperature, Standard Effective (SET): the temperature of an imaginary environment at 50% RH, <0.1 m/s air speed, and tr = ta in which the total heat loss from the skin of an imaginary occupant with an activity level of 1.0

Met and a clothing level of 0.6 CLO is the same as that from a person in the actual environment, with actual clothing and activity level.

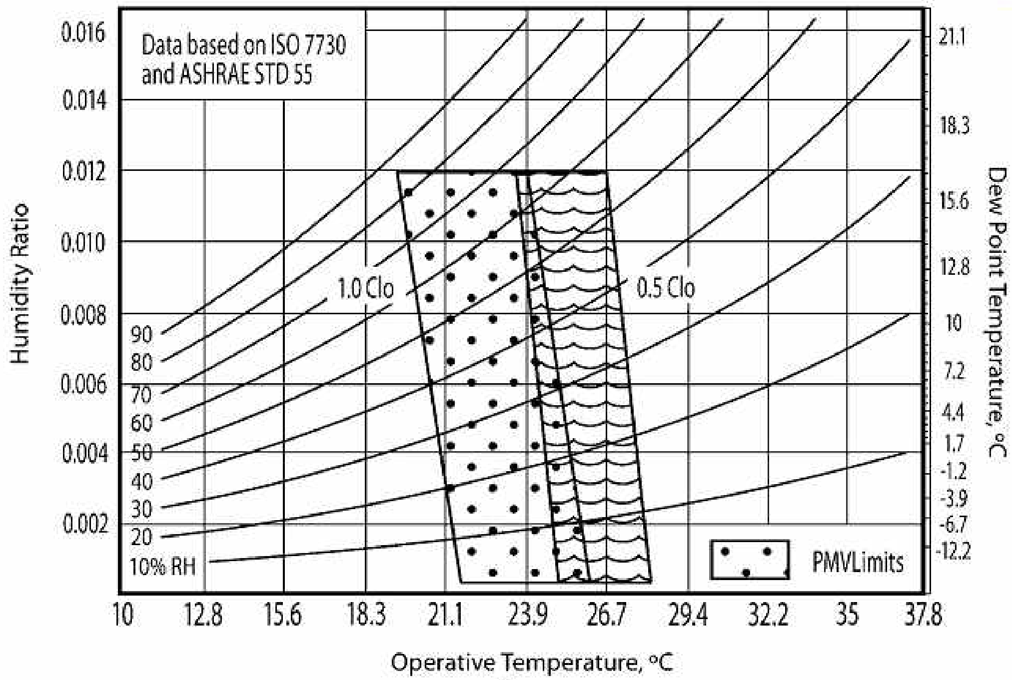
Water Vapor Pressure (pa): the pressure that the water vapor would exert if it alone occupied the volume occupied by the humid air at the same temperature.

Water Vapor Pressure, Saturated Dew-point (psdp): the water vapor pressure at the saturation temperature corresponding to the reference pressure and without any liquid phase.

Velocity, Mean (va): an average of the instantaneous air velocity over an interval of time.

Zone, Occupied: the region normally occupied by people within a space, generally considered to be between the floor and 1.8 m (6 ft) above the floor and more than 1.0 m (3.3 ft) from outside walls/windows or fixed heating, ventilating, or air-conditioning equipment and 0.3 m (1 ft) from internal walls.

Providing these definitions, then, graphic schemes are employed to comprehend the comfort zones for stated conditions. Two diagrams (Figure 2.11) show relationships between the humidity ratio and operative temperature in providing thermal comfort, in SI and Imperial. A third diagram (Figure 2.12) shows relationships between the increasing air speeds and temperature relative to thermal comfort. It is noteworthy to point out, the operative temperature can be presumed to be the same as the air temperature in a zone in certain conditions where there is no significant source of radiation in a space, and where high-performance walls/windows with low U-Value are used. (More information on operative temperature in Appendix A). Finally, illustrated ranges of thermal comfort can extend using proper passive cooling or heating strategies. For passive cooling, natural ventilation, high mass cooling, high mass cooling with night ventilation and evaporative cooling are suggested, as opposed to direct, indirect, and isolated gain for passive heating (Figure 2.13).



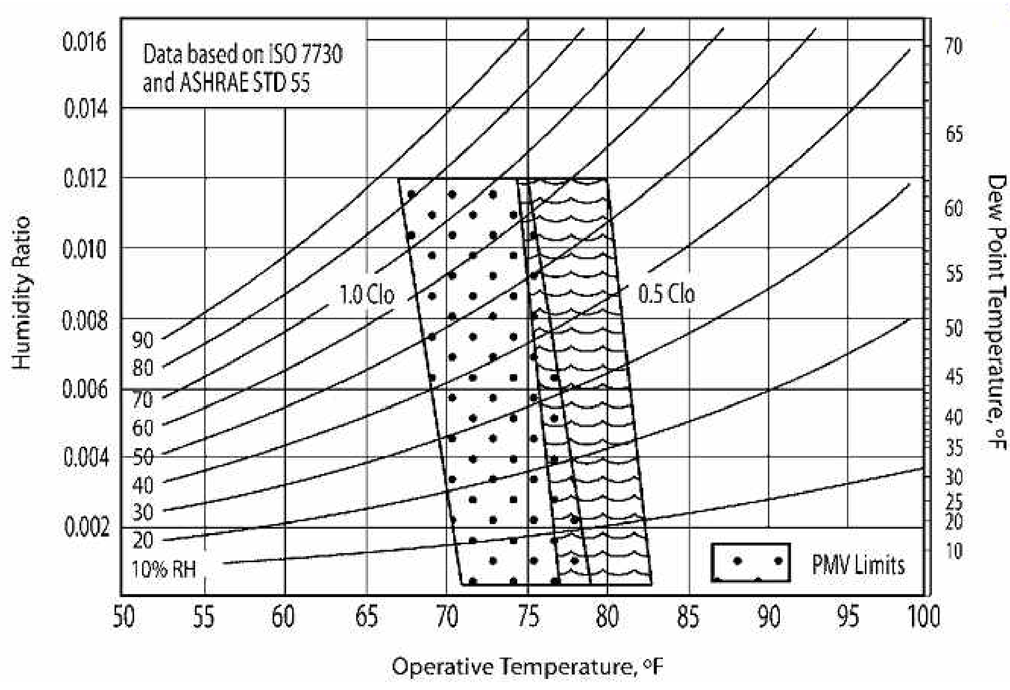


Figure 2.11
Diagrams show relationships between the humidity ratio and operative temperature within thermal comfort, in SI and Imperial (Source: ANSI/ASHRAE Standard 55-2004 Comfort Zone; Redrawn by Nathan Majeski; Reprinted with Permission of the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., from ANSI/ASHRAE Standard 55-2004, Thermal Environmental Conditions for Human Occupancy).

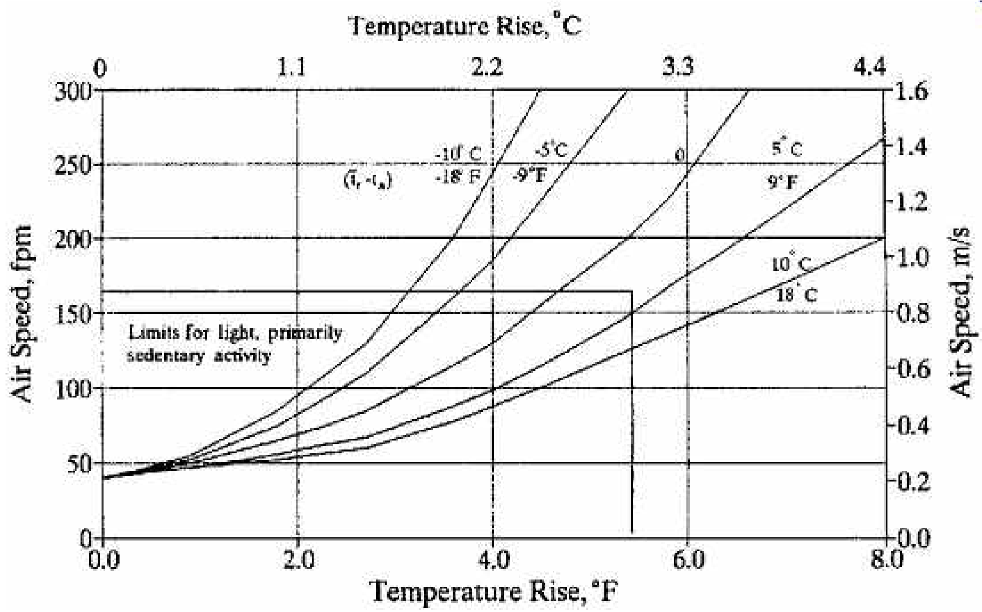


Figure 2.12
Diagrams show Relationships between increasing air speeds and temperature relative to thermal comfort (Source: The American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., from ANSI/ASHRAE Standard 55-2004, Thermal Environmental Conditions for Human Occupancy).

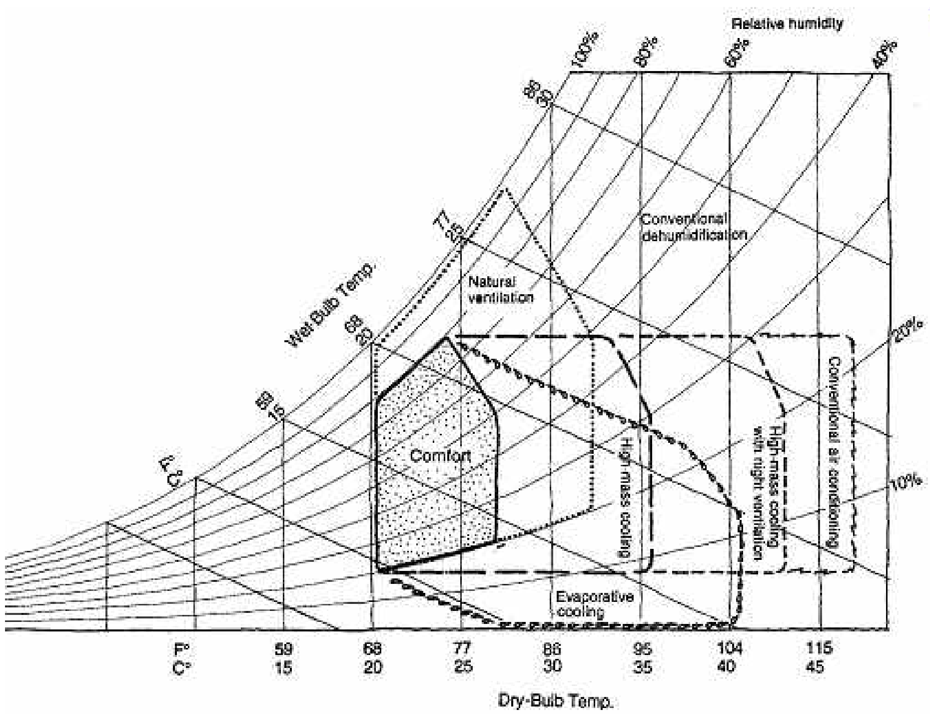


Figure 2.13
Diagram shows potential passive strategies for the extension of comfort (Source: Grondzik et al, 2010, p. 104; also see passive cooling design strategies by climate (Milne and Givoni, 1979)).

2.4 Thermal Comfort in Theory

This section focuses on the theoretical background, or, more specifically, the mathematical aspects of thermal comfort and elements affecting the concept, mainly using the 2009 ASHRAE Fundamentals Handbook (pp. 4.1-4.3), as major reference. It was earlier discussed that thermal comfort deals two categories of factors: environmental (temperature, humidity, radiation, and air movement) and non-environmental (individuals' activity and clothing choices). The following sections would first describe non-environmental factors closely linked to the psychrometric charts presented earlier, proceeding by renditions of environmental aspects with an emphasis on investigating HVAC applications. The investigation requires grasps of the principles related to the concept of *Heat Transfer,* as an important factor related to the creation, usage, and transformation of thermal energy.

2.4.1 Operative Temperature

Looking at Figure 2.11 on thermal comfort, the relationship between operative temperature and relative humidity is illustrated. This section explains the concept of operative temperature in a comparison to air temperature (dry bulb). Based on ASHRAE:

> Operative temperature is the average of the air temperature and the mean radiant temperature weighted, respectively, by the convective heat transfer coefficient and the linearized radiant heat transfer coefficient for the occupant. For occupants engaged in near sedentary physical activity (with metabolic rates between 1.0 met and 1.3 met), not in direct sunlight, and not exposed to air velocities greater than 0.20 m/s (40 fpm), the relationship can be approximated with acceptable accuracy by:

$$t_o = \frac{(t_a - t_r)}{2}$$

Where:

t_o = operative temperature,

t_a= air temperature, and

t_r= mean radiant temperature.

In addition, required air speed amounts to offset excessive temperature is shown in Figure 2.12. Using the following equation, a linear interpolation between the boundaries of 0.5 to 1.0 CLO can be applied in case of in-between values of clothing insulation to find out comfortable operative temperature ranges.

$$t_{min,Icl} = \frac{[(I_{cl} - 0.5 \text{ clo})\, t_{min,1.0clo} + (1.0 \text{ clo} - I_{cl})\, t_{min,0.5clo}]}{0.5 \text{ clo}}$$

$$t_{max,Icl} = \frac{[(I_{cl} - 0.5 \text{ clo})\, t_{max,1.0clo} + (1.0 \text{ clo} - I_{cl})\, t_{max,0.5clo}]}{0.5 \text{ clo}}$$

Where

$t_{max,Icl}$ = upper operative temperature limit for clothing insulation I_{cl}

$t_{min,Icl}$ = lower operative temperature limit for clothing insulation I_{cl}, and

I_{cl} = thermal insulation of the clothing in question (CLO)

2.4.2 Heat Transfer

Energy transferred due to temperature difference is known as heat transfer. This is a condition in which energy would move from warmer to cooler areas via three main methods: Convection, Conduction, and Radiation in a single-phase flow. In a given building, the interior atmosphere is generally impacted by simultaneous thermal transfer via the flow of heat through airflow by ventilation and infiltration (*Convection*), a solid material such as envelope assembly measured by U or R values (*Conduction*), emission by means of electromagnetic waves (*Radiation*) via fenestration, and transfer of energy by phase changes- which is associated with a two-phase flow.

2.4.2.1 Convection

Newton's law of cooling defines the rate of heat transfer for a surface of area A_s with temperature of t_s contacted with an in motion fluid such as air with temperature of t_∞ as:

$$q = h_c\, A_s(t_s - t_\infty) = \frac{(t_s - t_\infty)}{1/(h_c\, A_S)}$$

Where:

q is the rate of heat transfer

h_c is the *heat transfer coefficient* in $W/m^2 . K$

$1/(h_c\, A_S)$ is the convection resistance in K/W.

If $t_\infty > t_s$ (heat transfer from fluid to surface), the formula will be:

$$q = h_c\, A_s(t_\infty - t_s) = \frac{(t_\infty - t_s)}{1/(h_c\, A_S)}$$

Design Application: *the convection equation shows how the rate of heat transfer in a building is proportional to* <u>*area of exterior surface*</u> *exposed to ambient air. This notion highlights the necessity of taking an informed design decision. This also shows the set interior temperature difference with ambient air temperature- which is amongst the characteristics of a given site's climatic condition. This should be fully studied before a design option is proposed.*

2.4.2.2 Conduction

For a solid material such as a wall with the surface area of A_c for which one side has temperature of t_{s1} and the other side has temperature of t_{s2}, heat transfer of q happens from the warmer to cooler side of the wall. The heat transfer rate also depends on the thickness and material properties of the wall represented by *thermal conductivity.* Heat transfer, then, can be calculated as:

$$q = k\frac{(t_{s1} - t_{s2})A_c}{L} = \frac{(t_{s1} - t_{s2})}{L/(kA_c)}$$

Where:

q is the rate of heat transfer from one side to the other side

L is the wall thickness

k is the *thermal conductivity* in $W/m . K$

$L/(kA_c)$ is the *conduction resistance* in K/W.

__Design Application:__ the conduction equation shows how rate of heat transfer in a building is proportional to the <u>area of exterior surface</u> exposed to ambient air, their <u>thickness</u> and thermal <u>properties</u> (specifically R-Value), and also the set interior temperature difference with ambient air temperature- which is again characteristics of a given site's climatic conditions.

2.4.2.3 Radiation

Thermal emission or transmission at surface of substances in form of waves or photons of varying frequencies when its temperature is above absolute zero is defined as radiation. Unlike the other two stated forms of heat transfer, radiation does not require another medium to transport photons. A surface that absorbs all radiation incidents, *black surface* emits maximum energy at a given temperature. Stefan Bolzmann law specifies the heat emission from a black surface as:

$$q_{emitted,black} = A_s\, \sigma\, T_s^4$$

Where *black body* emissive power in W/m^2 is assumed to be:

$$E_b = \sigma\, T_s^4$$

And,

T_s is absolute surface temperature

K and $\sigma = 5.67 * 10^{-8}\ W/(m^2 . K^4)$ are Stefan Bolzmann constants

The emission per unit time per unit area is also as below if a surface is not black:

$$E = \varepsilon\sigma\, T_s^4$$

Where:

E is emissive power

ε is emissivity while $0 < \varepsilon < 1 \text{ or } = 1$ (for a black surface $\varepsilon = 1$

In addition, surfaces that are not black do not absorb all incident radiation. Therefore, the absorbed radiation is:

$$q_{absorbed} = \alpha A_s G$$

Where:

α is *absorptivity* (the fraction of incident radiation absorbed)

G is *irradiation* (the rate of radiant energy incident on a surface per unit area of the receiving surface due to emission and reflection from surrounding surfaces where for a black surface $\alpha = 1$)

For a gray surface, however, it is assumed that both ε and α are independent of wavelength and ($\alpha = \varepsilon$). The rate of energy exchange via radiation for two facing surfaces depends on relative size, relative orientation and shape, temperature, and emissivity and absorptivity. Yet, for a small surface of A_s at constant temperature of t_{surr} , the radiation from on surface from the surrounding is the black body emissive power of the surrounding $E_{b,surr}$.

If $t_s > t_{surr}$, net heat loss from gray surface A_s in the radiation exchange with the surrounding at t_{surr} is:

$$q_{net} = q_{emitted} - q_{absorbed} = \varepsilon A_s E_{bs} - \alpha A_s E_{b,surr} = \varepsilon A_s \sigma(T_s^4 - T_{surr}^4)$$

If $t_s < t_{surr}$,

$$q_{net} = \frac{E_{bs} - E_{b,surr}}{1/(\varepsilon A_s)}$$

2.4.3 Heat Flux

The heat flux in W/m^2 for convection, conduction, and radiation can be respectively written as:

$$q'' = \frac{q}{A_c} = h_c (t_s - t_\infty)$$

$$q'' = \frac{q}{A_c} = \frac{k(t_{s1} - t_{s2})}{L}$$

$$q''_{net} = \frac{q_{net}}{A_s} = \varepsilon\sigma(T_s^4 \text{-} T_{surr}^4)$$

***Design Application:** the radiation equations show how rate of heat transfer in a building is, yet again, proportional to the area of exterior surface exposed to sunrays, their color, texture, and material- which influence reflection/absorption properties, and also the ambient air temperature- which is, again, characteristics of a given site's climatic conditions.*

2.5 Thermal Comfort and Energy Loads

As one of the primary objectives of a successful building in regards to the notion of "good," which is extensively discussed in the Preface section, buildings should be designed in ways to provide ultimate comfort for their occupants. Towards this objective, thermal comfort plays a key role, demanding energy applications for bringing the indoor temperature within the comfort range. This is accomplished mainly via heating, cooling, dehumidification, and, in some cases, humidification. The energy associated with the sensible and latent heat is further discussed in the proceeding sections.

2.5.1 Cooling and Heating Loads

As mentioned, buildings can gain heat through three different heat transfer methods: conduction, convection, and radiation. At times and seasons not within the comfort of occupants, the accumulated heat should be removed by cooling the interior spaces, leading to cooling loads. Walter Grondzik et al (2010) identify the heat gain venues through the following components: (a) roof and walls, (b) glass, (c) outdoor air, (d) people, (e) light, (f) equipment, and (g) latent heat gain (pp. 282-283). Buildings also lose heat through their enclosures, if exposed to possibilities of cold ambient air. The heat that is lost would bring the demands of adding more heat to the interior spaces, leading to heating loads. These concepts are further clarified in the upcoming sections.

2.5.1.1 Cooling Loads

Cooling loads are determined based on the two categories of: sensible and latent loads. Sensible loads are due to heat gain from opaque surfaces, transparent fenestration surfaces, airflow introduction via ventilation and infiltration, appliances, and building occupants. Latent loads, however, are primarily correlated with humidity of the ambient air, when penetrating into a building, as well as with the humidity discharged from the occupants. Other miscellaneous causes include activities such as bathing, cooking, or laundry. The following rules for the sensible, latent, and total heat gains via volumetric airflow are offered by 2009 ASHRAE Fundamental Handbook (pp. 17.1-18.35):

$$q_s = C_s Q \Delta t$$

$$q_l = C_l Q \Delta W$$

$$q_t = C_t Q \Delta h$$

$$q_t = q_s + q_l$$

Where:

q_s, q_l, q_t are sensible, latent, and total heat transfer rates in W

C_s is air sensible heat factor in W/(L.s.K), which is around 1.23 at sea level

C_l is air latent heat factor in W/(L.s), which is around 3010 at sea level

C_t is air total heat factor in W/(L.s) per kJ/kg enthalpy h, which is around 1.2 at sea level

Q is air volumetric flow rate in L/s

Δt is air temperature differences across the process in K

ΔW is air humidity differences across the process in $\mathrm{kg_w/kg_{da}}$, and

Δh is air entalphy differences across the process in Kj/kg

Various types of sensible heat gains ensue while the latent heat gain types are left out, to be further discussed in the forthcoming “Ventilation Thermal Load” section.

Opaque surfaces

Opaque surfaces such as walls, roofs, floors, and ceilings generally gain heat from the temperature difference across the surfaces and the surfaces' solar gains incident. The Residential Load Factor (RLF) method is used to approximately estimate this type of heat gain as:

$$q_{opq} = A \times CF_{opq}$$

$$CF_{opq} = U\ (OF_t \Delta t + OF_b + OF_r DR)$$

Where:

q_{opq} is opaque surface cooling load in W

A is net surface area in m²

CF is surface cooling factor in W/m²

U is construction U-factor in W/(m².K), which is suggested by ASHRAE for different climatic conditions

Δt is cooling design temperature difference in K

DR is cooling daily range in K

$OF_t, OF_b, and\ OF_r$ are opaque surface cooling factors related to construction-specific physical characteristics seen in table 7 of 2009 ASHRAE Fundamental Handbook (p. 17.9)

The slab floors heat gain is specified by:

$$q_{opq} = A \times CF_{slab}$$

$$CF_{slab} = 1.9 - 1.4 h_{srf}$$

Where:

A is slab area in m²

CF_{slab} is slab cooling factor in W/m²

h_{srf} is effective surface conductance in W/m²

1.9 is constant in W/m²

1.4 is factor in K

The solar heat gain from building surfaces is impacted by Sol-Air (2009 ASHRAE Fundamental Handbook, p. 28.5):

> Sol-air temperature is the temperature of the outdoor air that, in the absence of all radiation changes, gives the same rate of heat entry into the surface as would the combination of incident solar radiation, radiant energy exchange with the sky and other outdoor surroundings, and convective heat exchange with the outdoor air.

Sol-air is given by:

$$q/_A = \alpha E_t + \ h_o(t_o + t_s) - \varepsilon \Delta R$$

Where:

α is absorptance of surface for solar radiation

E_t is total solar radiation incident on surface in W/m²

h_o is coefficient of heat transfer by long-wave radiation and convection at outer surface in W/(m².K),

t_o is outdoor air temperature in °C

t_s is surface temperature in °C

ε is surface hemispherical emittance

ΔR is difference between long-wave radiation incident on surface from

sky and surroundings and radiation emitted by blackbody at outdoor air temperature in W/m²

Therefore,

$$q/_A = \ h_o(t_e - t_s)$$

Transparent Fenestration Surfaces

Transparent fenestrations such as windows, skylight, and glass doors are the main elements that affect radiation traits of the heat transfer. These can also gain heat via their transparent glass surfaces. The radiation part could either be via direct or diffused solar beams.

Direct beam solar heat gain through fenestration is given by:

$$q_b = AE_{t,b}SHGC(\theta)IAC(\theta,\omega)$$

Defused solar beam is given by,

$$q_d = A(E_{t,d} + E_{t,r})(SHGC)_D\ IAC_D$$

Conductive heat gain is calculated based on the equation below,

$$q_c = UA(T_{out} - T_{in})$$

Finally, the total heat gain will be given as:

$$Q = q_b + q_d + q_c$$

Where:

q_b is direct beam solar gain in W

q_d is diffused beam solar gain in W

q_c is conductive solar gain in W

Q is total heat gain by fenestration in W

A is window area in m²

$E_{t,b}, E_{t,d}$, and $E_{t,r}$ are beam, sky diffuse, and ground-reflected diffuse irradiance in W/m²

$SHGC(\theta)$ is beam solar heat gain coefficient as a function of incident angle of θ

$(SHGC)_D$ is diffuse solar heat gain coefficient or hemispherical SHGC

t_{in} is inside temperature in °C

t_{out} is outside temperature in °C

$IAC(\theta,\omega)$ is indoor solar attenuation coefficient for beam solar heat gain coefficient

IAC_D is indoor solar attenuation coefficient for diffuse solar heat gain coefficient, and

U is overall U-factor including frame and mounting in W/(m².K)

The described equations were simplified methods for calculating heat transfer in terms of conduction, convection, and radiation. In practice, however, there is a time delayed response due to buildings thermal mass, which is disregarded in these equations. TRNSYS software applies a technique to calculate a building's transient heat conduction in which the stated time delay is considered via Conduction Transfer Function (CFT) method. This method is primarily developed on the concept of Comprehensive Room Transfer Function (CRTF) proposed by John Seem in his doctoral dissertation: Modeling of Heat Transfer in Buildings.

The procedure of buildings' transient heat transfer through walls and transparent surfaces are comprehensively explained in TRNSYS Multizone Building Modeling's manual under Mathematical Description of Type 56. The summarized explanation can be also found in Appendix G.

Occupants

The emission rate of humans' sensible and latent heat for different activities are illustrated (Figure 2.14). Careful considerations of the heat gain factors are essential in estimating a total heat gain, especially, for building types that admit at times higher number of users such as amphitheaters or movie salons.

Degree of Activity		Total Heat, Btu/h		Sensible Heat, Btu/h	Latent Heat, Btu/h	% Sensible Heat that is Radiant[b]	
		Adult Male	Adjusted, M/F[a]			Low V	High V
Seated at theater	Theater, matinee	390	330	225	105		
Seated at theater, night	Theater, night	390	350	245	105	60	27
Seated, very light work	Offices, hotels, apartments	450	400	245	155		
Moderately active office work	Offices, hotels, apartments	475	450	250	200		
Standing, light work; walking	Department store; retail store	550	450	250	200	58	38
Walking, standing	Drug store, bank	550	500	250	250		
Sedentary work	Restaurant[c]	490	550	275	275		
Light bench work	Factory	800	750	275	475		
Moderate dancing	Dance hall	900	850	305	545	49	35
Walking 3 mph; light machine work	Factory	1000	1000	375	625		
Bowling[d]	Bowling alley	1500	1450	580	870		
Heavy work	Factory	1500	1450	580	870	54	19
Heavy machine work; lifting	Factory	1600	1600	635	965		
Athletics	Gymnasium	2000	1800	710	1090		

Figure 2.14
Humans' sensible and latent heat for different activities (1997 ASHRAE Fundamental Handbook, p. 28.8).

Lighting and Appliances

Sensible heat gain of electric lighting, which mainly emits from lightbulbs, is calculated using the following equation:

$$q_{el} = W F_{ul} F_{sa}$$

Where:

q_{el} is heat gain in W

W is total light wattage in W/m²

F_{ul} is lighting use factor, and

F_{sa} is lighting special allowance factor

In addition, heat gain from generic appliances can be calculated by the equation below:

$$q_s = q_{input} F_U F_R$$

or

$$q_s = q_{input} F_L$$

Where:

q_s is appliance's sensible heat gain in W

q_{input} is appliance' nameplate or rated energy input in W

F_U is appliance' usage factor, and

F_R is lighting radiation factor

F_L is ratio of sensible heat gain to the manufacture's rated energy input

Shading devices such as overhangs, fins, louvers, or building projections could demand more sophisticated calculations for being enabled in accurately estimating the amount of solar radiation on fenestration or on opaque walls. Proper design for shading devices on a building is a weighty issue, which can play drastically into lowering solar heat gain, and, as result, lowing a building's cooling loads. The

ASHRAE Fundamental Handbook chapter on “Fenestration“ offers further details about shading devices and their impact on heat gain.

2.5.1.2 Heating Loads

Heat loss takes place by means of exterior surfaces that are above, at, or below grade. It can also happen via surfaces that are adjacent to a buffer space. In addition to these, infiltration can be seen as another venue for heat loss, occurring in concurrence with the other stated methods.

Above Grade Surfaces

For calculating heat loss through all the surfaces above the grade, they must all be treated identically as follows (2009 ASHRAE Fundamental Handbook, p. 18.30):

$$q = A \times HF$$

$$HF = U\Delta t$$

Where

HF is the heating load factor in W/ heat gain in W/m².

Below Grade Surfaces

For below grade surfaces such as walls, the following equation is applied:

$$HF = U_{avg}(T_{in} - T_{gr})$$

Where:

U_{avg} is average U-factor for below-grade surface in W/(m².K)

T_{in} is below-grade space air temperature in °C

T_{gr} is design ground surface temperature in °C from the equation below space air temperature in °C

The minimum ground surface temperature for heat loss calculation can be given by:

$$T_{gr} = mean\, T_{gr} - A$$

Where:

$mean\, T_{gr}$ is mean ground temperature in °C, estimated from the annual average air temperature

A is ground surface temperature amplitude in °C

T_{gr} is design ground surface temperature in °C from the equation below space air temperature in °C

The average U-factor that is indicated for the below-grade surfaces, and for walls, in particular, the equation below is utilized:

$$U_{avg,bw} = \frac{2k_{soil}}{\pi(z_1 - z_2)} \times [\ln\left(z_2 + \frac{2k_{soil}R_{other}}{\pi}\right) - \ln\left(z_1 + \frac{2k_{soil}R_{other}}{\pi}\right)]$$

Where:

$U_{avg,bw}$ is average U-factor for wall region defined by z_1 and z_2 in W/(m².K)

k_{soil} is soil thermal conductivity in W/(m.K)

R_{other} is total resistance of wall, insulation, and inside surface resistance in (m².K)/W

z_1, z_2 are depth of top and bottom of wall segment under consideration in m

For floors, this equation is given:

$$U_{avg,bf} = \frac{2k_{soil}}{\pi w_b} \times [\ln\left(\frac{w_b}{2} + \frac{z_f}{2} + \frac{k_{soil}R_{other}}{\pi}\right) - \ln\left(\frac{z_f}{2} + \frac{k_{soil}R_{other}}{\pi}\right)]$$

Where:

$U_{avg,bf}$ is average U-factor for floor in W/(m².K)

w_b is basement width as the shorter dimension in m

z_f is floor depth below grade in m

At Grade Surfaces

For at grade surfaces such as slabs, the following equation is used:

$$q = p \times HF$$

$$HF = F_p \Delta t$$

Where:

q is heat loss through perimeter in W

F_p is heat loss coefficient per meter of perimeter in W/(m.K)

p is perimeter of floor or exposed edge of it in m

In addition, the equation below is utilized for heat loss in order to create unconditioned or semi-conditioned buffer spaces:

$$HF = U(T_{in} - T_b)$$

Where T_b is the buffer space air temperature in °C.

2.5.1.3 Humidification/Dehumidification Loads

The humidification and dehumidification of the introduced air, which must be within the range of the occupants' comfort, is a part of the latent heat gain aspect, to be further elaborated in the "Ventilation Thermal Loads" section.

2.6 Buildings Environmental Health

Previous sections have discussed the concept of comfort in occupied buildings, specifically, thermal comfort and its required energy uses. A healthy environment is another aspect that needs to be examined to secure users' satisfaction. The World Health Organization (WHO) defines health as "a state of complete

physical, mental and social well-being and not merely the absence of disease or infirmity."[38] Various elements can impact the health and well-being of a building's indoor environment, amongst which air quality is playing a substantial role. This is more critical when one thinks of indoor environments wherein people spend most of their time. Sick Building Syndrome (SBS) and Building-Related Illness (BRI) are two common issues that have raised the designers' responsibility in addressing indoor health. SBS, taking slightly varied definitions, generally refers to "a range of symptoms that an occupant experiences while present in the building (Liddament, 1996, p. 39)."[39] ASHRAE 2009 Fundamental makes clearer that:

> SBS describes a number of adverse health symptoms related to occupancy in a "sick" building, including mucosal irritation, fatigue, headache, and, occasionally, lower respiratory symptoms and nausea. There is no widespread agreement on an operational definition of SBS. Some authors define it as acute discomfort (e.g., eye, nose, or throat irritation; sore throat; headache; fatigue; skin irritation; mild neurotoxic symptoms; nausea; building odors) that persists for more than two weeks at frequencies insignificantly greater than 20%; with a substantial percentage of complainants reporting almost immediate relief upon existing the building.

Air contaminants can be put in different categories in terms of their pollutant types (*gaseous*, *organic*, or *particulate)*, or their pollutant effects (*odors*, *irritants*, *toxic particulate substances*, *biological contaminants,* and *radon and soil gases*). Notwithstanding the contaminants' source and the type of effect a contaminant could have, the introduction of fresh air into the indoor spaces can reduce the possibilities of unhealthy atmosphere or, at least, can possibly dilute it. Yet, some serious contaminants such as radon, asbestos, and pesticides should be initially completely excluded, eliminations seriously considered both during the design phase and the construction process. The understandings and remediation strategies for contaminants are essential in enhancing buildings' indoor air quality (Figure 2.15). Existing odors and moldiness is uncomfortable, as Grondzik et al (2010) put, and buildups of pollutants such as formaldehyde and radon gas occurring in buildings are dangerous. Fresh airflow can best help in removing these pollutants (p. 207). According to Liddament (1996), ventilation is needed:

> … to provide oxygen for metabolism and to dilute metabolic pollutants (carbon dioxide and odour). It is also used to assist in maintaining good indoor air quality by diluting and removing other pollutants emitted within a space but should not be used as a substitute for proper source control of pollutants. Ventilation is additionally used for cooling and (particularly in dwellings) to provide oxygen to combustion appliances. Good ventilation is a major contributor to the health and comfort of building occupants (p. 20).

[38] Bibliographic citation: Preamble to the Constitution of WHO, adopted by the International Health Conference, New York, 19 June - 22 July 1946; signed on 22 July 1946 by the representatives of 61 States (Official Records of WHO, no. 2, p. 100) and entered into force on 7 April 1948. The definition has not been amended since 1948. Retrieved from: http://www.who.int/suggestions/faq/en/, date accessed: June 18, 2017.
[39] Martin W. Liddament (1996). A Guide to Energy Efficient Ventilation. 1996. AIVC: Coventry.

The energy required concerning ventilation depends on the amount of airflow and related conditioning levels to bring the need air flow within the occupants' comfort zone. Around 30% of the Energy Use Intensity (EUI) in buildings is consumed for ventilation and exfiltration airflows (Liddament, 1996, p. 26). This highlights the significance of ventilation consideration for generating and increasing energy efficiency, which has impacts both in terms of cost reduction and environmental benefits. Contemporary design and construction must rethink the integration of smarter ventilation solutions. This should happen via an integrated process and building system approach, taken as a crucial factor with a high priority from the early stages of architectural design. The sections to follow aim to present some grasps of the concept as well as evaluate the impact of context and its existing conditions on air flow within buildings. These are then coupled with a presentation of alternative design solutions as options.

Pollutant	Sources	Effects	Control Strategies
Excess moisture[a]	Cooking (heating open liquids), washing, exhaling	Increases growth of fungi, bacteria, and dust mites	Exhaust ventilation at source; dehumidification
Carbon dioxide (CO_2)	Human respiration	Minor discomfort at high concentrations; "stuffiness"	CO_2 is a good indicator of the ventilation rate in tightly enclosed spaces or where occupancy is high
Carbon monoxide (CO)	Incomplete combustion: furnaces, stoves, fireplaces, motor vehicle exhaust	Headaches, dizziness, sleepiness, muscle weakness, potentially lethal	Sealed combustion burners, adequate combustion air, safe exhaust flues
Nitrogen oxides	High-temperature combustion	Irritation, possible immune suppression	Safe exhaust flues, sealed combustion burners
Sulfur oxides	Combustion fuels containing sulfur (oil, coal)	Potential irritant, burning eyes, reduces lung function	Alternative fuels, safe exhaust flues, sealed combustion burners
Polynuclear aromatic hydrocarbons	Smoking, combustion of wood or coal, barbecuing, burnt food	Irritants and carcinogens	Prohibit smoking, lower temperature in cooking, use clean fuels, burn wood in enclosed firebox with adequate oxygen supply
Ozone	Laser printers, photocopiers, small motors, electronic air cleaners	Inflammation of bronchia, wheezing and shortness of breath, dizziness, asthma attacks	Remove sources or exhaust at source, maintain electronic air cleaners
Volatile organic compounds (VOCs) Formaldehyde	Particle board, interior laminated panels, glues, fabric treatments, paints	Burning eyes and nose, skin rash, shortness of breath, headaches, nausea, dizziness, fatigue	Use alternative materials, seal particle board if used, ventilate
Others	Paints, solvents, carpets, soft plastics, adhesives, caulkings, softwoods, paper products, cleaning and maintenance products	Intoxication, burning eyes and nose, shortness of breath, headaches, nausea, dizziness, loss of judgment, panic	Use alternative materials, age materials before installing, ventilate
Lead	Pre-1970s paint, pre-1985 pipes and solder, dust and soil near roads (residue from leaded gas)	Neurotoxic, especially if ingested by young children; learning disabilities, nausea, trembling, numbness of extremities	Identify and remove or seal old paint, replace pipes and solder, avoid foods grown by roadside
Pesticide residues[b]	Treated basements and foundations, treated ceiling and wall cavities, treated cabinets and closets, treated soil outside foundation	Neurotoxic or long-term risk of liver, kidney, and other diseases, including cancers	Identification and removal by expert if history known, sealing in pesticide if possible
Asbestos fiber	Pre-1975 steam pipe and duct insulation, furnace and furnace parts, pre-1980 reinforced vinyl floor tile, and fiber cement shingles and siding	Long-term cancer risk from inhaling fibers	Leave material undisturbed, get expert identification and removal if required, seal with special sealant and cover with sheet metal if not crumbling
Mineral and glass fiber	Thermal insulation, pipe insulation, fire-resistant acoustic tile and fabrics	Potential irritant, burning eyes, itching skin, long-term risk of lung damage and cancer	Handle only with respirator and gloves, seal and enclose, do not disturb in place
Fungus particles, dust mites	Grow in basements, damp carpet, bedding, fabrics, walls and ceilings, closets	Very allergenic, burning eyes and nose, sneezing, skin rash, congestion, and shortness of breath	Keep surfaces dry and clean, cover bedding and upholstery with barrier cloth, ventilate, use borax treatments to retard fungus
Hazardous bacteria (e.g., *Legionella*)	Standing warm water, untreated hot tubs, air-conditioning drain pans, humidifier reservoirs	Severe respiratory illness, potentially lethal	Prevent standing water, clean and treat tubs and reservoirs
Radon gas	Natural radioactivity in soils	Increased lifetime lung cancer risk	Seal foundation and floor drains, ventilate subsoil
Methane and other soil gases	Decomposing garbage in landfills, leaking sewage lines, toxic waste	Possibly explosive or toxic, nuisance odors	Know site history before building, remove soil if necessary, seal foundation and floor drains, ventilate subsoil

Figure 2.15
The table illustrates most common indoor air contaminants, and their impact and removal tactics. (Source: Grondzik et al, 2010, p. 207; adapted from original (Rousseau and Wasley, 1997)).

2.7 Ventilation; Indoor Air Quality

Indoor Air Quality (IAQ) is the key in providing a healthy environment for building occupants (Liddament, 1996, p.15). It is essential to discern that Americans spend about ninety percent of their time indoors (Cottrell, 2014, p. 11).[40] Conventionally, the health aspects of indoor environments were met through applications of natural ventilation, making buildings less efficient by increasing heating and cooling loads. With the introduction of excessive and uncontrolled ambient air into buildings in cold seasons, for instance, heating comfort became a crucial. In the case of hot seasons, the ambient air would be either too hot or humid. The BuildingGreen platform specifies three procedures for promoting fresh and uncontaminated air in buildings: finding the proper ventilation level, specifying products with no problematic chemicals emission, and adjusting pressure differentials to avoid involuntary permission of contaminated air.[41] The acceptable rate of IAQ is defined by ASHRAE Standard 62.1, 2007 as the "air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction." Grondzik et al (2010) present three primary rationales on the importance of IAQ in contemporary buildings. Firstly, people are spending most of their time in indoor environments. Secondly, the industrial era and the presence of various chemicals around built environment have been increasingly producing potential air contaminants. Thirdly, the energy crisis of 1973 has raised an awareness on energy issues, imposing careful attentions to the amount of introduced ambient air. As a result, four major issues are considered in offering an acceptable IAQ (p. 116):

1. Restrict initial contamination by careful selection of materials and equipment
2. Isolate inevitable pollution sources
3. Provide acceptable resource as well as filtering for fresh or reused air
4. Maintain clean condition for buildings and their equipment

Ventilation, after minimizing all potential pollution sources, will be the solution to address buildings' environmental health. Historically, ventilation has always been one of the main considerations towards human comfort in early dwellings. In traditional architectural schemes, long before the emergence of mechanical and electrical gears, natural ventilation methods had been integrated parts, assembled well into the making of buildings as whole systems. Such integrated systems were not added-on elements to the buildings, but embedded within, mostly under laws of nature, using many of the benefits of the surrounding

[40] Cottrell, M. (2014). *Guide to the LEED Green Associate V4 Exam*. John Wiley & Sons.
[41] BuildingGreen is a valuable online resource that, since 1985, have been assisting architects, designers and other sustainability-related professional in making their projects healthier and greener. This online platform has provided a reliable resource on healthy and sustainable design and construction strategies. Link: https://www.buildinggreen.com/about.

natural resources such as sun, wind, water, and earth. Modern architecture has also, at times, had the good intentions to aim at increasing human comfort levels, however, at other times, also closing the eyes to ecological consciousness. Modern approaches reached a point in time when a devotee, Le Corbusier (1991) dared to say: "a window is to give light, not to ventilate! To ventilate we use machines; it is mechanics, it is physics (p. 56)."[42]

A primary task within a designer's responsibilities should, thus, be to suggest sustainable strategies to deliver proper levels of ventilation. In this regard, two disparate types of approaches are possible: passive and active. Passive solutions include the design of appropriate types of fenestration, stack effect, under-slab ventilation, and pre-conditioned ventilation air. Active solutions demand exhaust fans, heating/cooling of makeup air, heat exchangers, desiccant cooling, task dehumidification and humidification, filters, locating air-cleaning equipment, ultraviolet (UV) radiation, individual space air cleansing, and controls for IAQ (Grondzik et al, 2010, pp.125-148). At this stage of the research, a pertinent question to be asked is: how much fresh air is desired for an acceptable IAQ? To answer this question, it is essential to investigate the function of a building (building type), its volume (building square footage), and the number of its occupants. ASHRAE specifies the minimum level of ventilation (Figure 2.16). Based on the table, as an example, the standard ventilation rate for an 80 m^2 office space with 8 people would be 44 L/s [(0.3 L/s. m^2 x 80 m^2) + (2.5 L/s x 8)], which is equal to 185.4 kg/h equivalent of 91.66 cfm. After all, the objective of reducing air contaminants can be achieved via ventilation, either naturally or by mechanical means, which will be discussed in further detail in the following sections.

[42] Le Corbusier (1991). *Precisions*. Cambridge, MA, MIT Press.

TABLE 6.2.2.1 Minimum Ventilation Rates in Breathing Zone *(Continued)*
(Table 6.2.2.1 shall be used in conjunction with the accompanying notes.)

Occupancy Category	People Outdoor Air Rate R_p cfm/person	People Outdoor Air Rate R_p L/s·person	Area Outdoor Air Rate R_a cfm/ft²	Area Outdoor Air Rate R_a L/s·m²	Notes	Default Values: Occupant Density (see Note 4) #/1000 ft² or #/100 m²	Default Values: Combined Outdoor Air Rate (see Note 5) cfm/person	Default Values: Combined Outdoor Air Rate (see Note 5) L/s·person	Air Class
General									
Break rooms	5	2.5	0.06	0.3	H	25	7	3.5	1
Coffee stations	5	2.5	0.06	0.3	H	20	8	4	1
Conference/meeting	5	2.5	0.06	0.3	H	50	6	3.1	1
Corridors	—	—	0.06	0.3	H	—			1
Occupiable storage rooms for liquids or gels	5	2.5	0.12	0.6	B	2	65	32.5	2
Hotels, Motels, Resorts, Dormitories									
Bedroom/living room	5	2.5	0.06	0.3	H	10	11	5.5	1
Barracks sleeping areas	5	2.5	0.06	0.3	H	20	8	4.0	1
Laundry rooms, central	5	2.5	0.12	0.6		10	17	8.5	2
Laundry rooms within dwelling units	5	2.5	0.12	0.6		10	17	8.5	1
Lobbies/prefunction	7.5	3.8	0.06	0.3	H	30	10	4.8	1
Multipurpose assembly	5	2.5	0.06	0.3	H	120	6	2.8	1
Office Buildings									
Breakrooms	5	2.5	0.12	0.6		50	7	3.5	1
Main entry lobbies	5	2.5	0.06	0.3	H	10	11	5.5	1
Occupiable storage rooms for dry materials	5	2.5	0.06	0.3		2	35	17.5	1
Office space	5	2.5	0.06	0.3	H	5	17	8.5	1
Reception areas	5	2.5	0.06	0.3	H	30	7	3.5	1
Telephone/data entry	5	2.5	0.06	0.3	H	60	6	3.0	1

GENERAL NOTES FOR TABLE 6.2.2.1

1 **Related requirements:** The rates in this table are based on all other applicable requirements of this standard being met.
2 **Environmental Tobacco Smoke:** This table applies to ETS-free areas. Refer to Section 5.17 for requirements for buildings containing ETS areas and ETS-free areas.
3 **Air density:** Volumetric airflow rates are based on dry air density of 0.075 lb_{da}/ft^3 (1.2 kg_{da}/m^3) at a barometric pressure of 1 atm (101.3 kPa) and an air temperature of 70°F (21°C). Rates shall be permitted to be adjusted for actual density.
4 **Default occupant density:** The default occupant density shall be used where the actual occupant density is not known.
5 **Default combined outdoor air rate (per person):** Rate is based on the default occupant density.
6 **Unlisted occupancies:** Where the occupancy category for a proposed space or zone is not listed, the requirements for the listed occupancy category that is most similar in terms of occupant density, activities, and building construction shall be used.

ITEM-SPECIFIC NOTES FOR TABLE 6.2.2.1

A For high-school and college libraries, the values shown for "Public Assembly Spaces—Libraries" shall be used.
B Rate may not be sufficient where stored materials include those having potentially harmful emissions.
C Rate does not allow for humidity control. "Deck area" refers to the area surrounding the pool that is capable of being wetted during pool use or when the pool is occupied. Deck area that is not expected to be wetted shall be designated as an occupancy category.
D Rate does not include special exhaust for stage effects such as dry ice vapors and smoke.
E Where combustion equipment is intended to be used on the playing surface or in the space, additional dilution ventilation, source control, or both shall be provided.
F Default occupancy for dwelling units shall be two persons for studio and one-bedroom units, with one additional person for each additional bedroom.
G Air from one residential dwelling shall not be recirculated or transferred to any other space outside of that dwelling.
H Ventilation air for this occupancy category shall be permitted to be reduced to zero when the space is in occupied-standby mode.

Figure 2.16
Minimum Ventilation Rates in Breathing Zones (Source: ANSI/ASHRAE Standard 62.1-2016, p. 14).

2.7.1 Ventilation Units

Ventilation rate can be described in several units. The followings are adapted AIVC's definitions:

Volumetric flow rate: A commonly expressed unit of ventilation and air infiltration indicated by liters/s (l/s) or m^3/s.

Per occupant air flow rate: The volumetric flow rate divided by the number of a space's occupants specifying flow rate for each occupant, which is expressed in terms of liters/second per person or l/s.p.

Unit area flow rate: Likewise, the air flow rate divided by the floor area of a building representative of a unit area value, which is defined by liters/second.m^2.

Air change rate: Sometimes, air flow is expressed based on hourly 'air change rate' (ach), which is volume of airflow rate into a room, zone, or building divided by its volume.

Mass flow rate: At times, airflow rate is expressed by the mass flow rate of air (kg/s) for determination of the thermal energy held by airflow.

2.7.2 Ventilation versus Infiltration

Air can travel into a building in two ways depending on how sealed or leaky the building is. This air introduction can happen intentionally, to provide fresh and healthy air (ventilation), or unintentionally, via cracks and small orifices on building envelopes (infiltration). The 2009 ASHRAE Fundamentals Handbook's (p. 16.1) description of ventilation is that it is the "intentional introduction of air from outside into a building." Infiltration is described as "the flow of outdoor air into a building through cracks and other unintentional openings and through the normal use of exterior doors for entrance and egress."

Both infiltration and ventilation are first and foremost influenced by natural forces (pressure difference resulting from temperature difference and wind) or mechanical forces. Negative pressure caused by a mechanical equipment can change the direction of airflow to be from building toward outside. This is called exfiltration, as opposed to the common direction of outside towards buildings. In a high-performance building, therefore, tightness of the envelope is central to energy efficiency, since the introduction of unintentional ambient air, typically with humidity, could demands more energy to bring it within the comfort zone. The relationship between airflow and buildings are discussed below (Figure 2.17).

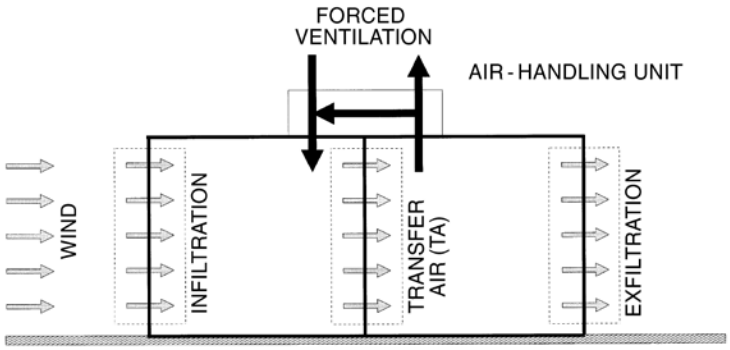


Figure 2.17
Diagram of Ventilation, Infiltration, Exfiltration, and Transfer Air in a two-space building. This illustrates the relationship between airflow and buildings while *Transfer air* (ta) is assumed to be the air movement between interior spaces no matter intentionally or not. (Source: 2009 ASHRAE, p.16.2).

2.7.3 Natural versus Forced Ventilation

Natural Ventilation has been the main IAQ solution for centuries much until the 20th century, when this was gradually replaced by mechanical systems. As implied from the name, natural ventilation is the introduction of ambient air into buildings via natural means without the aid of any mechanical equipment. Forced or mechanical ventilation both delineate deliberate flows of air into and out of buildings via means such as fans and intake and exhaust vents. Forced ventilation refers to the same process, but where mechanical systems are the main force of air introduction. In his report for AIVC, A Guide to Energy Efficient Ventilation, Liddament (1996) asserts that "ventilation is the process by which 'clean' air (normally outdoor air) is intentionally provided to a space and stale air is removed. This may be accomplished by either natural or mechanical means (p. 20)." The 2009 ASHRAE Handbook also defines natural ventilation as "the flow of air through open windows, doors, grilles, and other planned building envelope penetrations, and it is driven by natural and/or artificially produced pressure differentials (p. 16.1)."

Various strategies exist for natural ventilation, as David Etheridge (2011) lists: *single-sided ventilation* - which is buoyancy dependent, *cross ventilation* – which is wind dependent, *upward (stack) ventilation* – which is buoyancy and wind dependent, and *downward (top-down) ventilation* – which is also wind dependent (pp. 7-9).[43] *Mechanical Extract* ventilation, *Mechanical Supply* ventilation, *Mechanical Balanced 'Mixing'* ventilation, *Mechanical Balanced 'Displacement'* ventilation, and *Demand Controlled* ventilation are different strategies for mechanical ventilation (Liddament, 1996, pp. 100-114). Single-sided and cross ventilation (Figure 2.18) and stack ventilation (Figure 2.19) are depicted.

[43] David Etheridge (2011). *Natural Ventilation of Buildings: Theory, Measurement and Design.* John Wiley & Sons.

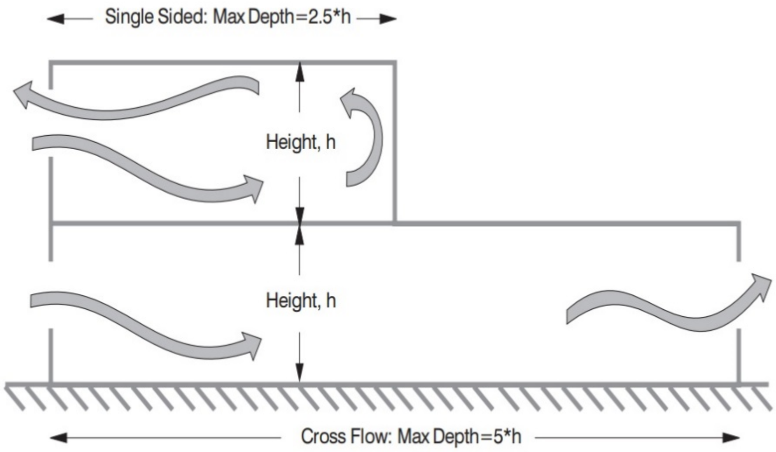


Figure 2.18
Single-sided and cross ventilation (Source: Liddament, 1996, p.95).

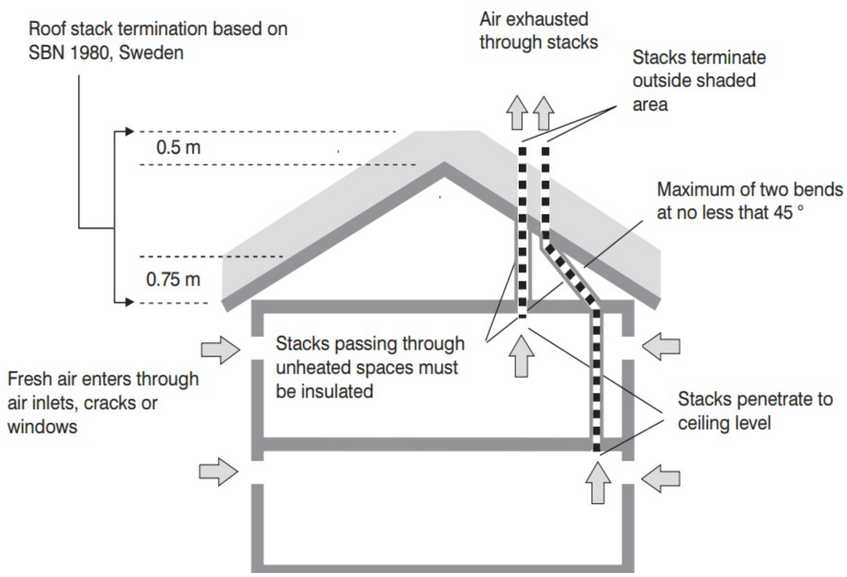


Figure 2.19
Stack ventilation (Source: Liddament, 1996, p. 97).

2.7.4 Advantages and Disadvantages of Natural over Forced Ventilation

A germane practice of natural ventilation is applied in the Persian vernacular architecture of Wind-Catchers. In this system, evaporative cooling is integrated to moderate ambient dry air via directing the air into underground streams. There were, historically, distinct techniques applied in Wind-Catcher construction, which were found in various locations across the Middle-East. The varieties can reveal the ways in which solutions to natural ventilation requirements were tweaked to best address context-specific and intended use. According to Etheridge (2011), the main advantages of natural, as opposed to forced, ventilation are: (a) greater sustainability, since it has been working for thousands of years without the added energy consumption

for mechanical ventilation, being around 25% today, (b) the occupants' preference in having control over their environment, as opposed to being isolated from the environment, (c) lower capital and operating cost, and (d) maximized uses of floor area for buildings that do not need room for mechanical systems. Several disadvantages are also named: (a) limitations in providing cooling in hot and, specifically, humid climates, (b) potential needs for either a chimney or an atrium that would reduce floor area, and (c) less flexibility to be able to correct the design, in case of errors (p. 5). In support, the AIVC Guide to Energy Efficient Ventilation (Liddament, 1996) lists the following advantages and disadvantages for natural ventilation (pp 98-99):

Advantages:

- Suitable for many types of buildings located in mild or moderate climates.
- The 'open window' environment associated with natural ventilation is often popular, especially in pleasant locations and mild climates.
- Natural ventilation is usually inexpensive when compared to the capital, operational and maintenance costs of mechanical systems.
- High air flow rates for cooling and purging are possible if there are plenty of openings.
- Short periods of discomfort during periods of warm weather can usually be tolerated.
- No plant room space is needed.
- Minimum maintenance.

Disadvantages:

- Inadequate control over ventilation rate could lead to indoor air quality problems and excessive heat loss. Air flow rates and the pattern of air flow are not constant.
- Fresh air delivery and air distribution in large, deep plan and multi-roomed buildings may not be possible.
- High heat gains may mean that mechanical cooling and air handling will prevent the use of natural ventilation.
- Natural ventilation is unsuited to noisy and polluted locations.
- Some designs may present a security risk.
- Heat recovery from exhaust air is technically feasible (Schultz, 1993) but not generally practicable.
- Natural ventilation may not be suitable in severe climatic regions.
- Occupants must normally adjust openings to suit prevailing demand.
- Filtration or cleaning of incoming air is not usually practicable.
- Ducted systems require large diameter ducts and restrictions on routing.

Disadvantage are related to shortcomings in terms of predictability as a result of wind speed/direction and buoyancy, depending on the climatic conditions of a building site, coupled with a building design. The idea of unpredictability is primarily associated with the amount, direction, and velocity of air flow, to be further analyzed in the upcoming section, "Ventilation in Theory."

2.8 Ventilation in Theory

This section discusses mathematical interpretations of natural and mechanical ventilation and detailed understandings of the elements that influence ventilation. The information is primarily based on the 2009 ASHRAE Fundamental Handbook and AIVC. Prior to identifying theories of ventilation, a focus is delivered on the concept of airflow below.

2.8.1 Air Flow

When there is a pressure difference between two locations, airflow will be formed. Air flow is, often, expressed by hourly ‘air change rate’ (ach), which is the airflow rate into a room, zone, or building divided by its volume. Therefore Air Exchange of I is calculated as:

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

Where:

Q = volumetric flow rate of air into space in m^3/s in SI (cfm in imperial)

V = interior volume of space in m^3 SI (ft^3 in imperial)

air exchange rate of 1 ACH in SI, thus, can be recognized as:

$$I = \frac{3600\ Q}{V}$$

In Imperial system,

$$I = \frac{60\ Q}{V}$$

While both volumetric and mass flows are used for the airflow rate, mass flow is more common for energy analysis. This is because air has altering volumes in different temperatures. As Liddament (1996) puts, “mass flow is needed to determine the thermal energy carried by the air stream. It is also widely used in ventilation and air flow calculation techniques (p. 35).” Typical units for volumetric flow are m3/s, l/s, cfm, and kg/s is common for the mass flow.

2.8.2 Temperature, Density, and Pressure Relationship

Generally, airflow has various physical characteristics, namely, *density*, *pressure*, and *temperature,* which are all interrelated. Based on Boyle's Law, density of ρ and pressure of P are proportional where air density, for instance, increases by pressure increase:

$$P \propto \rho$$

Based on Gay-Lussac's Law, pressure of P and temperature of T are also proportional. That is, pressure of air, for instance, increases if air temperature increases.

$$P \propto T$$

In addition, based on Charle's Law, temperature of T and density of ρ are inversely proportional meaning that density of air, for instance, decreases with increase in temperature:

$$\rho \propto {}^{1}/_{T}$$

If all these three are combined, then the ideal gas law (SI system) for dry air will be produces in which,

$$P \propto \rho T$$

or,

$$P = \rho R_d T$$

Where:

P is pressure in Pa

ρ is density in kg/m³

R_d is gas constant for dry air in SI equal to 287 J/kg/K, and

T is temperature in K

2.8.3 Ventilation

As discussed earlier, both infiltration and natural ventilation are primarily influenced by natural forces such as pressure difference resulted from temperature difference and wind. Following sections will articulate the impacts of various pressures induced by cracks, windows, stacks, and the role that wind plays in natural ventilation and infiltration. Unintentional (a) and intentional (b) airflow paths associated with a typical building are represented (Figure 2.20). For forced ventilation, natural forces are clearly less significant while mechanical forces governs the airflow's behavior. According to 1997 ASHRAE Fundamentals Handbook:

> Natural ventilation and infiltration are driven by (1) pressure differences across the building envelope caused by wind; (2) air density differences due to temperature differences between indoor and outdoor air (buoyancy, or the stack effect); and (3) the operation of appliances, such as combustion devices, leaky forced-air thermal distribution systems, and mechanical ventilation systems (p. 25.7).

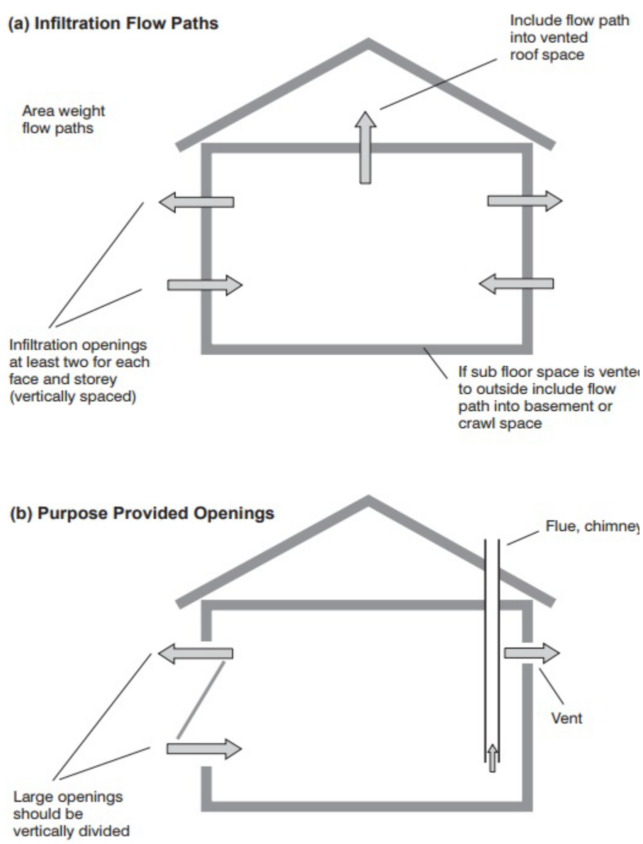


Figure 2.20
Demonstrations of a Typical Buildings' Airflow Paths (Liddament, 1996, p. 226).

A building exposed to wind enforces new static pressures on the envelope as a result of surrounding situations, surface orientation, air density, and wind speed and direction. This pressure distribution could be

independent of a building's inside pressure of P_i where there is no opening on the envelope if there is (1) no indoor-outdoor temperature difference, (2) no other forces on building, and (3) no machine device impacts air through the building. In this condition, the pressure differences are determined by the following equation:

$$\Delta P = P_o + P_w - P_i$$

Where:

ΔP is pressure difference between indoors and outdoors

P_o is static pressure at reference height in unobstructed flow

P_w is wind pressure in that area

P_i is interior pressure at reference height

On the one hand, the interior static pressure of P_i declines with height if there is no indoor-outdoor temperature difference. This decrease rate is based on the interior temperature ($-\rho_i g$) where ρ_i is the interior air density and g is the gravity acceleration. The interior static pressure, on the other hand, would be balanced in such a manner that the total airflow going into the building equals the total airflow going out. In the case where there is an indoor-outdoor temperature difference, both height and temperature differences influence the pressure difference of ΔP_s where $P_{i,r}$ is the interior static pressure at a reference height. The assumption, again, is that inflow is equal to outflow, according to the 1997 ASHRAE Fundamentals Handbook formula below (p. 25.7):

$$\Delta P = P_o + P_w - P_{i,r} + \Delta P_s$$

2.8.3.1 Wind Pressure

The pressure induced by the wind on any windward point of a building is positive while it is negative on a leeward orientation. The other two sides could be either positive or negative, depending on the wind direction. Assuming that no pressure losses or height changes occur, Bernoulli equation is used to assess the wind pressure:

$$P_w = \frac{1}{2}\rho C_p v^2$$

Where:

P_w is wind pressure in that point in Pa

ρ is air density in kg/m³

C_p is the wind pressure coefficient, and

v is local wind velocity at the reference height in m/s

Local wind velocity is a product of various factors such as terrain roughness and the height above ground, which might be different from the general local weather station data for wind performance in the area (Figure 2.21). For more accuracy, the equation below is employed where the height mentioned is typically assumed as the building height, according to Liddament (1996, p. 230).

$$U_z = U_m\, kz^a$$

Where:

U_z is wind speed at building height in m/s

U_m is wind speed at typical height of 10 m from weather station in m/s

z is the building height in m, and

k is terrain dependent constant derived from the table below in Figure 2.20

a is terrain dependent constant derived from the table below in Figure 2.20

Terrain Coefficient	k	a
open, flat country	0.68	0.17
country with scattered wind breaks	0.52	0.20
urban	0.35	0.25
city	0.21	0.33

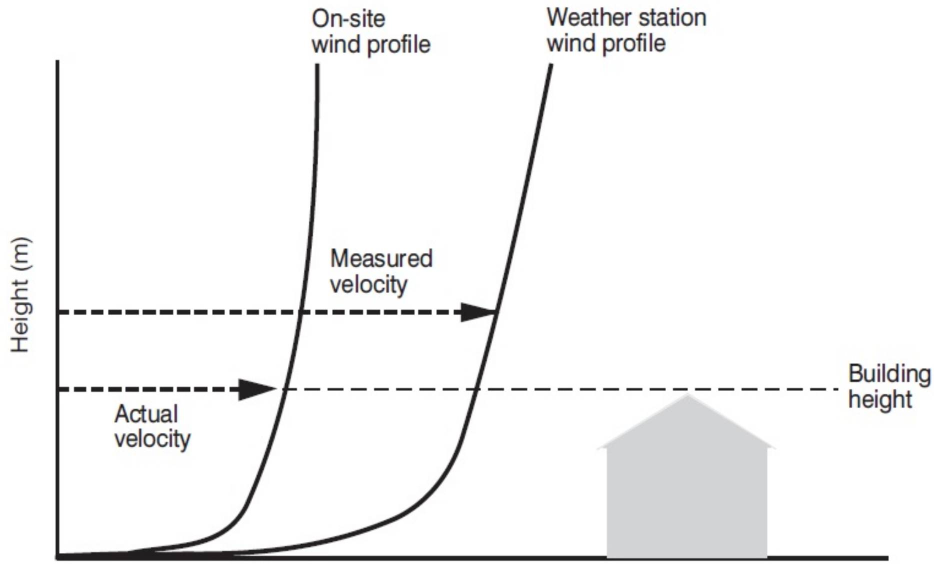


Figure 2.21
Impact of Terrain and Wind Profile on Local Wind Velocity (Source: Liddament, 1996, p. 231).

Design Application: *the wind pressure equation indicates the significance of both macro and micro climatic conditions of a site in creating pressure difference across a building envelope. Elements such as wind speed, building height, topography and its vegetation type, and the neighborhood density could impact the wind pressure applied for natural ventilation.*

2.8.3.2 Wind Pressure Profile

Besides the stated wind velocity, wind pressure coefficient is another factor for accurate usage in the estimation of wind pressure. The rationale is that, depending on a building orientation, form, and whether it is sheltered or not, the pattern of wind pressure could be dissimilar (basically illustrated in Figure 2.22). The correct wind pressure coefficient, thus, could be extracted from the tables locate in Appendix C, based on AIVC ventilation handbook (Liddament, 1996, pp. 258-260).

Moreover, the 2009 ASHRAE Fundamental Handbook (p.16.7) defines the Wind Pressure Profile as the wind surface pressure coefficient to be estimated from the following equation, developed by Walker and Wilson (1994):

$$C_p(\emptyset) = \frac{1}{2}\ \{[C_p(1)\ + C_p(2)](cos^2\emptyset)^{\frac{1}{4}}$$

$$+[C_p(1) - C_p(2)](cos\emptyset)^{\frac{3}{4}}$$

$$+[C_p(3) - C_p(4)](sin^2\emptyset)^2$$

$$+[C_p(3) - C_p(4)]sin\emptyset\}$$

Where

C_p is the wind surface pressure coefficient, dimensionless

$C_p(1)$ is the pressure coefficient when wind is 0° typically 0.6

$C_p(2)$ is the pressure coefficient when wind is 180° typically -0.3

$C_p(3)$ is the pressure coefficient when wind is 90° typically -0.65

$C_p(4)$ is the pressure coefficient when wind is 270° typically -0.65

$\emptyset$ is the wind angle measured clockwise from the normal to wall 1

The wind surface pressure coefficient estimated by this method is a simplified approach for a shoe-box building form. In real practice, however, building forms are not necessarily similar to a pure box. The surrounding setting of a building also varies from site to site resulting in different values for the wind pressure profile. If the level of building form's complexity does not allow using the estimated Cp discussed here, other advanced tool can be applied to accurately calculate wind surface pressure coefficient. Wind tunnel method, for instance, is a practical solution to resolve the mentioned issue. In addition, there are more advanced software that are specifically designed to predict airflow behavior around a building namely Computational Fluid Dynamic (CFD) analysis softwares.

Design Application: *the wind pressure profile equation, further, indicates the significance of both <u>macro and micro climatic conditions</u> of a site during the design process. Specifically, proper design of*

<u>fenestrations orientation</u> towards the prevailing wind via a site wind study is key in practical natural ventilation.

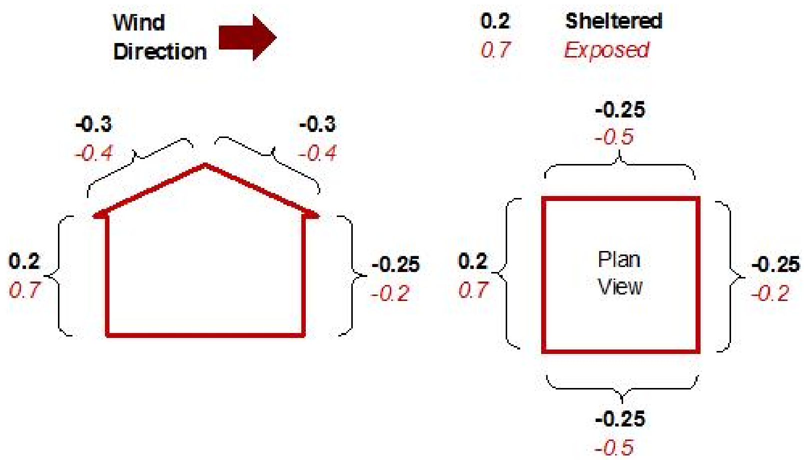


Figure 2.22
Simplified wind pressure coefficient for Local Wind, based on averaging and amalgamating measurement of data (Source: AIVC ventilation handbook, Liddament, 1996, p. 231).

2.8.3.3 Stack Pressure

Stack pressure is shaped if there is temperature difference, resulting in density differences in a stack of air outside or inside of a building. That is, stack pressure is a mass of a column of air imposing a hydrostatic pressure (2009 ASHRAE Handbook, p. 16.6). This effect occurs in proximity to a building envelope, mainly, because of an inside and outside temperature difference. It could also happen inside in an atrium, double height space, room, chimney or duct. Based on buoyancy effect, warmer air goes up, due to lower density and higher pressure, and cooler air with less pressure stays lower to the ground holding higher density. In a certain height, therefore, there is a pressure balance, called Neutral Pressure Level (NPL). Above this level, in an interior zone, the pressure is higher than the exterior and lower below the NPL, as diagrammed (Figure 2.23).

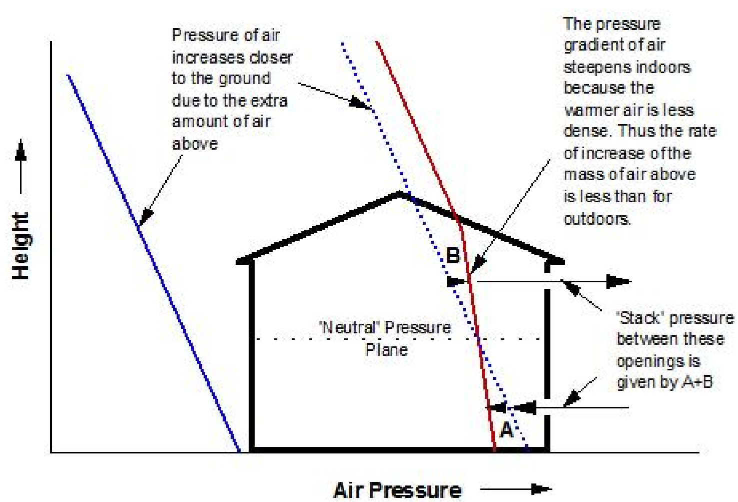


Figure 2.23
Stack Pressure Diagram (Source: AIVC Ventilation Handbook, Liddament, 1996).

Stack pressure for a single air column illustrated in Figure 2.24 is calculated based on the equation below, with the assumption that barometric pressure and temperature are constant over the height of interest (2009 ASHRAE Fundamental Handbook, p.16.7):

$$P_s = P_r - \rho g H$$

Where:

P_s is stack pressure in Pa

P_r is stack pressure at reference height in Pa

ρ is indoor or outdoor air density in kg/m³

g is the gravitational acceleration, 9.81 m/s², and

H is height above reference plane in m

If the vertical density gradient is neglected, then the equation can be used to calculate any horizontal leakage at certain vertical height as:

$$\Delta P_s = (\rho_o - \rho_i)g(+H_{NPL} - H) = \rho_o(\frac{T_i - T_o}{T_i})g(+H_{NPL} - H)$$

Where:

ρ_o is outdoor air density in kg/m³

ρ_i is indoor air density in kg/m³

H_{NPL} is neutral pressure level's above reference plane with no other driving forces in m

T_o is outdoor temperature in K

T_i is indoor or outdoor air density in K

g is the gravitational acceleration, 9.81 m/s², and

Diagrammed is the stack pressure distribution between two vertical fenestrations based on the stated relationship between pressure and height in regard with neutral pressure level (Figure 2.24).

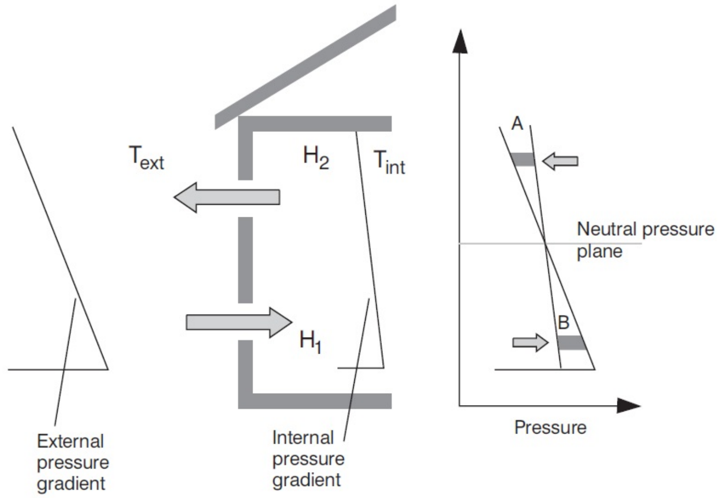


Figure 2.24
Two Vertical Openings' Stack Pressure distribution (Source: AIVC Ventilation Handbook, Liddamen, 1996, p. 232).

Design Application: *the stack pressure equations demonstrate how height of a building itself coupled with the height of fenestrations as well as each space's height influence pressure difference that is the main driving force for air movement. This role is more critical if a designer intends to have natural ventilation suitable for a certain site condition.*

2.8.3.4 Wind and Stack Combined Pressure

The driving forces of pressure difference causing airflow were elaborated in the previous section. Wind and stack pressure and how those can be estimated were also discussed. The total pressure, which is a combination of wind and stack pressure, is used in the calculation of cracks and windows airflow. Considering the two mentioned equations, the total pressure difference across an opening where indoor temperature is assumed to be uniformed is:

$$P_U = \frac{1}{2}\rho_o \, {U_H}^2$$

$$P_T = g\rho_o(\frac{T_i - T_o}{T_i})$$

Where:

P_U is wind parameter

ρ_o is outdoor air density in kg/m³

U_H is wind speed at a specific height in m/s

P_T is stack effect parameter

T_o is outdoor temperature in K

T_i is indoor or outdoor air density in K

g is the gravitational acceleration, 9.81 m/s², and

The pressure difference across a gap in general, then, is given by:

$$\Delta_P = s^2 C_p P_U + H P_T + \Delta P_I$$

Where:

Δ_P is the pressure difference across a gap in general

s is the shelter factor for the particular wind direction of Ø

C_p is the wind pressure coefficient

P_U is wind parameter

H is wind speed at a specific height

P_T is stack effect parameter, and

Δ_{PI} is the pressure that acts to balance inflows and outflows

Considering each stack and wind pressure and their combination, diagram (Figure 2.25) shows the inside and outside's pressure distribution over the height of a building regarding the wind direction.

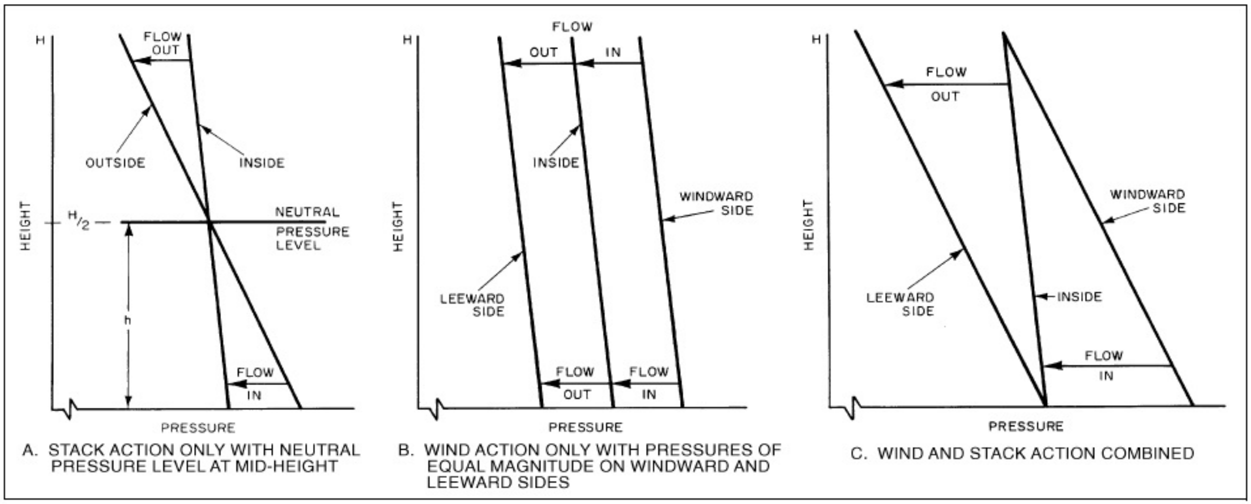


Figure 2.25
Pressure distribution over building height (Source: 1997 ASHRAE Fundamental Handbook, p. 25.10).

> Design Application: *the combined pressure equations diagrammed in the figure above can be used as a guideline in proper position of systems or fenestrations height suitable for both introducing and exhausting warmer or cooler air into a building. In other words, if the design intention is to naturally introduce fresh and cool air into a space, the opening should be closer to the floor while openings adjacent to ceiling can exhaust warmer polluted air affected by buoyancy. Obviously, wind direction should be also considered as it might change the pattern of air flow drastically.*

After the estimation of pressure difference across a building envelope, the airflow associated with smaller and larger openings as well as the natural ventilation could be theoretically calculated, elaborated in further detail in the next section.

2.8.4 Leakage Airflow

Cracks and gaps in building envelopes introduce airflow into the zones depending on the size and geometry of the opening plus the existing pressure difference between its two sides. Recently, buildings are made air tighter during construction as this has been considered as one of the main source of heat loss, heat gain, or undesirable humidity. The equation below, known as the *power law equation*, demonstrates the function of cracks in buildings.

$$Q = rc(\Delta p)^n$$

Where:

Q is the airflow through envelopes' small openings and gaps in kg/s

r is air density passing through the opening in kg/m³

c is flow coefficient in m³/(s.Pa^n)

Δp is pressure difference across the gap in Pa, and

n is pressure exponent, which is dimensionless and typically around 0.65 (2009 ASHRAE Fundamentals Handbook, p. 16.14).

AIVC Guide to Ventilation (Liddament, 1996) adds:

> The 'flow coefficient', C, is approximately related to the size of the opening and is normally expressed in terms of m³/s (or dm³/s) for each m² of porous surface area or for each m length of crack. The flow exponent, n, characterises the type of flow and varies in value between 0.5 for fully turbulent flow to 1.0 for completely laminar flow. Many building components have values in the range of 0.6 to 0.7 (p. 225).

Design Application: *Gaps and cracks in building envelopes should be carefully addressed by* <u>*proper material selection*</u> *in design process coupled with practical* <u>*construction details*</u> *that are well laid out in construction phase as well.*

2.8.5 Fenestration Airflow

Windows, doors, large openings, and vents intentionally designed on buildings' envelope are other ways of air introduction into a building. Considerations of a window design, its swing, size, position, and orientation are all critical in regards to natural ventilation. The role of *flat plate orifices* on airflow is represented in the orifice flow equation below:

$$Q_m = C_d \rho A \sqrt{\frac{2\Delta P}{\rho}}$$

Where:

Q_m is the airflow through larger openings in kg/s

C_d is discharge coefficient, which is around 0.61 for flat "plate surfaces"

ρ is air density passing through the opening in kg/m³

A is area of opening in m², and

Δp is pressure difference across the gap in Pa.

This equation was, thus, suggested based on the assumptions of:

$n = ½$ and $c = C_d A \sqrt{\frac{2}{\rho}}$

Design Application: *Looking at the equations above, it implies that any stated factor influencing pressure difference could be fully investigated in order to properly design for natural ventilation. Micro and macro climatic conditions such topography, vegetation type, air density, and wind velocity and its direction plus building design decisions such as building height, interior spaces' height, envelope form and orientation, fenestrations shape, its size, its height, and its orientation are all among the elements that are key to provide appropriate amount of airflow needed for occupants satisfaction.*

2.8.5.1 Wind-Driven Airflow

Natural ventilation systems are normally designed based on one-half of the seasonal average wind speed as this is lower in summer and the fact that wind directional frequencies would vary in different seasons. In order to design a proper size for opening only relying on wind, the following equation is used:

$$Q = C_v A U$$

Where:

Q is the airflow rate in m³/s

C_v is effectiveness of the opening where it is assumed to be 0.5 to 0.6 for perpendicular winds and 0.25 to 0.35 for diagonal winds

A is free area of inlet opening in m²

U is wind speed in m/s

2.8.5.2 Buoyancy-Driven Airflow

Airflow induced by stack effect is taking shape primarily as a result of buoyancy effect, to be estimated by the equation below if a building's internal resistance is not significant:

$$Q = C_D A\sqrt{2g\Delta H_{NPL}(T_i - T_o)/T_i}$$

Where:

Q is the airflow rate in m³/s

C_D is discharge coefficient for the opening

ΔH_{NPL} is height from midpoint of lower opening to NPL in m

T_i is indoor temperature in K

T_o is outdoor temperature in K

2.8.5.3 Ventilation Thermal Loads

When ambient air is introduced into a building, it needs to be conditioned to be within occupants' comfort zone. This air conditioning aspect is basically associated with heating, cooling, and dehumidification/humidification in response to the invited cold, hot, and humid/dry air, respectively. The air conditioning of fresh air accounts for around 20-50% of buildings' thermal loads (2009 ASHRAE Fundamentals Handbook, p. 16.11). Heating and cooling energy loads can be calculated using the following: (a) *Sensible Heat Equation,* while the energy consumption to control air moisture content via dehumidification/humidification is given by (b) *Latent Heat Equation*.

Sensible Heat Equation

$$q_s = Q\rho c_P \Delta t$$

Where:

q_s is sensible heat load in W

Q is the airflow rate in m/s

ρ is air density in kg/m^3, which is around 1.2 near sea level

c_p is specific heat of air in J/(Kg.K), which is around 1000, and

Δt is temperature difference between outdoors and indoors in K

This equation is also converted to the following equation for near sea level and adjusted indoor air density as:

$$q_s = 1230 Q \Delta t$$

a- Latent Heat Equation

$$q_l = Q \rho \Delta W \ (2501 + 1.805t)$$

Where:

q_l is latent heat load in kW

Q is the airflow rate in m/s

ρ is air density in kg/m^3, which is around 1.2 near sea level

ΔW is humidity ratio difference between indoors and outdoors, mass water/unit mass dry air in kg/kg

t is indoors and outdoors' average temperature in degree C

Below, this equation is simplified for near sea level and common comfort air temperature:

$$q_l = 3.01 \ \times 10^6 Q \Delta W$$

Thermal (energy) Transport as the energy for ventilation (Liddament, 1996, p. 242):

P_U is wind parameter

ρ_o is outdoor air density in kg/m^3

U_H is wind speed at a specific height in m/s

P_T is stack effect parameter

T_o is outdoor temperature in K

T_i is indoor or outdoor air density in K

g is the gravitational acceleration, 9.81 m/s^2, and

2.9 Summary and Transition to Chapter III

As based on the derivatives of some of the basic and complex concepts expounded in/by this chapter, the kind of design approach to be intended, and, also, stay within the philosophies of this dissertation, should be an integrated one. Such approach must be able to fuse all sub-systems as a whole to achieve high-performance built environments in entirety. The four major substances, the natural elements of sun, earth, wind, and water should, with no halt, at all times, be espoused as vital assets by the design process. As foundational as they are, these elements always remain as necessities whose integrations are to be continuously reassessed. These need to be re-thought into a better design process working towards the creation of the sort of architectural poetics elaborated in the Preface section. That is, as Crowther (1992) also reasserts, the role of an architect, designer, and planner rely on a "holistic perception that finds no separation among all facets of design nor any exclusion in the optimization of natural site-specific energies of sun, earth, air, and water (p.16)."[44] As a case in point, a vernacular architecture's example of such similarly inclusivist, ecological, high-performance, and integrated systems can be detected in the central parts of Iran and with the ideas formed in the diverse typologies found in Wind-Catchers. Another case in point of such informed systems is the more contemporary and practical example of the concept of a Double-Skin Façade (DSF).

This dissertation will, later, set a combination of the two systems, of the wind-catchers and DSFs, as complementary dimensions of a high-performance design prototype. DSF can be defined as a multilayered building component that, in its basic conditions, is containing an external glass facade, an intermediate cavity space for airflow, and an inner façade primarily located out of the glass surface. The dissertation takes this as an inclusivist ecological architectural system in which day-lighting, natural ventilation, acoustic, visual and thermal comfort, tectonics (the poetics of joineries and construction), aesthetics, and social issues could be addressed inclusively. Regarding the benefits of DFSs, however, one dimension remains debated and

[44] Richard L. Crowther (Ed.). (1992). *Ecologic Architecture*. Butterworth-Heinemann.

partially problematic: the economic considerations. Through integration, innovation and enhancement, this dissertation aims to also enhance and inform the economic performance of a DSF system, which is to be accomplished by optimizing its energy demands. The statement above should be taken as an introduction to the next chapter, followed by further investigations on applied research methodologies discussed in its subsequent chapter, “Design Inquiry.”

3.1 Introduction

Building envelope, if conceived as a "responsive skin,"[45] can serve as a critical component of an ecological building. It makes the transition between outside and inside, protecting inside from the undesirable outside conditions while creating privacy by outlining a property. It is also strictly linked to the environmental, social, and economical aspects of buildings and their contextual surroundings. An envelope's relation to the building is akin to that of the skin to the body of a plant, animal or human being. Therefore, it should act in a flexible, adaptive, and dynamic manner. That can also mean a proper adaptation to its context, in a creative fashion, also leading to a more visually appealing invention. Building skin, thus, is a living organism. In addition to the envelope, the earth as the second major natural source, if integrated into architectural design as a system, can also become another innovative component of an ecological building. The energy stored in the earth could be employed to respond to buildings' energy demands. The fact that the earth's temperature has less fluctuation in comparison to the outside temperature is to be considered as an asset, which can be used for moderating the built environments' air and water demands.

If the research could be more ambitious, building skins should breathe. Building skins should be multi-layered while each layer is playing different roles for properly responding to a building's surroundings. Building skins should be self-healing to be able to constantly maintain themselves. Most importantly, building skins should develop as advanced energy generators capable of regulating received energies based on their needs. Ideally, at the end, when a building life span is over, the skin must return to the cradle of the ecosystem. Technically, building skins should also be able to manage moisture, heat and air transfer as well as radiation. A building envelope linked into the earth, can achieve a higher performance while also supporting all characteristics rendered above. Such responsive interactions with the surroundings can create better places for the building occupants. Aligned with this dissertation's values, a naturally-ventilated, double-skin facade (DSF) that is additionally linked into the mother earth is seen as a product of this point of view. This is an initial effort to accomplish the other, more ambitious objectives, rendered in the Preface section, towards the making of the "good."

This chapter's focus is on building envelope and geothermal systems as building components, the integrations of which could be remaking them into functioning as ecological systems as a whole. Each of

[45] Schittich, Christian, Werner Lang, and Roland Krippner (2006). *In Detail - Building Skins*. München: Ed. Detail [u.a].

these elements could complementarily address other required and desired qualities in buildings such as day-lighting, natural ventilation, and thermal comfort.

3.2 Buildings Envelope

This section concentrates on various parameters related to the understandings of ecological building envelopes such as the notions and definitions of skin in general and the skin's comprehensive relations to architecture, more specifically, to the ideas on *ecological architectural poetics* discussed in earlier chapters.

3.2.1 Skin

Merriam-Webster[46] defines skin as: (1) the external limiting tissue layer of an animal body, especially, the double-layered covering of a vertebrate body consisting of an outer epidermis and an inner dermis, and (2) an outer covering of a fruit or seed, and (3) a membranous film or scum shaping on boiling milk or drying pain. As the main physical separator between the human body and its outside world, skin protect the body against physical and chemical effects. The concept of skin can define a threshold between exterior and interior spaces in buildings.[47] Skin also functions as an organ which regulates the moisture balance and temperature of body while breathing odors out through glands. That is one of the most essential features of the human body's immune system. Human skin can furthermore showcase what is happening inside when one is feeling down, guilty, ashamed, lying, and etc. It is an elastic organ that can expand and contract, quickly repairing damages, renewing itself every month. As Hausladen et al (2007) put it:

> The skin performs an important function in the body's response to a range of climatic information and regulates its emission of heat with the help of heat and cold receptors, blood vessels, sweat glands and hairs. The thermal conductivity of the skin is changed by its temperature-controlled blood supply. When it is hot, the blood vessels close to the skin's surface receive their maximum supply of blood to increase the rate of heat emission. When it is cold, the blood supply and hence the heat loss are reduced (p. 12).

Biological beings adopt and form different skin types. In plants, the color and forms of leaves or even the existence or absence of those are linked to temperature, light, humidity, and wind. In cacti, for instance, all

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[46] Skin. (n.d.). Retrieved July 27, 2017, from https://www.merriam-webster.com/dictionary/skin.
[47] Gerhard Hausladen, Michael De Saldanha, and Petra Liedl (2007). *Climateskin: Building-Skin Concepts that can do more with less Energy*. Birkhäuser.

these are related to the plants' need to survive in hot and dry conditions. It is noticeable that plants with darker leaves can adapt better to their environments compared to those that are brighter or multi-colored. Like plants, animals are covered with a variety of skins types. What follows is an explanation of some based on a categorization conducted by Tombazis (1996, pp. 52-53):[48]

- Soft skinned animals with short or longer furs such as cats or dogs functioning as insulation
- Hard skinned animals which their hardness is for security such as crocodiles or rhinoceros
- Loose skin animals such as elephants functioning as a flexible protection
- Scaled skins in different species of reptiles which shed their skins
- Spiked animals for which their prickles are for protection such as porcupines or hedgehogs
- Shelled species which their shell becomes both their home and shield protecting the internal soft body from predators. The shell's texture and color reveals their surrounding environment
- Feathered animals, for which feathers works both as an insulation layer and regulators of flights
- Thick coated animals with elaborated furs helping them maintain constant body temperature such as bears

According to Tombazis (1996), lessons learned from animal skins are:

1- The proper adaption to its climatic condition and natural setting
2- The adaptation to changing condition of temperature or needs of hiding or flight
3- The vast diversity and enhancements linked to various conditions, and finally
4- The resulting aesthetic beauty

3.2.2 Garment

Garment is an artificial skin next to the natural skin that can protect human beings from weather and unwelcome outside influences. It performs as a "second skin" that is also adaptable, enabling users to put it on or take it off based on the situation. People living in colder climates adapt to the weather conditions by wearing multiple layers of clothing to overcome the cold. In contrast, people in hot and dry climates would cover themselves with thinner and lighter fabrics to protect against solar radiation. In general, clothing protects against solar radiation, wind, cold, and/or heat, but it should not prevent the skin from "breathing." This notion is the main reason that organic natural materials that can work best in different climatic conditions can be seen as finest clothing materials. Clothing, in addition to protection and way of breathing, serves cultural expressions, representing users' diverse identities, traditions, or styles of fashion. In view of that, "clothing can emphasize or help the actual self in setting the scene for the ideal apparent self and therefore serves to promote reality or compensate for it (Hausladen et al., 2007, p. 13).

[48] Alexandros N. Tombazis (1996). *On Skins and Other Preoccupations of Architectural Design*. Renewable energy, 8(1-4), 51-55.

3.2.3 Building

Building is a human-made configuration which is envisioned for sheltering or supporting any temporary or permanent sort of habitation. It is to satisfy users' needs mainly linked to safety, privacy, and comfort; those are mostly protections against extreme solar radiation and temperature, precipitation, and wind. Buildings are different in terms of function, form, structure, material, and style. Buildings have also been altered in the course of history due to different reasons such as contextual conditions (weather condition, site, culture, available material, land price…), aesthetics, and user needs. Buildings, then, have also been converted to objects or canvasses of artistic expression as early as when cave dwellers had started using colors and printing images in their cave settlements. Performing as the next layer to the skin and garment, buildings act as the "third skin" that separates the interior/inside, as a place of comfort and protection, versus the exterior/outside, as a place that might be harsh and unsafe (Hausladen et al., 2007). Today, as most individuals are spending more and more times inside buildings in cities and towns, the interior climate of buildings becomes central to achieving occupant satisfaction. To create an architecture that is after the "good," more and more complex aspects related to occupants' satisfaction must be taken into account, further deeply. Occupants' satisfaction is to be seen related not merely to physical factors such as temperature, humidity, light, and air quality, but also to other, rather subjective and qualitative parameters such as how they perceive the environments and their abilities to understand and control building operation systems. As Hausladen et al. (2007) argue, occupant comfort is essential for better productivity in buildings:

> Office buildings are not only workplaces but also an important source of corporate prestige. The more authentically the company's concept is depicted by the building, the more sustainable the effect on those outside and the sense of identification of the employees inside (p.14).

3.2.4 Building and Ecology

Architectural schemes, in earlier times and in various cultures, had typically been better integrated with their contextual climatic surroundings as the only possible ways to enhance comfort conditions. Integrations became characteristic practices of periods when electrical and mechanical systems had not been invented or entered into the building industry for abundant use. Later on, although initially with better intentions and more constructive mentalities, modern architectural undertakings have also intended towards increasing human comfort levels in buildings. However, there were also times when a rational matter such as the ecological consciousness was not being much part of the design vocabularies applied in the process of architectural making. The marginalization is perceived, in part, due to a 20th-century's aggregating reliance

on the expenditure of high-tech mechanical and electrical building systems, instead of more low-tech, natural systems.

In this day and age, ecologically-aware worldviews have already become common trends. Informed design vocabularies associated with these perspectives, their subsistence and enhancements, should, with no doubt, strongly continue as fundamental goals in the field of architecture. It is critical that designs assimilate allied theoretical frameworks into the process from the earliest stages possible and in every aspect of a building design. A high-performance design rooted in ecological architecture and embedding its criteria can largely diminish the built environment's dependency on exhaustible energy sources. Instead, non-fossil energy sources such as sun, earth, water, and wind must be reexamined employed to supply building demands, also embracing lessons learned from vernacular architectures in their diverse histories. Furthermore, using native, recyclable, and eco-friendly materials with efficient embodied energies in buildings is also able to enhance this ecological worldviews in the field of architecture. Likewise, in regards to contemporary ecological concerns, the notion of energy management coupled with ideas on buildings' durability offer other important paradigms to contemporary architectural theories and practices.

3.2.5 Building Skin

Building facade is a transition between outside and inside, protecting interiors from undesirable exterior conditions while creating privacy by outlining a property. Building facade is also important in terms of aesthetics and cultural functions, which, in ways, could also be seen as representations of the internal life of buildings and faces of cities. As a result of inventions in advanced structural systems, modern and contemporary building envelopes have been enabled to function separately from a building's loadbearing structures. More recently, ecological discourses on sustainability have also been opening up new horizons in the field of architecture. New discourses have demanded much more integrations of the relevant environmental concepts into architecture, from early stages of a building design. Schittich et al (2006) classify building skins based on the four major concepts of function, aesthetic, construction, and ecology (p. 29). Amongst the four, this dissertation mainly elaborates on the two aspects of function and ecology, while the aesthetics and construction concepts also come in with some degrees of attention.

3.2.5.1 Building Skin and Function

There is a direct relationship between interior climates and components of a building skin and, as a result, between these two and the building occupants' comfort. As Linda Brock (2005) defines, the skin "keeps rain and snow out while controlling the relative humidity of the interior. It stops wind and sun when deemed uncomfortable, allowing passage when desired. Warmth and coolness are regulated by envelope, as are fire and sound (p. 3)."[49] Altogether, building skins should control the following aspects:

Moisture: Uncontrolled condensation creates moisture that can damage delicate interior materials. The sources of damage are divided into water vapor diffusion and air leakage, which is stronger than water vapor. The solution to control this problem is tied to local building climates as well as the implementation of water barriers and proper flushing. In addition, extensive research is needed to analyze the facade shapes and building location's climatic conditions to likewise control issues such as icing and snow accumulation. Water ingress from rain, snow, and ice should be controlled to avoid any destruction to skin components.

Heat Transfer: Heat transfer occurs through convection (thermal transfer through flow of air or water), conduction (the flow of heat through a solid material measured by U value and R value), radiation (the transfer of energy through space by means of electromagnetic waves similar to the manner that electromagnetic light waves transfer light), and transfer of energy by phase changes. While these mechanisms have different physical manifestations, they often happen concurrently in the same system. Heat transfer of the facade, on the one hand, is one of the largest consumers of fossil fuels in the field of construction. Human body, on the other hand, tolerates specific ranges of comfort through a combinations of wet and dry bulb temperatures. To provide this comfort condition, it is critical to increase a building envelope's thermal resistance and to reduce air transmission down to healthy levels. Appropriate detail design is an additional essential factor in order to avoid thermal bridging, while recognizing major thermal transmittances from insignificant ones. Heat transfer, thus, must be well managed to decrease heat loss/gain, if undesirable. Low emissivity coatings on glass and the use of insulation as well as appropriate material selections, for instance, are among the arrangements that can help reaching this target.

Air Transfer: It is important to think about undesired air flow to control water admission, vapor migration, and passage of conditioned air. Air barrier systems, vapor retarders, and insulation and appropriate pores sealing are utilized to resolve the issue. Air leakage can also lead to distinct problems from moisture and heat transfer as scent, smoke, and contaminated air transfer is undesirable. A few archetypal examples are plenum spaces providing vent to underground garages of residential, retail, and office spaces, "a transfer of odors and noise among rooms abutting a common facade cavity, as well as pressure differentials developed by mechanical systems, and more recently by legislation as nicotine smokers utilize egress doors that develop a stack effect in adjacent spaces." [50]

[49] Linda Brock (2005). *Designing the Exterior Wall*. Haboken: John Wiley & Sons.
[50] Lecture by: Karol Kazmierczak (?), Building Design for the New Decade: Facade Engineering -How To Design a Functional Building Enclosure, In *Design for the new Decade Conefernce*, June 10, Miami, Retrieved from: http://www.aia.org/aiaucmp/groups/aia/documents/pdf/aiab083247.pdf, Date Accessed: September 10, 2012.

Radiation: The quest for natural light to express openness, vision and simplicity in architecture has shaped a tendency toward transparency. This introduction of deeper light into the building has led occupants to face thermal discomfort via radiation and glare problems. These issues could partly be resolved by appropriate design of shading devices. Therefore, there should be a balance between unwelcomed heat and light coming into buildings through transparency, and more specifically, the use of glass.

Sound insulation and fire protection are other essential factors related to comfort that a building skin should address. External and internal noise should be reduced to meet human comfort, and building skins must provide users with safety by preventing fire and explosions and by postponing scattering of smoke and flame. One way to address such concerns is through proper material selection and insulation. Schittich et al (2006) outline the different functions for a building skin as: lighting, ventilation, protection from humidity, insulation against heat/cool, wind protection, sun protection, glare protection, visual protection, visual contact/transparency, safety/security, prevention of mechanical damage, noise protection, fire protection, and energy gain (p. 29). Among these, the function of "insulation against heat/cool" is linked to indoor air temperature; "lighting, sun protection, and glare protection" is associated with luminance and lighting intensity; "protection from humidity" is related to relative humidity; and "ventilation and wind protection" are linked to air change rates. Main comfort factors are shortened below (pp. 29-31):

- Indoor air and surface temperature which varies from 18-24˚C (65-75˚F). In summer, it could go up to 27˚C while 18˚C could also be comfortable if it is adjusted to relative humidity. The surface temperature also should not change more that 2-3 K from the indoor air temperature.
- Relative humidity which fluctuate in between 30-70% depending on the indoor temperature.
- Air change rate which changes from 0.3/h during unoccupied to 1.1/h during occupied conditions. That is fresh air intake of 40-60 m^3/h per person while air velocity would not exceed 0.15 m/s.
- Luminance and light intensity which ranges from 300 lx for workstations near windows to 500 lx for standard cubicle offices. It would increase to 1000 lx for open plan offices with medium reflective surfaces. For lighting intensity, evenly distributed light with appropriate control glare control is central.

3.2.5.2 Building Skin and Aesthetics

Besides their technical functions, facade components should ideally be integrated into a more holistic and visually-appealing formation interacting with their surroundings. Antoniades (1980) describes aesthetics also as a matter "concerned with what is "good," what is art, what are its origins and evolution, what is and what should be its role in the social life. Architectural Aesthetics refers to all of above with reference to architecture

(p. 23)."[51] Building envelopes should maintain aesthetic qualities in order to project an attractive image for the building. Lateral load created by wind or earthquake and gravity loads have been typically managed by building skin elements, but, as discussed earlier, advanced building technologies have led contemporary envelopes to be able to function separately from load-bearing structures. This opportunity has allowed building designers to conquer most of the structural constrains that they had previously been faced with in conventional building facades. At the same time, the shift and the possibility of using larger amounts of glass surfaces on building facades and the resulted capacity for having further transparency in a building skin were additional outcomes of these technological advancements. Enhanced skin aesthetics, hence, have been able to create further visual contact between building occupants and their outside environments, also leading to higher user satisfaction. Architectural expressions such as openness, view and minimalism have become the design impetus towards more transparency and tectonic expressions. Such desires have demanded further utilization of progressive structural systems coupled with more glass.

3.2.5.3 Building Skin and Construction/Structure

In terms of construction, careful attention is needed to building detailing and material selection, factors that, to a great extent, have excessive impacts on higher performance of buildings, both from the energy management and aesthetics standpoints. Strong commitments should be made to buildings' construction qualities as resulted from factors such as the construction type, building function, climate, and culture that are informing decision-making procedures. According to Brock (2005), an efficient building process, right usage of materials, higher construction quality and speed all lead to more durability for buildings, also satisfying stylistic and functional needs of clients (p. 332).[52]

3.2.5.4 Building Skin and Ecology

Essentially, there are a number of different ways that most contemporary buildings are required to consume energy, namely by: heating, cooling, ventilation, lighting, and plug load. Except for the plug load,

[51] Anthony C. Antoniades (1980). *Architecture and Allied Design: An Environmental Design Perspective*. Kendall/Hunt Publishing Company.
[52] Linda Brock (2005). *Designing the Exterior Wall: An Architectural Guide to the Vertical Envelope*. Hoboken, N.J: John Wiley.

which is related to devices working with electricity, the other requirements are typically provided by the energy expended through highly developed mechanical and electrical systems. This approach results in greater energy consumptions, and, accordingly, leading to the depletion of natural and environmental resources. Architects, by carefully considering environmental performance criteria from the earliest stages in building design, can decrease the need for high-tech systems and reduce energy demand. This is particularly the case when the environmental criteria related on building skins are well considered.

Besides, architects also vary in their approaches in treating building skins. Some architects perceive the building skin as having the same qualities and attributes as that in ancient buildings, with massive stone, untreated timber, brick masonry, and/or exposed concrete. Some others, however, appreciate colorful graphic images on fragile glass or glowing media and illuminated screens. There is another point of view, which is the one that this study values the most, in which a building skin is perceived as a "responsive skin" serving as an ecological building component (Schittich et al, 2006, p. 9), or, as Mostafavi et al (1993) likewise assert, "finishing ends construction, weathering constructs finishes (p. 5)."[53] This means that, the heat transfer, water ingress, water vapor diffusion, radiation, and air movement through the building envelope are all very important issues related to the climate that any building envelope must manage. Building envelopes, thus, have to respond to different ranges of climatic conditions, from a hot and humid day in summer to a cold sunny day in winter, functioning similar to what skin does for human body (Brock, 2005, p. 13). This is in accord with Werner Lang's argument (Schittich et al, 2006):

> …increased CO2 emissions and shortage of fossil fuels have precipitated a shift toward greater ecological awareness. As questions pertinent to sustainable building take center stage in the planning process, this shift calls for a fundamental reconsideration of building concepts and the form and design of the building skin (p.29).

This statement would raise ecological questions on what the energy consumption of the building skin would be during construction, use and demolition. An ecological skin should be able to accomplish the highest degree of functionality, not just after it is built but, throughout the building lifespan with no extreme need for regeneration or maintenance. Material selection for building skins is an equally important aspect due to the ways different materials have significant and, often, distinct impacts on the environment. Best selected materials are those that are extracted and/or manufactured locally, have degradation resistance, and are reusable, recyclable, eco-friendly, and efficient in terms of their embodied energy. These are main characters

[53] Mohsen Mostafavi & David Leatherbarrow (1993). *On weathering: the life of buildings in time*. MIT Press.

defined as "envelope durability."[54] After comparing various organic skins such as plants, animals, and human skin with numerous functions in response to their contextual surroundings, Tombazis (1996) attempted to apply the possibilities to building skin. He asked: "Could we envisage the skin of a building:

- Being a dynamic multifunctional enclosure
- Being multi-layered, each layer, if this was to be more appropriate, playing a different role, such as reflecting heat, water proofing etc.,
- Different from part to part of a building, depending say on its orientation exposure or subject to mechanical damage,
- Incorporating special features as a result of different needs such as wind deflection, shading etc.,
- Regulating the amount of water or air penetration or loss as a means of controlling humidity, quality of air and temperatures,
- shedding its most outer part in a sense of recycling and self-renewal
- Self-healing in a way that maintenance and repair would be an ongoing process and not a once off major necessity after a lot of damage has already been effected,
- Performing as a generator harvester of solar energy and other useful resources such as water
- A reasonable and diurnal regulator of energy to be reflected or absorbed, as needed, by way of change of colour and texture (p. 54)."

Although some of these attitudes toward the making of building skins may appear as highly ambitious, some have already been applied in design. Remarkably, long prior to the time such statements are made, some of these ideas had already been successfully implemented in vernacular architectural schemes from around the world, in far different climatic conditions. The dissertation's aim towards an inclusivist design approach, to reach the "good" in architecture, relies much on that efforts should be made to design ecological building skins to address most of Tombazis' selections indicated above. This dissertation study argues for the viability of such statement mainly via implementing passive solutions such as natural ventilation, solar heat gain, solar heat control, preheating and precooling, ventilation, and day lighting. The following section is a discussion on the role of building skins relating to thermal performance, ventilation, and daylighting.

3.2.6 Ecological Building Skin and Thermal Performance

Ecological design extremely depends on buildings' skins which are able in sensibly responding to contextual conditions. The understanding of heat transfer that happens across a building skin and making appropriate climatic decisions, thus, is essential. Heat transfer via conduction is related to the amount of building surface adjacent to the outside while heat transfer through convention relates to the air exchange

[54] Building Envelope Design Principles, In *SEFC SUB AREA 2A: Rezoning Submission*, pp. 135-138, Retrieved from: http://www.firestopcaulking.com/PDF/buildingenvelope.pdf, Date Accessed: September 10, 2012.

rate between inside and outside. This reveals the central function of the geometry of building skin and the impacts of its detailing on decreasing building energy utilization. Another factor is the skin color, lighter colors being more suitable for hot climates and darker colors more appropriate for cold climates. Glass, also, is a very unique material as it can gain a huge amount of heat through solar radiation, and loose it through conduction. This characteristic of glass can make it into the best solution for some climates and possibly the worst decision for certain climates, if not appropriately selected and designed in relation to the other design components. Conventional building skins needed to have high R-value as well as reduced ventilation rates. This approach has made buildings to become disconnected from their context while ventilation, mold, and air quality have also been turned into problematic issues.

3.2.7 Ecological Building Skin and Ventilation

In earlier times and in various cultures, as discussed, architectural designs were usually integrated with contextual climatic conditions in order to enhance comfort conditions. Through an ecological perspective, buildings were able to provide natural ventilation by design of opposite openings as well as application of stack effect. In some hot and dry climates such as the central regions of Iran wind-catchers were designed to direct fresh air into cooler areas under the ground and in buildings' basements with ponds, and then to recirculate it to other building areas, implementing the concepts of buoyancy and stack effect. The concept of stack effect finds further relevance in taller buildings as it creates higher negative pressure to direst warmer air toward up, and accordingly, sucking fresh air from the openings. For contemporary buildings, the idea of natural ventilation through openings in the skin can be sufficient if the depth of the space is not more than 2.5 times of its height, depending on the method of opening as well as its location and orientation. Therefore, building skins play an important role in the natural air exchange in buildings.

3.2.8 Ecological Building Skin and Day-Lighting

There is an inherent connection between light and architecture, although the term day-lighting is comparatively new. In the design process of vernacular architecture, when electricity and artificial lights were not in existence, day-lighting applications were considered as a key design factor. Today, appropriate decisions made toward benefitting best from natural light could vastly enhance the performance of an

ecological building. This is mainly due to lowering a building's energy utilization as well as increasing its occupants' social and psychological satisfaction, happiness and productivity in space. In this procedure, building skin functions as a filter controlling the natural light's penetration to set a balance between excessive heat gain and natural light. Shading and reflecting devices such as overhangs, blinds, louvers, blades, fins, and light shelves incorporated on the skin are also important to assist for achieving this goal. An appropriately designed, south-facing envelope with an optimized amount of transparency can allow the penetration of natural light during cold seasons as well as solar heat gain while providing natural light and avoiding overheating occurrence during the summer. Applying proper day-lighting techniques can most effectively contribute to an all-inclusive sustainable design approach, raising the enclosure from being a mere envelope to becoming the architecture itself.

After all, architects and their creations have significant impacts on decreasing buildings' energy demand as linked to mechanical HVAC and electrical devices. An appropriate design can impact by eliminating the needs for such adhesive systems, something that was also practiced in the passive house movement. The most important factor in this procedure is to identify and implement relevant passive systems for each design project to lower the energy demands at initial stages. Then, active solutions such as PV panels can be applied to address what is still remaining as building energy demands.

3.3 Double-Skin Facade (DSF)

Double-skin facade is a multilayered formation to provide daylight, indoor air quality, natural ventilation, thermal and visual comfort, acoustics isolation, and aesthetic while reducing buildings' energy utilization. It consists of an external facade, an intermediate space, and an inner facade. The purpose of the outer layer is protection against external conditions, mainly climatic conditions and noise. The intermediate space could vary between 4 to 80 inches (10-200 cm). Openings in this facade allow for ventilation of the intermediate, and accordingly, inner spaces. That is feasible through thermal buoyancy and wind, and, in some situations, the stack effect. In some special conditions, the openings of the outer skin might be eliminated to achieve higher performance. Usually, shading devices are employed in the intermediate space to avoid overheating and consequently, higher cooling loads typically during hot seasons. Basically, the inner skin is double-pane glazing for thermal purposes and the outer skin is single-pane glass. DSF, as Boake et al (2003) denote:

> …is essentially a pair of glass "skins" separated by an air corridor. The main layer of glass is usually insulating. The air space between the layers of glass acts as insulation against temperature extremes, winds, and sound. Sun-shading devices are often located between the two skins. All elements can be arranged differently into numbers of permutations and combinations of both solid and diaphanous membranes (pp. 1-2). [55]

Solar properties of a DSF as the "third skin" are akin to that of a single skin facade. Yet, a thermal buffer area is also shaped to reduce heat loss and enable passive solar gains because of the additional skin. During cold seasons, preheated air in the cavity could be directed inside the building while also functioning in terms of natural ventilation. During hot seasons, though, the potential outside breeze, or precooled air in some cases, could be directed to the inner space to provide natural ventilation. It is also likely to have overheating problems in hot seasons if the hot air in the cavity is not properly ventilated. The Belgian Building Research Institute define a DSF as followed (Loncour, 2004):

> A double skin façade can be defined as a traditional single façade doubled inside or outside by a second, essentially glazed façade. Each of these two façades is commonly called a skin. A ventilated cavity - having a width which can range from several centimeters to several meters - is located between these two skins. Automated equipment, such as shading devices, motorized openings or fans, are most often integrated into the façade. The main difference between a ventilated double façade and an airtight multiple glazing, whether or not integrating a shading device in the cavity separating the glazing, lies in the intentional and possibly controlled ventilation of the cavity of the double facade.[56]

Different strategies in DSFs' operation should be aligned with the climatic conditions, building context, and building type, which could be implemented to achieve higher building performance in various situations. As mentioned earlier, the function of a second skin to the building is similar to the concept of garments as second skins for the human body (Oesterle et al, 2001, p. 12).[57] "Like the skin and clothing of humans, this raiment, too, fulfills the tasks demanded of it by performing a number of functions made possible by means of the appropriate design and construction (Schittich et al, 2006, p. 29)."

[55] Boake, Terri Meyer, Kate Harrison, David Collins, Andrew Chatham, and Richard Lee (2003). Understanding the General Principles of the Double Skin Façade System.
[56] X. Loncour, A. Deneyer, M. Blasco, G. Flamant, and P. Wouters (2004). Ventilated Double Façades–Classification & Illustration of Façade concepts. *Belgian Building Research Institute*, 8-17.
[57] E. Oesterle, Lieb, Lutz, & Heuzler (2001). *Double-skin Façades*. Prestel.

3.3.1 Background on DSF

The concept of DSF is, in conception, a European architectural trend as energy prices are considerably higher in Europe. The first DSF example was applied in the Steiff Factory in Giengen/Brenz near Ulm, Germany in 1903 (Neubert, 1999; and Crespo, 1999).[58] Main reasons for the conception were daylighting enhancement purposes and an overcoming of the region's cold and windy weather. The success of this application led to the construction of two new additions with the same DSF system in 1904 and 1908, which are still in use. The next building with double-skin skylight in the core hall was Post Office Savings Bank built 1904-1912 in Vienna. This building was initially designed by Otto Wagner, the winner of the bank's design competition in 1903. Later towards the end of the 1920s, as Crespo explains, double-skin buildings adapted other priorities:

> Two cases can be clearly identified. In Russia, Moisei Ginzburg experimented with double skin stripes in the communal housing blocks of his Narkomfin building (1928). Le Corbusier was designing the Centrosoyus, also in Moscow. A year later he would start the design for the Cite de Refuge (1929) and the Immeuble Clarte (1930) in Paris…an exactly regulated mechanical ventilation system…and le mur neutralisant...neutralizing walls are made of glass or stone or both of them. They consist of two membranes which form a gap of a few centimeters. Through this gap which is enveloping the whole building in Moscow hot and in Dakar cold air is conducted. By that the inner surface maintains a constant temperature of 18° C. The building is tightened hermetically! In the future no dust will find its way into the rooms. No flies, no gnats will enter. And no noise….[59]

Until the late 1970s and the early 1980s, the construction of buildings with DSF was not developed much further. Later, towards the middle of the 1980s, however, the combination of environmental concerns and aesthetics led to the growth of the DSF concept in buildings such as the offices of Leslie and Godwin. The application of the DSF concept was further rationalized in the 1990s from both technical and political viewpoints, generating new paradigms for the design of green and ecological buildings (Streicher, 2005, pp. 11-12).[60]

Despite their ever-increasing application in the European architectural contexts, DSFs are still not that popular in the United States; very few of them have since been proposed or constructed. More recent DSF applications in the United States have primary been included in residential high-rises and educational institutions. The Occidental Chemical Center, also known as the Hooker Building, in Niagara Falls, New York

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[58] S. Neubert (1999). Doppelfassaden. In *Ein Beitrag zur Nachhaltigkeit, Ecole Polytechnique Federale de Lausanne*
Ana Maria Leon Crespo (1999). 3x2: Three takes on double skins. Harvard University.
[59] Ana Maria Leon Crespo. History of the Double Skin Façades. Retrieved from: http://envelopes.cdi.harvard.edu/envelopes/content/resources/PDF/doubleskins.pdf. Date Accessed: February 23, 2014.
[60] Wolfgang Streicher (2005). BESTFAÇADE - Best Practice for Double Skin Façades. *WP 1 Report "State of the Art."* EIE/04/135/S07.38652. Retrieved from: http://www.bestfacade.com/textde/01_history_gesamt.htm. Date accessed: February 23, 2014.

can be taken as an earlier one built in North America. Designed by Cannon Design Inc. and finished in 1980, the Occidental Chemical has not been extensively widely accepted for becoming a precedent in the design of commercial buildings. Another example is the Prudential Life Insurance Company's building in Princeton, N.J. designed by SOM in the late 1980s. There is no constructed building with DSF in the United States to be noted in the 1990s. It was not until the early 20th century that such buildings began to develop in the United States. A European firm in charge of various double-facade buildings, Arup Associates designed the Seattle Justice Center in 2001. Other examples, "Une Façade Intelligente" in Montreal, Canada also started in the winter 2002 and the Telus Building in Vancouver, British Columbia has been recently completed. Other notable examples are Manulife Financial, Boston, Massachusetts in 2003 by SOM, and the Genzyme Center, Cambridge, Massachusetts in 2003 by Behnisch Behnisch and Partner. As Jeff et al (2010) list, there are about sixteen buildings with DSF systems in US, as of 2010, (also illustrated on the map; multi-story DSF configurations are listed in bold (pp. 27-29).[61]

- **New York Presbyterian Hospital, NewYork, NY**
- **USC Eli and Edith Broad Center, Los Angeles, CA (2010)**
- **Cambridge Public Library, Cambridge, MA (2009)**
- Cleveland Art Gallery, Cleveland OH (2009)
- Art Institute of Chicago - Modern Wing, Chicago, IL (2009)
- **Information Commons, Loyola University, Chicago IL (2008)**
- Riverhouse – One River Terrace, New York, NY (2008)
- **UMass Medical School, Worcester, MA (2004)**
- **Foundry Square, San Francisco, CA (2003)**
- Genzyme Center, Cambridge, MA (2003)
- Manulife Financial, Boston, MA (2003)
- **Seattle Justice Center, Seattle, WA (2002)**
- Levine Hall, Philadelphia, PA (2001)
- **Yazaki North American, Canton, MI (2000)**

[61] Jeff Vaglio, Mic Patterson, & Stacey Hooper (2010). Emerging Applications and Trends of Double-Skin Facades. In *Proceedings for the International Conference on Building Envelope Systems and Technologies (ICBEST, Vancouver*.

- Occidental Chemical Building, Niagara Falls, NY (1982)
- University of Michigan Biomedical Science Research Building

Figure 3.1
Sixteen U.S. Buildings with DSF Systems, as of 2010 (Source: Jeff Vaglio, Mic Patterson, & Stacey Hooper, 2010).

3.3.2 Types of DSF

The performance of a double-skin facade is strictly related to its chosen means for ventilation within its intermediate space. The modes of ventilation could be natural (buoyancy driven), forced (mechanically driven) or mixed (both natural and forced). In terms of the DSF construction, Oesterle et al (2001) are proposing four major types of consisting of box window, shaft-box facades, corridor facade, and multistory facade, the explanation of each is as followed (pp. 12-32):

Box window: horizontal and vertical partitioning divide the facade in smaller and independent boxes.

Shaft box type: a set of box window elements are located in the facade. These elements are linked via vertical shafts located in the facade. This way the shafts guarantee an elevated stack effect.

Corridor facade: horizontal partitioning, in this case, is realized for acoustical, fire security or ventilation reasons.

Multistory facade: in this type, no horizontal or vertical partitioning exists between the two skins. The air cavity ventilation is realized via large openings near the floor and the roof of the building.

Based on the origin of the air flow, there would be two distinct types of “from outside” and “from inside.” This approach is the case for the destination of the air flow as well: “toward outside” and “toward inside.” There could be another approach for classification of DSFs, on top, in terms of partitioning, which introduces “horizontal,” “vertical,” and “without” horizontal partitioning (Poirazis, 2004, pp. 176-177).[62] The dissertation stuyd’s main reference for definition and understanding of the different DSF types is the following classification suggested (Loncour et al, 2004):[63]

Type of ventilation: natural and mechanical

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[62] H. Poizaris, (2004). *Double skin facades for office buildings*.

[63] Loncour, X., A. Deneyer, M. Blasco, G. Flamant, and P. Wouters (2004). Ventilated Double Façades–Classification & Illustration of Façade concepts. *Belgian Building Research Institute*, 8-17.

Origin of the airflow: from inside and from outside
Destination of the airflow: towards inside and towards outside
Airflow direction: to the top and to the bottom (only in case of mechanical ventilation)
Width of the air cavity: narrow (10 - 20 cm) and wide (0.5 – 1m)
Partitioning: horizontal (at the level of each story) and no horizontal partitioning.

3.3.3 Double-Skin Facade Performance

Main concepts leading to the emergence of DSFs in Europe were the increase of transparency and desirable interior environments while decreasing energy demands. Some previous studies claim that DSFs are not generally ecological, but are only appropriate for the climatic conditions of the green continent. It is argued that in hot climates, solar gain during hot seasons would overheat the cavity temperature. The overheating issue, thus, will lead to more required cooling loads causing building with DSF to demand more energy. Gratia et al (2007) state that the addition of a double-skin always causes an increase in the cooling loads, and if the strategies of natural cooling are not applied, the energy cost of the building with double-skin will be more important (pp. 605-619).[64]

Other literature sources suggest that DSFs are very climate oriented since their effort is to have more interaction between a buildings' inside and outside. This dimension could demand the use of more specific DSF types and HVAC strategies that are more adaptive to the building's context. Passive ventilation in summer is possible even for multi-story buildings and significant energy saving is possible if natural ventilation could be exploited through the use of double-skin facade (Wong et al. 2008).[65] Applying ventilated DSF with controlled shading device systems can be a new efficient way for commercial buildings in hot-summer and cold-winter zones for meeting the task of sustainable building design in China (Zhou et al 2010).[66] In contrast to some other studies on this subject, double-skin facades decrease heating energy demands without significantly increasing the number of hours with excessive temperatures (Hoseggen et al., 2008).[67] Hoseggen et al assert that, from the economic standpoints, energy savings associated with the use of DSFs do not defend the additional costs related to their construction; therefore, choosing them as options

[64] Elisabeth Gratia and André De Herde (2007). Are Energy Consumptions Decreased with the Addition of A Double-Skin?. *Energy and Buildings*, *39(5)*, 605-619.
[65] P. C.Wong, D. Prasad, and M. Behnia (2008). A New Type of Double-Skin Façade Configuration for the Hot and Humid Climate. *Energy and Buildings, 40(10)*, 1941-1945.
[66] Juan Zhou and Youming Chen. (2010). A review on applying ventilated double-skin facade to buildings in hot-summer and cold-winter zone in China. *Renewable and Sustainable Energy Reviews, 14(4)*, 1321-1328.
[67] R. Høseggen, B. J. Wachenfeldt, and S. O. Hanssen (2008). Building Simulation as an Assisting Tool in Decision Making: Case Study: With or Without a Double-Skin Facade?. *Energy and Buildings, 40(5)*, 821-827.

must be done for other reasons than economy. A DSF “leads to about 10–15% energy saving for cooling in the peak of summer because of heat exhausted by natural ventilation, 20–30% energy for heating in winter because of the greenhouse effect (Xu et al., 2007, pp. 2014-2023).”[68] Significant energy saving is resulted if a multi-story DSF is integrated with an HVAC system as a preheating space (Choi et al, 2012).[69] Accordingly, by considering appropriate blind locations, color, and the opening of a double-skin system, cooling load can be decreased by 23.2% (Gratia et al, 2007). Ultimately Zhou et al. (2010) have quantified characteristics of a DSF to attain higher performance:

> It is of necessity to analyze the dynamic thermal performance of the DSF, which depends closely on the chosen ventilation means within its intermediate space, the performance and location of the shading system, the material of the glazing facades, the geometry size of the cavity and the construction of the double-skin facade and so on (pp. 1321–1328).

In general, acoustic insulation, thermal insulation, energy saving and reduced environmental impacts, transparency, natural ventilation, low U-value, and protection of shading and reflecting devices are main benefits of DSFs, while the higher construction cost, overheating, reduces square footage, additional maintenance, increased construction weight, and glare are main DSFs’ drawbacks (Poirazis, 2004, pp.179-182).

3.4 Geothermal Energy (Earth-Tubes)

Geothermal, as a renewable energy, is produced and stored in the earth; geo (earth) plus thermal (heat) is earth’s heat energy. It “is stored in rock and in trapped vapour or liquids, such as water or brines; these geothermal resources can be used for generating electricity and for providing heat (and cooling)” (International Energy Agency, 2013).[70] Due to the thermal energy constantly being generated inside the core and the radioactive deterioration of particles in the crust, the earth is warmer at deeper layers (MIT-led Interdisciplinary Panel, 2006).[71] A geothermal energy system’s benefits are its simplicity and low environmental impact, operating cost, and maintenance cost. No need for supplemental heat, exposed

[68] Lei Xu and Toshio Ojima (2007). Field Experiments on Natural Energy Utilization in a Residential House with a Double Skin Façade System. *Building and Environment, 42(5)*, 2014-2023.
[69] Wonjun Choi, J. Joe, Y. Kwak, & J. H. Huh (2012). Operation and Control Strategies for Multi-Storey Double Skin Facades during the Heating Season. *Energy and buildings, 49*, 454-465.
[70] International Energy Agency (2013). *Geothermal*, Retrieved from: http://www.iea.org/topics/geothermal/, Date Accessed: February 22, 2014.
[71] MIT-led Interdisciplinary Panel (2006). *The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century.* Cambridge, MA: Tester, Jefferson et al., section 2.2.6.

outdoor equipment, along with level seasonal electric demand and longer life expectancy are other indicated benefits (Geothermal Heat Pump Consortium, 2004). [72]

The temperature at around seven feet under the ground is relatively constant, and is around 50 to 73 °F (10-23 °C). It is due to the fact that the underground temperature at that level is not influenced by the immediate outside climatic condition. This temperature also depends on the climatic conditions above the ground level and soil characteristics. Despite the other clean natural energy resources, geothermal is available 24 hours a day, year round. The maximum surface temperature and the maximum soil temperature at this level, also, have a lag time around eight weeks, useful in summer cooling and winter heating.[73] The soil temperature is always warmer during cold seasons and colder during hot seasons. "While the margin of variation is small, seasonal changes in ground temperature give geothermal heat pumps a dependable and permanent wintertime heat source and summertime heat sink (U.S. Department of Energy, 2011)."[74]

Earth-tubes consist of a piping system typically buried 6 to 12 feet below the ground level. Fresh air is directed to these tubes where it gets either preheated or precooled. Then, it could either be redirected to various building spaces or to the mechanical systems. Ground Source Heat Pump (GSHP) is one of the popular ever-growing applications of geothermal systems. GSHP relies on the reasonably constant temperature of shallow ground to provide buildings' heating, cooling or domestic hot water. Earth tube, thus, could be mostly used to preheat or precool air either to be utilized for passive or mechanical systems whilst saving a huge amount of energy specifically in extreme climatic conditions.

3.4.1 Background on Geothermal

Around 10,000 years ago with the settlement of Paleo-Indians at hot springs, according to archaeological evidences, the first geothermal application in North America happened. The springs were used as a source of heat, healing, and cleaning. In 1807, the first European who visited the Yellowstone area, John Colter

[72] Geothermal Heat Pump Consortium (2004). *Information for Evaluating Geoexchange Applications.* New York State Energy Research and Development Authority (NYSERDA) pp. 5-6.
[73] John Bartok (2012). Geothermal Heat for Greenhouses, Retrieved from: http://www.extension.org/pages/27790/geothermal-heat-for-greenhouses#.UwO-SvldVqU, Date Accessed: February 22, 2014.
[74] U.S. Department of Energy (2011). *Energy Efficiency and Renewable Energy*, Retrieved from: http://energy.gov/sites/prod/files/guide_to_geothermal_heat_pumps.pdf, Date Accessed: February 22, 2014.

encountered hot springs leading to establishment of “Colter's Hell.” The city of Hot Springs, Arkansas was founded in the same year, were the first commercial use of geothermal took place in 1830.[75]

In 1864, homes and dwellings were built near the springs to take advantages of the natural heat specifically in Hot Lake Hotel near Grande, Oregon. In 1892, a water system was piped from hot springs to town buildings for the first time serving 200 homes and 40 downtown businesses in Boise, Idaho. In Klamath Falls, Oregon, hot springs water was piped to various homes. In 1930, the first geothermal energy applied in a commercial greenhouse initiated in Boise, Idaho. The system used a 1000-foot well. The first downhole heat exchanger (DHE) was also developed by Charlie Lieb to heat his house.[76]

In 1940, the first residential space geothermal heating occurred in Reno, Nevada. In 1948, Professor Carl Nielsen developed the first ground-source heat pump for his personal residence’s use. In addition, the first electricity generated from geothermal resources happened in Hawaii in 1981. In 1987, geothermal fluids were used for gold recovery in the first geothermal-enhanced heap leaching project in Round Mountain, Nevada. The U.S. geothermal industry grew increasingly in 2011 and through the first quarter of 2012 while it has been making progress to the date.[77]

3.4.2 Types of Geothermal

Based on Bartok’s (2012) classification, geothermal systems have three categories: “low-temperature” (around 50°F through soil near the surface), “medium-temperature” (between 140 to 300°F through thermal wells and springs), and “high-temperature” (over 300°F through steams from geysers).[78] These types also fall into two generic types of “shallow” (such as GSHPs) and “deep” (such as power plants and direct-use systems). In addition, closed-loop as opposed to open-loop or vertical as opposed to horizontal or pond is another way to classify geothermal system. The availability of variables such as space, water, bedrock type, temperatures, and capital would demand different system type. These options are explained as followed:

Closed-loop systems: systems which are more environmentally friendly as they are sealed, and do not exchange fluid with their context. Normally, this fluid contains antifreeze liquid for equipment’s protection.

[75] ibid
[76] ibid
[77] ibid
[78] John Bartok (2012). Geothermal Heat for Greenhouses, Retrieved from: http://www.extension.org/pages/27790/geothermal-heat-for-greenhouses#.UwO-SvldVqU, Date Accessed: February 22, 2014.

Open-loop systems: Systems which discharge the fluid mainly water through injection into a well or surface water. These systems might be protected from water quality issues through a heat exchanger. Depending on the application of stated options, the following systems can be imagined:[79]

Closed-Loop Vertical Bore Ground Heat Exchangers
Closed-Loop Horizontal Ground Heat Exchangers
Closed-Loop Surface Water Ground Heat Exchangers
Open-Loop Heat Exchangers

3.5 Summary and Transition to Chapter IV

Up to this point, major concepts, theories and substance of the dissertation are elaborated. The next chapter-Chapter IV: Methodology- will detail out methodological processes. More specifically, elements such as the research's statement, relevance, question, emphasis, assumption, context, modeling, design, method, and quality will be discussed.

[79] Peter Darby (2007). Geothermal Heat Pump Consortium. In *Information for Evaluating Geoexchange Applications* (2nd ed). Washington, D.C. 8, 9-28-09; 10-1-09.

Chapter IV: Methodology

4.1 Introduction

A search for "good" in architecture is an inspiring challenge for many committed architects. Although many may accept it as concept, design processes may lead diverging solutions. This, in part, can be due to diversity of perceptions, itself different in times and from various standpoints. This search for good can be traced back in time, when Vitruvius (born 84 BC) had introduced the three principles of commodity (*commoditas*), firmness (*firmitas*), and delight (*venustas*). These three for long had been the key principles that good architecture was after.[80] From then onward, new intellectual discourses in each period have been drawing the attentions to some other aspects that should be impacting the architectural design such as environment-behavior studies emerged in the 1960s and sustainability materialized in the 1970s. Connecting to these past and existing concerns, this dissertation continues the search for "good" in architecture, perceived by being after inclusive design solutions that can address all issues that could and should be considered from various standpoints. This, admittedly, is a far too broad problem demanding sophisticated, if not epic, design solutions responsive to various ecologies of the culture, history, economy, technology, aesthetic, and anything that matters. Studying each of these disciplines and their practical impact on design is beyond the scope of a single doctoral dissertation. In this study, however, the effort is primarily fixated on the energy evaluation linked to ecological dimensions of architectural design.

Architectural design prior to the invention of modern technologies in various cultures was typically context-responsive in order to achieve comfort. With positive intentions aiming to achieve the good, modern architecture also made constructive attempts at increasing human comfort levels. However, ecological consciousness was less considered in the process, partially due to the availability and uses of advanced building technologies coupled with the lack of a profound understanding of the "good" in design. Recently, environmental awareness has added another dimension to the design process. As a result, an enhanced ecological attitude throughout the process is now considered as a key value. Lately, the integration of this idea as a theoretical framework into the early stages of design has also been recognized. Today, an ecological design approach can be a context-responsive solution that diminishes the built environments' dependency on exhaustible energies by using natural resources such as sun, earth, wind and water. Energy management, thus, has become an essential concern and a new paradigm in contemporary architecture.

In line with the added energy management demands, building performance evaluation becomes indispensable, made possible via the use of cutting-edge computer software tools throughout a design

80 Vitruvius & T. G. Smith (2003). *Vitruvius on Architecture*. Monacelli.

process. Simulation softwares, for instance, are employed to evaluate and validate decision-making processes that increase the performance of built environments. This perspective must impose further drastic amendments to architectural programming. In view of that, chapter I of this dissertation has suggested the "Evaluative-Based Programming" as a more dynamic, consensus-oriented, performance-driven, software-aided, and foresighted approach that can embrace the entire process of architectural delivery. Evaluation, as extensively discussed in chapter 1, becomes the essence of an architectural programming aiming at high-performance solutions. This approach early in the programming phase attempts to help reaching the "good" in architecture.

The chapter on methodology elaborates on what is to be studied, why, and how the study is conducted. Starting with the Research Statement, the "what" is discussed: an integrative supplemented solution with goals to increase performance of a DSF. Moving to the Research Relevance, the chapter describes the "why;" the significance of studying DSFs. Next, the Research Questions pose a set of related inquiries and the Research Emphasis describes the research focus. The three proceeding sections, Research Method, 4. Research Quality, and Data Analysis, go through the "how" of the study, discussing, for instance, main research strategies and key explanations on how the research questions would be answered.

4.2 Research Statement

Elaborating on the "what," this dissertation is a case study of an enhanced DSF system,[81] proposed as an integrated design option. More specifically, the research is conducted via a quantitative energy evaluation on the performance of the proposed DSF concept by simulating it via a computerized model. Through the theoretical lens of the introduced "evaluative-based" approach to programming regarding energy, the premise shaped that the economic performance of the building with a naturally ventilated DSF system could enhance if the system gets linked into the mother earth via earth-tubes. The main idea is the assimilation of a more energy-efficient ventilation system by means of naturally precooled/preheated air. The study speculates that this combination, of the optimized DSF and its connections to the earth, could resolve DSF's disadvantage of overheating, leading to a lower building energy utilization intensity (EUI), which would then increase the economic performance of a DSF system. The enhanced system is expected to function as a passive system

[81] DSF is a multilayered building component that in a basic condition contains an external glass facade, an intermediate cavity space for airflow, and an inner façade primarily out of glass.

in conjunction with mechanical systems, in the form of a hybrid organization. To assure the system's compatibility with all restricted cases and extreme contextual situations, a hybrid version that is a combination of both passive and high-tech mechanical systems is envisioned. In the end, the outcome of this case study could also reveal the validity and practicality of the suggested "evaluative-based" approach towards ecological design.

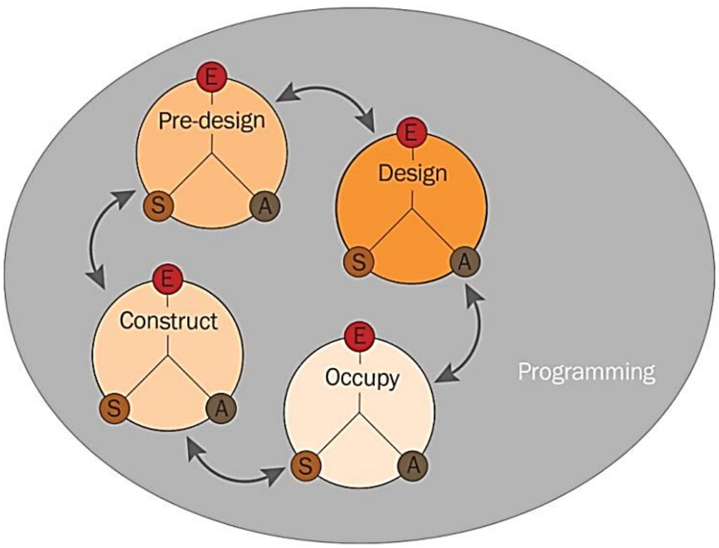


Figure 4.1
Diagram shows the general architectural delivery process and relationship between programming and design (Source: Adapted by Author).

In this evaluative-based approach, programming and design are not separated, and are in a cyclical relationship influencing each other. Simultaneous evaluation in the entire process of architectural delivery is the essence of this performance-driven solution. Mainly inspired by Duerk's (1993) programming approach,[82] this entire design process can become an integral part of a programming approach that includes other sectors within construction, occupancy, and post occupancy (Figure 4.1). That is, design becomes a component of programming as a whole and evaluation becomes a vital factor constantly considered to analyze and synthesize each given stage of pre-design, design, construction, and occupancy (Figure 4.2). All decisions, thus, from very early stages, even before design is initiated to years after it is used, are continually weighed

[82] Donna Duerk (1993). *Architectural Programming: Information Management for Design*. New York: Van Nostrand Reinhold.

to validate their positive impacts on the built environments' performance. As the focus and to limit the scope of this dissertation, the study only evaluates the energy performance of a DSF.

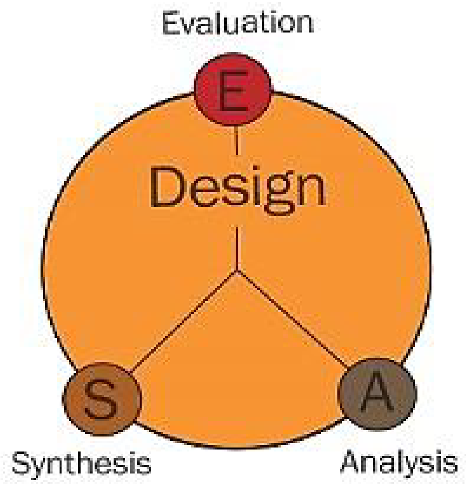


Figure 4.2
Scheme shows the relation of evaluation to design in a non-linear process (Source: Adapted by Author).

4.3 Research Relevance

Elaborating on the "why," why it is important to study Double-Skin Façade (DSF) systems, this dissertation supports an architectural design approach that is constructed upon the notion of *Poetics Pursues Performance.* This, as explained earlier, would also need to be a practical strategy to assure the making of "good" and be an integrated one. All design components must be fused as a whole to achieve high-performance built environments. DSFs are used as a concrete example derived from the inclusivist design viewpoint. DSFs are sophisticated architectural systems in which day-lighting, natural ventilation, acoustic/visual/thermal comfort, tectonic, and aesthetics are addressed, altogether. In addition to their beneficial environmental aspects, DSFs generate spatial possibilities that foster social interaction and occupants' productivity. Despite DSFs' numerous advantages, their economic efficiency, in comparison to conventional building envelopes, is reported controversial. This dissertation conducts meticulous simulations and profound evaluations of a DSF system as a prototype solution to inventively enhance some of the economic drawbacks of this pioneering system. The goal, consequently, is to showcase a design approach capable to achieve high-performance built environments.

Finding innovative applications of the design of building envelopes is also the study's overarching objective. Looking at the history of architecture, it becomes evident how architectural styles have mostly been linked to the building envelope. That is, from classical to contemporary postmodern, most architectural classifications are associated with building envelopes. Envelopes also play significant roles, having close associations with many environmental, social, and economical aspects of buildings. Moreover, the envelope can also become a component of an ecological development. The relation of a building envelope to the building itself is akin to that of the skin to the body of a plant, animal or human being. Accordingly, a DSF in a building could resemble having the function of a garment for the human body. If an envelope is appropriately designed while also ecologically responsive to its contextual surroundings, it can positively enhance the building performance. In his article, On Skin and Other Preoccupations of Architectural Design, Tombazis (1996) writes:

> What I believe important, is to recognize that the skin of a building should be considered as part of a living organism and that it should be flexible, adaptive and dynamic and not necessarily static in its existence. I believe it both useful and necessary, to look and think of the overall envelope of buildings, which means both skin and aperture, in a different way. We do not need more technology or complicated gadgets. What we need is more sophistication in our way of thinking (p. 55).

DSF is chosen as a product of an inclusivist viewpoint to improve the performance of buildings; it is a low-tech ecological solution. It is a practical solution to improve outdoor and indoor environments. Yet, its success from an economic standpoint is controversial. Based on previous studies (Gratia et al, 2007; Wong et al., 2008; Zhou et al., 2010; Hoseggen et al., 2008; Choi et al., 2012; & Poirazis, 2004), the use of DSFs at different climatic contexts has been disputed. That is mainly due to the issues of overheating during hot seasons, causing an increase in energy costs, as well as DSFs' exceeding construction and maintenance costs, in general. As a result, new studies should address DSFs' economic challenges that could evaluate and ostensibly validate novel solutions. Following sections explicate the proposed integrative and complemented solution, how it is expected to resolve DSFs' overall applications and how the study is conducted.

4.4 Research Question

A suitably-designed DSF addressing the issue of overheating can reduce a building's energy utilization intensity. This fine-tuning balances DSF's application despite its exceeding construction and maintenance

cost in comparison to conventional building envelopes. To investigate the new solution and process of reaching that, the study asks the following questions:

1- *How could the design practice eliminate the overheating issue associated with DSFs in order to make them generally applicable to most contextual conditions?*

2- *How do various components of an integrated DSF interact and function to shape a high-performance system as a whole?*

As far as energy efficiency is concerned, one could always think of consuming less. Employing natural non-fossil energy resources through low-tech systems could be another solution. An ideal concept would be to generate energy or to convert the available natural energies to the desired energy forms. Potentially, a well-designed DSF combined with the concept of earth-tubes[83] could address most of these issues. It admits the maximum solar energy as the major natural source whilst it controls the undesired sunlight. A DSF provides improved day-lighting by diffusing most of the direct sunlight, which eliminates the issue of glare. The cavity shaped by the second skin could also function as a thermal buffer to moderate buildings temperature against harsh external conditions. Acoustic insulation is another advantage of the second skin as a buffer. In addition, DSF promotes the idea of natural ventilation through the intermediate layer, the cavity.

This dissertation argues that the optimized DSF system with careful admissions of natural ventilation is the essence of a DSF's practicality. The combination of an already enhanced DSF and an earth-tube could rationalize DSF's application in ecological buildings. In the proposed concept, fresh air or potential outside breezes should be directed to the underground earth-tubes where it could be either precooled or preheated, depending on the outside climatic condition.

During cold seasons, the preheated air via the earth-tube concept is directed to the cavity in order to be exposed to the sun. Then, it gets warmer, and depending on its temperature might be channeled as the required fresh air, either:

a- *to the building's interior spaces* directly when both its temperature and humidity levels are close enough to human comfort zone (Figure 4.3a); or

[83] Earth-tubes consist of a piping system typically buried 6 to 12 feet below the ground level. Fresh air is directed to these tubes where it gets either preheated or precooled. Then, it could either be redirected to various buildings' spaces or to the mechanical systems.

b- *to the mechanical systems* as the air supply and, then, to the building's interior spaces (Figure 4.3b & 4.3c). This exchange could ensue interchangeably if the moderated air in the cavity (sunspace) is directly introduced to the building spaces (office zones), as a hybrid system that demands less energy load for heating.

During hot seasons, however, the precooled air via the earth-tube concept will be directed both to the cavity to moderate DSF's temperature and be exhausted from the outlet on top of the DSF (in order to avoid the issue of overheating), and either:

c- *to the building's interior spaces* directly as the required fresh air, when both its temperature and humidity are close enough to the human comfort zone, via an enclosed duct that is not impacted by outside hot or humid condition (Figure 4.4a); or

d- *to the mechanical systems* as the air supply and, then, to the building's interior spaces (Figure 4.4b & 4.4c). Similarly, the moderated air via the duct could also be first directed to the interior spaces as the fresh air needed for ventilation in a hybrid system.

Considering these four operational systems, there will be various possible options for the combination of hot and cold seasons, depending on a site's climatic conditions. Several other variables relevant to a DSF's operation and construction could be considered to classify various kinds of DSFs. Main factors in those variables include: type of ventilation, origin of airflow, destination of airflow, airflow direction, width of air cavity, and partitioning (Flamant et al, 2002).[84] Installing louvers as the shading device is another variable to be combined with the application of relevant control strategies in order to avoid any unwanted airflow. These variables would help in creating diverse DSF types to best meet the projected operation and positively enhance a building's ecological performance. Success and challenges of the proposed, integrated system in correlation with the indicated variables will be discussed in the Findings and Conclusions chapter. Altogether, this dissertation launch this enquiry with the following hypothesis:

- *In a non-residential building, an optimized double-skin facade linked into the earth would eliminate the issue of overheating in hot seasons; therefore, it would minimize its Load Intensity (LI) to an extent that can turn it into a practical solution.*

[84] G. Flamant, X. Loncour, & P. Wouters. (2002, October). Performance Assessment of Active Façades in Outdoor Test Cells. *In 23rd AIVC and EPIC 2002 Conference*, Lyon, France (pp. 23-26).

Figure 4.3a
DSF integrated with the earth-tube, system’s function in winter days (Type 1)

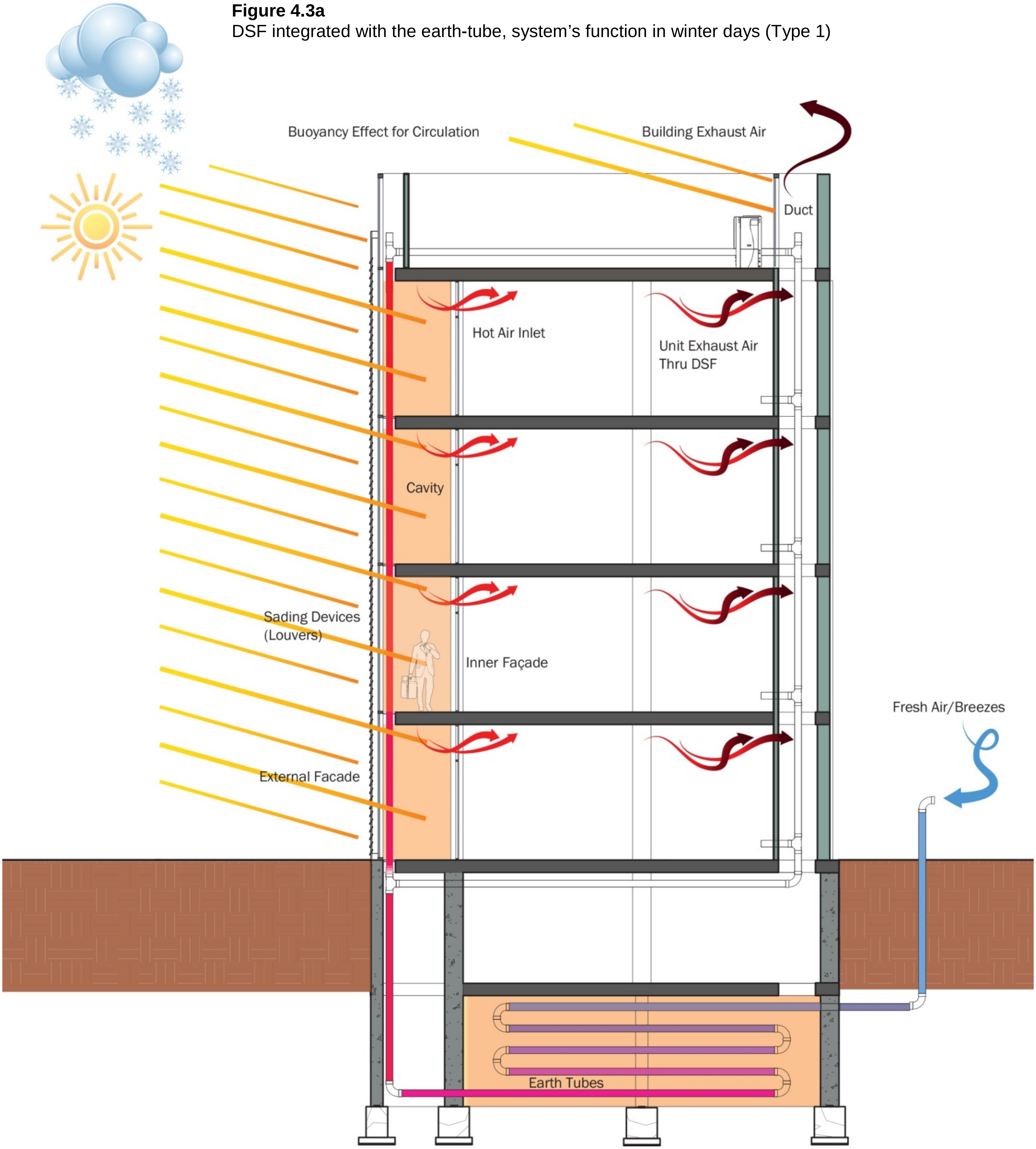


Figure 4.3b
DSF integrated with the earth-tube, system's function in winter days (Type 2)

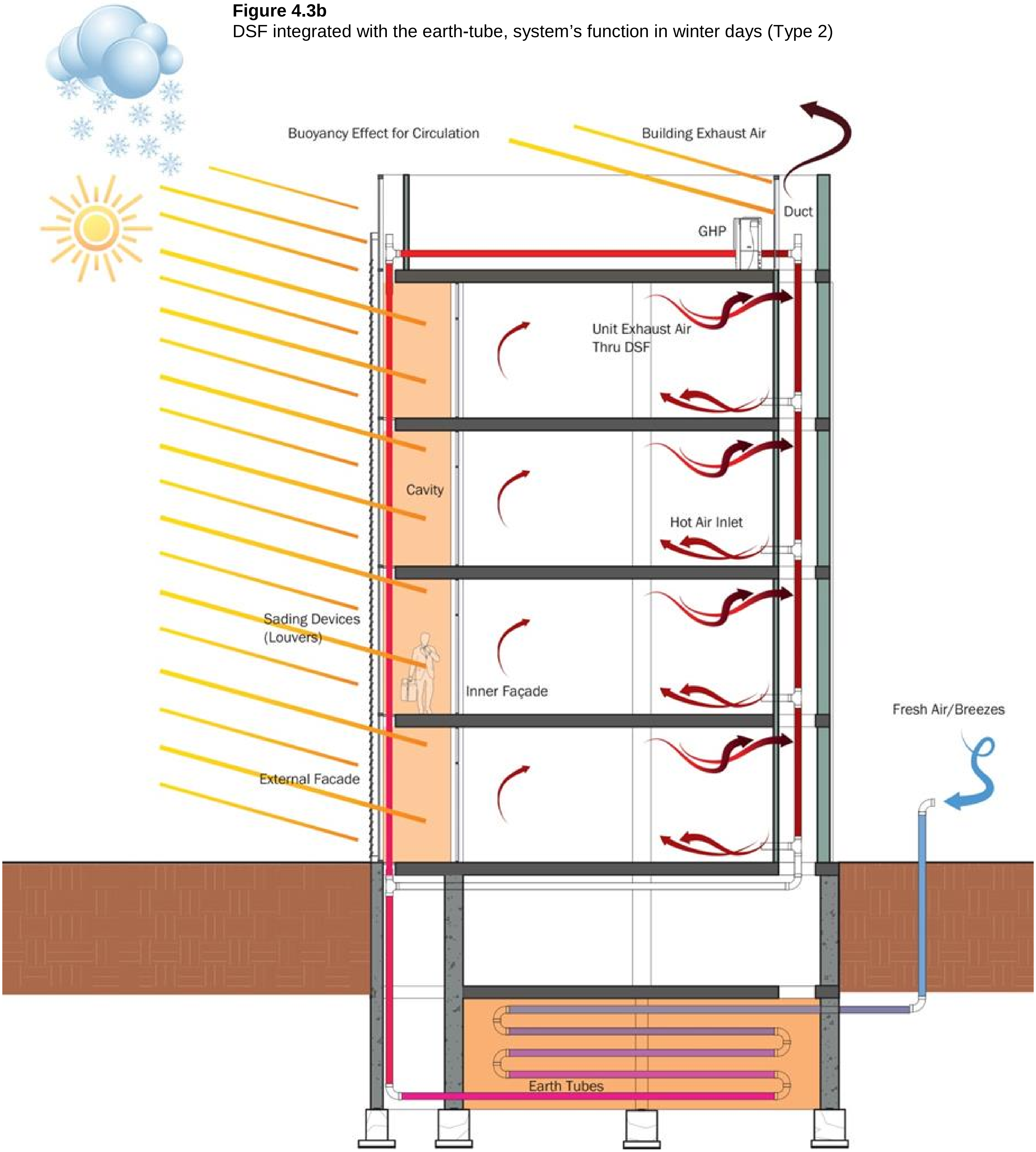


Figure 4.3c
DSF integrated with the earth-tube, system's function in winter nights (Type 2)

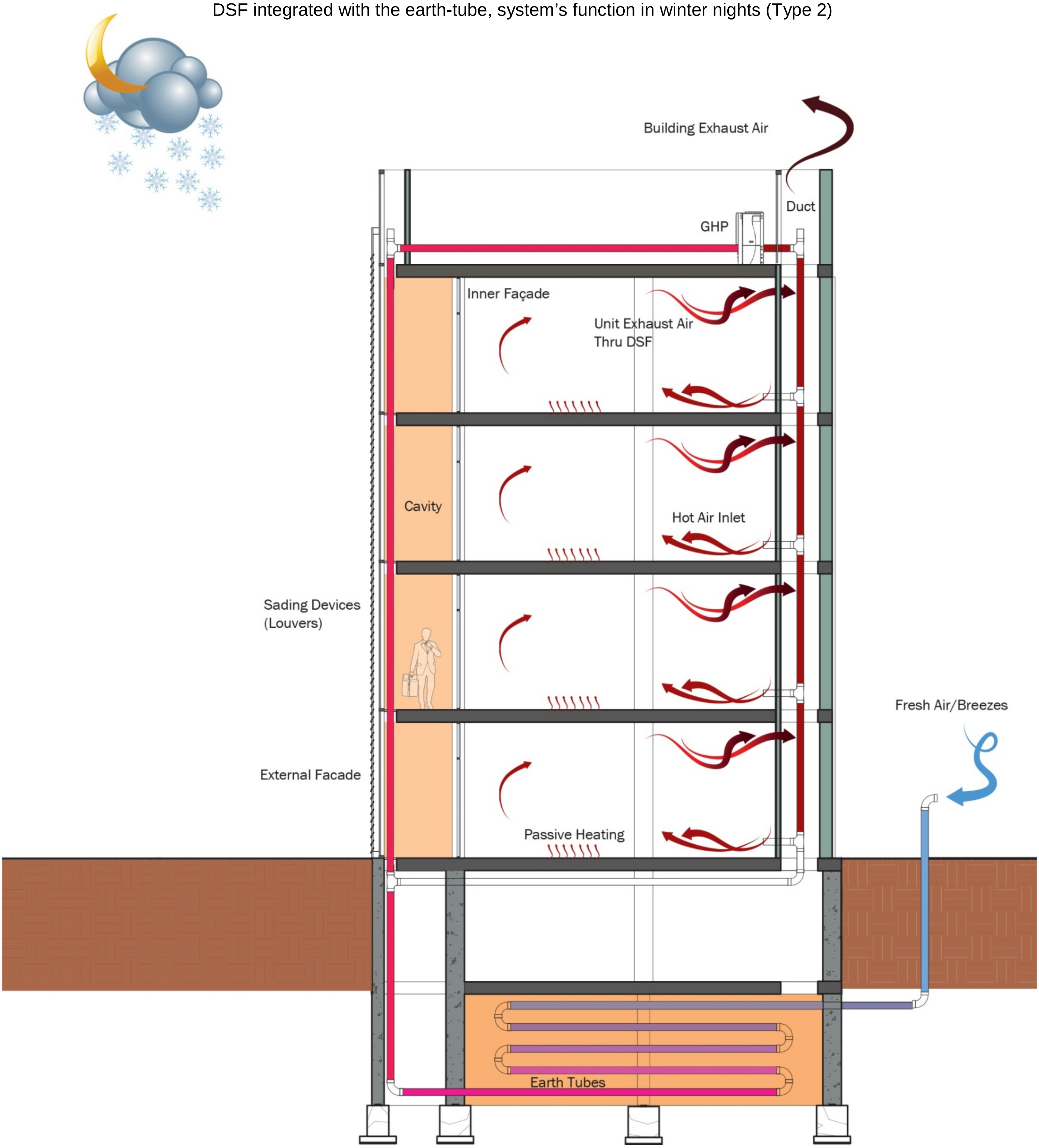


Figure 4.4a
DSF integrated with the earth-tube, system's function in summer days (Type 1)

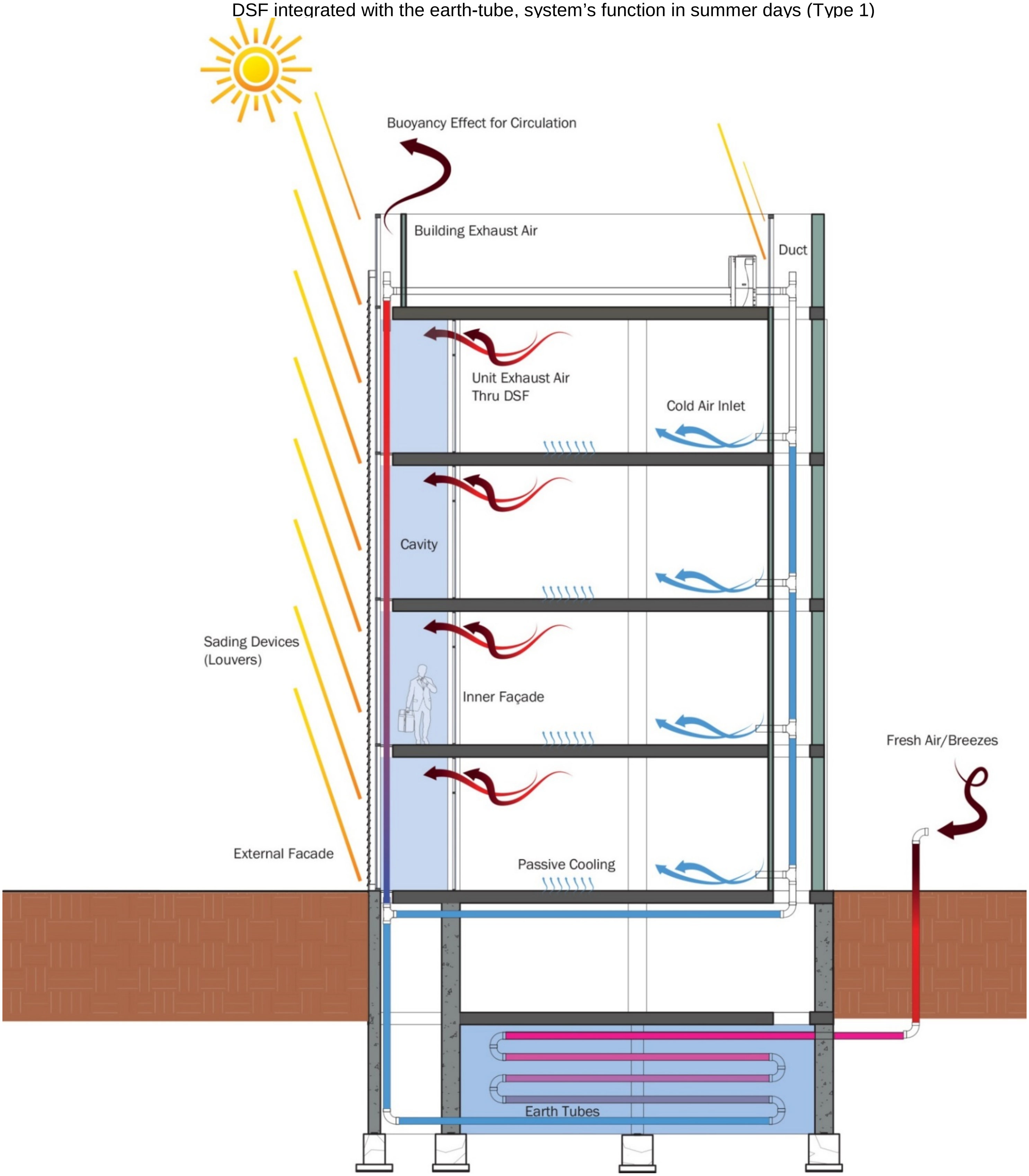


Figure 4.4b
DSF integrated with the earth-tube, system's function in summer days (Type 2)

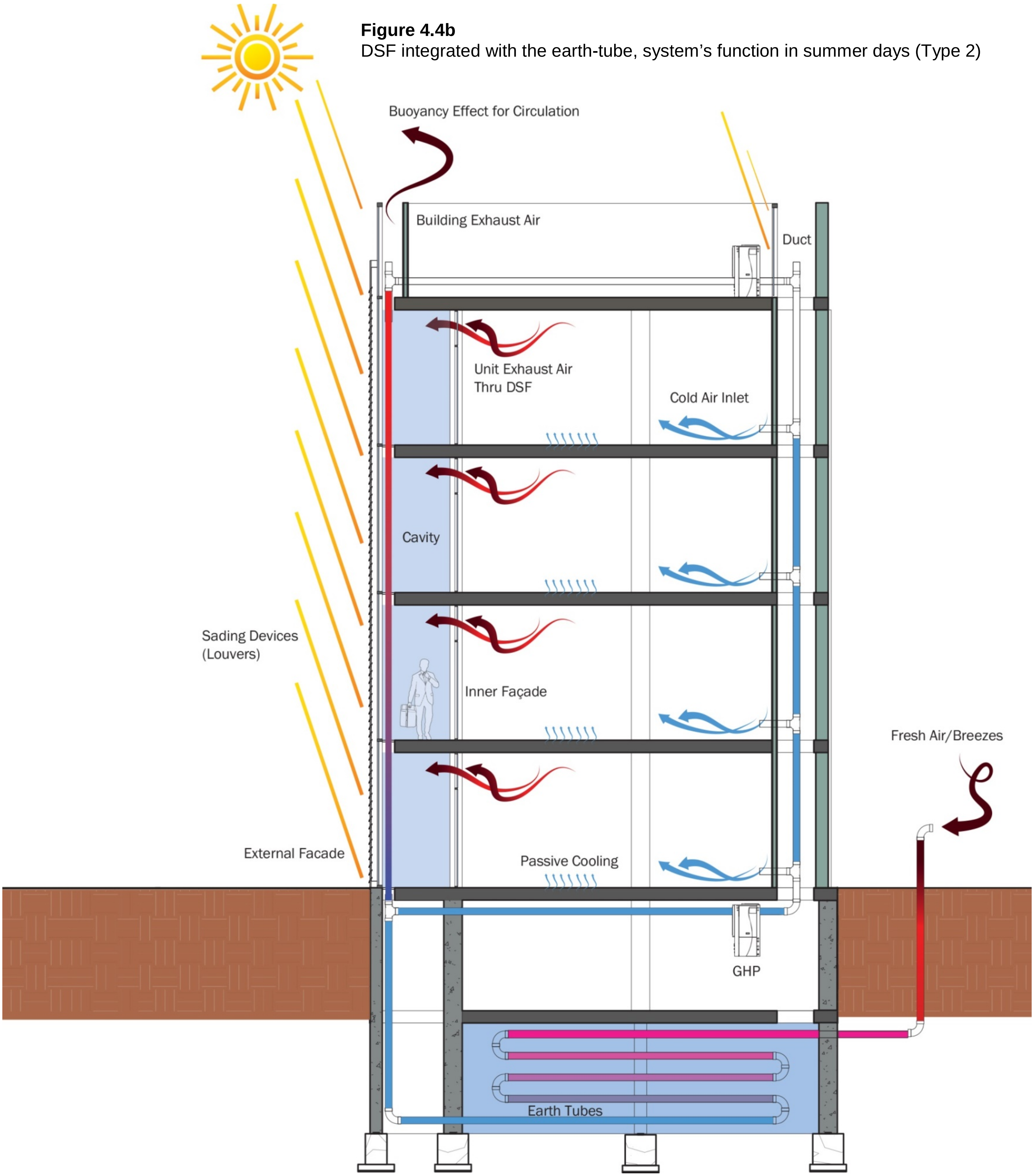
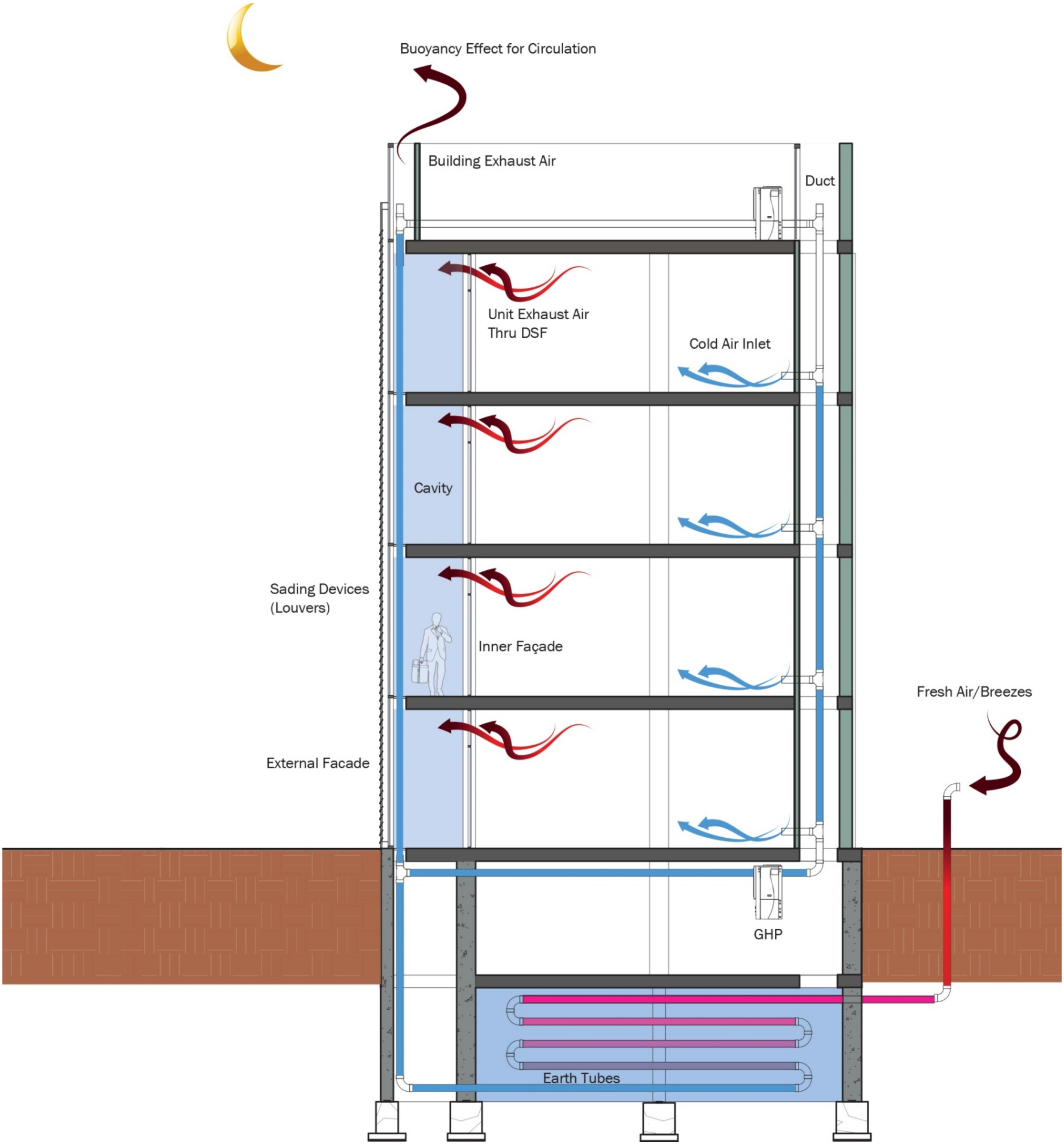


Figure 4.4c
DSF integrated with the earth-tube, system's function in summer nights (Type 2)



4.5 Research Emphasis

Working towards the "good," as the essence of design for committed architects discussed earlier, is an expansive idea. This can be reached, however, if design solutions address all issues to be considered from the standpoints of all potentially associated disciplines and people. The broad indication demands excessive open-mindedness. In a similar vein, high-performance design solutions must embrace inclusivist approaches considering all aspects of ecology: culture, history, economy, technology, aesthetic, and anything that matters.

While also valuing impacts of other disciplines on the design of high-performance built environments, the dissertation only concentrates on ecological aspects. To be more precise, the study's focus is on the Load Intensity (LI) of buildings related to thermal comfort (cooling, heating, humidification/ dehumidification, and ventilation). Simply put, it is about the impact of design decisions on buildings' needs for HVAC systems. Basically, a buildings' EUI is a result of heating, cooling, humidification/ dehumidification, ventilation, and providing hot water, lighting, and electricity combined (Figure 4.5). In order to limit the scope of this study, the energy needed for providing hot water is not considered while a standard level of lighting and electricity use is presumed. The hypothetical model of the study is prototyped that is a four-story non-residential building on a basement with a naturally ventilated DSF system. What follows is the elaboration of the further detailed assumptions prepared for conducting the study:

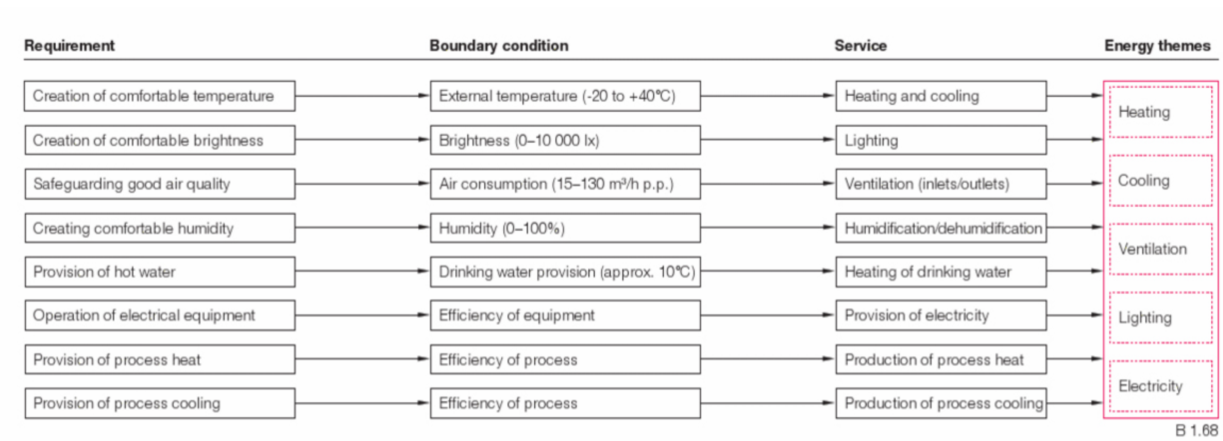


Figure 4.5
Energy Utilization Intensity in Buildings (Source: Hegger et al, 2008).[85]

[85] Mark Hegger, Fuchs, M., Stark, T., & Zeumer, M. (2008). Energy Manual. *Sustainable Architecture, Department of Architecture, Darmstadt Technical University, Munich, Germany*.

4.6 Research Assumptions

The proposed DSF system operating by both means of natural and mechanical ventilation will be examined. The origin of the airflow starts with ambient air to first enhance the DSF, and, then, it will be linked into the earth via underground earth tubes. Horizontally, the positive direction of airflow is assumed to be from ambient to double-skin and from there to office spaces, where the air is ultimately exhausted toward outside (for this south-facing, nonresidential building, it is always from south to north). Vertically, it is considered positive if the airflow direction is from the bottom to top of the building. The destination of the airflow is both towards inside and outside of the building, which are coming in four different ways depending on the season and time of the day. Three options of a wide (2m), medium (1m), and narrow (0.5m) is projected for the depth of the DSF. The air cavity, sunspace, has horizontal partitioning at the level of each story where each levels is connected to lower and upper level through floor and ceiling grills. For minimizing the impact of solar heat gain in hot seasons, a louver system is designed outside the exterior skin, expected to create 70% shading during hot seasons while it does not impact heat gain during cold seasons. The stated 70% shading in hot seasons can also be achieved by the design of proper overhangs possibly integrated with light-shelf. Based on the stated assumptions, a sample module in a hypothetical non-residential building with a basement and four floors above the grade is modeled using Energy-Plus plugin for SketchUp (Figure 4.6). TRNSYS, a transient systems simulation program, and CONTAM, a software for airflow analysis, are applied to simulate annual load intensity (Q_Heat+ Q_Cool +Q_Humidification + Q_Dehumidification) of this module with the variables, stated in the Research Question section. For the purpose of analyzing different degrees of effectiveness from those variables for various climates, three typical U.S. climates are selected, and for each climate and DSF depth, 12 different alternatives are developed plus 4 conventional building options that are common between each climate. Considering the three measurement options for the depth of DSFs and possible alternative options, 120 simulation runs in total are evaluated. These runs include 4 conventional building options common between all the three DSF depth, 4 buffer-type DSF system in which the cavity (sunspace) can be disconnected from outside air as an attached enclosed space, or either mechanically or naturally ventilated. The next 4 options are related to an HVAC-contributing DSF system integrated with a mechanically ventilated building. Finally, the stated HVAC-contributing DSF system is integrated with a naturally ventilated building for the last 4 options.

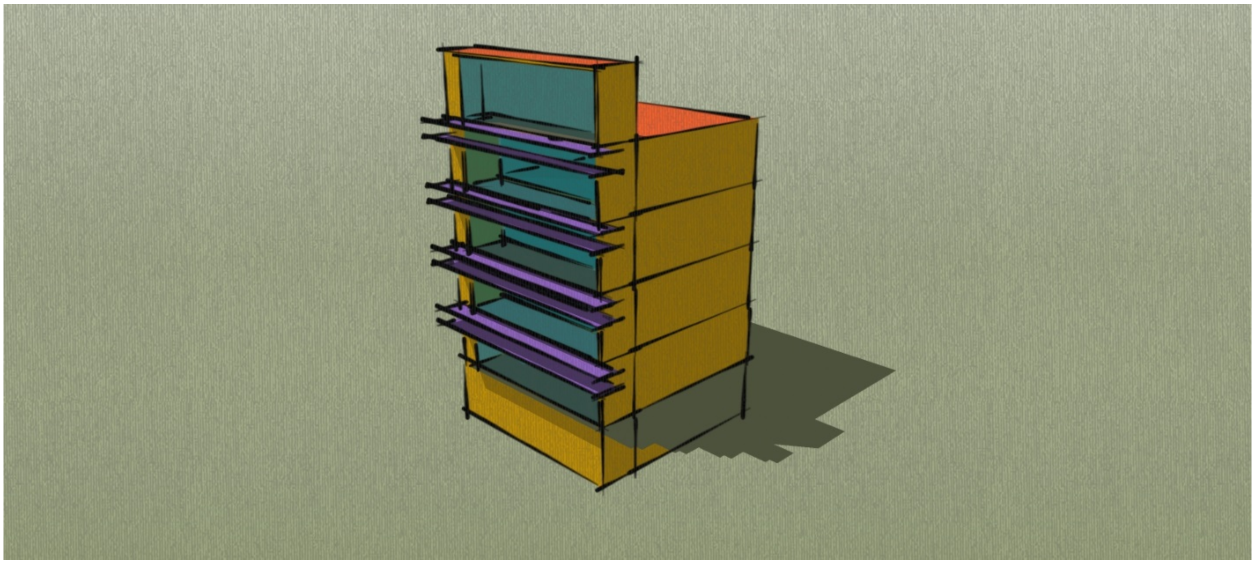


Figure 4.6
The 4-story building with integrated DSF and the adjacent duct created in Sketch-Up to be used in TRNSYS software (Source: Author).

Below is the list of simulation runs. The first digits indicate the run number modeled in TRNSYS, the digits just after the “DSF” represents the depth of it, and the letters are associated with the type of HVAC system modeled in CONTAM:

Run1 A (4-Story Shoe Box No HVAC): a hypothetical conventional 4-story building with an unconditioned basement with no DSF, which is unoccupied and unconditioned. CONTAM is not integrated in this option, since there is no provided ventilation for this shoe-box building.

Run2 B (MC 4-Story Full HVAC): a conventional, occupied, and *Mechanically Conditioned* 4-story building with an unconditioned basement and no DSF. CONTAM is integrated in this option, since there is a provided ventilation rate for this building. Note that the building is fully dependent on HVAC systems where the DSF functions as a thermal buffer.

Run3 B (MC 4-Story Construction EShading Full HVAC): The same as the previous run, except that *Construction* types for building components were optimized in this option, using suggested ASHRAE’s U-values for each climatic condition. (Figure 4.7, 4.8, and 4.9 show what ASHRAE suggests as U-Values for each of the three climate zones, of 2, 3, and 6). In addition, a 70% external shading device in hot seasons is assumed to be in front of the south windows where the device does not have any impact on cold seasons in terms of heat gain.

Run4 B (MC 4-Story Construction Shading Full HVAC): The same as the previous run, while an optimized passive shading is integrated. It includes 1.1 m-depth overhang at the height of 3m for all climates instead of the 70% Eshading device. Also, an added 1.1 m-depth light-shelf at the height of 2.2m is designed just for Phoenix and Atlanta in southern façade. This option (Run4 B) is an integrated shading system that is called *BASALINE* hereafter.

Run5 C (MC 4-Story DSF2 Full HVAC): The same as the previous run, except that the shading devices are eliminated by the attachment of a DSF with no airflow connection neither to the building nor to the outside. The ventilation rate is provided via the southern ducts directing air from outside to the office zone during the occupancy hours. (The digit after the DSF represents the depth of it, which is 2 m in this case).

Run6 C (MC 4-Story DSF2 Shading Full HVAC): The same as the previous run, while a passive *Shading* on the southern glazing is assumed to be the same as the baseline for each climate.

Run7 D (MC 4-Story MV DSF2 Full HVAC): The same as the previous run, while the DSF is *Mechanically Ventilated* by three 110cfm capacity fans (on north, east, and west sides), on top of the sunspace, located 2.8 m above level 5 for exhausting air in hot seasons. The fans do not function during the cold seasons to shape an enclosed DSF. Note that there is still no connection between the sunspace and office zones, and the DSF is just functioning as a thermal buffer.

Run8 E (MC 4-Story NV DSF2 Full HVAC): The same as the previous run while the DSF is *Naturally Ventilated* by three self-regulating vents on the exact same spot as the fans in previous option. These vents would only allow maximum airflow of 110 cfm in the positive direction of the top sunspace to the outside.

Run9 F (MV 4-Story MV DSF2 Semi HVAC): The same as the previous run while the *Mechanically Ventilated* DSF is integrated into the HVAC system where the pre-heated air in the sunspace is introduced to the office zones during cold seasons when building is occupied.

Run10 F (MV 4-Story MV DSF2 Semi HVAC Hypo): The same as the previous run while the *Mechanically Ventilated* DSF is linked into the earth via the earth-tubes (Hypocaust system) below the building, where the pre-conditioned air in the air-tubes is directed into either the duct [to be introduced to the office zones in hot seasons] or sunspaces [to be exposed to cold season sunlight before directed to the office zones]. There are 14 earth-tubes with 20 m length, 0.5 m exterior diameter, 0.05 m thickness, heat conductivity of 7.2 kJ/(hr K.m), heat capacity of 1000 kJ/K m3, and exchange coefficients of 7 kJ/hr K m^2 and 14 kJ/hr K m^2)/(m/s). Their material is assumed to be somewhere between characteristics of concrete and the soil around them.

Further Information about detail of the earth-tubes can be seen in Appendix E.

Run11 G (MV 4-Story NV DSF2 Semi HVAC): The same as the Run9, except that the DSF is *Naturally Ventilated* via the three self-regulating vents stated earlier.

Run12 G (MV 4-Story NV DSF2 Semi HVAC Hypo): The same condition as the previous run while the DSF is linked into the earth via earth-tubes.

Run13 H (NC 4-Story MV DSF2 No HVAC): The same as Run9 except the building is now *Naturally Conditioned* with proper controlling systems, such as the introduction of air from sunspaces into the office zones via a 8 x 0.2 m opening at the height of 0.3 m (floor to the mid-height of the window). In addition, to avoid overheating issue, the building is ventilated with the same self-regulating vents with the maximum of ASHRAE suggestion for each office during the unoccupied hours in hot seasons. This is very similar to the idea of night-purge except the air is introduced from the ducts instead of ambient. The three fans are the same for the exhaust of air in the top of DSF.

Run14 H (NC 4-Story MV DSF2 No HVAC Hypo): The same condition as the previous run, while the DSF is linked into the earth via earth-tubes.

Run15 I (NC 4-Story NV DSF2 No HVAC): The same as run as Run13 where the extra self-regulating vents with maximum ASHRAE ventilation rate are used for each office zone as a passive night cooling strategy. Note that the use of self-regulating vent assists in not allowing the airflow from offices into the sunspaces while the airflow direction and amount is akin to that of fans.

Run16 I (NC 4-Story NV DSF2 No HVAC Hypo): The same condition as the previous run, while the DSF is linked into the earth via earth-tubes.

Table 5.5-2 *Building Envelope* Requirements for Climate Zone 2 (A,B)*

Opaque Elements	*Nonresidential* Assembly Maximum	Insulation Min. *R-Value*		*Residential* Assembly Maximum	Insulation Min. *R-Value*		Semiheated Assembly Maximum	Insulation Min. *R-Value*	
Roofs									
Insulation entirely above deck	U-0.039	R-25 c.i.		U-0.039	R-25 c.i.		U-0.173	R-5 c.i.	
Metal building[a]	U-0.041	R-10 + R-19 FC		U-0.041	R-10 + R-19 FC		U-0.096	R-16	
Attic and other	U-0.027	R-38		U-0.027	R-38		U-0.053	R-19	
Walls, above Grade									
Mass	U-0.151[b]	R-5.7 c.i.[b]		U-0.123	R-7.6 c.i.		U-0.580	NR	
Metal building	U-0.094	R-0 + R-9.8 c.i.		U-0.094	R-0 + R-9.8. c.i.		U-0.162	R-13	
Steel-framed	U-0.084	R-13 + R-3.8 c.i.		U-0.064	R-13 + R-7.5 c.i.		U-0.124	R-13	
Wood-framed and other	U-0.089	R-13		U-0.089	R-13		U-0.089	R-13	
Wall, below Grade									
Below-grade wall	C-1.140	NR		C-1.140	NR		C-1.140	NR	
Floors									
Mass	U-0.107	R-6.3 c.i.		U-0.087	R-8.3 c.i.		U-0.322	NR	
Steel joist	U-0.038	R-30		U-0.038	R-30		U-0.069	R-13	
Wood-framed and other	U-0.033	R-30		U-0.033	R-30		U-0.066	R-13	
Slab-on-Grade Floors									
Unheated	F-0.730	NR		F-0.730	NR		F-0.730	NR	
Heated	F-0.900	R-10 for 24 in.		F-0.860	R-15 for 24 in.		F-1.020	R-7.5 for 12 in.	
Opaque Doors									
Swinging	U-0.370			U-0.370			U-0.700		
Nonswinging	U-0.310			U-0.310			U-1.450		
Fenestration	Assembly Max. U	Assembly Max. *SHGC*	Assembly Min. *VT/SHGC*	Assembly Max. U	Assembly Max. *SHGC*	Assembly Min. *VT/SHGC*	Assembly Max. U	Assembly Max. *SHGC*	Assembly Min. *VT/SHGC*
Vertical Fenestration, 0% to 40% of *Wall*		(for all frame types)			(for all frame types)			(for all frame types)	
Nonmetal framing, all	0.37	0.25	1.10	0.37	0.25	1.10	0.93	NR	NR
Metal framing, fixed	0.54			0.54			1.20		
Metal framing, operable	0.65			0.65			1.20		
Metal framing, entrance door	0.83			0.77			0.83		
Skylight, 0% to 3% of *Roof*									
All types	0.65	0.35	NR	0.65	0.35	NR	U-1.80	NR	NR

* The following definitions apply: c.i. = *continuous insulation* (see Section 3.2), FC = filled cavity (see Section A2.3.2.5), NR = no (insulation) requirement.
a. When using the *R-value* compliance method for *metal building roofs*, a thermal spacer block is required (see Section A2.3.2).
b. Exception to Section 5.5.3.2 applies for *mass walls* above *grade*.

Figure 4.7
Building Envelope Requirements for Climatic Zone 2 (A,B) (Source: ASHRAE).

Table 5.5-3 *Building Envelope* Requirements for Climate Zone 3 (A,B,C)*

Opaque Elements	*Nonresidential* Assembly Maximum	*Nonresidential* Insulation Min. *R-Value*	*Residential* Assembly Maximum	*Residential* Insulation Min. *R-Value*	Semiheated Assembly Maximum	Semiheated Insulation Min. *R-Value*
Roofs						
Insulation entirely above deck	U-0.039	R-25 c.i.	U-0.039	R-25 c.i.	U-0.119	R-7.6 c.i.
Metal building[a]	U-0.041	R-10 + R-19 FC	U-0.041	R-10 + R-19 FC	U-0.096	R-16
Attic and other	U-0.027	R-38	U-0.027	R-38	U-0.053	R-19
Walls, above Grade						
Mass	U-0.123	R-7.6 c.i.	U-0.104	R-9.5 c.i.	U-0.580	NR
Metal building	U-0.094	R-0 + R-9.8 c.i.	U-0.072	R-0 + R-13 c.i.	U-0.162	R-13
Steel-framed	U-0.077	R-13 + R-5 c.i.	U-0.064	R-13 + R-7.5 c.i.	U-0.124	R-13
Wood-framed and other	U-0.089	R-13	U-0.064	R-13 + R-3.8 c.i. or R-20	U-0.089	R-13
Wall, below Grade						
Below-grade wall	C-1.140	NR	C-1.140	NR	C-1.140	NR
Floors						
Mass	U-0.074	R-10 c.i.	U-0.074	R-10 c.i.	U-0.137	R-4.2 c.i.
Steel joist	U-0.038	R-30	U-0.038	R-30	U-0.052	R-19
Wood-framed and other	U-0.033	R-30	U-0.033	R-30	U-0.051	R-19
Slab-on-Grade Floors						
Unheated	F-0.730	NR	F-0.540	R-10 for 24 in.	F-0.730	NR
Heated	F-0.860	R-15 for 24 in.	F-0.860	R-15 for 24 in.	F-1.020	R-7.5 for 12 in.
Opaque Doors						
Swinging	U-0.370		U-0.370		U-0.370	
Nonswinging	U-0.310		U-0.310		U-0.360	

Fenestration	*Nonresidential* Assembly Max. U	*Nonresidential* Assembly Max. *SHGC*	*Nonresidential* Assembly Min. *VT/SHGC*	*Residential* Assembly Max. U	*Residential* Assembly Max. *SHGC*	*Residential* Assembly Min. *VT/SHGC*	Semiheated Assembly Max. U	Semiheated Assembly Max. *SHGC*	Semiheated Assembly Min. *VT/SHGC*
Vertical Fenestration, 0% to 40% of Wall		(for all frame types)			(for all frame types)			(for all frame types)	
Nonmetal framing, all	0.33	0.25	1.10	0.35	0.25	1.10	0.87	NR	NR
Metal framing, fixed	0.45			0.49			1.20		
Metal framing, operable	0.60			0.60			1.20		
Metal framing, entrance door	0.77			0.68			0.77		
Skylight, 0% to 3% of Roof									
All types	0.55	0.35	NR	0.55	0.35	NR	1.70	NR	NR

* The following definitions apply: c.i. = *continuous insulation* (see Section 3.2), FC = filled cavity (see Section A2.3.2.5), NR = no (insulation) requirement.
a. When using the *R-value* compliance method for *metal building roofs*, a thermal spacer block is required (see Section A2.3.2).

Figure 4.8
Building Envelope Requirements for Climatic Zone 3 (A,B,c) (Source: ASHRAE).

Table 5.5-6 *Building Envelope* Requirements for Climate Zone 6 (A,B)*

Opaque Elements	*Nonresidential* Assembly Maximum	*Nonresidential* Insulation Min. *R-Value*	*Residential* Assembly Maximum	*Residential* Insulation Min. *R-Value*	Semiheated Assembly Maximum	Semiheated Insulation Min. *R-Value*
Roofs						
Insulation entirely above deck	U-0.032	R-30 c.i.	U-0.032	R-30 c.i.	U-0.063	R-15 c.i.
Metal building[a]	U-0.031	R-25 + R-11 *Ls*	U-0.029	R-30 + R-11 *Ls*	U-0.060	R-19 + R-19
Attic and other	U-0.021	R-49	U-0.021	R-49	U-0.034	R-30
Walls, above Grade						
Mass	U-0.080	R-13.3 c.i.	U-0.071	R-15.2 c.i.	U-0.151[b]	R-5.7 c.i.[b]
Metal building	U-0.050	R-0 + R-19 c.i.	U-0.050	R-0 + R-19 c.i.	U-0.094	R-0 + R-9.8 c.i.
Steel-framed	U-0.049	R-13 + R-12.5 c.i.	U-0.049	R-13 + R-12.5 c.i.	U-0.084	R-13 + R-3.8 c.i.
Wood-framed and other	U-0.051	R-13 + R-7.5 c.i. or R-19 + R-5 c.i.	U-0.051	R-13 + R-7.5 c.i. or R-19 + R-5 c.i.	U-0.089	R-13
Wall, below Grade						
Below-grade wall	C-0.092	R-10 c.i.	C-0.063	R-15 c.i.	C-0.119	R-7.5 c.i
Floors						
Mass	U-0.051	R-16.7 c.i.	U-0.051	R-16.7 c.i.	U-0.087	R-8.3 c.i.
Steel joist	U-0.032	R-38	U-0.032	R-38	U-0.052	R-19
Wood-framed and other	U-0.027	R-38	U-0.027	R-38	U-0.051	R-19
Slab-on-Grade Floors						
Unheated	F-0.510	R-20 for 24 in.	F-0.434	R-20 for 48 in	F-0.730	NR
Heated	F-0.688	R-20 for 48 in.	F-0.671	R-25 for 48 in.	F-0.860	R-15 for 24 in.
Opaque Doors						
Swinging	U-0.370		U-0.370		U-0.370	
Nonswinging	U-0.310		U-0.310		U-0.360	

Fenestration	*Nonresidential* Assembly Max. U	*Nonresidential* Assembly Max. *SHGC*	*Nonresidential* Assembly Min. *VT/SHGC*	*Residential* Assembly Max. U	*Residential* Assembly Max. *SHGC*	*Residential* Assembly Min. *VT/SHGC*	Semiheated Assembly Max. U	Semiheated Assembly Max. *SHGC*	Semiheated Assembly Min. *VT/SHGC*
Vertical Fenestration, 0% to 40% of Wall		(for all frame types)			(for all frame types)			(for all frame types)	
Nonmetal framing, all	0.30	0.40	1.10	0.30	0.40	1.10	0.45	NR	NR
Metal framing, fixed	0.36			0.36			0.51		
Metal framing, operable	0.45			0.45			0.59		
Metal framing, entrance door	0.68			0.68			0.77		
Skylight, 0% to 3% of *Roof*									
All types	0.50	0.40	NR	0.50	0.40	NR	0.85	NR	NR

* The following definitions apply: c.i. = *continuous insulation* (see Section 3.2), FC = filled cavity (see Section A2.3.2.5), *Ls* = *liner system* (see Section A2.3.2.4), NR = no (insulation) requirement.

a. When using the *R-value* compliance method for *metal building roofs*, a thermal spacer block is required (see Section A2.3.2).

b. Exception to Section 5.5.3.2 applies for *mass walls* above *grade*.

Figure 4.9
Building Envelope Requirements for Climatic Zone 6 (A,B) (Source: ASHRAE).

4.6.1 Context

As far as the climate is concerned, the following three cities, each representative of the main U.S. climatic conditions, are chosen: Minneapolis (MN) [representative of continental climates with cold winters and hot summers, known as zone 6 by ASHRAE], Atlanta (GA) [representative of humid subtropical climates with mild winters and hot summers known as zone 3 by ASHRAE], and Phoenix (AZ) [representative of subtropical arid climates with extremely hot summers and warm winters, known as zone 2 by ASHRAE]. In terms of weather data, the Typical Meteorological Year (TMY2) data sets of National Solar Radiation Data Base (NSRDB) will be used. For construction types, the three building envelope requirements for climatic zones of 2, 3, and 6 from ASHRAE are used.

4.6.2 Occupancy Schedule

The office building is presumed to be occupied from 8:00 am to 18:00 pm during working days and not occupied during weekends. Accordingly, building is conditioned during the same timeframe in terms of heating and cooling while the ventilation fans in the office zones start functioning at 7:00 am to guarantee indoor air quality by the time the building is occupied at 8:00 am.

4.6.3 Comfort conditions

Although people's comfort zones could be different related to various climatic, cultural, or mental characteristics of each individual or cultural group, in this study 20-24 degree centigrade (68-75.2 degree Fahrenheit) and 50% relative humidity is presumed as the comfort zone. It means that, during the occupancy schedule, mechanical systems would start functioning when it is colder than 20°C in cold seasons, warmer than 24°C in hot seasons, and higher than 50% relative humidity (to be dehumidified) while humidification is rarely applied.

4.6.4 Heating and Cooling Set-point/Set-back

The amended ASHRAE Standard 90.1, Section 6.4.3.2 suggests to have heating setback as to 55 degrees Fahrenheit (13°C) or lower and cooling setback as to 90 (32°C) or higher. Yet, the heating system is assumed to be: (+10 Occupancy Schedule + 10°C), and the cooling system is presumed to be: (-11 Occupancy Schedule + 35°C). That is, the building is heated if the zone temperature is below 20°C during the occupancy as well as below 10°C during the timeframe that the zone is not occupied. Likewise, the building is cooled if the zone temperature is above 24°C during occupancy and 35°C during not occupancy

timeframe. This decision is made to decrease the impact of a substantial temperature difference between the defined comfort and office zone temperatures at the start time the building is used, 8:00 am.

4.6.5 Heat Gains and Infiltration

Besides sun as the main source of natural heating, three other sources of building heat gain are considered in this simulation: people, electrical appliances, and artificial lighting. As far as infiltration is concerned, the air change infiltration is specified based on the 2009 ASHRAE Fundamental Handbook.

4.6.7 Modeling

Available since 1975 with a modular structure, TRNSYS is a comprehensive energy simulation software that is capable of predicting the energy demand of a defined zone based on given inputs such as the zones' area, orientation, walls or windows type, heating or cooling type, weather data, etc. The simulated sample module in this study is a three-zone (office zone, Sunspace zone, and duct zone) unit with three exterior walls where the forth and possibly fifth walls are adjacent to the DSF, duct, or outside (for options without a DSF system). All the adjacent zones above and beneath have identical temperatures set-points, unless it is adjacent to the unconditioned basement or roof. All details of the floors, windows, and walls were initially shaped by the software's default, and the proposed construction type for optimizing the building performance is in accordance with ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) standards. The construction type used in TRNSYS for Zone 2 (Phoenix), zone 3 (Atlanta), and zone 6 (Minneapolis) are available in the Appendix D associated to .bui file of the TRNSYS model for Run16 I. The following generic assumptions demonstrated in figure 4.10 are also made in association with the elements influencing the building LI in TRNSYS (type 56):

- ***Number of Levels:*** 4 conditioned stories on an un-conditioned basement
- ***DSF orientation:*** South
- ***South/Adjacent Window:*** 2.7x8.6 m = 23.22 m^2
- ***Office Zones Area/Volume:*** 8x10x3 m = 240 m^3
- ***Sunspace Zones Area/Volume:*** 2x9x3 m = 54 m^3, 1x9x3 m = 27 m^3, or 0.5x9x3 m = 13.5 m^3,
- ***Duct Area/Volume:*** 2x1x3 m = 6 m^3, 1x1x3 m = 3 m^3, or 0.5x1x3 m = 1.5 m^3,
- ***Infiltration:*** constant value of 0.1 1/hr
- ***Construction Type:*** chosen based on the suggested ASHRAE climate zones of 2,3,and 6

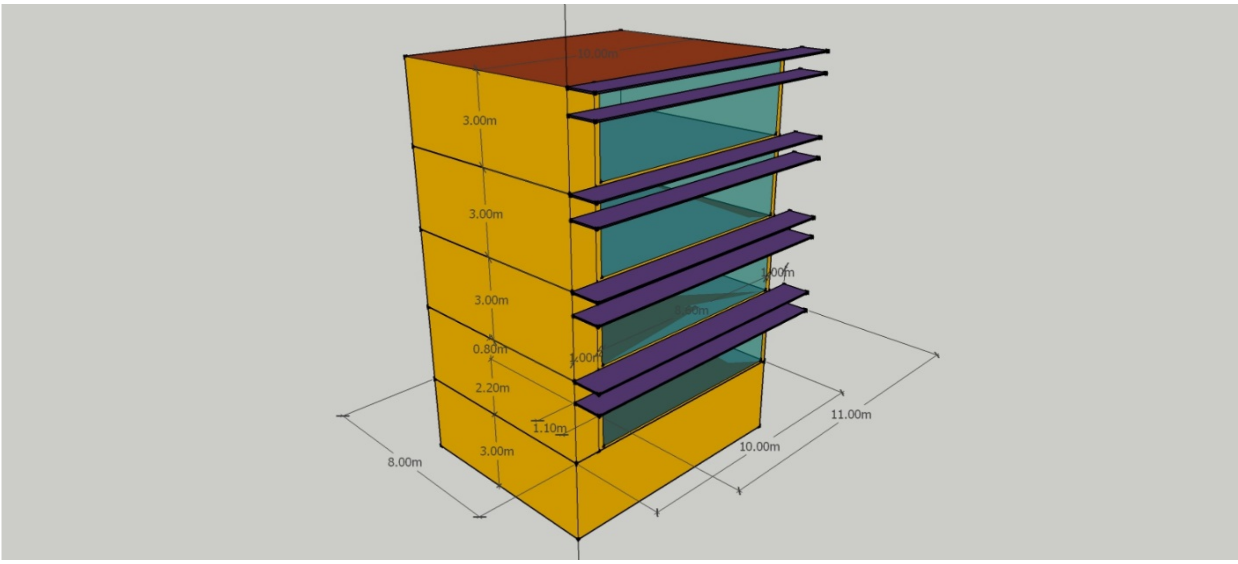


Figure 4.10
Building and Shading Devices Dimensions

- ***Ventilation and number of Occupants:*** the required airflow rate/exchange rate was defined for each office zone following ASHRAE minimum ventilation rate for area and the number of occupants:

  Office 1: 6 people and 80 m^2 area requires 164.3 kg/hr

  Office 2: 4 people and 80 m^2 area requires 143.2 kg/hr

  Office 3: 8 people and 80 m^2 area requires 185.4 kg/hr

  Office 4: 6 people and 80 m^2 area requires 164.3 kg/hr

- ***Office Schedule:*** working days Monday through Friday 8:00 -18:00 and weekends of Saturday and Sunday
- ***Comfort Type:*** office activities

  Clothing factor: 1 clo

  Metabolic rate: 1.2 met

  Relative Air Velocity: 0.1 m/s
- ***Heating:*** set as an input of [10 x Schedule + 10] (setback is 10 degree centigrade)
- ***Cooling:*** set as an input of [-11 x Schedule + 35] (setback is 35 degree centigrade)
- ***Dehumidification:*** set as 50% Relative Humidity
- ***Humidification:*** N/A

- ***Radiation/Solar to Air factor:*** 0.4 with furniture
- ***Radiation/Solar to Air factor:*** 0.4 without furniture
- ***Zone Capacitance:*** 80x3x1.2x10=2880 kj/K with furniture
- ***Zone Capacitance:*** 80x3x1.2=2880 kj/K without furniture
- ***Initial Values:*** temperature of 20 degree centigrade and relative humidity of 50%
- ***Heat Gains:***

  Occupants: assumed to be seated with light work such as typing (based on iso 7730's table will be 150 W which includes Sensible heat of 75 W as well as latent heat of 75 W)

  Computers: 140W (PC with Monitor) x Schedule x Number of Occupants

  Artificial Lighting: 10W/m², convective part of 40% fluorescent tube

  Others: 2 printers with 276 kJ/hr radiative power, 522 convective power, and no absorbing humidity during the office hours

In addition, the following assumptions are made in the CONTAM software (Run7 D as an example) to simulate the different proposed options' airflow characteristics in terms of amount and direction (Figure 4.11):

- ***Number of Levels:*** 4 ventilated stories on a naturally ventilated basement
- ***Level-1 Zones:*** Office-1 and Sunspace-1
- ***Level1 Zones:*** Office1, Sunspace1, and Duct1
- ***Level2 Zones:*** Office2, Sunspace2, and Duct2
- ***Level3 Zones:*** Office3, Sunspace3, and Duct3
- ***Level4 Zones:*** Office4, Sunspace4, and Duct4
- ***Level5 Zones:*** Sunspace5
- ***Level-1 Airflow Paths:*** *Sunspace opening* (8 x 0.2m) with variable wind pressure profile based on AIVC graph at 2.8m relative height, *Duct Backdraft* at 0.3m relative height (this will be changed to an opening with 0.6m² cross section area starting from Run13), and *VentOut One-Way Flow Orifice* (opening) with variable wind pressure profile based on AIVC graph at 2.8m relative height and cross section area of 0.1m² for exhaustion.
- ***Level1-4 Airflow Paths:*** *One-Way Flow Orifice Floor Grill with 1.6m²* cross section area at 0 height, *One-Way Flow Orifice Shaft with 2m²* cross section area at 0 height, *Sunspace Backdraft* at 2.8m relative height that is closed for this option (this will be changed to an opening with cross section of 1.6m² at the height of 0.3m for naturally ventilated building options starting from Run13), *Duct*

Backdraft at 0.3m relative height, and *a 164.3/143.2/185.4/164.3 kg/hr Constant Mass Flow Fan* with variable wind pressure profile based on AIVC graph at 2.8m relative height that function during the occupancy schedule . This backdraft is changed to a 0.6m² opening starting from Run13.

- ***Level5 Airflow Paths:*** *One-Way Flow Orifice Floor Grill with 1.6m²* cross section area at 0 height, and *three 110 cfm Constant Mass Flow Fan* with variable wind pressure profile based on AIVC graph at 2.8m relative height that have a controller to turn them off when ambient air is colder than 18°C and turn them on when the ambient air is warmer than 20°C. These fans are replaced by self-regulating vents for options with naturally ventilated DSF.
- ***DSF orientation:*** South
- ***Office Zones Area/Volume:*** 8x10x3 m = 240 m³
- ***Sunspace Zones Area/Volume:*** 2x9x3 m = 54 m³, 1x9x3 m = 27 m³, or 0.5x9x3 m = 13.5 m³,
- ***Duct Area/Volume:*** 2x1x3 m = 6 m³, 1x1x3 m = 3 m³, or 0.5x1x3 m = 1.5 m³,
- ***Office Schedule:*** working days Monday through Friday 7:00 -18:00 and weekends of Saturday and Sunday

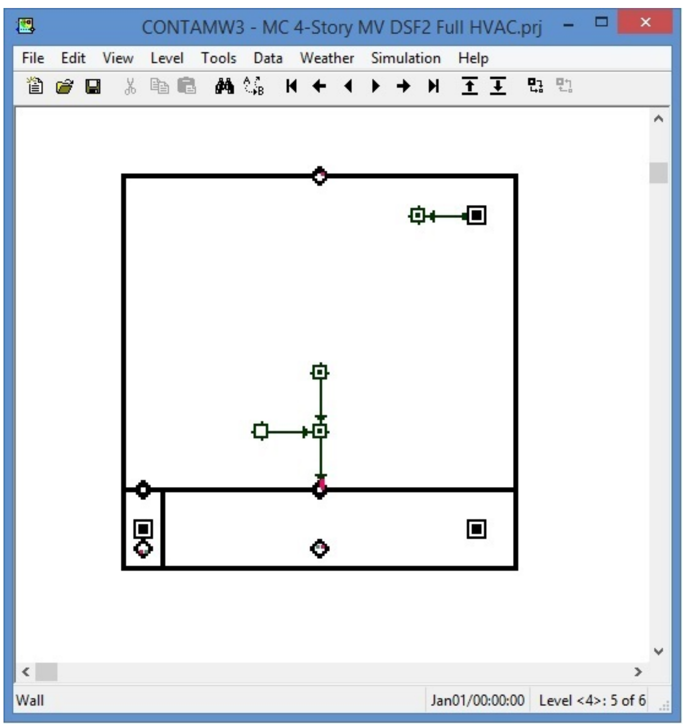


Figure 4.11
Building Airflow Modeling Defined in CONTAM

4.7 Research Design

Previous sections deliberated the “what” and “why” of the study. This section is discussing the “how,” in terms of research design and the ways in which the study is conducted, including considerations on relevant methodologies and their characteristics as well as data collection techniques and tactics. Architectural design deals with human beings and their complexity as the users (Duerk, 1993). A system of inquiry suitable for this research would not merely rely on the existence of a single logical reality. Instead, it must factor non-deterministic issues into the reality, to be recognized with some degrees of probability. Understanding the active role of building occupants as collaborating subjects in buildings is essential to making any proposed design solution pragmatic and viable. In the case of this study, the Load Intensity (LI) is not taken as fully objective, which can be accurately measured, independent of the occupants’ behaviors. Evaluating the study’s premises demand an experimental research design, mainly, using simulation methods as quantitative means for testing the hypothesis. Based on Groat and Wang’s (2002) definition,[86] an experimental research related to the study has the following characteristics:

1- *Use of a treatment or independent variable*: this is a combination of different variables that will be used for the DSF’s operation (air supply origin, air destination, shading device position, narrow and wide air cavity)

2- *Measurement of one or more dependent outcome variable*: this is the EI taken out from the conducted simulation for each of different independent variables.

3- *Designation of a unit of assignment as applied independent variables*: that is the DSF system.

4- *Use of a comparison or control group, which is the comparison of different treatments*: this is related to the comparison of different LIs.

5- *Focus on causality, which is inherently perceived in any research containing the above characteristics*: there are potential differences on the outcome variables caused by altering various treatments/independent variables.

[86] Linda N. Groat, & David Wang (2002). Chapter 2: System of Inquiry and Standards of Research Quality. In *Architectural Research Method* (251-255), New York: J. Wiley.

4.7.1 Method

The method applied in this dissertation is a combination of "instrumental case study"[87] and simulation techniques. At the first stage, the research is conducted on the concept of a DSF system as an instrumental case study to showcase the application of the proposed design approach (chapter 1) in ecological design. As Yin (1994) puts, the case study method's strength is in its capacity to generalize to theory (p. 13).[88] The DSF system is used as a case to illustrate how evaluation should be applied for any aspect of the design decision-making and throughout the process, as also articulated as the basis of Chapter I's introduced "evaluative-based" programming. The second stage contains the major methodological application of the dissertation. This part is a simulation analysis via a computer model of a naturally ventilated DSF system in a hypothetical nonresidential building where the air supply is initially preheated/precooled through an earth tubes system. Simulation is used as a suitable technique to help generating data by means of an imitation of the actual real situation, and showing how the proposed system can develop over time. The method is beneficial in its ability to project future conditions and predict building use and behavior patterns. Simulation is also very useful for complex and large-scale situations, particularly, in an experimental research context.[89] The type of simulation that is used falls into the category of "analog simulation" defined by Clipson (1993),[90] which is mentioned to be suitable for an environmental system. Computer simulation, thus, is the major research method as there is also a high level of harmony between simulation and experimental research.

Despite its strengths, the simulation method also has some limitations. Asserted by Groat and Wang (2002), some limitations can relate to the accuracy of replication, completeness of input data, cost and workability, and programmed spontaneously. The research design for this dissertation study has been working diligently towards overcoming the challenges related to replication accuracy by using TRNSYS as a

[87] Robert E. Stake (1998). Case Studies. In Norman Denzin & Yvonna Lincoln (Eds.). *Strategies of Qualitative Inquiry* (86-109). Thousand Oaks, Calif.: Sage Publications.
As Robert Stake defined, quoted by Groat and Wang (2002, p. 355), the instrumental case study "is of secondary interest to the theory that can be established from it." The other form of case study, what Stake (1998) calls "intrinsic," is "undertaken because one wants better understanding of this particular case."
[88] R. K. Yin (1984). *Case Study Research: Design and Methods*. Beverly Hills, California: Sage. Publications.
[89] As Wang (2002) put it: "Experimental research isolates a context and identifies variables that can be manipulated to see how they affect other variables. Simulation research also isolates contexts and manipulates variables; in these respects it is related to experimental research. Some cases of experimental research use simulation comfortably as the primary tactic. Clipson's iconic category (e.g., testing of materials or building products) is often experimental research operationalized by simulation (p. 283)."
[90] Colin Clipson (1993). Simulation for Planning and Design. In Robert W. Marans & Daniel Stokols (Eds.). *Environmental Simulation* (30-34). New York: Plenum Press.
Clipson suggests four types of simulation: *iconic, analog, operational,* and *mathematical.* The first two types are related to physical contexts; iconic simulation represents the testing of material and products while analog represents a dynamic simulation of a real or projected physical system. Operational simulation has more to do with people's interaction within physical context focusing on role-play as the means of data gathering. Mathematical models are numerical coding systems capturing actual relationship in computable abstract values (Groat & Wang, 2002).

reliable software. TRNSYS is capable of replicating complex systems such as DSFs while considering all needed inputs for the prediction of the annual LI, as output. The completeness of input data is also carefully addressed. For instance, TMY2, Typical Meteorological Year data sets of National Solar Radiation Data Base (NSRDB) is used in TRNSYS as a trustworthy input for the climatic conditions of the three listed cities. The model, of a nonresidential building with DSF created in SketchUp, is another attempt made for accurately replicating the reality. Cost and workability and programmed spontaneously are the two concerns that the addressing of which do not seem to have much relevance in this fully quantitative dissertation project. Addressing these two may become more essential in rather qualitative studies involving people. The next section brings out other concerns related to research quality in further details.

4.7.2 Research Quality

Next to the defined research method comes the question on how to trust the results. As classified by Groat and Wang (2002), four different quality measures are used in a post-positivist system of inquiry similar to this study: (1) Internal validity, (2) External validity, (3) Reliability, and (4) objectivity (pp. 21-43). Addressing these helps in generating high-quality results. What follows would explain this dissertation study's strategies for each factor:

> *Internal validity:* "establishing a causal relationship, whereby certain conditions are shown to lead to other conditions, as distinguished from spurious relationships." To avoid mistakes and conflicting explanations and consider all relevant factors important for the data production, a solution is to look at the LI of an existing building with a DSF system, simply made feasible by looking at monthly energy bills, and compare it to the basic DSF model simulated by TRNSYS. A comparison between the LI of the proposed, basic DSF model and other simulated DSF systems from the studied DSF literatures is used as yet another trustful source. This study would then rely on and use the simulation results if matching with other resources.

> *External validity:* "establishing the domain to which a study's findings can be generalized." As explicitly mentioned in the hypothesis, the simulation is run under any climatic condition. Therefore, the meteorological data of the four typical climatic conditions of hot and dry, hot and humid, temperate, and cold are used in the process of simulation. This precisely means that the result can be generalizable to any climate although specific strategies should be taken into account for optimizing the system based on each contextual condition. In addition, building types and their proper programming should be considered, as the outcome of the study may not be applicable to all situations.

> *Reliability:* "demonstrating that the operations of a study-such as data collection procedures-can be repeated, with the same result." This notion is the function of no biases and errors so that the research can be repeated with the same results. Since the result of simulation is based on annual LI of different options, the results are quite reliable if the input data are the same.

Objectivity: "establishing correct operational measures for the concepts being studied." It means not to be subjective in the process of simulation or being biased. In the case of this DSF simulation, no subjectivity is involved as the software calculates the results.

4.7.3 Data Analysis, Interpretation, and Inscription

The tactic applied for the gathering, analysis, and interpretation of data or evidence is quantitative-deductive, that is, to say, the dependency on manipulation of incidents measured through numbers coupled with the independency of the researcher and subject of analysis. The main method for demonstrating results relies on the graphs extracted from TRNSYS. These graphs are primarily representative of various zones or systems' humidity, temperature, solar radiation, energy demands, and airflow. The Excel software is used for the creation of tabular information, employed for statistical analysis and data interpretation. Different envelope options are compared progressively to examine validity of the proposed design. A conventional single-skin-facade building with around 90% of façade glazing is first simulated so that the enhanced DSF attached to it could, in comparison, be best evaluated. In addition, a conventional DSF system without earth-tubes that uses dissimilar ventilation strategies, as opposed to a DSF integrated with earth-tubes with comparable ventilation strategies is modeled, considering the previously stated variables. Finally, a quantifiable comparison between the LIs and the results' analysis help identifying the best environmental option for each climate. At the final stage, the impact of each variable in correlation with other variables is elaborated via the concept of "*main effect*." The *main effect* is the change in the response as we move from initial to the enhanced version of that variable (Box, G. E. P.)This process determines in what ways and to what extents the initial hypothesis would be applicable.

4.8 Summary and Transition to Chapter V

This chapter has examined various traits involved in the dissertation study in terms of what knowledge associates with the concept, qualities and quantities of DSFs, why it is supposed that this system is significant area of research, and how the system is considered within the study. Further, details related to the applied simulation method as well as assumptions made to model the proposed, integrated system were discussed. In the next chapter, Results and Findings will be included. Results are primarily the graphs that have been extracted from the software, in a coupling process from TRNSYS (for the whole energy analysis) and CONTAM (for the airflow analysis).

Chapter V: Results and Findings

5.1 Proposed Design Alternatives

Following sections illustrate the results extracted from the softwares' coupled process. Results were based on the following 16 design options for three different depths of 0.5,1, and 2 meters and in three distinct climatic conditions of Minneapolis, Phoenix, and Atlanta, as listed below:

1- Run1 A (4-Story Shoe Box No HVAC)
2- Run2 B (MC 4-Story Full HVAC)
3- Run3 B (MC 4-Story Construction Eshading Full HVAC)
4- Run4 B (MC 4-Story Construction Shading Full HVAC), assumed to be the ***BASELINE***
5- Run5 C (MC 4-Story DSF2 Full HVAC)
6- Run6 C (MC 4-Story DSF2 Shading Full HVAC)
7- Run7 D (MC 4-Story MV DSF2 Full HVAC)
8- Run8 E (MC 4-Story NV DSF2 Full HVAC)
9- Run9 F (MV 4-Story MV DSF2 Semi HVAC)
10- Run10 F (MV 4-Story MV DSF2 Semi HVAC Hypo)
11- Run11 G (MV 4-Story NV DSF2 Semi HVAC)
12- Run12 G (MV 4-Story NV DSF2 Semi HVAC Hypo)
13- Run13 H (NC 4-Story MV DSF2 No HVAC)
14- Run14 H (NC 4-Story MV DSF2 No HVAC Hypo)
15- Run15 I (NC 4-Story NV DSF2 No HVAC)
16- Run16 I (NC 4-Story NV DSF2 No HVAC Hypo)

5.2 Results

This section demonstrates the results of each of the sixteen, previously listed simulation runs. The first four runs are representative of conventional buildings common in a single climate. The second four runs are representative of a buffer type DSF for which there is no air introduction to offices. The last eight runs are based on a DSF that contributes to HVAC system via introduction of air to offices for each of the three indicated climates (Minneapolis, Phoenix, and Atlanta), and also each of the three DSFs' depth (0.5, 1, and 2 meters), offered in the following order. Due to high quantities of resulted graphs, ONLY the prototyped

building with the 2-meter DSF depth located in Minneapolis will be presented in detail in this chapter while the other simulation runs will be placed in the Appendix H and I sections in the following order:

- *Minneapolis*

1- <u>Minneapolis, Conventional Buildings (4 runs)</u>

2- <u>Minneapolis, 2 m DSF depth (12 runs)</u>

3- Minneapolis, 1 m DSF depth (12 runs)

4- Minneapolis, 0.5 m DSF depth (12 runs)

In addition, the order of the graph results extracted from TRNSYS (maximum of 10 graphs for each) and their related units are as follows:

a) Generic Minneapolis Irradiations *(kJ/hr m²)*
b) Generic Minneapolis Temperatures *(°C)*
c) Zones Temperature *(°C)*
d) Zones Relative Humidity *(%)*
e) Office Load Intensity *(kJ/hr)*
f) Total Offices Load Intensity *(kJ/hr)*
g) Offices-Ambient Airflow *(kg/hr or 1/hr)*
h) Sunspaces/Ducts-Offices Airflow *(kg/hr or 1/hr)*
i) Sunspace/Duct-Sunspace/Duct Airflow *(kg/hr or 1/hr)*
j) Air-Tubes Temperature and Energy *(°C and kJ/hr)*

5.2.1 Graphs Extracted from TRNSYS Software

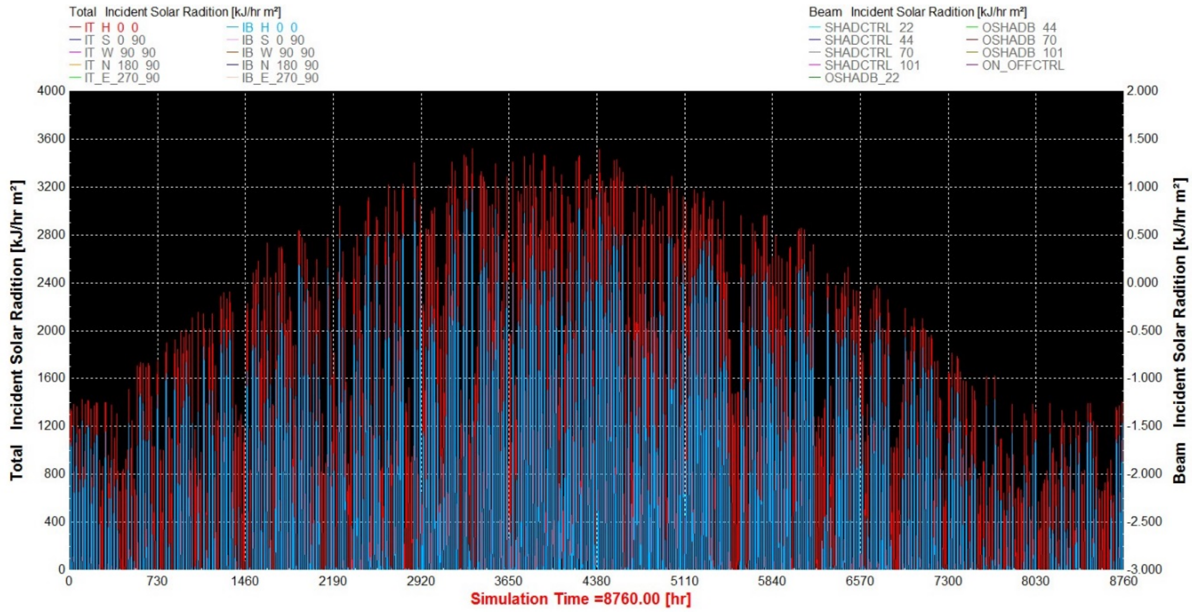
A brief explanation of each graph is provided below as these graphs are meant to be taken as self-explanatory. The horizontal axis of graphs always illustrates the hourly results in a year, total of 8760 hours. The vertical axis that is different for each graph typically shows radiation, temperature, relative humidity, energy, or airflow, comprehensively explained as followed:

- The Generic Climate's Irradiations graph is basically presenting the annual amount of Minneapolis's total solar radiation on horizontal surfaces (IT_H_H_O) and total beam radiation (IB_H_H_O) in metric system of kJ/hr m^2.
- The Generic Climate's Temperatures graph demonstrates the annual ambient temperature (T_AMB) fluctuation, the dew point temperature (T_DEW), and the soil temperature (T_SOIL) for depths of 1.5, 3, 4.75, and 6.5 in Celsius centigrade *(°C)*.
- The Zones Temperature graph is also presenting the annual temperature variation for Office 2 (T_OFF2) on level 2 of the building as well as the soil temperature (T_SOIL) for both depths of 1.5 and 3m related to below grade boundary walls and slab in Celsius centigrade *(°C*).
- The Zones Relative Humidity graph indicates the annual relative humidity of each climate's ambient (T_AMB) and the office 2's air (RH_OFF2) in *(%).*
- The Office Energy Use Intensity illustrates the offices' energy use intensity of heating (Q_HEAT), cooling (Q_COOL), humidification (Q_HUM), and dehumidification (Q_DEHUM) in different levels specifically office2 for this graph in (kJ/hr). This energy is with reference to the thermal comfort defined for the interior spaces.
- The Total Offices Energy Use Intensity presents all the 4 offices energy use intensity as LI_Total in *(kJ/hr).*
- The Offices-Ambient Airflow graph represents the introduced airflow amount _which is the same as the exhausted amount_ for each office (EXF_OFF2), this should be based on the ASHRAE suggested ventilated rate. In this graph, office2's ventilation rate of 143.2 *kg/hr* is shown.
- The Sunspaces/Ducts-Offices Airflow graph also represents the airflow amount for each office coming from either ducts or sunspaces in *kg/hr* specifically office 2 (DUC2_OFF2 or (Sun2-OFF2) and its ventilation exchange rate (VENT_OFF2) in *1/hr.*
- The Sunspace/Duct-Sunspace/Duct Airflow represents the airflow between sunspaces and the ducts (SUN_2_OFF_2) in specifically in level 2 in *kg/hr.*
- The Air-Tubes Temperature and Energy graphs is primarily related to the earth-tube system performance in terms of the temperature going out of the system (T_OUT) after being either pre-cooled or pre-heated. This T_OUT temperature is compared with the ambient temperature of T_AMB and the Sunspace in below grade (T_SUN_1). The energy related to this temperature and phase changing of humid air is respectively shown by P_SBL and P_LAT.

5.3 Results for 2-Meter Depth DSF in Minneapolis

In the order stated above, this section focuses on the Minneapolis results for the 2-meters DSF option, interpreting and evaluating them in further details. For more clarification, each of the first four runs graph's explanations is added on the same page. At a next stage, explanations are provided for every new graph to help with a thorough understanding of logics behind each. Sixteen simulation run option graphs from the coupled TRNSYS and CONTAM software process for the 2-meter DSF depth are as followed:

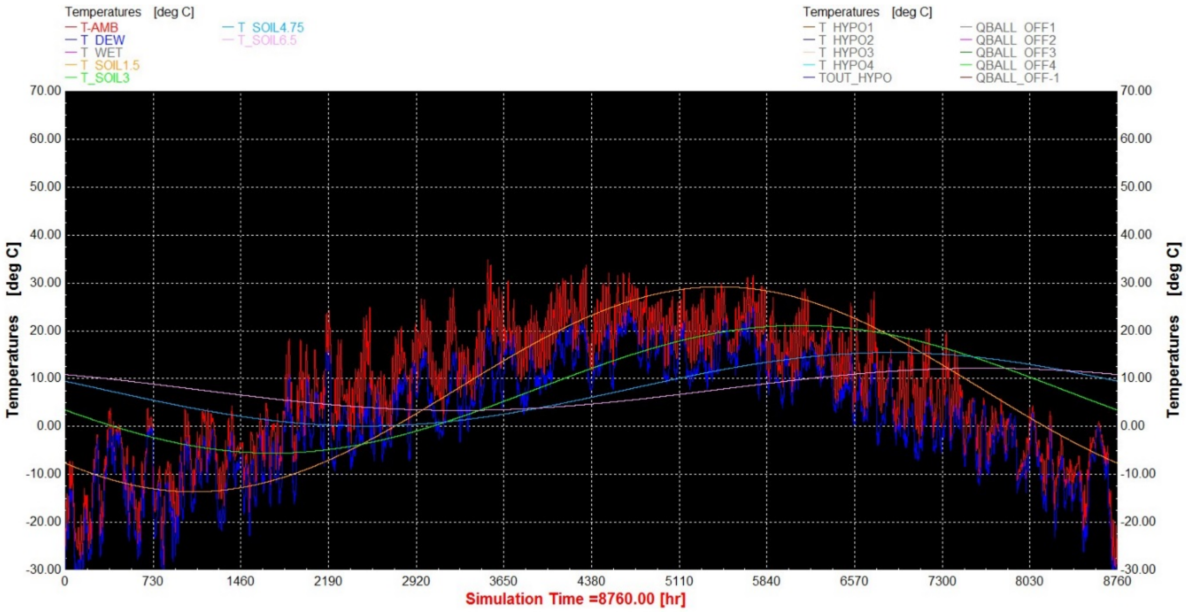
Generic Minneapolis Irradiations (kJ/hr m²)



- Minneapolis Solar Radiation Graph Explanation:

Solar radiation graph is independent of the options defined for each run, and is linked to the climatic characteristics of each location. The amount of solar radiation is important to be studied because it can have direct impacts on the zones' heat gain via the building envelope, specifically through fenestrations. In the climate of Minneapolis, in this case, the 8760 hourly level of radiation throughout a year is illustrated above. The total beam radiation (IB_H_H_O) in cyan in Minneapolis reaches to maximum of 3000 kJ/hr m² in June and July (around the hour of 4380) in a comparison to 3500 kJ/hr m² in Phoenix and 3200 kJ/hr m² of Atlanta. The red graphs represent total solar radiation on horizontal surfaces (IT_H_H_O), which is a combination of beam and diffused Minneapolis annual radiation. Generally, the total radiation in red, thus, is greater than the beam radiation in cyan, and in this case, it fluctuates throughout the course of a year with a maximum of 3500 kJ/hr m² in hot seasons. The maximum of total solar radiation is around 3900 kJ/hr m² in Phoenix hot seasons whereas it is lower in Atlanta. Yet it Atlanta, it reaches to almost the same level in late July. See Appendix H for more details on the referenced Phoenix and Atlanta solar radiation graphs.

Generic Minneapolis Temperatures (°C)

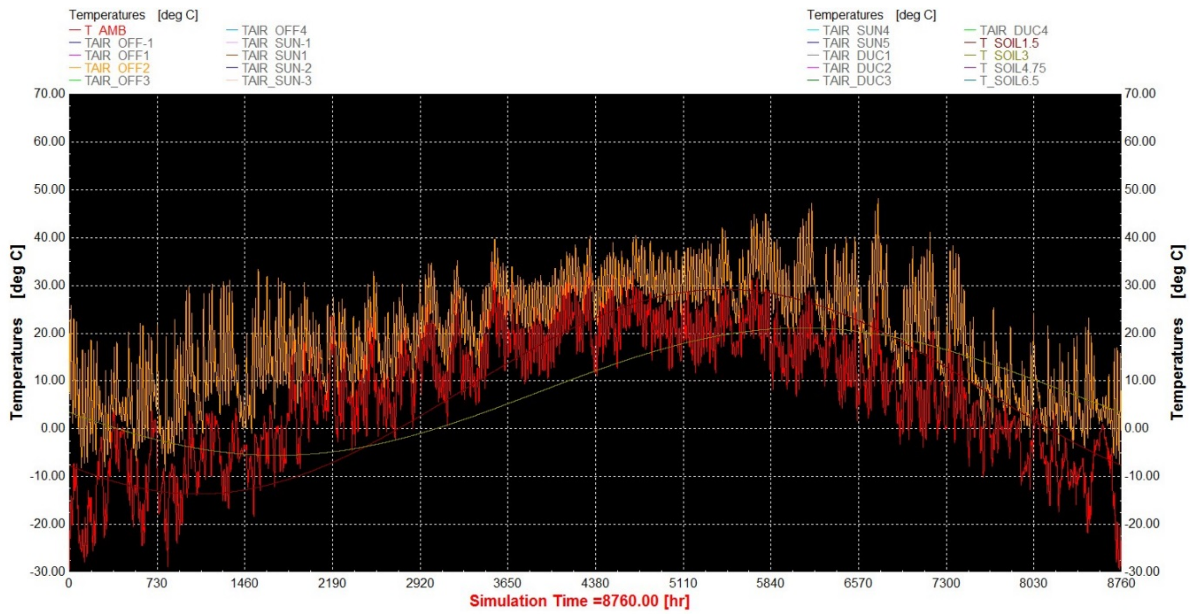


- Minneapolis Temperature Graph Explanation:

Similar to solar radiation, the ambient/dew/wet as well as the soil temperatures are independent of the defined runs. These temperatures are also essential to be studied for each climate as those would primarily influence the heat gain and possibly saturation through building envelopes both above and below grades. For the above grade, ranging from -30 to 70°C in the graph, ambient temperature (T_AMB) is shown in red and dew temperature (T_DEW) in blue. For the below grade, the soil temperature (T_SOIL) in various depths of 1.5m (the average soil temperature adjacent to the basement walls), 3m (the average soil temperature adjacent to the basement slab and top surface of proposed earth-tubes), 4.75m (the average soil temperature around the earth-tubes), and 6.5m (the average soil temperature adjacent to the lower surface of earth-tubes) are presented. In Minneapolis, ambient temperature fluctuates from -30°C in late December to 35°C in hot seasons while it ranges from around -3°C to 47°C in Phoenix and around -11°C to 35°C in Atlanta. Accordingly, soil temperatures at the depth of 4.75 below grade, expected to be close to the earth-tubes air temperature of T_OUT Hypo, ranges from around 0 to 15°C in Minneapolis, 20 to 28°C in Phoenix, and 15 to 18°C in Atlanta. See Appendix H for further information.

Zones Temperature (°C)

Run1A (4-Story Shoe Box No HVAC)

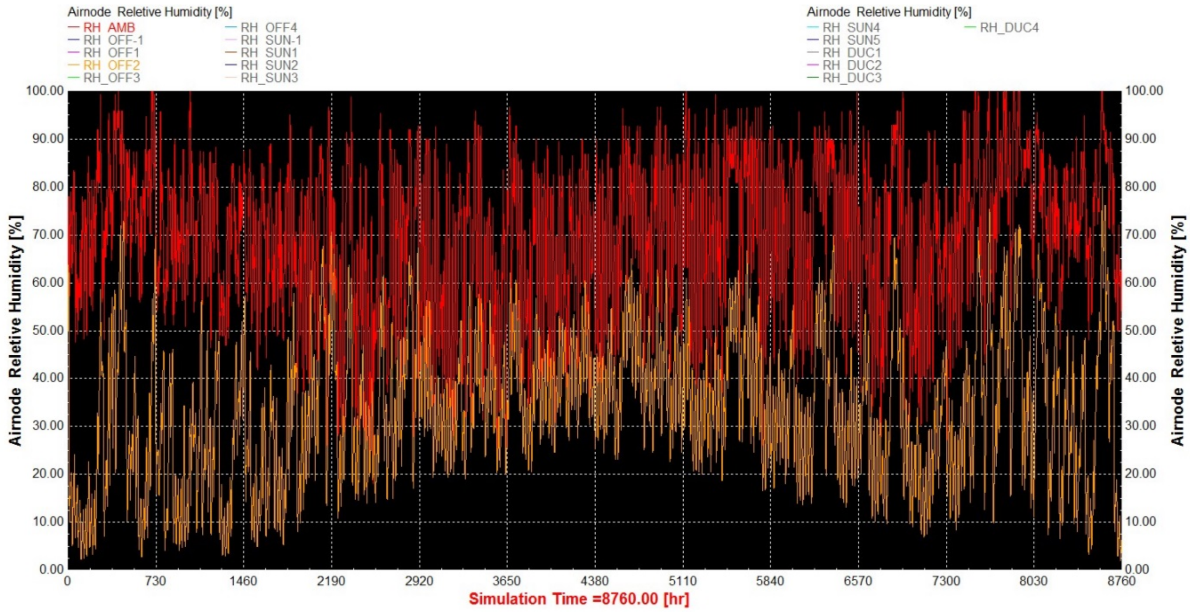


- Zones Temperature Graph Explanation:

This graph is specifically related to the Run1 A that is a shoe-box building without any HVAC system for heating/cooling/dehumidification/humidification. The office2's temperature throughout a year in yellow (TAIR_OFF2) is compared with the ambient air temperature in red (T_AMB) coupled with the soil temperatures (T_SOIL) at 1.5 and 3m. Compared to the ambient air (from -30 to 35°C), the graph displays a warmer temperature in office2 for all the times (from -8 to 48°C). This is due to the fact that the building is relatively tight in terms of envelope construction type for storing heat. That is gained from ambient temperature and solar radiation through the windows during the day. This higher temperature demands more energy to bring it within the assumed comfort zone of 20 to 24°C. Also, the soil temperatures adjacent to below grade walls and the basement slab have clearly less fluctuation (from -13 to 29°C for depth of 1.5m and from -5 to 21°C), mainly influencing the basement zone's temperature.

Zones Relative Humidity *(%)*

Run1A (4-Story Shoe Box No HVAC)

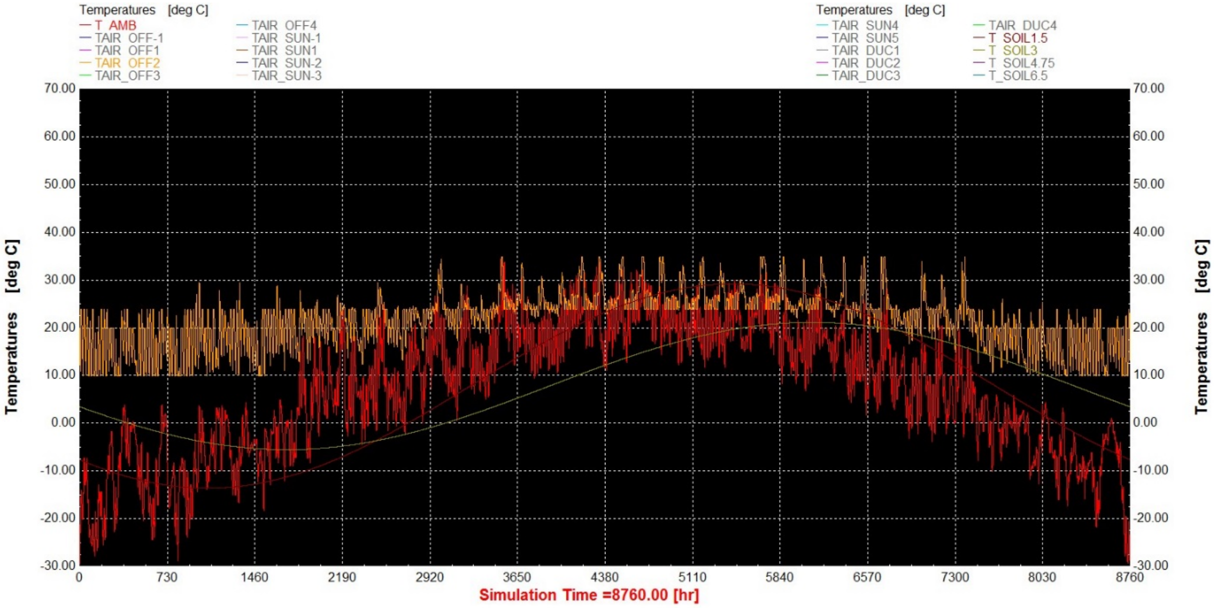


- Zones Relative Humidity Graph Explanation:

Associated with the Run1A, the office2's relative humidity percentage throughout a year in yellow (RH_OFF2) is compared with the ambient air's relative humidity in red (RH_AMB). Compared to the ambient relative humidity (from around 30 to 100%), the graph displays a lower humidity percentage in office2 for all the times (around 2 to 75%). This is again due to the fact that the building is relatively tight in terms of envelope construction with the assumed 0.1 1/hr for infiltration. Solar radiation via windows could also affect relative humidity percentage. This lower relative humidity is obviously closer to the assumed comfort zone of maximum 50% leading to less LI in case the zones are conditioned, additionally elaborated in the next simulation runs.

Zones Temperature (°C)

Run2 B (MC 4-Story Full HVAC)

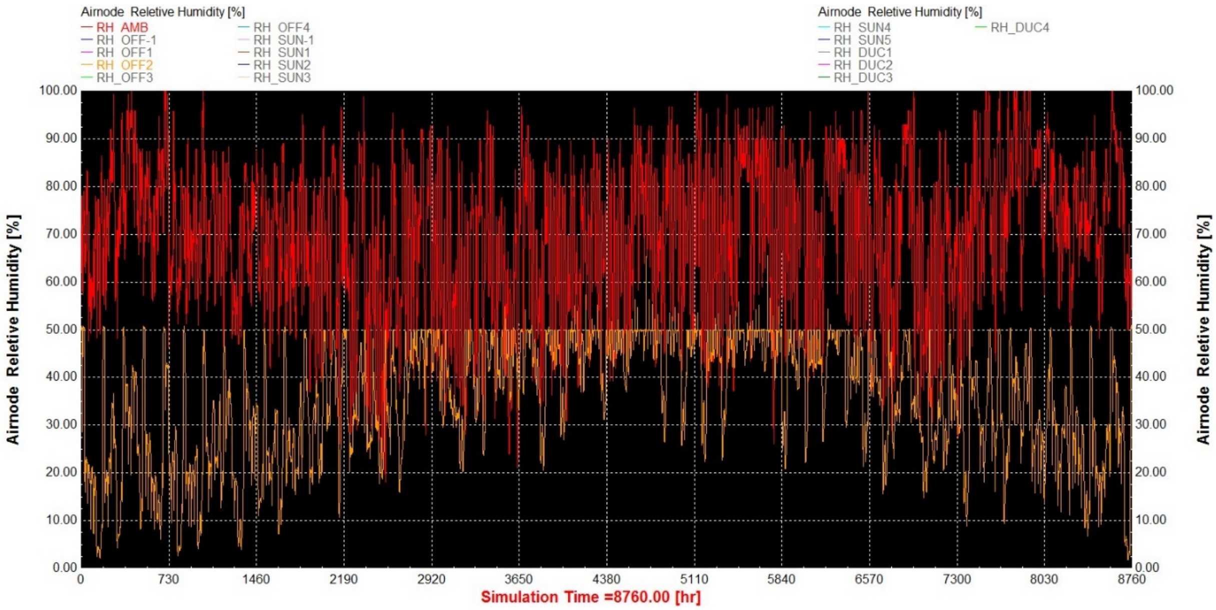


- Zones Temperature Graph Explanation:

This graph is related to the Run2 B: the same option as the previous one, with the main difference that the office zones are conditioned via an HVAC system that provides ventilation through heating and cooling. This generally accounts for 50% of the whole LI in an office building. The office2's temperature throughout a year in yellow (TAIR_OFF2) is compared with the ambient air temperature in red (T_AMB) coupled with the soil temperatures (T_SOIL) at 1.5 and 3m. Compared to the ambient air (from -30 to 35°C), the graph displays a more moderate temperature within comfort zone in office2. This is for the whole year ranging from the set points of 20 to 24°C during the occupancy schedule of 8:00 am to 6:00 pm and for the setbacks of 10 to 35°C during the time office building is not occupied. Because of the HVAC system used for conditioning the office zones in general, and office 2 shown in the graph, specifically, the office temperature has less fluctuation compared to the ambient air temperature of -30 to 35°C. This temperature control will impact the LI, elaborated in more detail in the Energy graph. Similar to previous runs, the soil temperatures adjacent to below grade walls and the basement slab have clearly less fluctuation (from -13 to 29°C for depth of 1.5m and from -5 to 21°C) influencing the basement's temperature.

Zones Relative Humidity (%)

Run2 B (MC 4-Story Full HVAC)

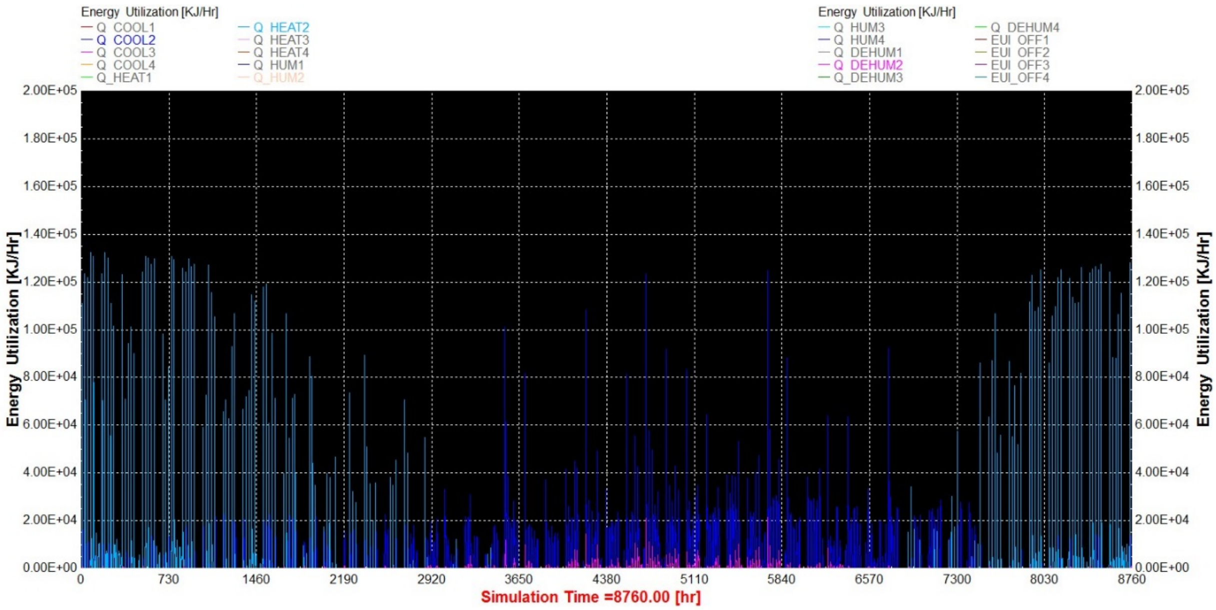


- Zones Relative Humidity Graph Explanation:

The office2's relative humidity percentage throughout a year in yellow (RH_OFF2) is compared with the ambient air's relative humidity in red (RH_AMB). Compared to the ambient relative humidity (around 30 to 100%), the graph displays a lower humidity percentage in office2 for all the times starting from around 2 to the maximum of 50% defined for the offices' comfort zone. It is assumed that there is no need for humidification for offices as HVAC system decreases the relative humidity percentage via dehumidification during the office occupancy schedule, if it is higher than 50%. Based on the graph, this happens mainly during hot seasons, increasing the total LI related to dehumidification loads. The dehumidification load is elaborated in the next Office Energy Use Intensity graph.

Office Load Intensity *(kJ/hr)*

Run2 B (MC 4-Story Full HVAC)

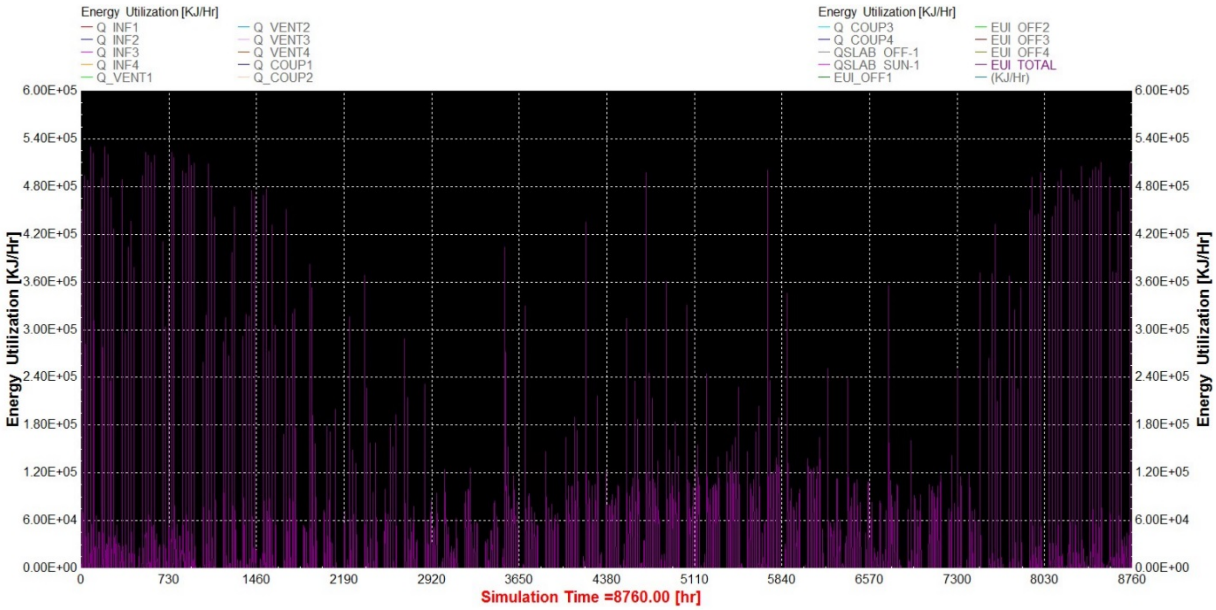


- Zones Energy Use Intensity Graph Explanation:

The graph shows the office2's LI related to HVAC throughout a year where: the energy load of heating (Q_HEAT2) below 20°C in cold seasons is in cyan, the energy load of cooling (Q_COOL2) above 24°C in hot seasons is in blue, the energy load of dehumidification (Q_DEHUM2) for relative humidity of greater than 50% normally in hot seasons is in magenta, and the humidification loads (Q_HUM2) are generally zero as there is no minimum restriction assumed for the office zones. It is noteworthy that ventilation is provided through introduced fresh air either through heating or cooling. It is implied from the graph that the annual LI is primarily due to heating loads up to 130,000 kJ/hr, which is expected in the cold climate of Minneapolis. Cooling loads are next, up to around 120,000 kJ/hr, as also expected for a relatively hot and humid summer in Minneapolis, whilst dehumidification loads are less significant with up to around 20,000 kJ/hr.

Total Offices Load Intensity *(kJ/hr)*

Run2 B (MC 4-Story Full HVAC)

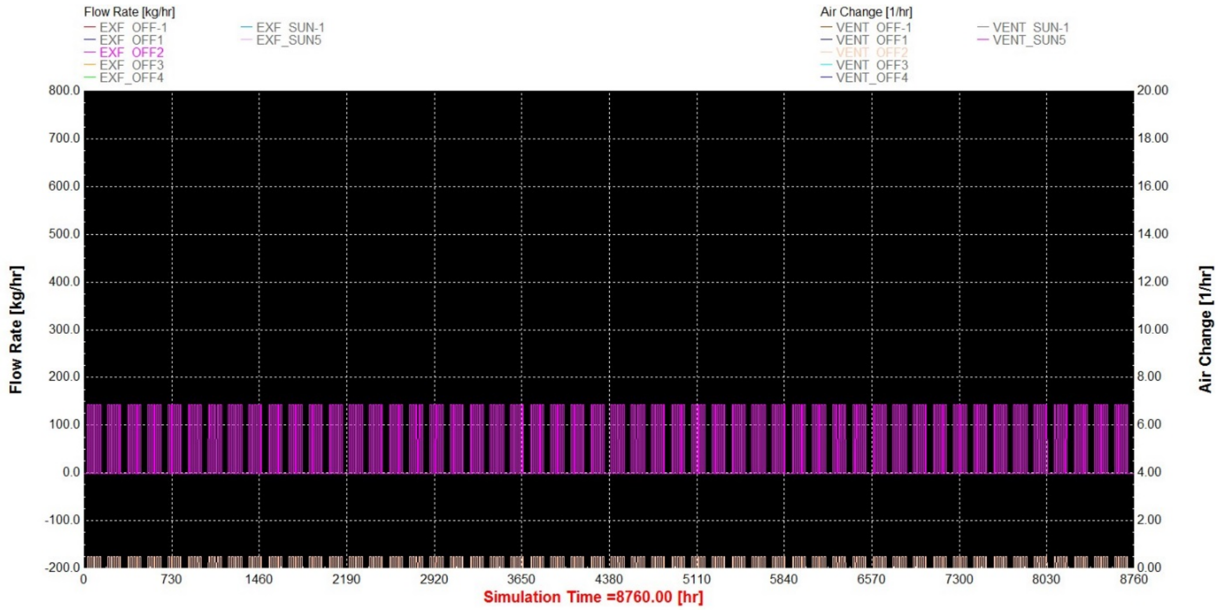


- Zones Total Energy Use Intensity Graph Explanation:

The total LI (LI_TOTAL) illustrated with darker magenta is the sum of LI for all the four offices only relates to the building loads regarding heating, cooling, dehumidification, and rarely humidification throughout a year disregarding types of mechanical systems providing it. It is implied from the graph that the total annual LI is primarily due to heating loads with a maximum of 530,000 kJ/hr, which is expected in the cold climate of Minneapolis and LI of up to 130,000 kJ/hr for each of the four offices.

Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run2 B (MC 4-Story Full HVAC)

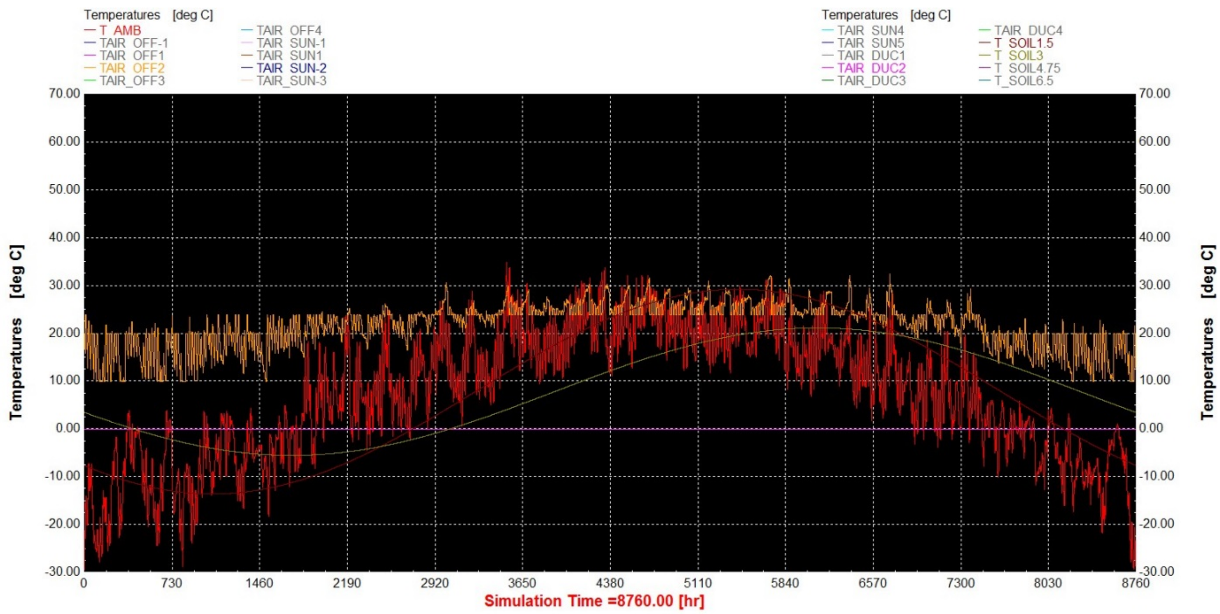


- Offices-Ambient Airflow Graph Explanation:

The amount of ventilation rate for Office2 was specified in the software considering the ASHRAE suggestion of 143.2 kg/hr for the 80 m² office that has 4 occupants. The office2's exfiltration graph (EXF_OFF2) in magenta clearly exemplifies the stated ventilation rate during the building occupancy that is equally exhausted via a fan on the northern wall. The exchange rate of the office2 (VENT_OFF2) in pink can also be seen in the lower portion of the graph. Considering the volume of the zone, the exchange rate will be around 0.6/hr demonstrated in the graph, also as expected. It is noted that the ventilation rate of 0 to 800 kg/hr should be read from the units on the left side of the graph as opposed to the exchange rate of 0 to 20 on the right side.

Zones Temperature *(°C)*

Run3 B (MC 4-Story Construction Full HVAC)

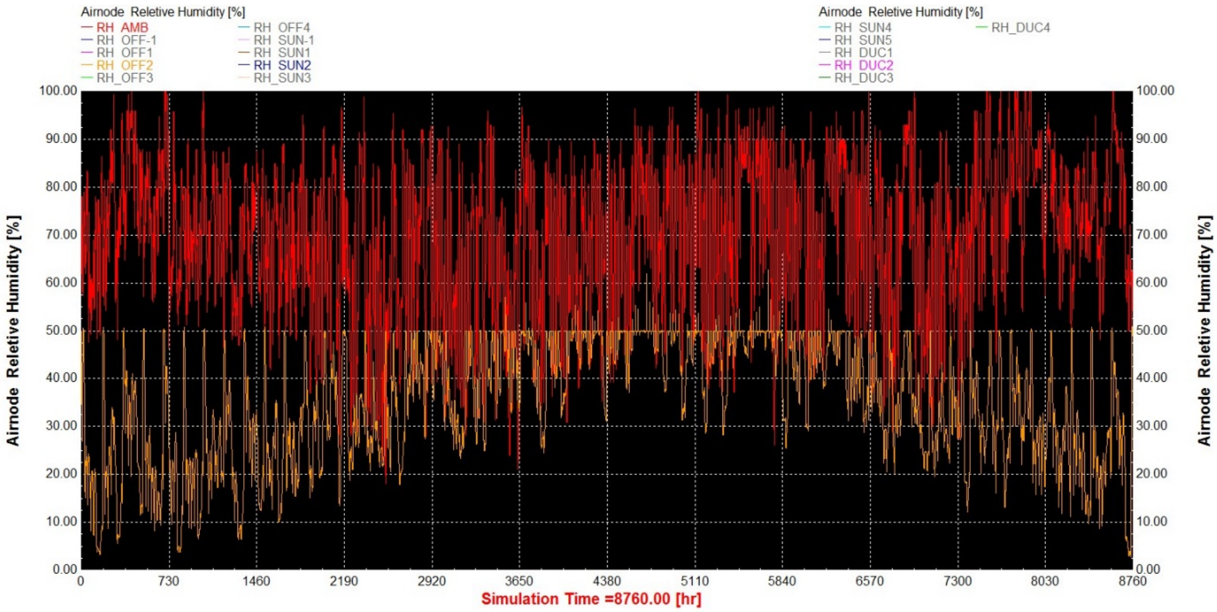


- Zones Temperature Graph Explanation:

The zones temperature graph is associated with the Run3 B; a conventional building with HVAC system for heating/cooling/dehumidification/humidification the same as the previous run while the envelope construction types are optimized based on the ASHRAE suggestions of zone 6 and a 70% external shading is assumed whenever the zone temperature goes above 20°C with a 4°C upper dead band. The office2's temperature throughout a year in yellow (TAIR_OFF2) is compared with the ambient air temperature in red (T_AMB) coupled with the soil temperatures (T_SOIL) at 1.5 and 3m. In comparison to the ambient air of Minneapolis, ranging from -30 to 35°C, the graph displays a more moderate temperature in office2 for the whole year ranging from set points of 20 to 24°C during the occupancy schedule of 8:00 am to 6:00 pm and the setbacks of 10 to 35°C during the time office when the building is not occupied. Due to the assumptions used for conditioning the office zones in general and the proposed building envelope's optimized construction types, the office temperature has less fluctuation compared the previous runs. It is also expected to see significant change in LI, and the next following graphs for the LI should confirm this statement.

Zones Relative Humidity (%)

Run3 B (MC 4-Story Construction Full HVAC)

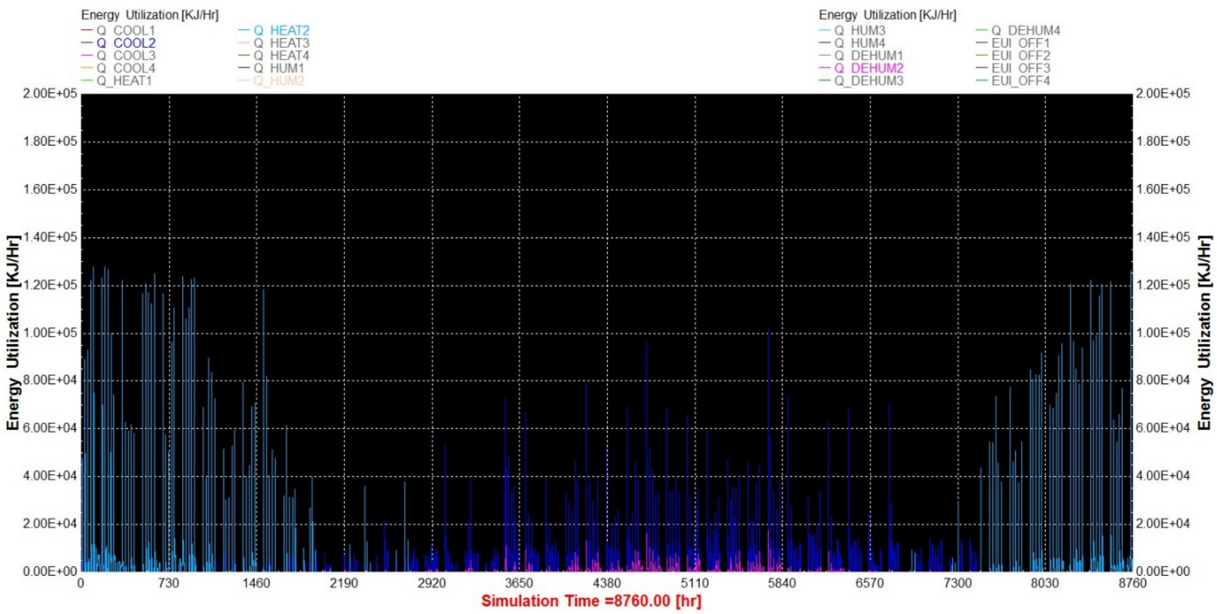


- Zones Relative Humidity Graph Explanation:

The office2's relative humidity percentage throughout a year in yellow (RH_OFF2) is compared with the ambient air's relative humidity in red (RH_AMB). In comparison to the ambient relative humidity (around 30 to 100%), the graph displays a lower humidity percentage in office2 for all the times from around 2 to the maximum of 50% defined for the offices' comfort zone. It is assumed that there is no need for humidification for offices while the HVAC system is decreasing the relative humidity percentage via dehumidification during the office occupancy schedule, if it is higher than 50%. Based on the graph, this occurs mainly during hot seasons, increasing the total LI linked to the dehumidification loads. This dehumidification load can be seen in more detail in the next Office Energy Use Intensity.

Office Load Intensity *(kJ/hr)*

Run3 B (MC 4-Story Construction Full HVAC)

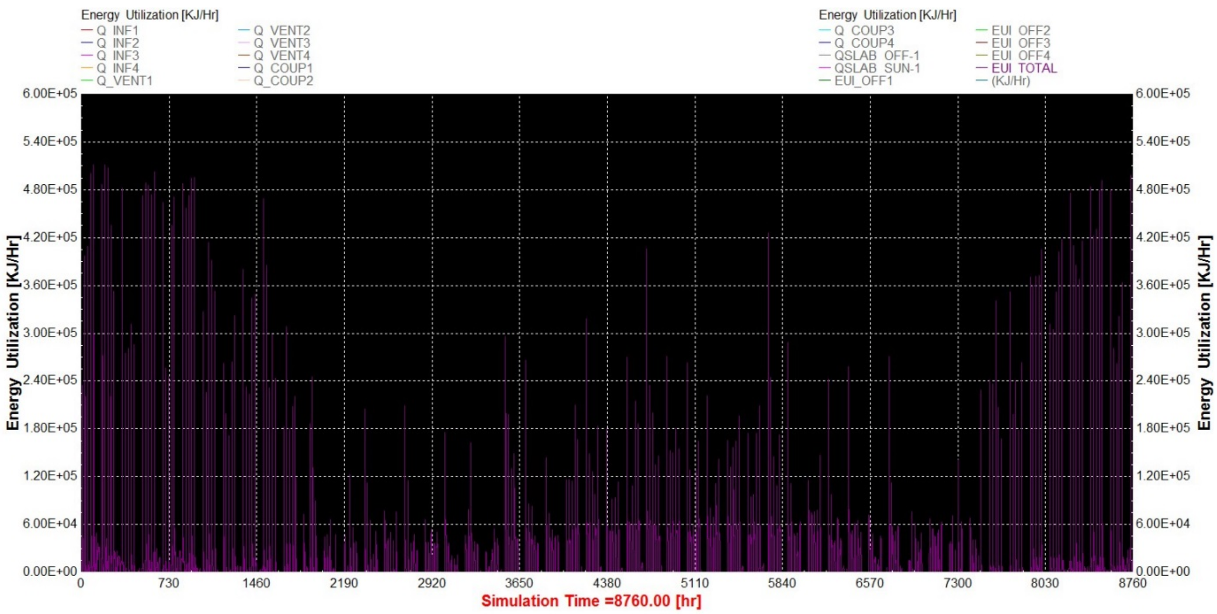


- Zones Energy Use Intensity Graph Explanation:

The office2's LI demonstrated above relates to HVAC throughout a year where: the energy load of heating (Q_HEAT2) below 20°C in cold seasons is in cyan, the energy load of cooling (Q_COOL2) above 24°C in hot seasons is in blue, the energy load of dehumidification (Q_DEHUM2) for relative humidity of greater than 50% normally in hot seasons is in magenta, and the humidification loads (Q_HUM2) are generally zero as there is no minimum restriction assumed for the office zones. The memo is that the ventilation is provided through introduced fresh air either through heating or cooling. It can be implied from the graph that the annual LI is primarily due to heating loads up to 130,000 kJ/hr, which is expected in the cold climate of Minneapolis. The cooling loads are next, up to around 100,000 kJ/hr, as likewise expected for a relatively hot and humid summer in Minneapolis, whilst dehumidification loads are less significant with up to around 18,000 kJ/hr.

Total Offices Load Intensity *(kJ/hr)*

Run3 B (MC 4-Story Construction Full HVAC)

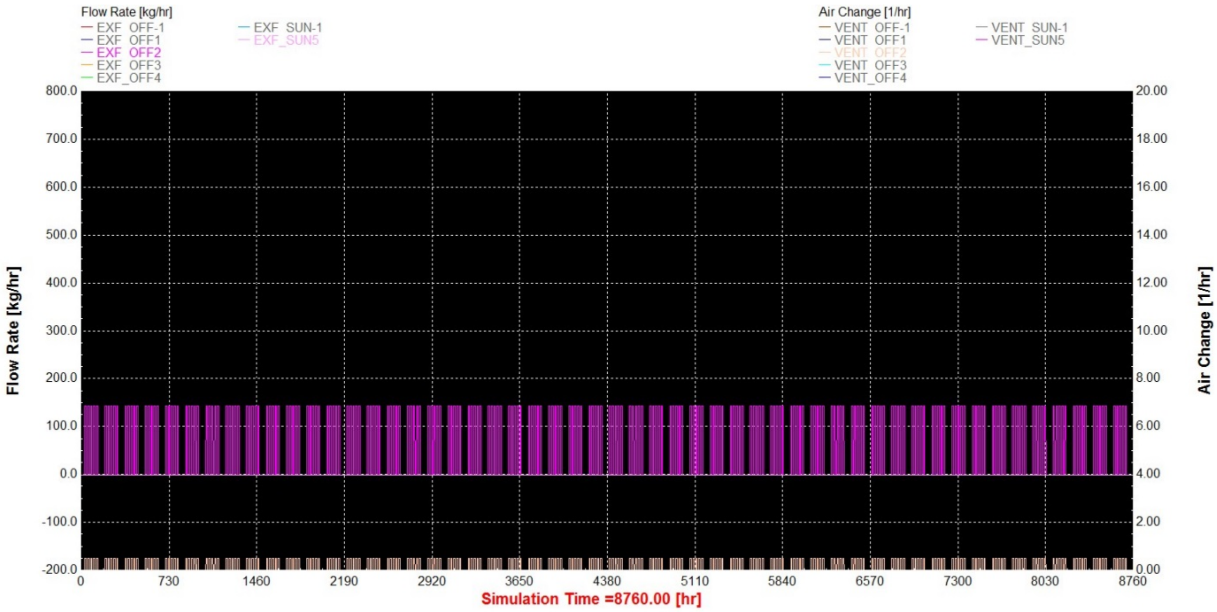


- Zones Total Energy Use Intensity Graph Explanation:

Similar to previous graphs, the total LI (LI_TOTAL) in darker magenta regarding the HVAC throughout a year is shown in this graph as the sum of LI for all four offices. In the same way as other previous graphs, this graph can imply total annual LI primarily due to heating loads with maximum of 510,000 kJ/hr, also expected in the cold climate of Minneapolis and LI of up to 130,000 kJ/hr for each of the four offices. By comparing this option's LI result (Run3 B) with the previous option (Run2 B), it can be seen that LI has decreased from 117.69 to 74.82 kwh/m² (37.31 to 23.72 kBTU/ft²).

Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run3 B (MC 4-Story Construction Full HVAC)

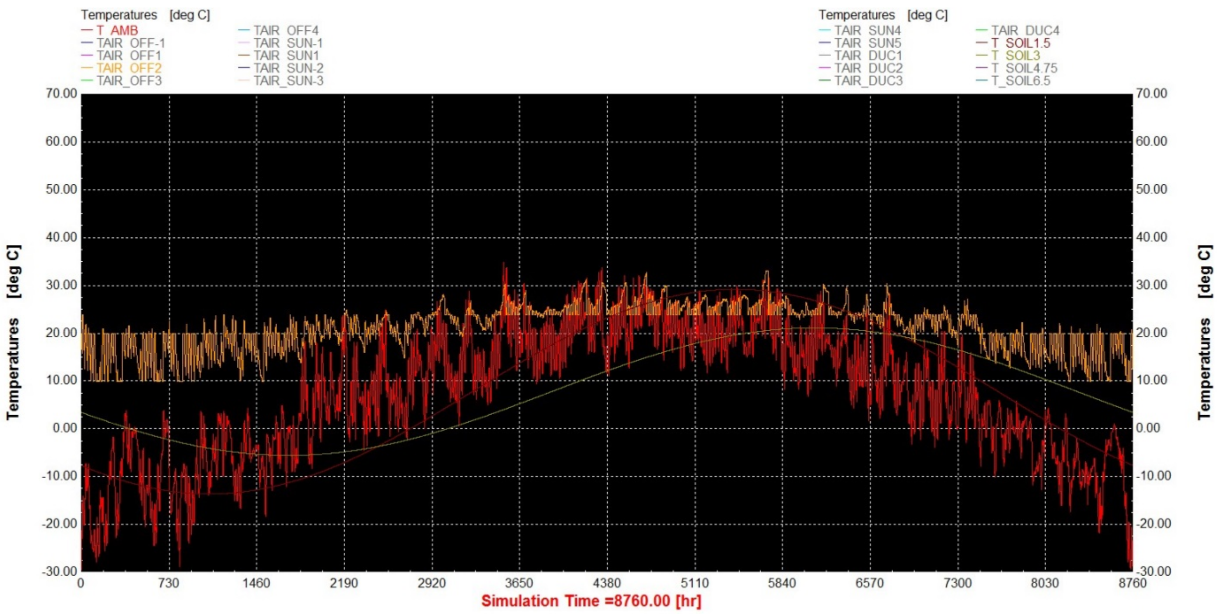


- Offices-Ambient Airflow Graph Explanation:

The amount of ventilation rate for Office2 is suggested to be143.2 kg/hr for the 80 m² office with four occupants. The office2's exfiltration graph (EXF_OFF2) in magenta elucidates the stated ventilation rate during the building occupancy that is equally exhausted via a fan on the northern wall. The exchange rate of the office2 (VENT_OFF2) in pink can also be seen in the lower portion of the graph. Considering the volume of the zone, the exchange rate will be around 0.6/hr demonstrated in the graph, as expected.

Zones Temperature *(°C)*

Run4 B (MC 4-Story Construction Shading Full HVAC)

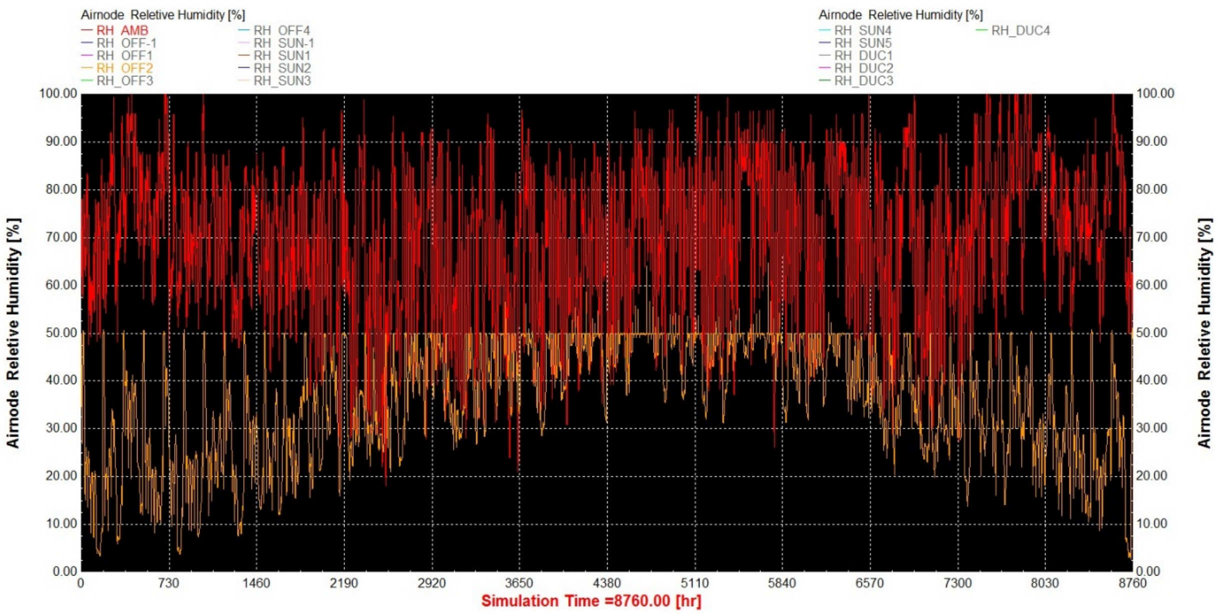


- Zones Temperature Graph Explanation:

This zones temperature graph is related to the Run4 B: the "baseline," yet, with the modification that, instead of the 70% external shading assumed for the baseline, *a light-shelf with the depth of 1.10m and the height of 2.2m from the floor is designed in front of the south facing window (just for Atlanta and Phoenix) with an overhang of the same depth placed 0.8m above it*. The office2's temperature throughout a year in yellow (TAIR_OFF2) is compared with the ambient air temperature in red (T_AMB) coupled with the soil temperatures (T_SOIL) at 1.5 and 3m. In comparison to the ambient air of Minneapolis, ranging from -30 to 35°C, the graph displays a significantly moderate temperature in office2 for the whole year ranging from set points of 20 to 24°C during the occupancy schedule of 8:00 am to 6:00 pm and setbacks of 10 to 35°C during the time office building is not occupied. Over again, due to the HVAC system used for conditioning the office zones in general and the particularly proposed building envelope optimized construction types coupled with the stated shading devices (just overhang in this case), the office temperature has less fluctuation compared to the ambient air temperature as well as the previous runs. It is, therefore, expected to see a decrease in LI, and the energy graphs approve it. The soil temperatures remain the same as climate-oriented items.

Zones Relative Humidity *(%)*

Run4 B (MC 4-Story Construction Shading Full HVAC)

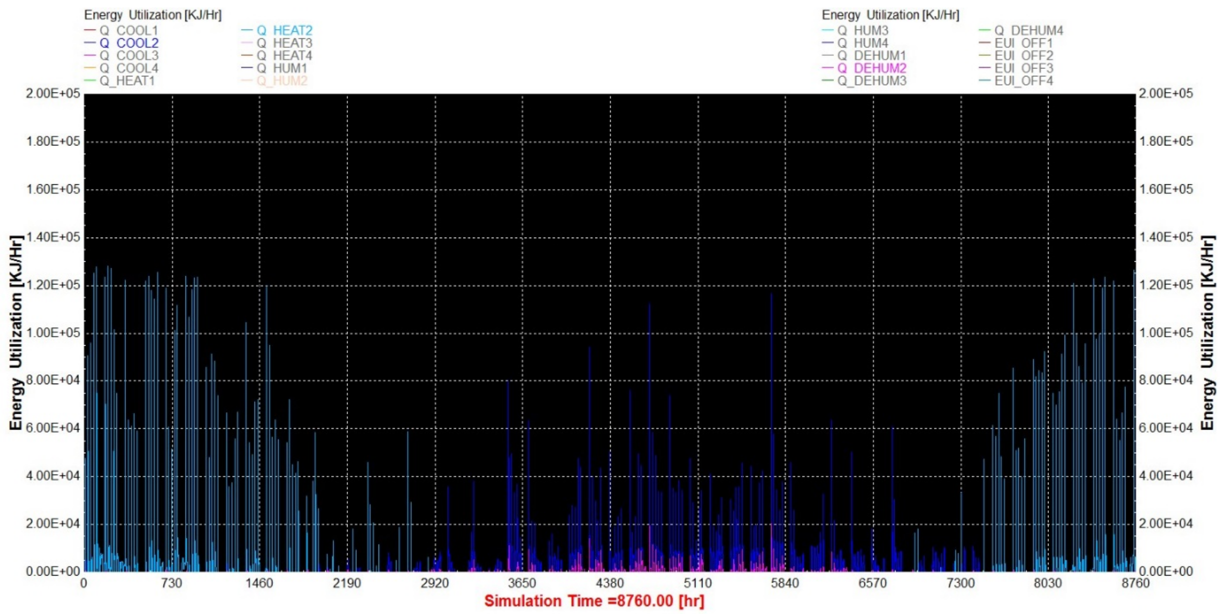


- Zones Relative Humidity Graph Explanation:

The office2's relative humidity percentage throughout a year in yellow (RH_OFF2) is compared with the ambient air's relative humidity in red (RH_AMB). In comparison to the ambient relative humidity (around 30 to 100%), the graph displays a lower humidity percentage in office2 for all the times from around 2 to the maximum of 50% defined for the offices' comfort zone. Comparing this graph with the previous run's graph (Run3), the relative humidity is now slightly higher, which is mainly related to the effect of two different strategies for shading: 70% external shading during hot seasons as opposed to an overhang. The next Office Energy Use Intensity graph displays changes in dehumidification.

Office Load Intensity *(kJ/hr)*

Run4 B (MC 4-Story Construction Shading Full HVAC)

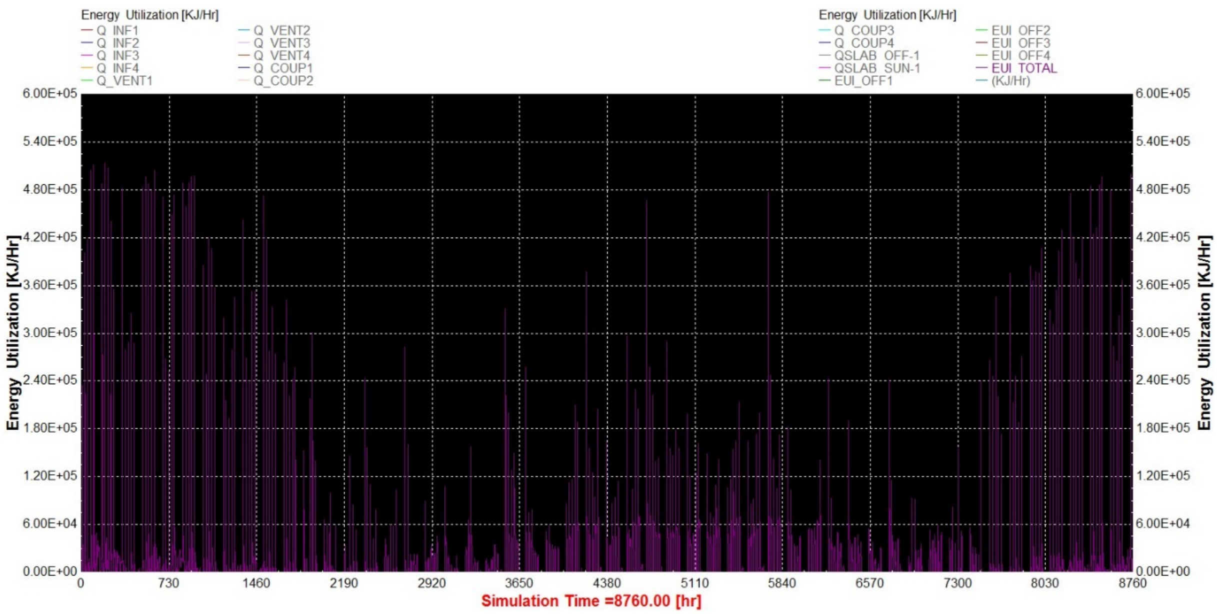


- Zones Energy Use Intensity Graph Explanation:

This graph implies that the annual LI is primarily associated with heating loads expected in the cold climate of Minneapolis. The cooling loads are next, also expected for the relatively hot and humid summer of Minneapolis, whilst dehumidification loads are less significant. If this graph is put in parallel to the previous graph, the heating load shows a slight decrease, while, on top, the cooling loads are slightly increased. This is causing minor changes in total LI of the two options as a result of the two different stated shading strategies.

Total Offices Load Intensity *(kJ/hr)*

Run4 B (MC 4-Story Construction Shading Full HVAC)

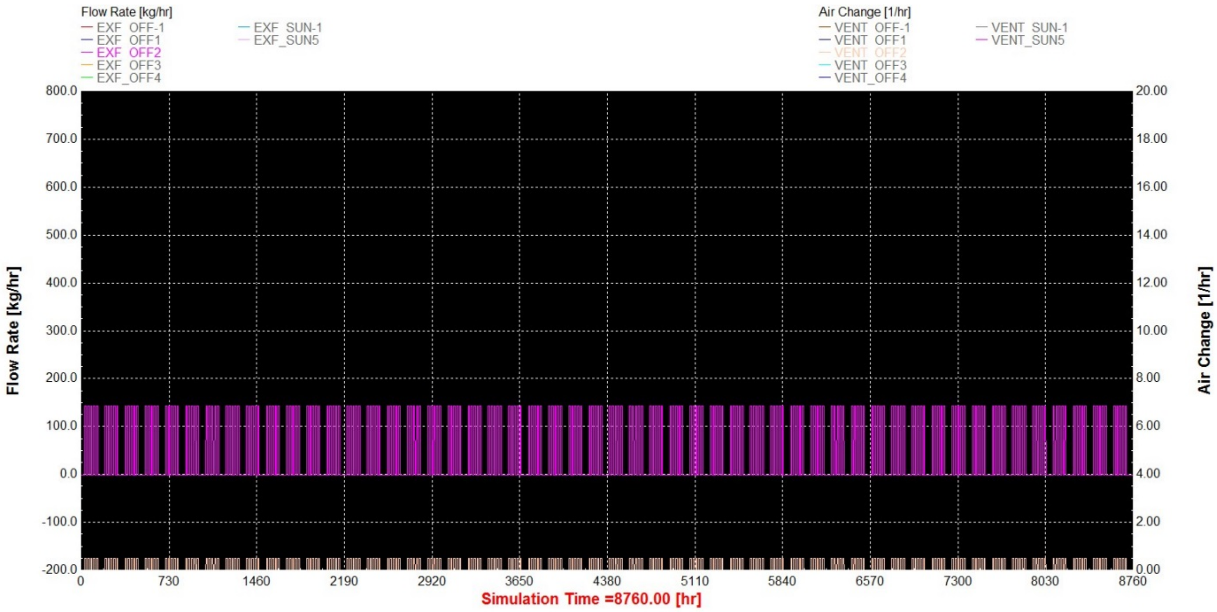


- Zones Total Energy Use Intensity Graph Explanation:

Looking at the above graph, it is clear that the total annual LI is primarily due to heating and then cooling loads in cold winter and hot summer of Minneapolis, respectively. By comparing run3 and run4's graphs (the baseline), it is also revealed that the 70% assumed external shading is a realistic assumption since the examined integrated light-shelf and overhang option (just overhang in this case) in run4 is at least performing around 10% better. By comparing this option's LI result (Run4 B) with the previous option (Run3 B), it is noticed that LI has decreased from 75.46 to 71.57 kwh/m² (23.92 to 22.69 kBTU/ft²). This option was examined to assure that the 70% external shading is a feasible solution that can be added to the DSF for its higher efficiency, and will not be considered as the optimized conventional option, since the next option of DSFs have the same type of shading as the baseline.

Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run4 B (MC 4-Story Construction Shading Full HVAC)

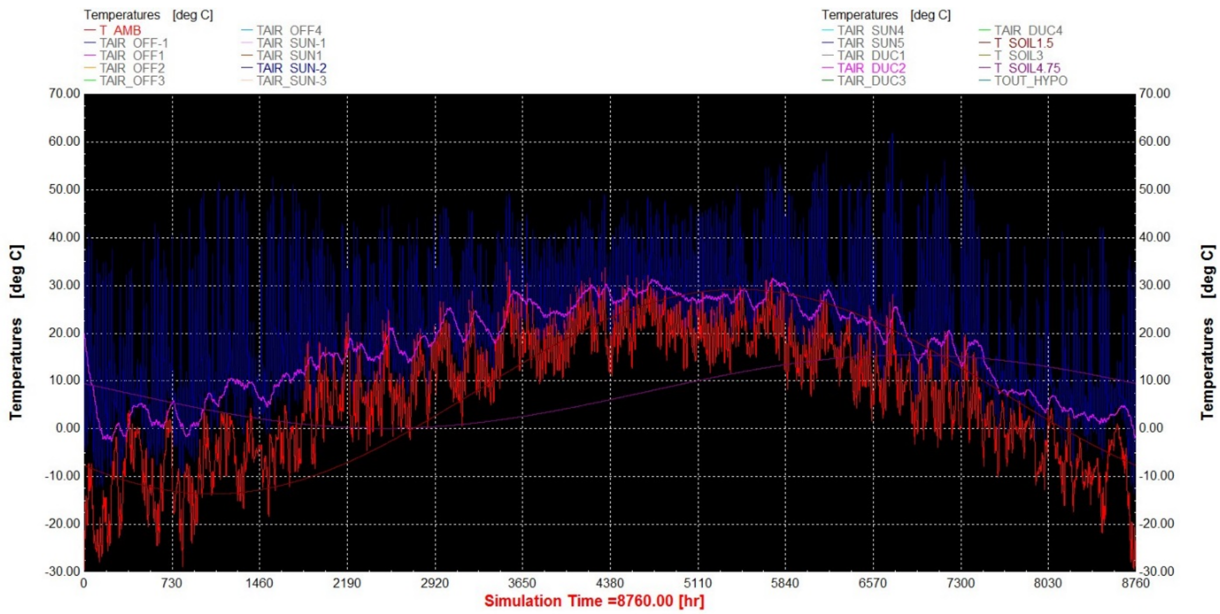


- Offices-Ambient Airflow Graph Explanation:

This graph gives details about the suggested ASHRAE ventilation rate of be143.2 kg/hr during the occupancy schedule for Office2 with 80 m² office with four occupants in exfiltration format (EXF_OFF2). The exchange rate of the office2 (VENT_OFF2) in the lower portion of the graph around 0.6/hr is another way to examine the intended ventilation rate assumed by the two coupled software for the purpose of clarifying the model's, hence, methodological validity.

Zones Temperature *(°C)*

Run5 C (MC 4-Story DSF2 Full HVAC)

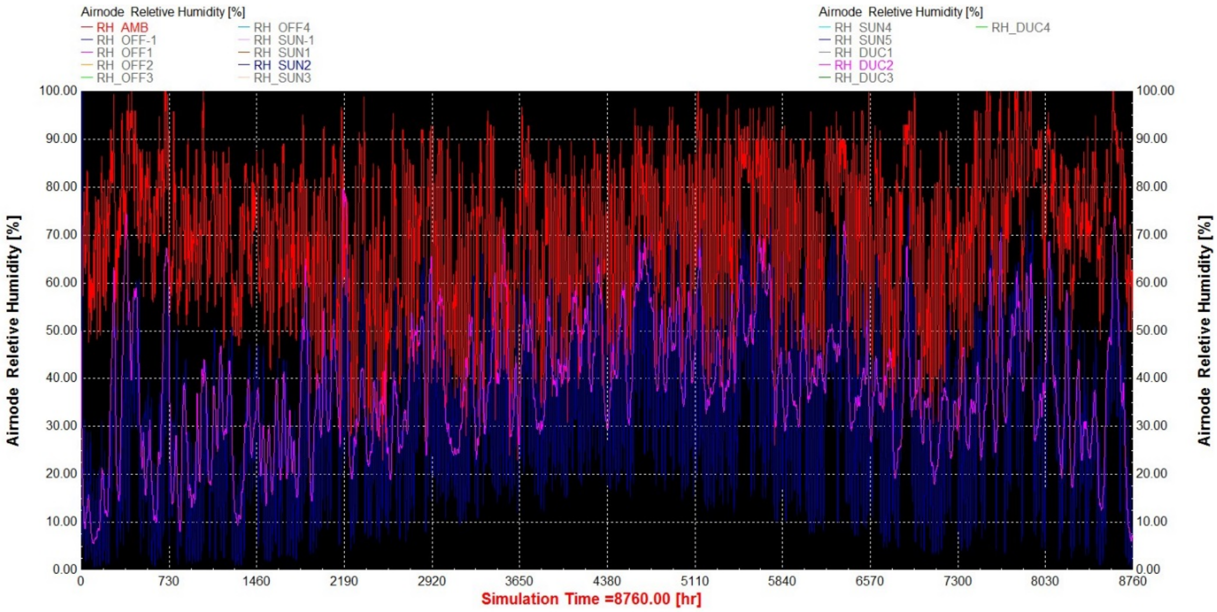


- Zones Temperature Graph Explanation:

The zones temperature graph illustrated above is related to the Run5 C: the baseline whereas an enclosed, 2-meter depth DSF is attached in front of the south façade without any air introduction, neither from ambient to the DSF nor from the DSF into the office zones. The 70% external shading assumed for the baseline is not yet added to this option in order to to examine the role of the external shading device in decreasing LI of the building. In this graph, the temperature of ambient air (T_AMB) in red can be compared with the temperature of the sunspace (TAIR_SUN2) in blue and the duct (TAIR_DUC2) in magenta as there will be air supply through these two zones into the building for ventilation, heating, and cooling purposes. The soil temperatures (T_SOIL) at 1.5 and 3m can also be judged with the ambient air temperature for air-tube integration possibilities. It is essential to note that the air temperature in the sunspaces are always warmer than the offices, assisting to properly control air introduction into the offices, which is more efficient during cold seasons. For hot seasons, the supply air is via the ducts that normally have cooler and less humid air in comparison to the ambient air. Comparing this option's LI with the baseline (Run4 B) shows LI increase from 71.57 to 76.95 kwh/m² (22.69 to 24.39 kBTU/ft²).

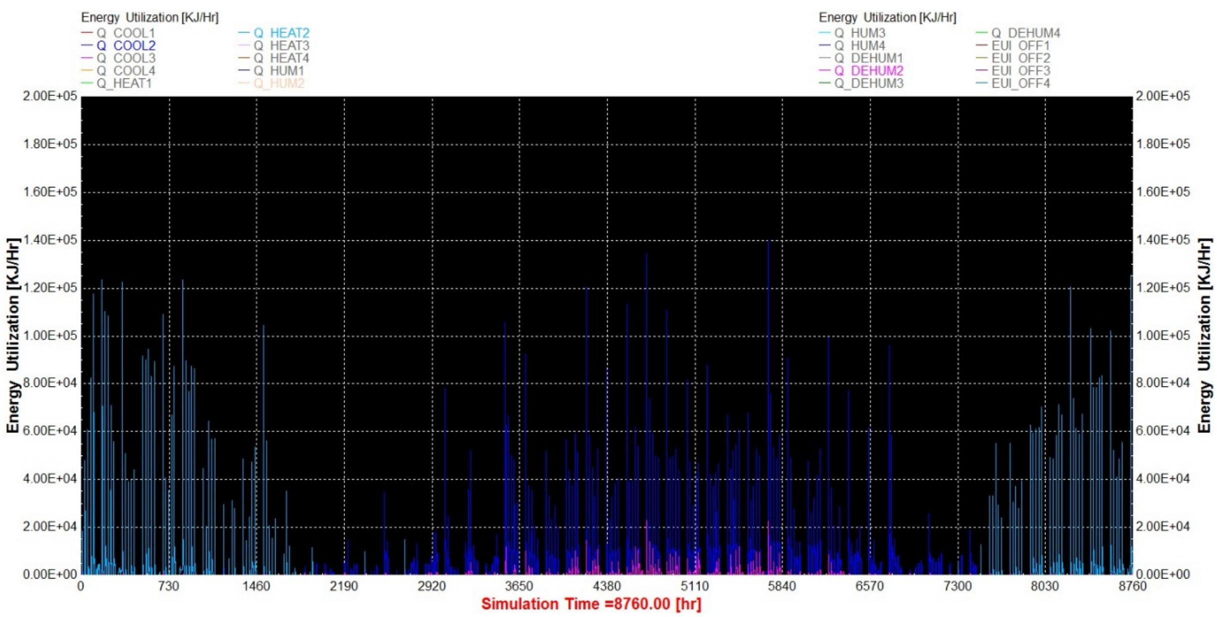
Zones Relative Humidity *(%)*

Run5 C (MC 4-Story DSF2 Full HVAC)



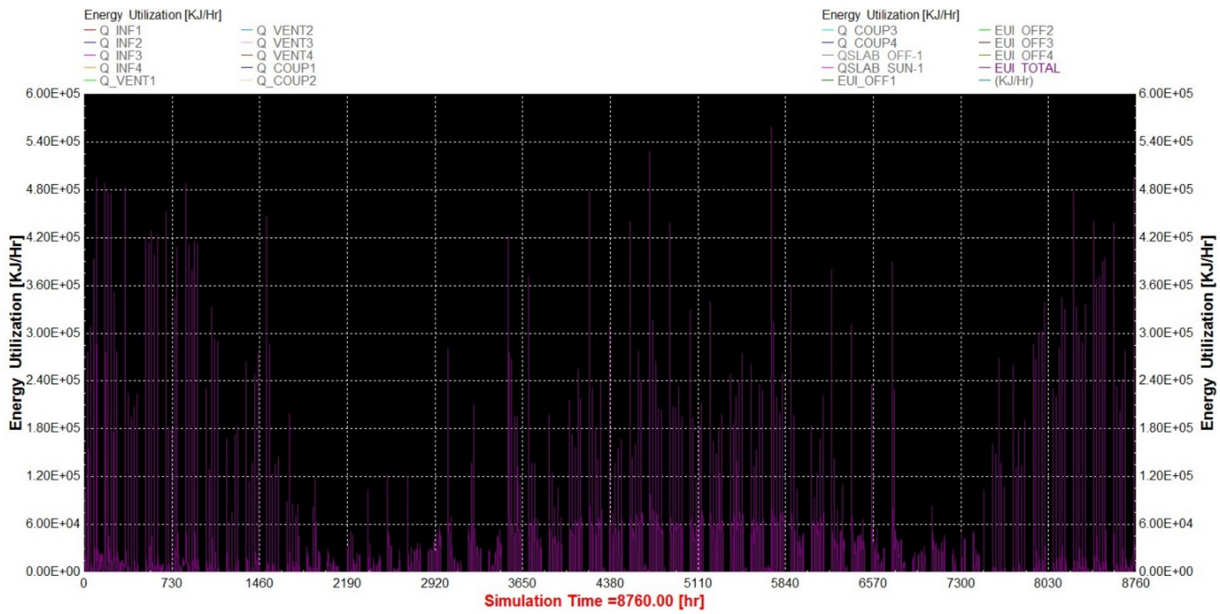
Office Load Intensity *(kJ/hr)*

Run5 C (MC 4-Story DSF2 Full HVAC)



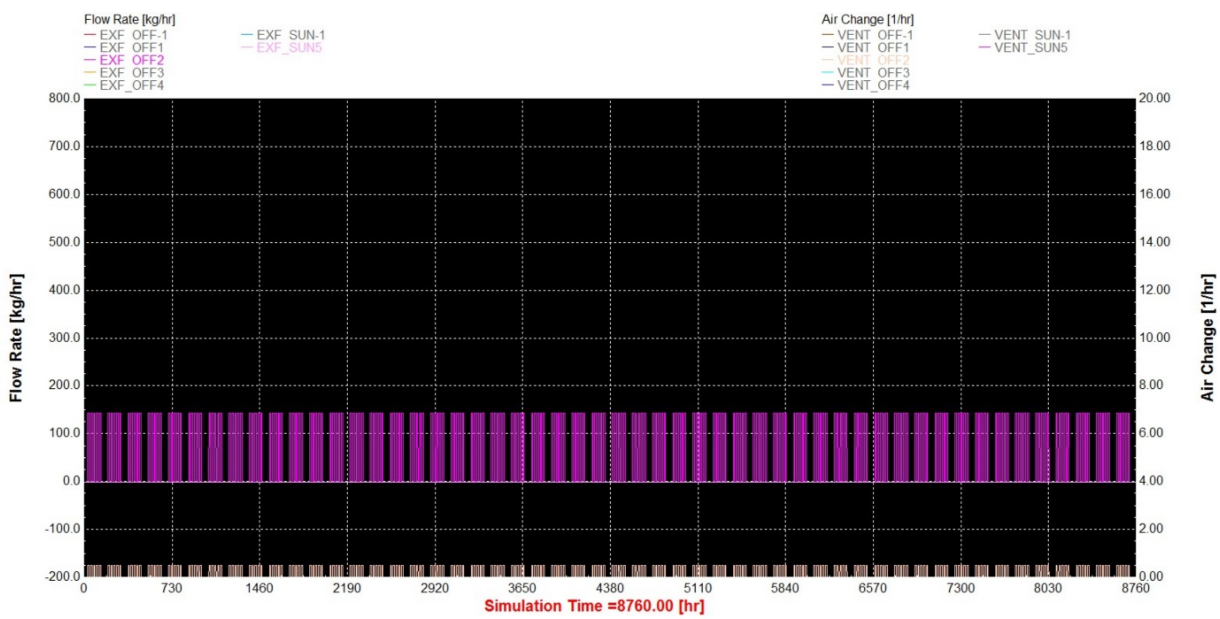
Total Offices Load Intensity *(kJ/hr)*

Run5 C (MC 4-Story DSF2 Full HVAC)



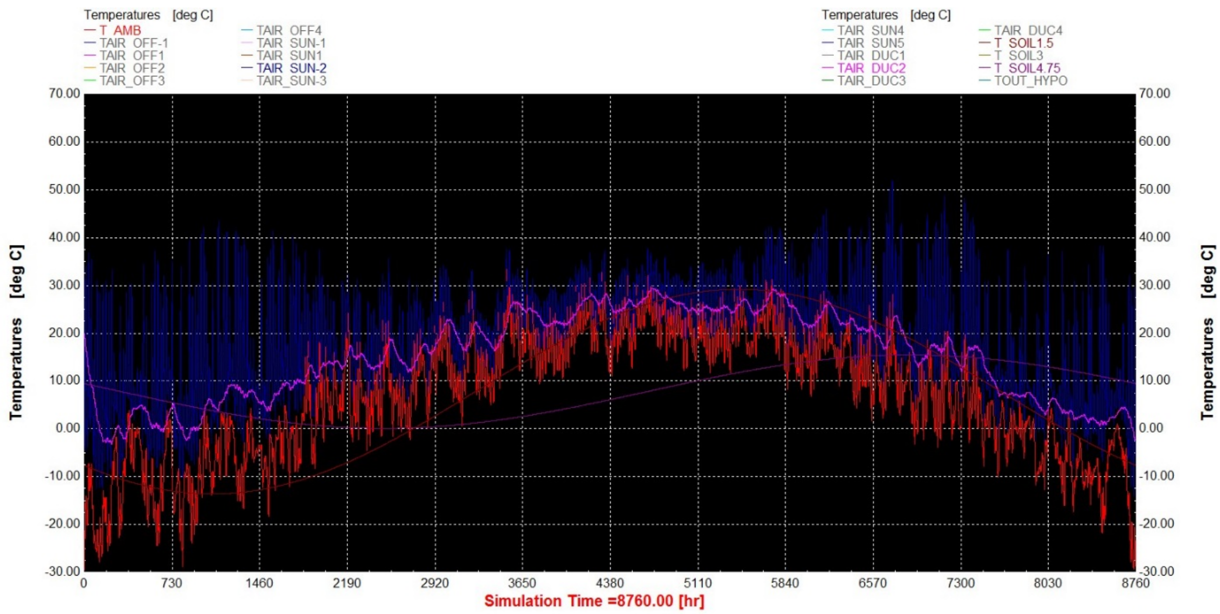
Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run5 C (MC 4-Story DSF2 Full HVAC)



Zones Temperature *(°C)*

Run6 C (MC 4-Story DSF2 Shading Full HVAC)

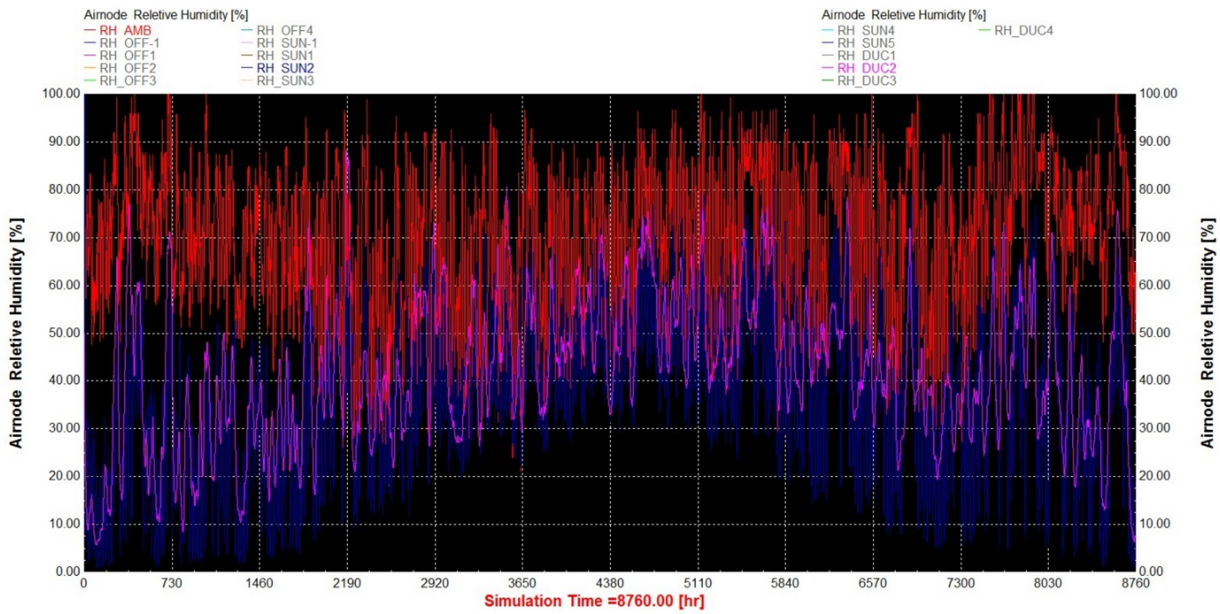


- Zones Temperature Graph Explanation:

The graph above correlates with the zones temperature for the Run6 C: the baseline, with the difference that an enclosed, 2-meter depth DSF is attached in front of the south façade without any air introduction neither from ambient to the DSF nor from the DSF into the office zones. The 70% external shading assumed for the baseline is now placed in front of the DSF so that the conventional building results of the baseline could be properly compared with the DSF options, presented from now on. That is the main alteration between the previous Run 5 and this run (Run6 C). From now on, thus, all next options do include this external shading. By comparing this graph and the one associated with the previous run without external shading, it is noticeable that the sunspace2's air temperature in now closer to the comfort zone. This is revealed as expected, resulting in more efficient LI, a result to be further scrutinized in next related energy graphs. Comparing this option's LI result (Run6 C) with the baseline (Run4 B) shows that the LI reduction from 71.57 to 67.06 kwh/m² (22.69 to 21.26 kBTU/ft²).

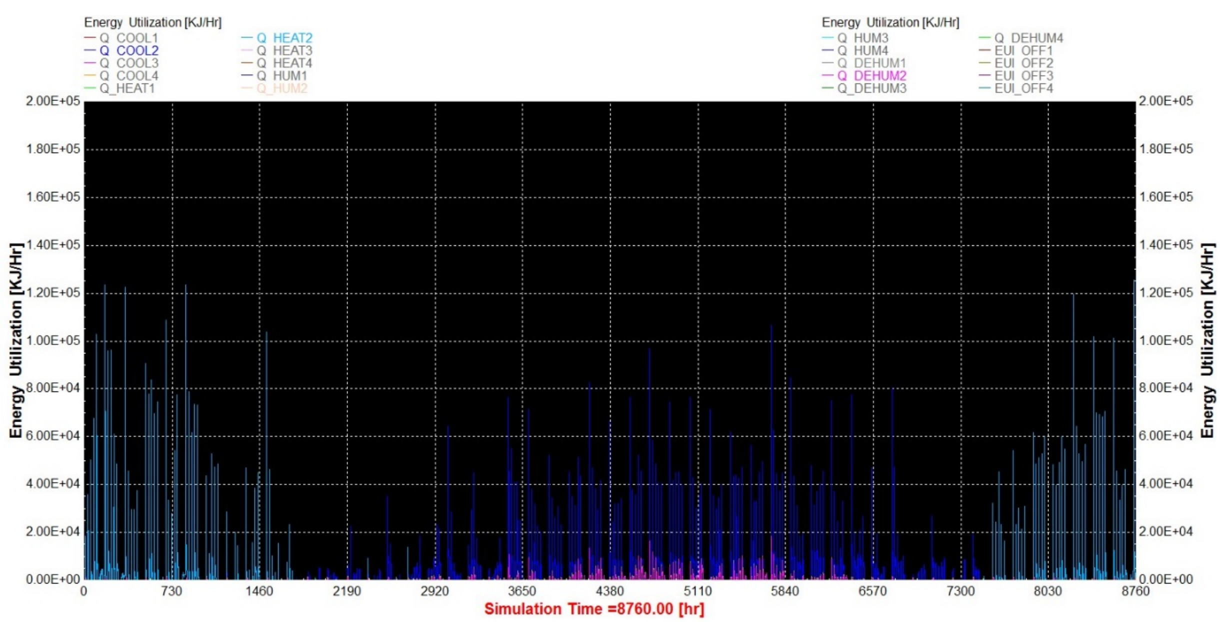
Zones Relative Humidity *(%)*

Run6 C (MC 4-Story DSF2 Shading Full HVAC)



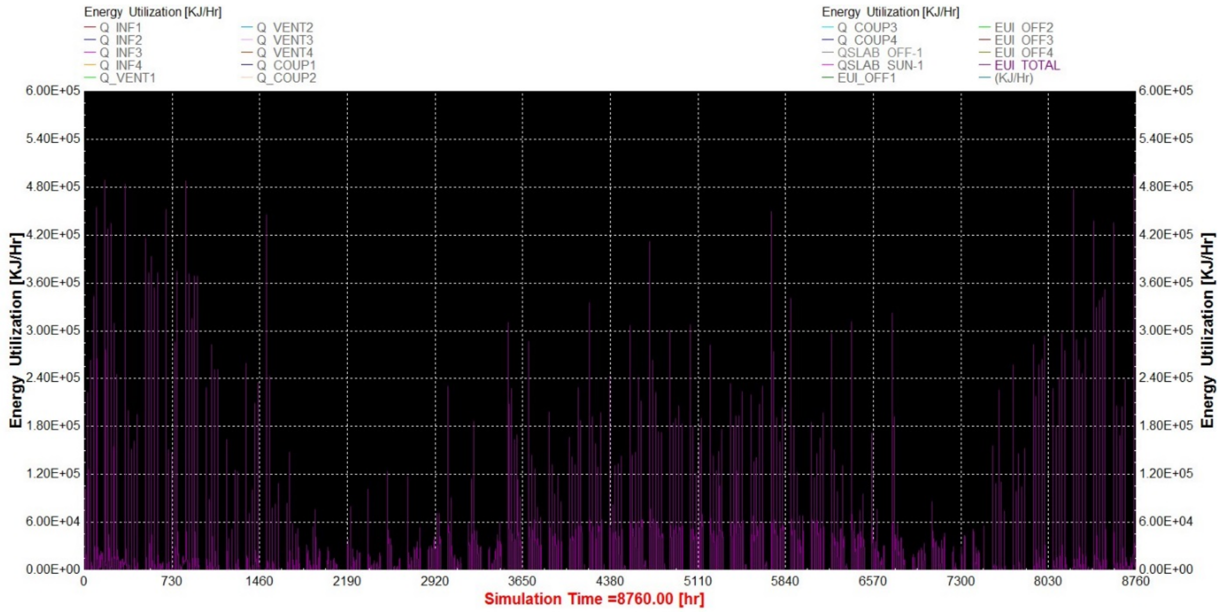
Office Load Intensity *(kJ/hr)*

Run6 C (MC 4-Story DSF2 Shading Full HVAC)



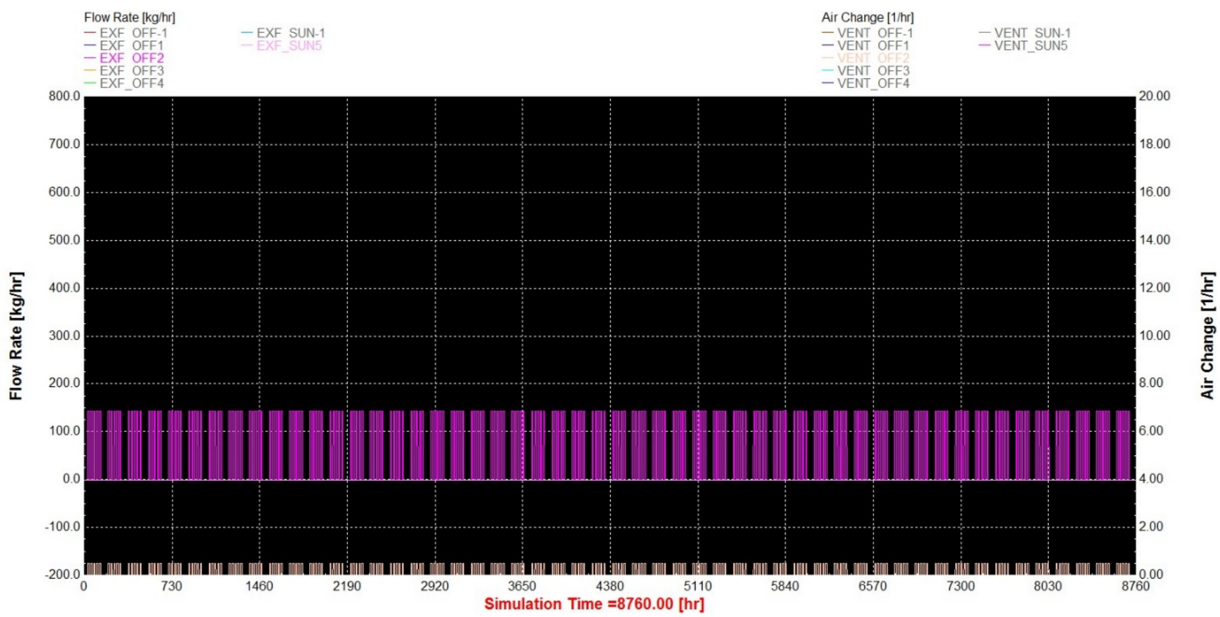
Total Offices Load Intensity *(kJ/hr)*

Run6 C (MC 4-Story DSF2 Shading Full HVAC)



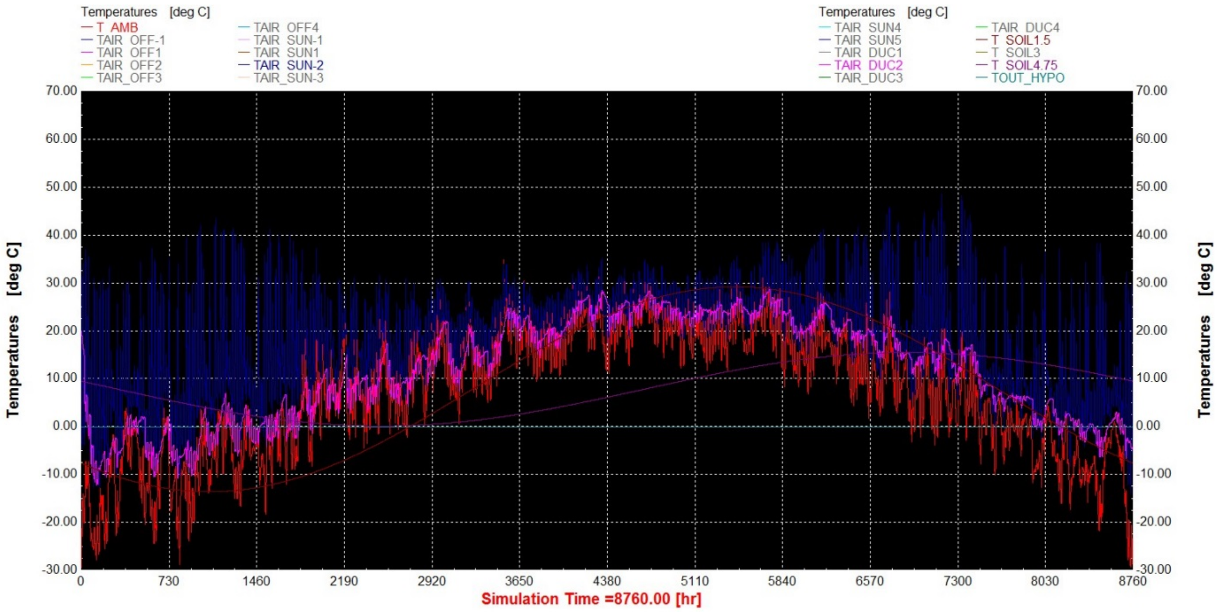
Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run6 C (MC 4-Story DSF2 Shading Full HVAC)



Zones Temperature *(°C)*

Run7 D (MC 4-Story MV DSF2 Full HVAC)

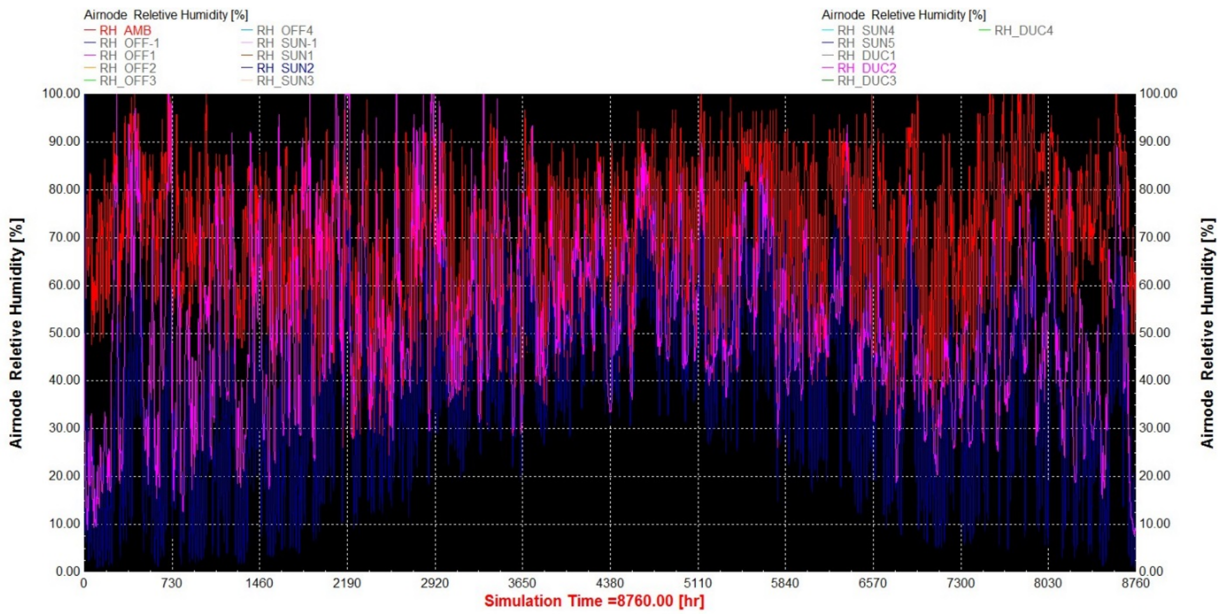


- Zones Temperature Graph Explanation:

This zones temperature graph is the outcome of the Run7 D: the baseline, wherein a 2-meter depth, mechanically ventilated DSF is attached in front of the south façade. This is primarily functioning as a thermal buffer, which is defined, still, without any air introduction from the DSF into the office zones. By comparing this graph and the one associated with the previous run, one with no ambient air introduction into the DSF, a slight decrease in LI is realized making the sunspace air even closer to the comfort zone during hot seasons.

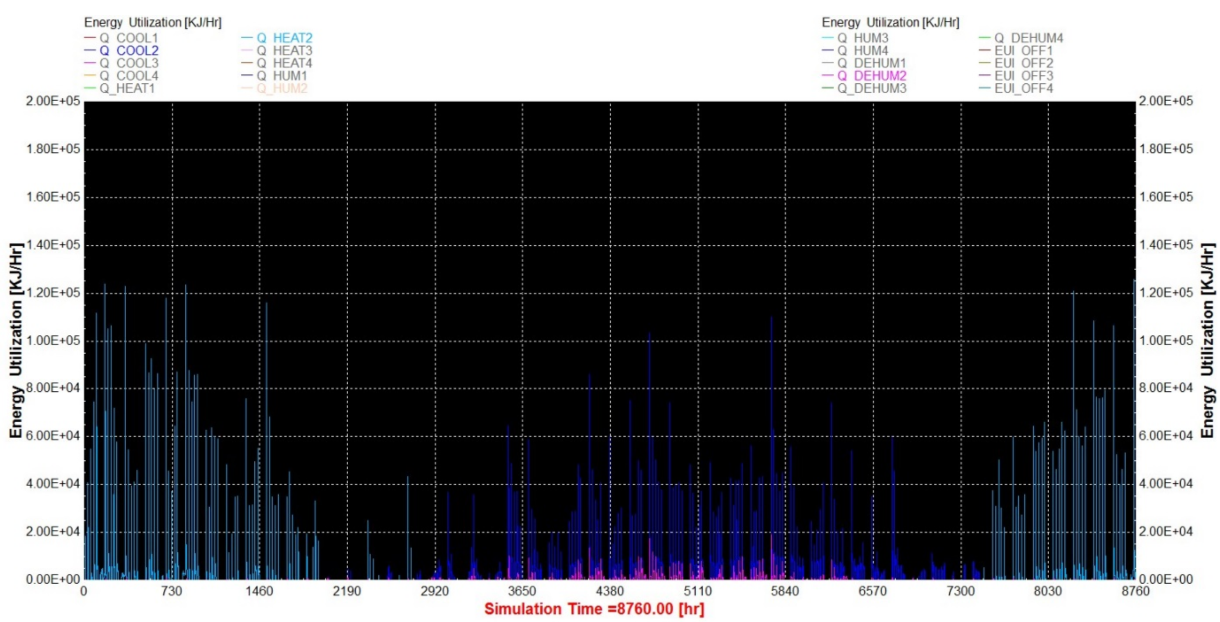
Zones Relative Humidity *(%)*

Run7 D (MC 4-Story MV DSF2 Full HVAC)



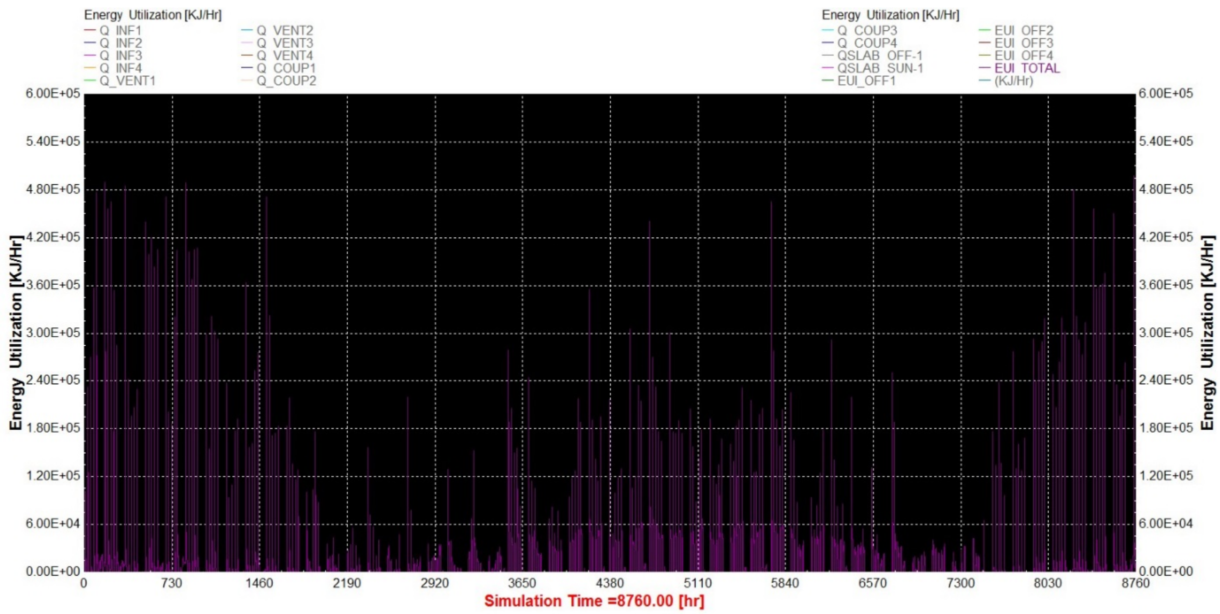
Office Load Intensity *(kJ/hr)*

Run7 D (MC 4-Story MV DSF2 Full HVAC)



Total Offices Load Intensity *(kJ/hr)*

Run7 D (MC 4-Story MV DSF2 Full HVAC)

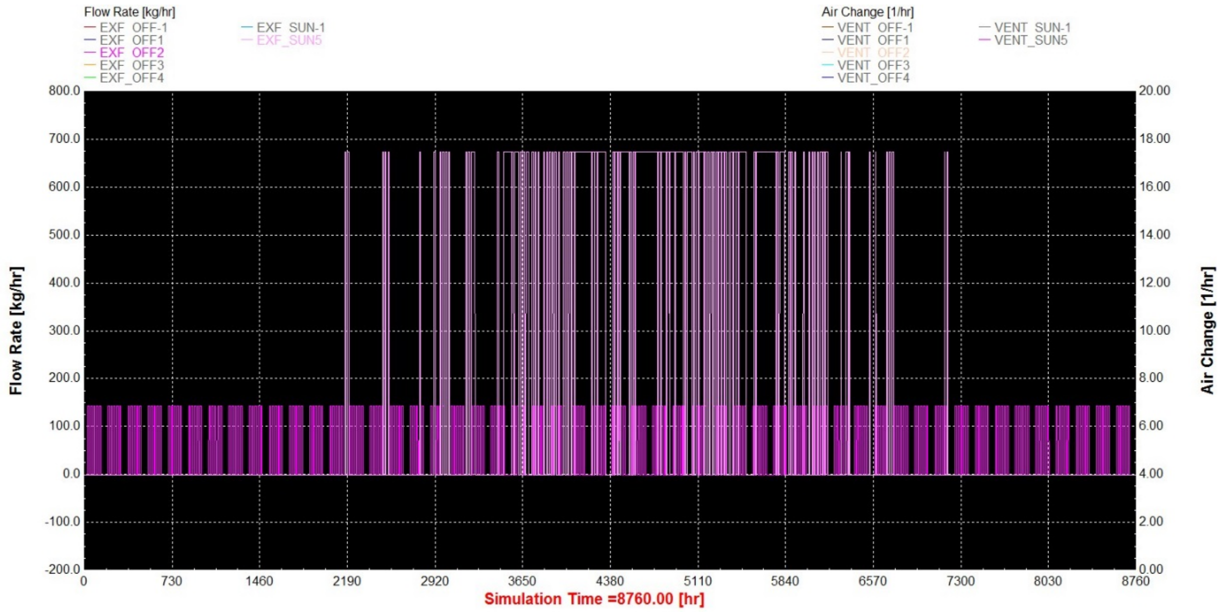


- Zones Total Energy Use Intensity Graph Explanation:

Comparing this option's LI result (Run7 D) with the baseline (Run4 B), the LI drop is observable from 71.57 to 63.39 kwh/m² (22.69 to 20.10 kBTU/ft²). This proves the positive role of DSF exhaustion in lowering the system's LI.

Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run7 D (MC 4-Story MV DSF2 Full HVAC)

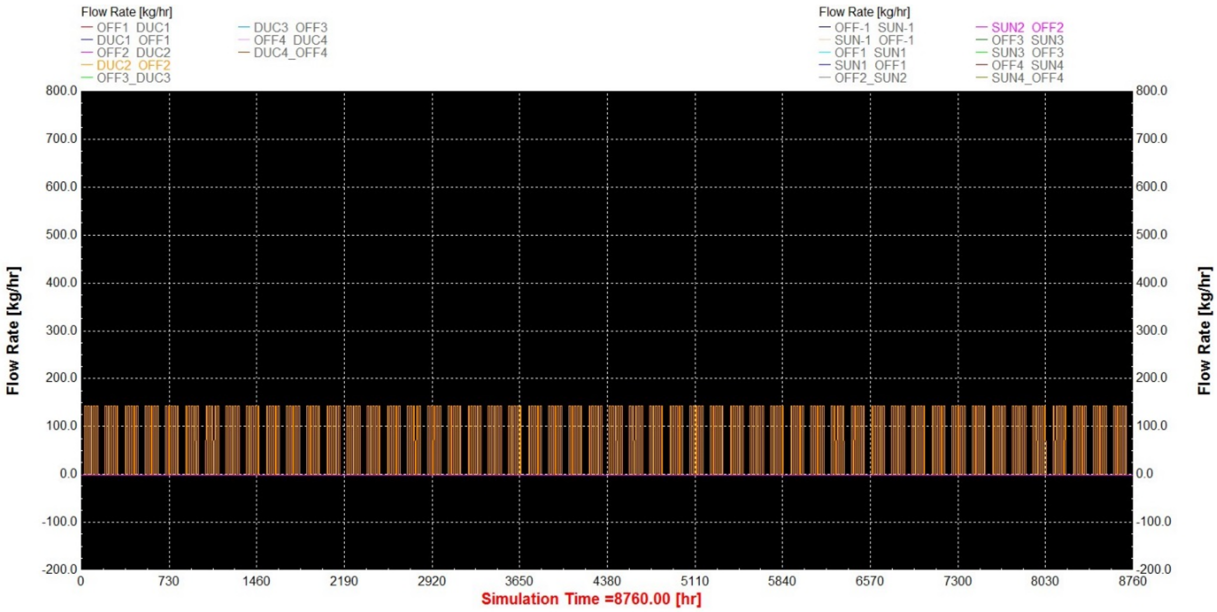


- Offices-Ambient Airflow Graph Explanation:

The suggested ASHRAE ventilation rate of be143.2 kg/hr during the occupancy schedule for Office2 is shown in this graph in an exfiltration format (EXF_OFF2). In addition, the amount of airflow exhausted from the top sunspace (EXF_SUN5) through the three 110 cfm fans is illustrated in pink. A side note is that 330 cfm is equal to 674 kg/hr in standard condition, which is exactly what can be seen for the sunspace exhaust via sunspace 5 in the graph above.

Sunspaces/Ducts-Offices Airflow *(kg/hr or 1/hr)*

Run7 D (MC 4-Story MV DSF2 Full HVAC)

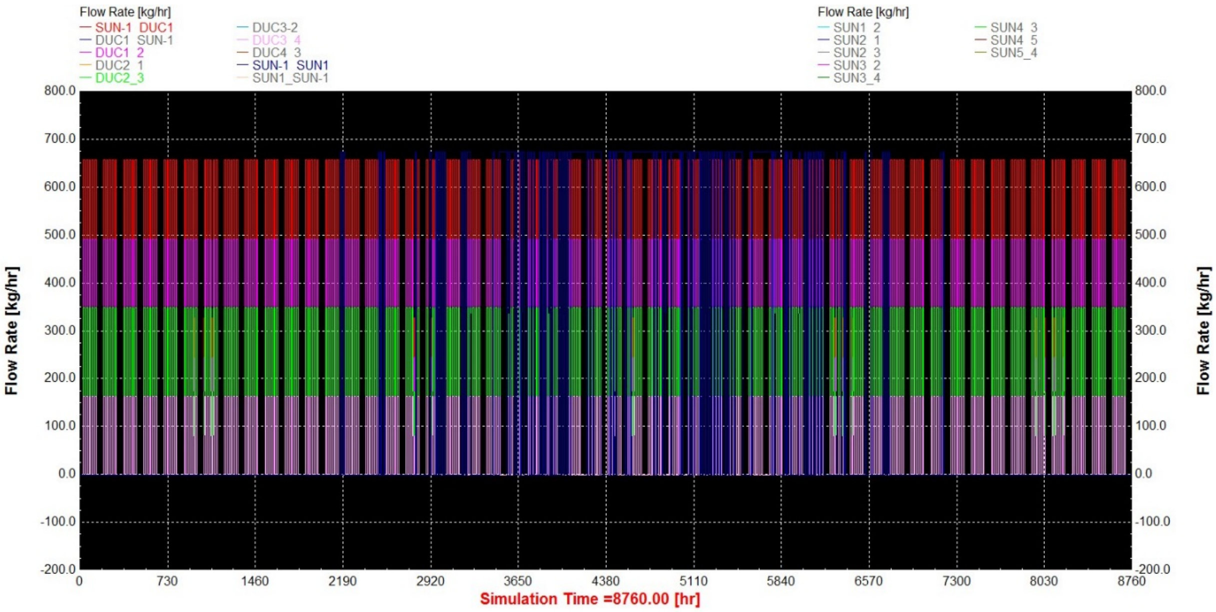


- Offices-Ambient Airflow Graph Explanation:

The suggested ASHRAE ventilation rate of be143.2 kg/hr during the occupancy schedule that was stated for Office2 is demonstrated in this graph in the form of an airflow introduced from duct2 to the office (DUC2_OFF2) in brown. This is the main air supply for fresh air as there is no air introduction between the DSF and the offices in this option.

Sunspace/Duct-Sunspace/Duct Airflow *(kg/hr or 1/hr)*

Run7 D (MC 4-Story MV DSF2 Full HVAC)

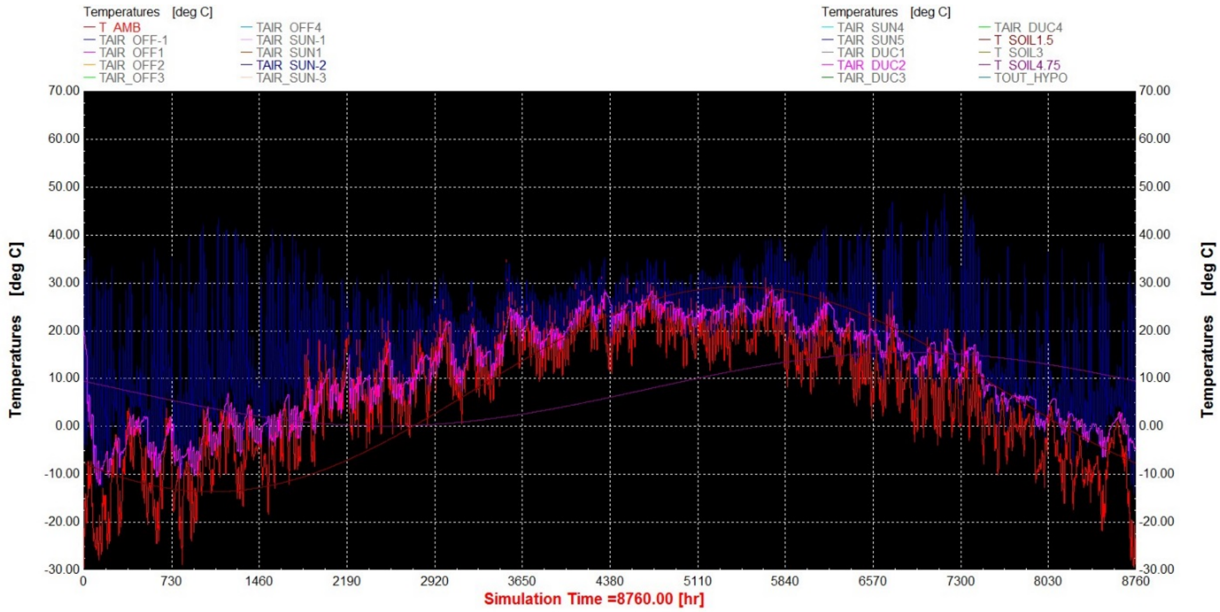


- Sunspace/Duct-Sunspace/Duct Airflow Graph Explanation:

The pointed out ASHRAE ventilation rate for each office is examined in this graph, as a result of the number of occupants in each office zone coupled with the zone area. The graph is also demonstrating positive direction of airflow for the vertical connections between sunspaces- for DSF exhaust purposes -and the ducts- for offices ventilation purposes- in form of (Sun-1_SUN1) in blue, (Sun-1_Duct1) in red, (Duc1_2) in magenta, (Duc2_3) in green, and (Duc3_4) in pink. The amount of airflow required for offices' ventilation (164.3+ 143.2+185.4+164.3=657.2 kg/hr) as well as 674 kg/hr sunspaces' exhaust in each level is also shown in this graph.

Zones Temperature *(°C)*

Run8 E (MC 4-Story NV DSF2 Full HVAC)

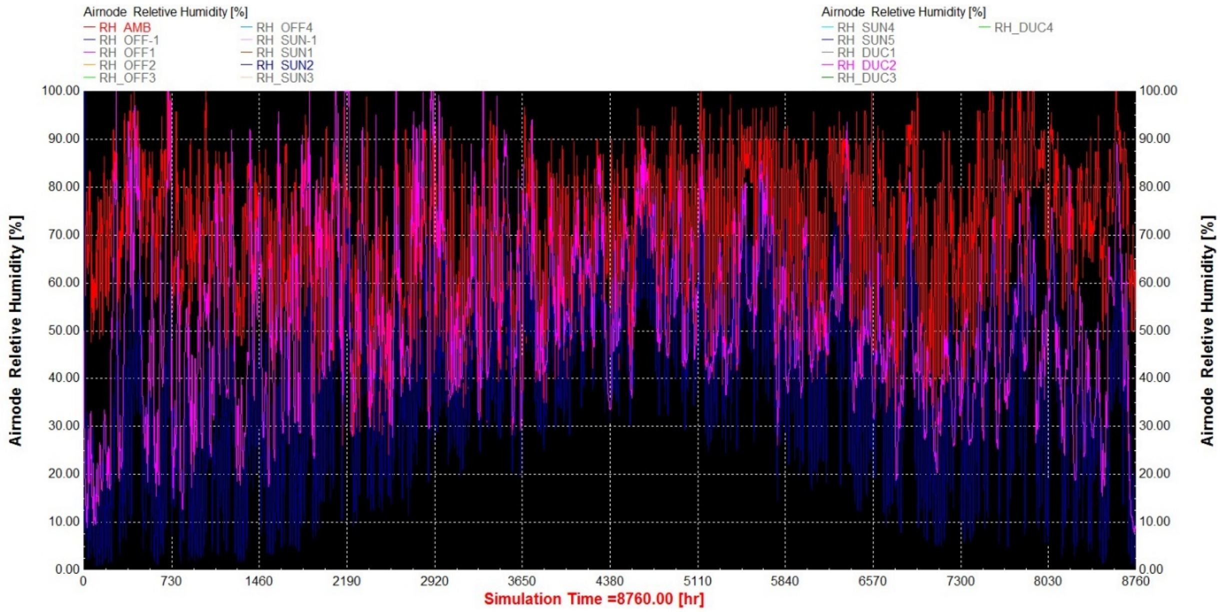


- Zones Temperature Graph Explanation:

This zones temperature graph relates to the Run8 E: the baseline wherein a 2-meter depth, naturally ventilated DSF is attached in front of the south façade primarily functioning as a thermal buffer, still without any air introduction from the DSF into the office zones. This option, therefore, is very similar to the previous option with the difference that the DSF is naturally ventilated. By comparing this graph and the one associated with the previous run, in which the DSF was mechanically ventilated, an insignificant increase in LI is realized, confirming the possibilities of naturally ventilated DSF without the issue of overheating, at least in this climate. In fact, the difference will be in the LI increase of 63.39 to 63.53 kwh/m² (20.10 to 20.14 kBTU/ft²). Comparing this option's LI result (Run8 E) with the baseline (Run4 B), it can be observed that LI has still decreased from 71.57 to 63.53 kwh/m² (22.69 to 20.14 kBTU/ft²).

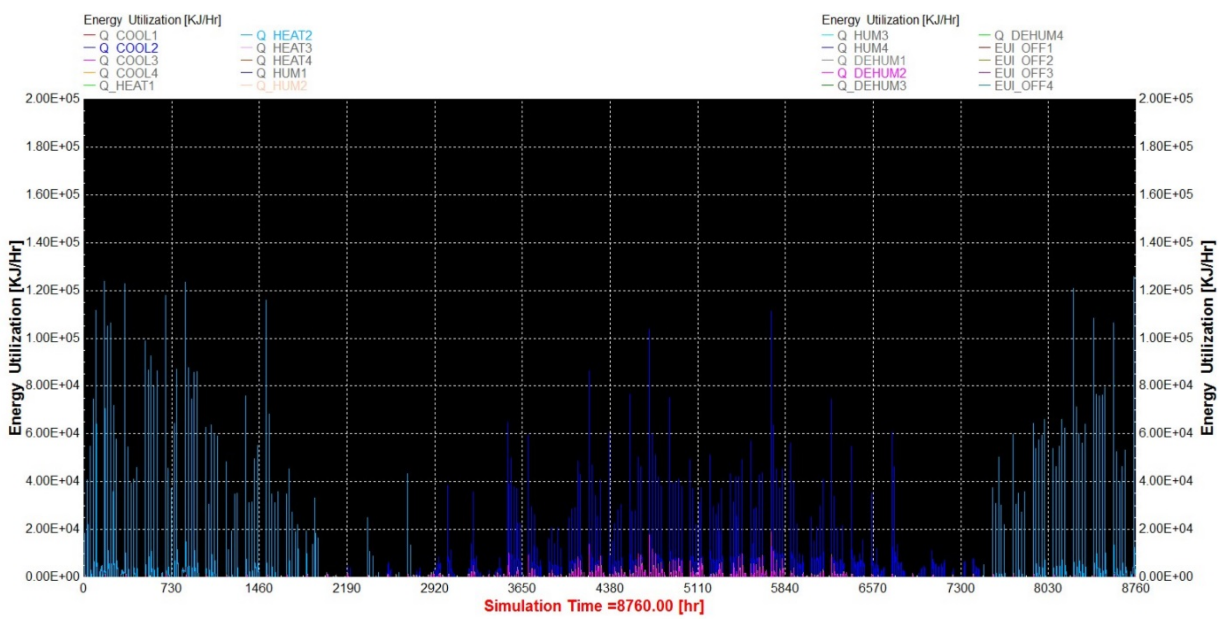
Zones Relative Humidity *(%)*

Run8 E (MC 4-Story NV DSF2 Full HVAC)



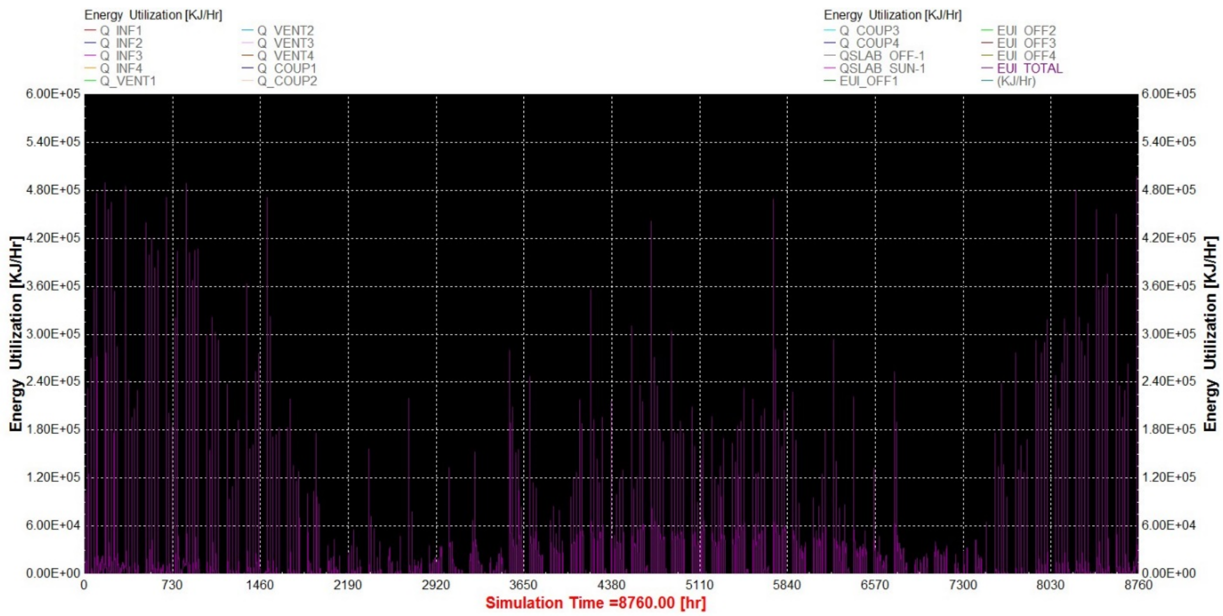
Office Load Intensity *(kJ/hr)*

Run8 E (MC 4-Story NV DSF2 Full HVAC)



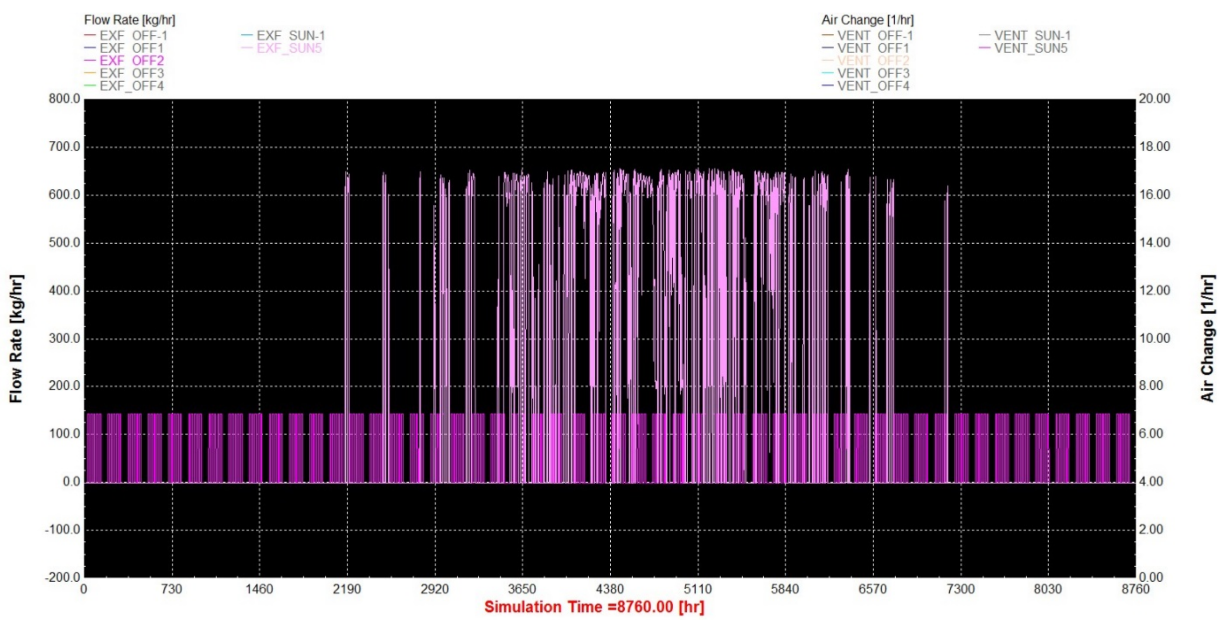
Total Offices Load Intensity *(kJ/hr)*

Run8 E (MC 4-Story NV DSF2 Full HVAC)



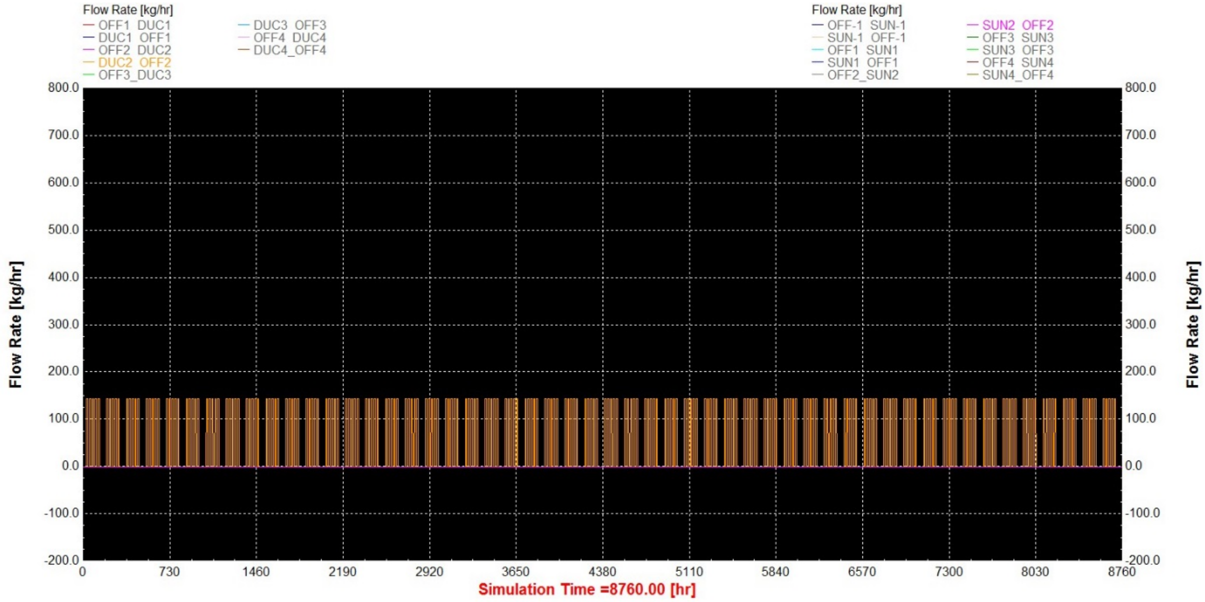
Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run8 E (MC 4-Story NV DSF2 Full HVAC)



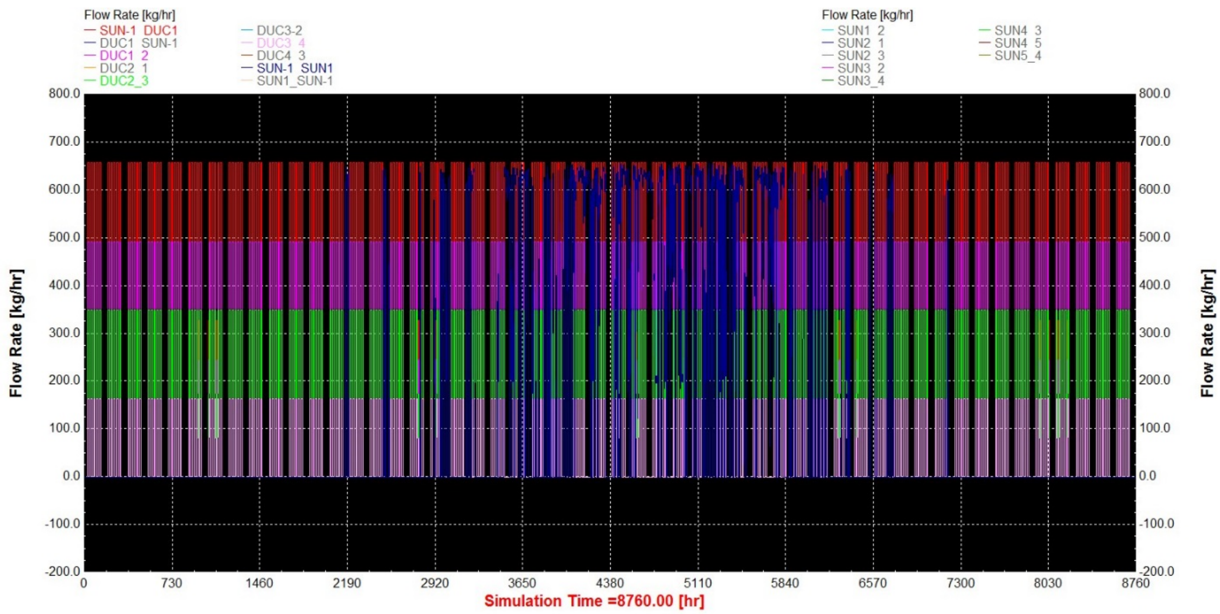
Sunspaces/Ducts-Offices Airflow *(kg/hr or 1/hr)*

Run8 E (MC 4-Story NV DSF2 Full HVAC)



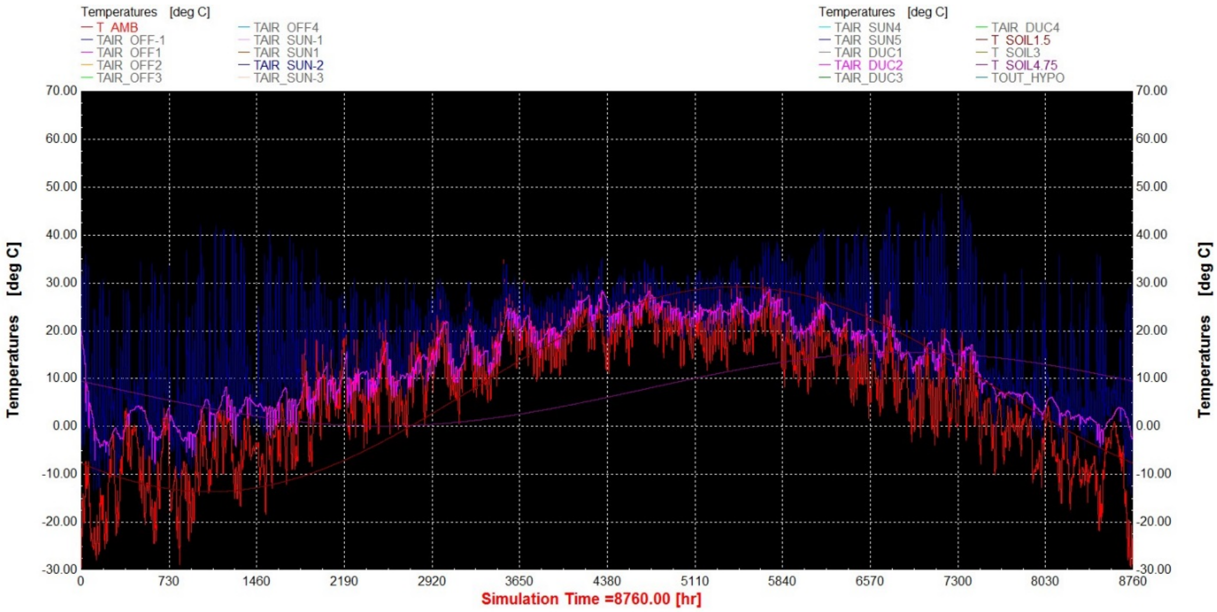
Sunspace/Duct-Sunspace/Duct Airflow *(kg/hr or 1/hr)*

Run8 E (MC 4-Story NV DSF2 Full HVAC)



Zones Temperature *(°C)*

Run9 F (MV 4-Story MV DSF2 Semi HVAC)

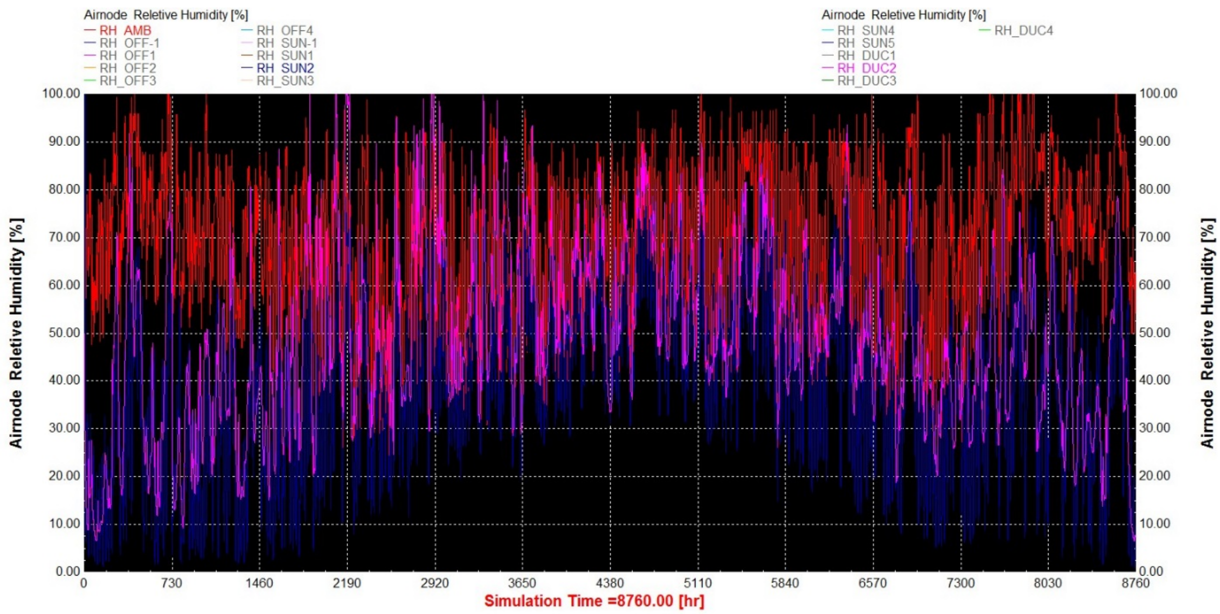


- Zones Temperature Graph Explanation:

The zones temperature graph shown here is associated with the Run9 F: the baseline wherein a 2-meter depth, mechanically ventilated DSF is attached in front of the south façade. This is primarily functioning as an HVAC contributor with air introduction from both ambient air to the DSF and from the DSF into the office zones. By comparing this graph and the one related to the previous run, in which the DSF was mainly functioning just as a thermal buffer, an insignificant increase in LI is noticeable confirming the possibilities of using the pre-conditioned air in DSF cavity as the source of air supply instead of using extreme condition of ambient air. Comparing this option's LI result (Run9 F) with the baseline (Run4 B) shows an LI decrease from 71.57 to 60.83 kwh/m² (22.69 to 19.28 kBTU/ft²).

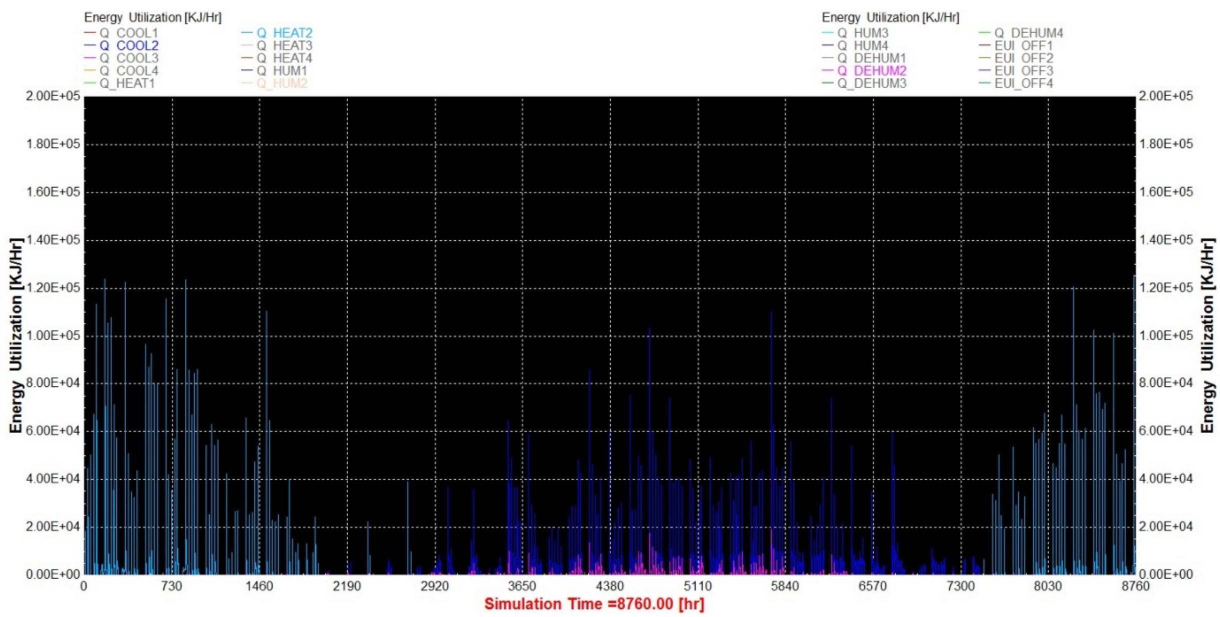
Zones Relative Humidity *(%)*

Run9 E (MV 4-Story MV DSF2 Semi HVAC)



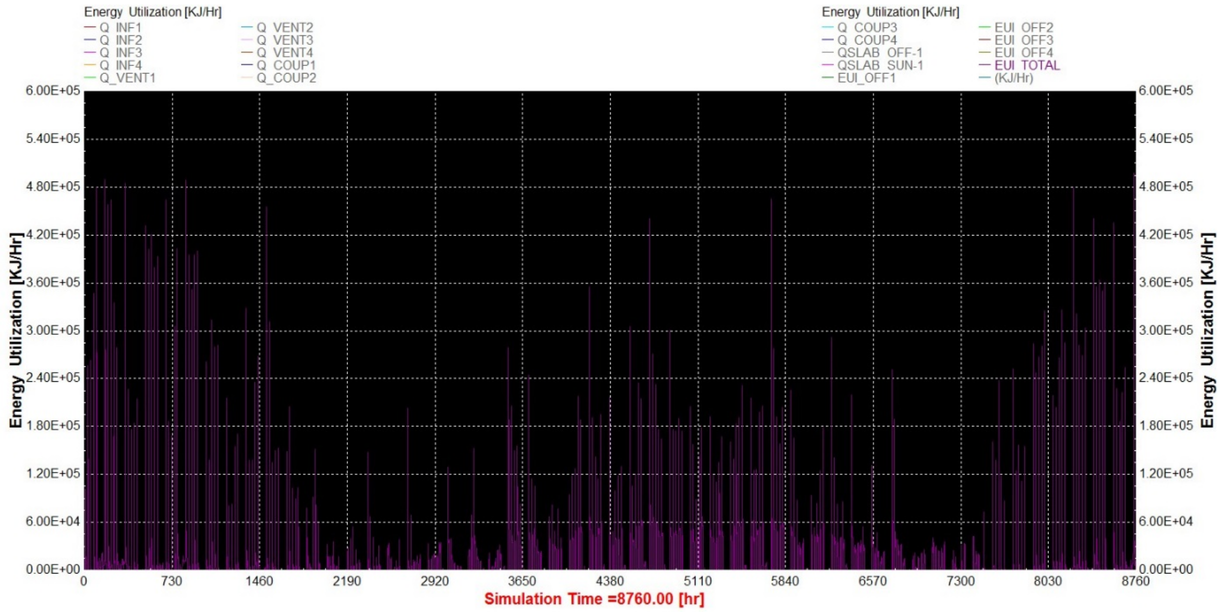
Office Load Intensity *(kJ/hr)*

Run9 F (MV 4-Story MV DSF2 Semi HVAC)



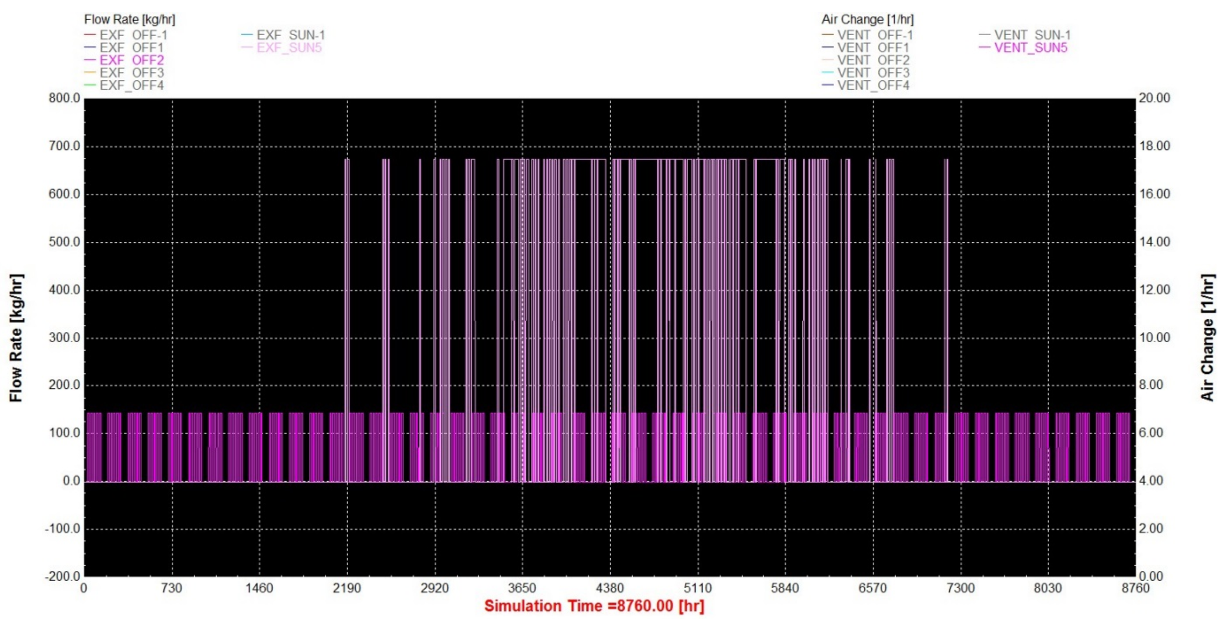
Total Offices Load Intensity *(kJ/hr)*

Run9 F (MV 4-Story MV DSF2 Semi HVAC)



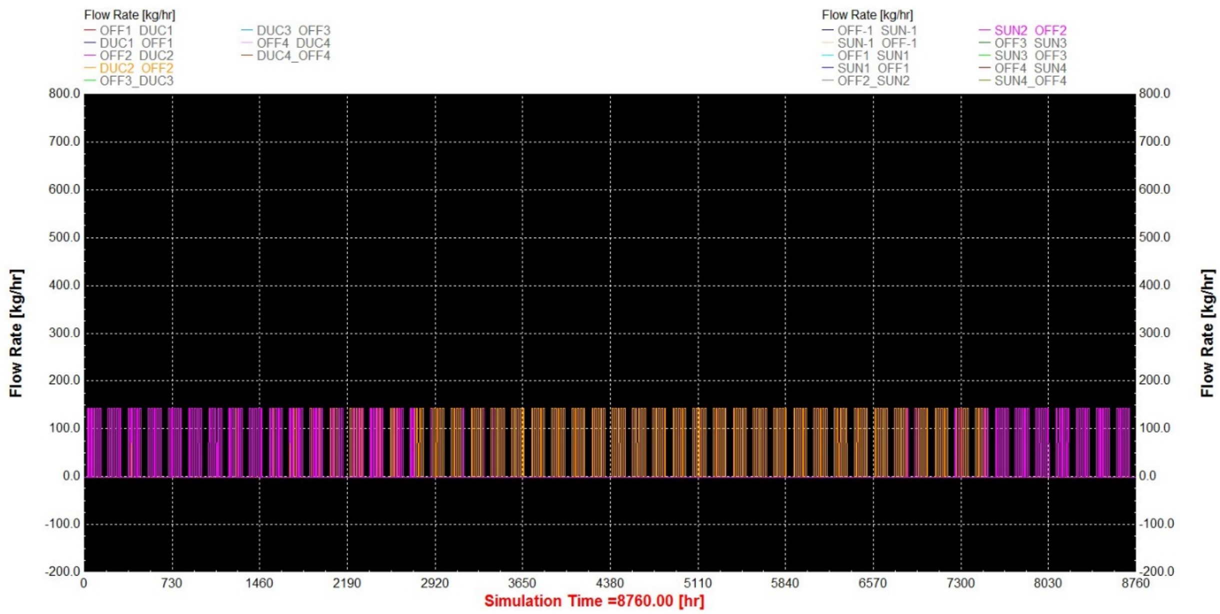
Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run9 F (MV 4-Story MV DSF2 Semi HVAC)



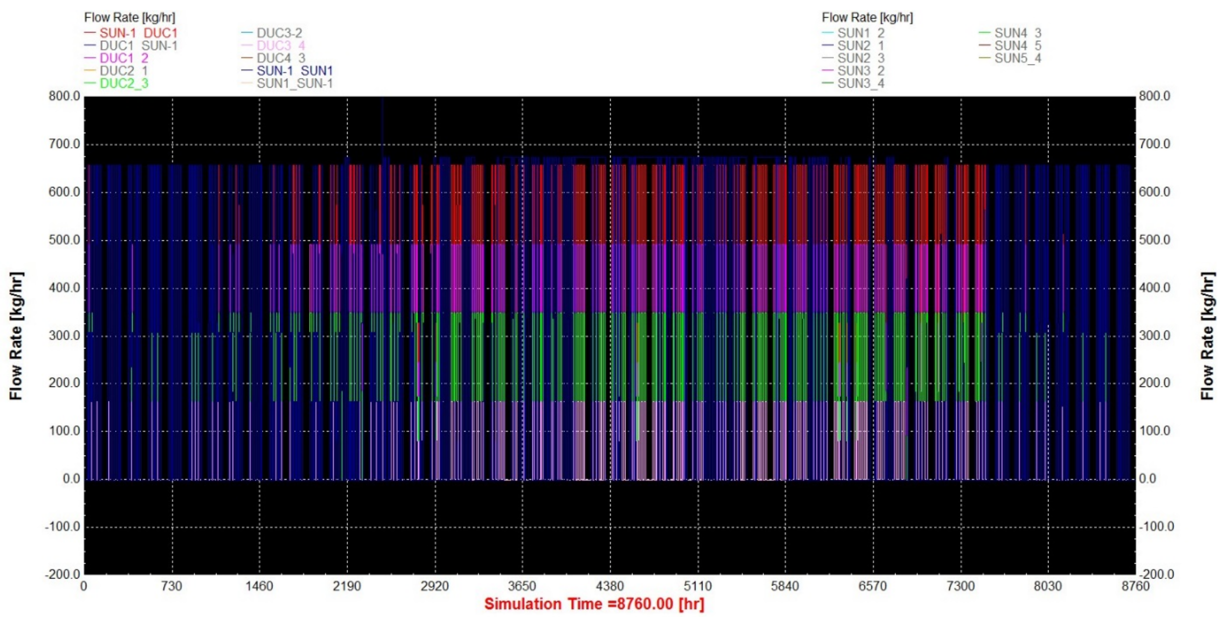
Sunspaces/Ducts-Offices Airflow *(kg/hr or 1/hr)*

Run9 F (MV 4-Story MV DSF2 Semi HVAC)



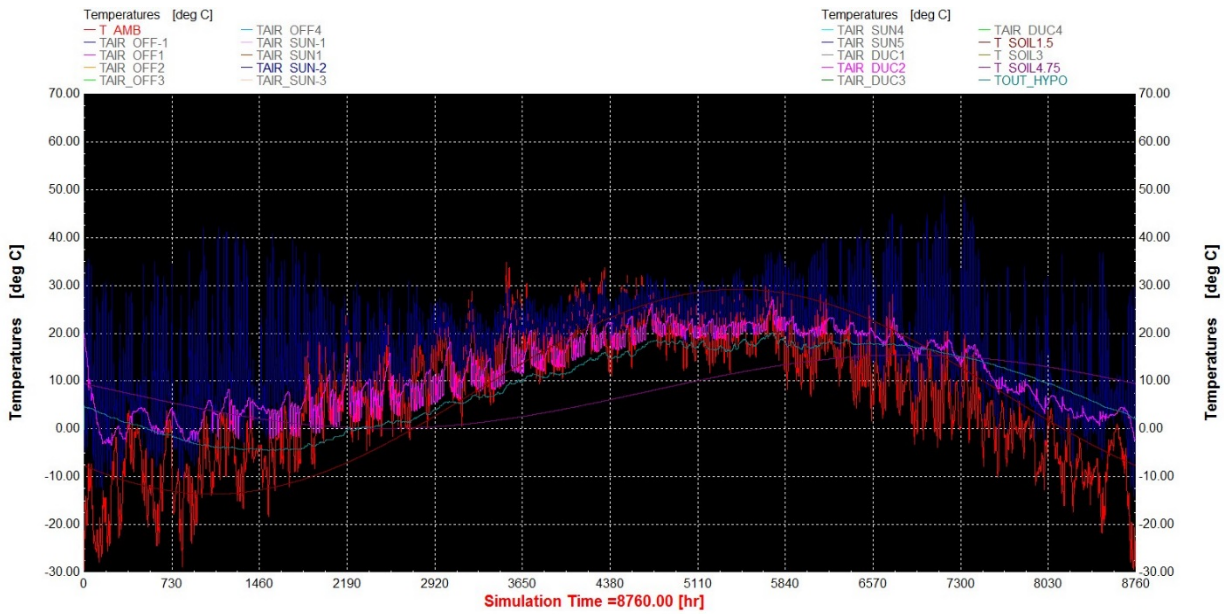
Sunspace/Duct-Sunspace/Duct Airflow *(kg/hr or 1/hr)*

Run9 F (MV 4-Story MV DSF2 Semi HVAC)



Zones Temperature *(°C)*

Run10 F (MV 4-Story MV DSF2 Semi HVAC Hypo)

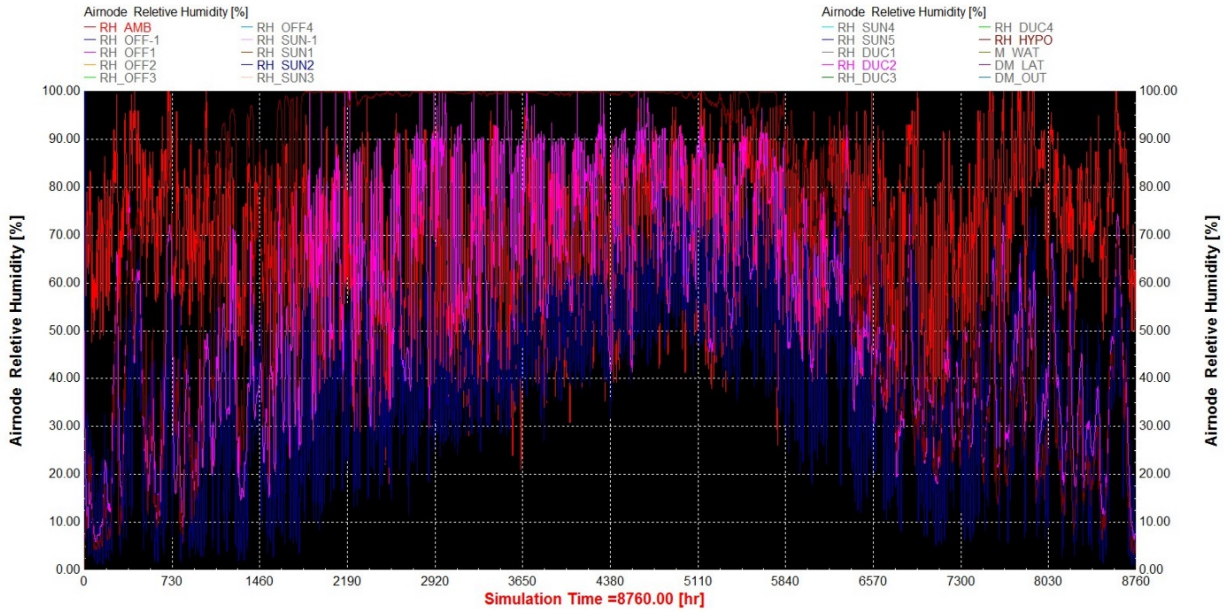


- Zones Temperature Graph Explanation:

The zones temperature graph illustrated above is related to the Run10 F: the baseline wherein a 2-meter depth, mechanically ventilated DSF is attached in front of the south façade primarily functioning as a HVAC contributor with air introduction from both earth-tube system to the DSF and from the DSF into the office zones. This option, therefore, is very similar to the previous option whereas the DSF is now linked into the ground through air-tubes. By comparing this graph and the one associated with the previous run, in which the DSF was not connected to the earth, a decrease in LI is observed, confirming the capacity of earth-tube systems in lowering DSF systems' LI, at least in this climate. In fact, the difference in the LI is a decrease from 60.83 to 56.41 kwh/m² (19.28 to 17.88 kBTU/ft²). In addition, by comparing this option's LI result (Run10 F) with the baseline (Run4 B), it can be detected that LI has decreased from 71.57 to 56.41 kwh/m² (22.69 to 17.88 kBTU/ft²).

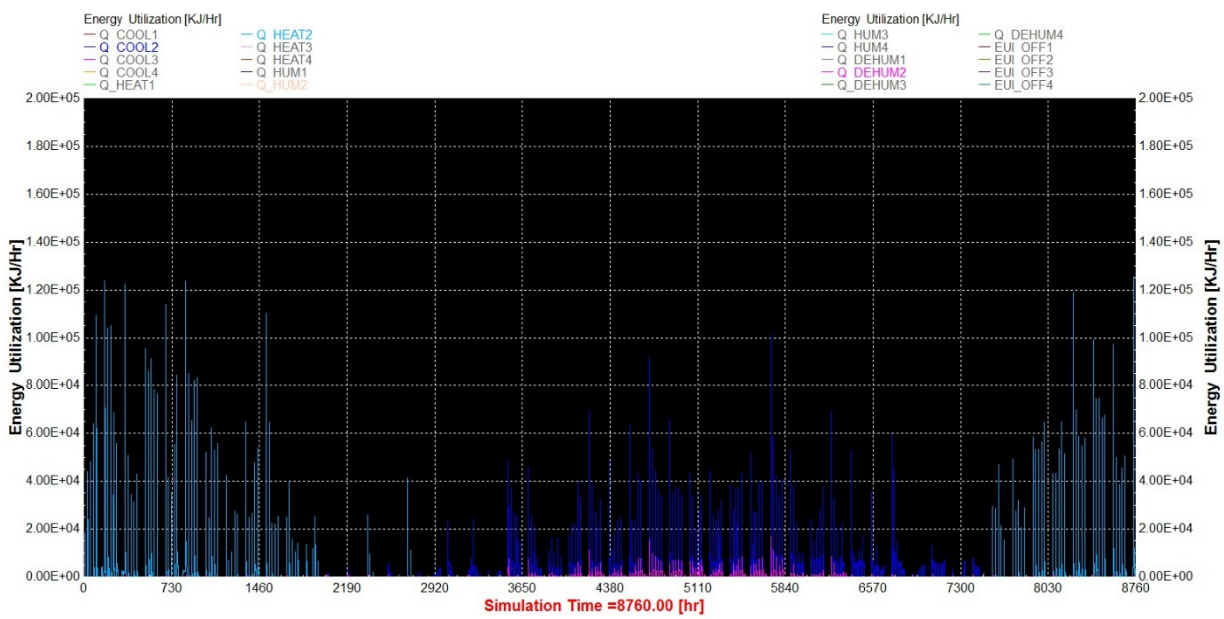
Zones Relative Humidity *(%)*

Run10 F (MV 4-Story MV DSF2 Semi HVAC Hypo)



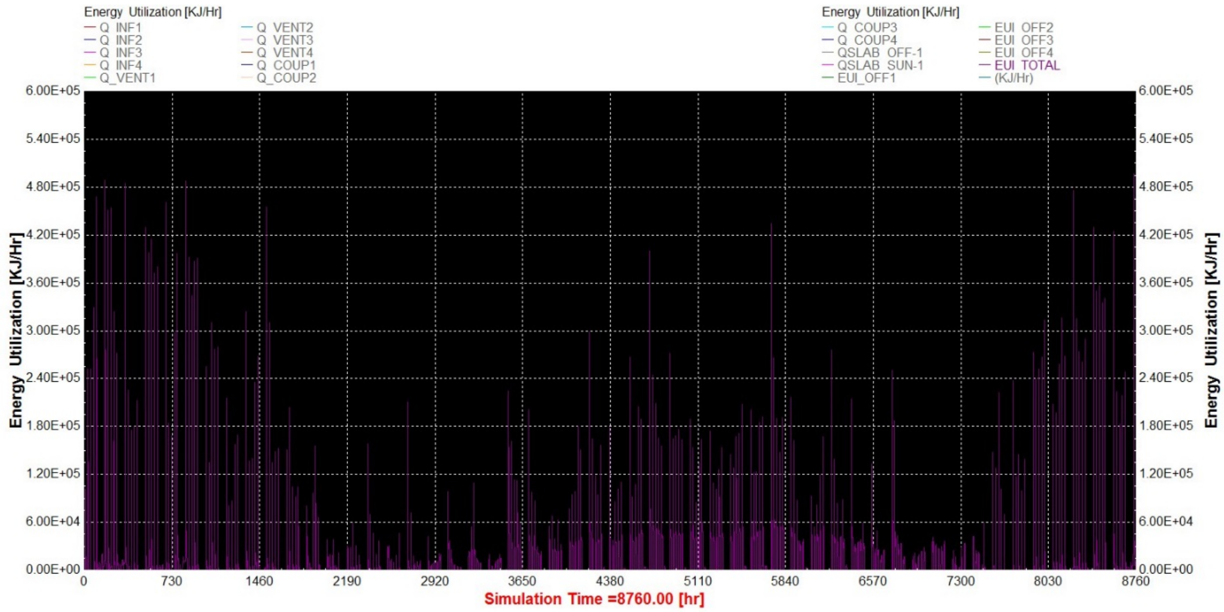
Office Load Intensity *(kJ/hr)*

Run10 F (MV 4-Story MV DSF2 Semi HVAC Hypo)



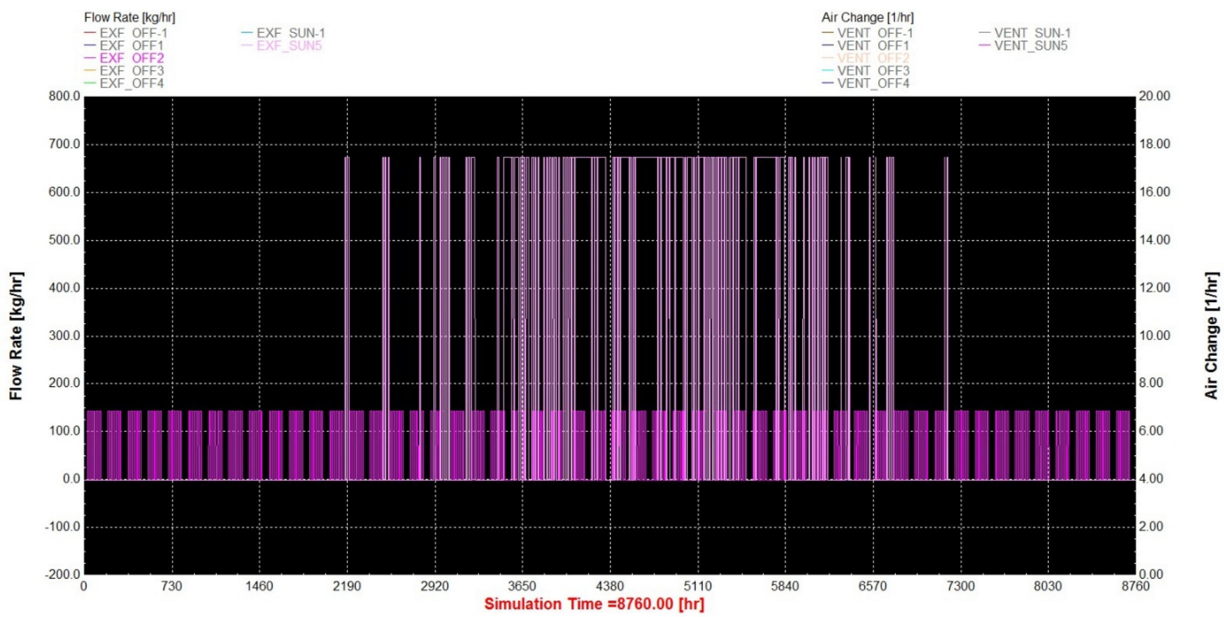
Total Offices Load Intensity *(kJ/hr)*

Run10 F (MV 4-Story MV DSF2 Semi HVAC Hypo)



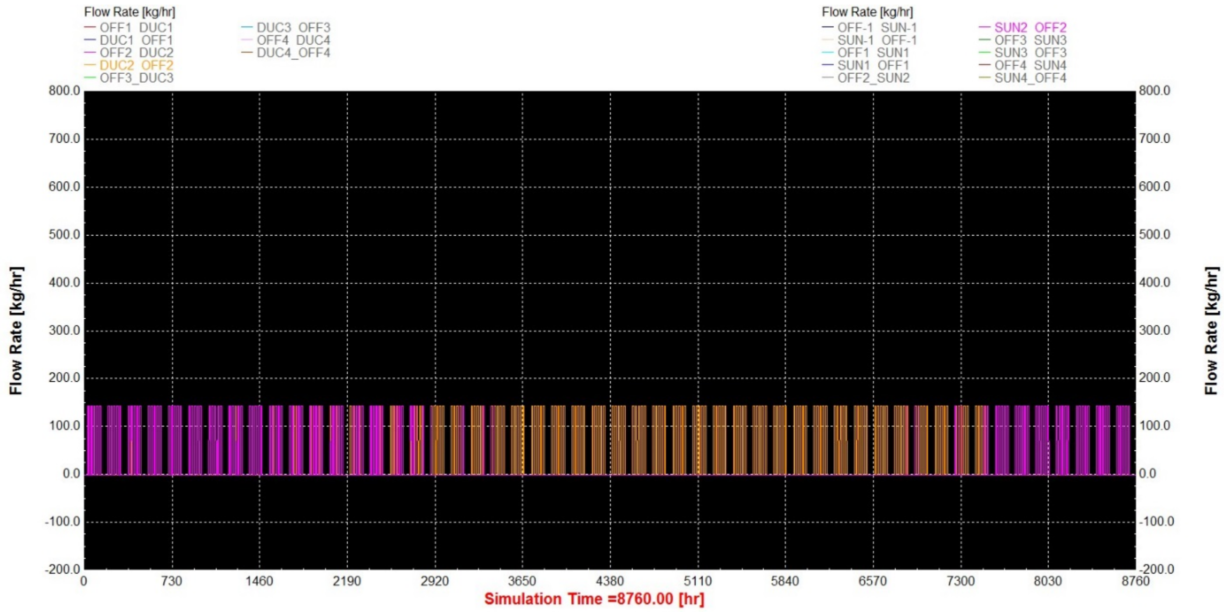
Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run10 F (MV 4-Story MV DSF2 Semi HVAC Hypo)



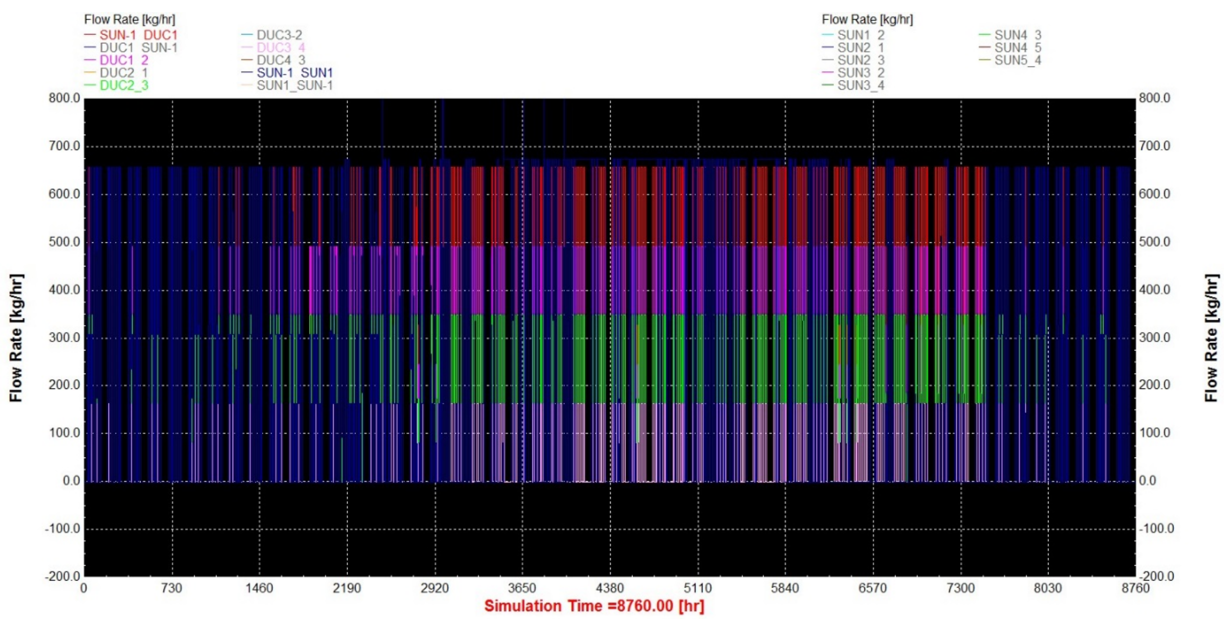
Sunspaces/Ducts-Offices Airflow *(kg/hr or 1/hr)*

Run10 F (MV 4-Story MV DSF2 Semi HVAC Hypo)



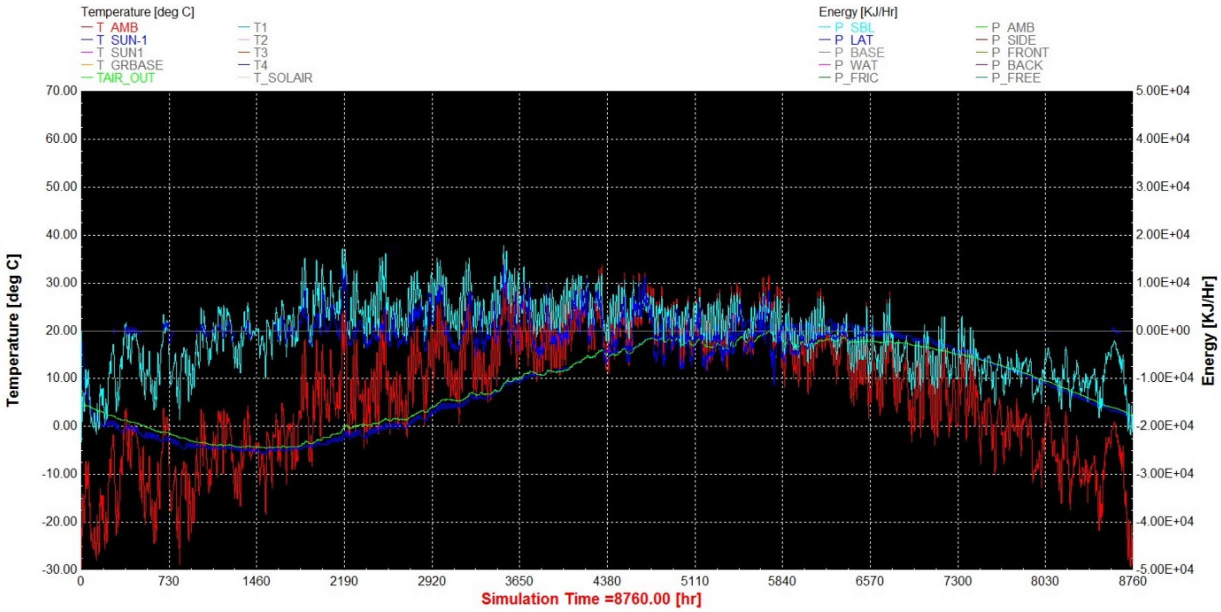
Sunspace/Duct-Sunspace/Duct Airflow *(kg/hr or 1/hr)*

Run10 F (MV 4-Story MV DSF2 Semi HVAC Hypo)



Air-Tubes Temperature and Energy *(°C and kJ/hr)*

Run10 F (MV 4-Story MV DSF2 Semi HVAC Hypo)

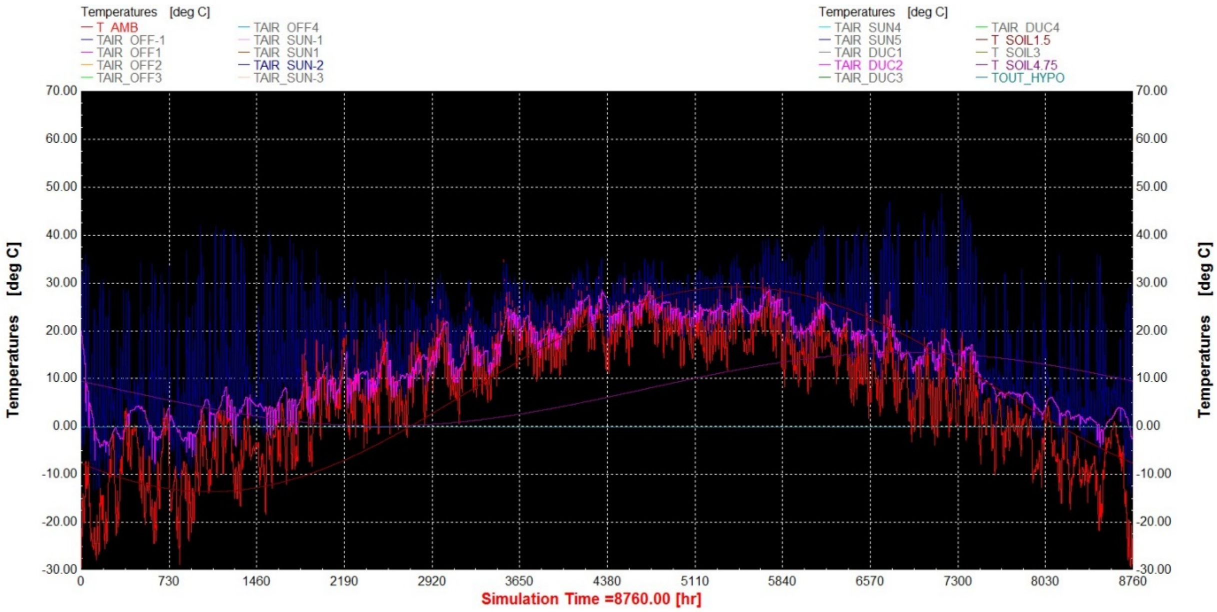


- Air-Tubes Temperature and Energy Graph Explanation:

This air-tube temperature and energy graph is primarily related to the earth-tube system's performance. The outcome includes a comparison between ambient air temperature (T_AMB), temperature of the basement sunspace (T_SUN_1), and the temperature of air-tubes when exiting the system (TAIR_OUT) to be introduced into the basement sunspace. It also shows the sensible energy related to heat transfer between the soil around earth-tubes and the system (P_SBL) as well as the latent energy related to phase changing of potential air moisture in earth-tubes (P_LAT). This can be seen as a highly informative graph, in which one can see how the temperature of pre-conditioned air in the earth-tubes can be evaluated specifically with the ambient air temperature as a way to decrease LI.

Zones Temperature *(°C)*

Run11 G (MV 4-Story NV DSF2 Semi HVAC)

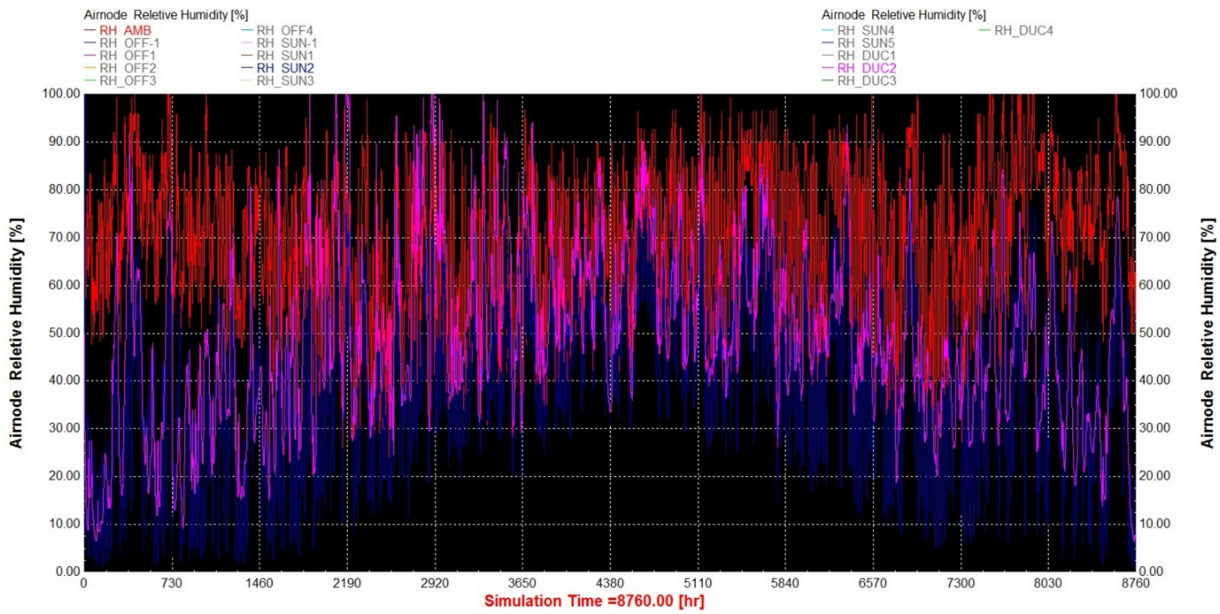


- Zones Temperature Graph Explanation:

The zones temperature graph depicted here is associated with the Run11 G: the baseline wherein a 2-meter depth, naturally ventilated DSF is attached in front of the south façade primarily functioning as a HVAC contributor with air introduction from both ambient air to the DSF and from the DSF into the office zones. This option, thus, is similar to the Run9 F, except that the DSF is naturally ventilated.

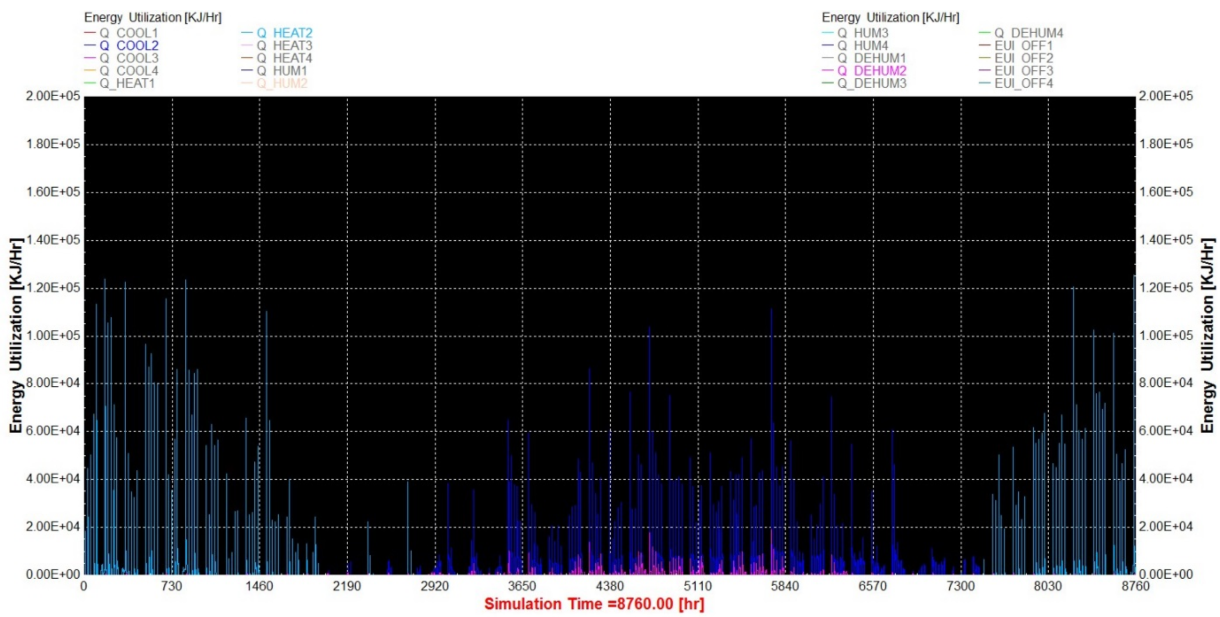
Zones Relative Humidity *(%)*

Run11 G (MV 4-Story NV DSF2 Semi HVAC)



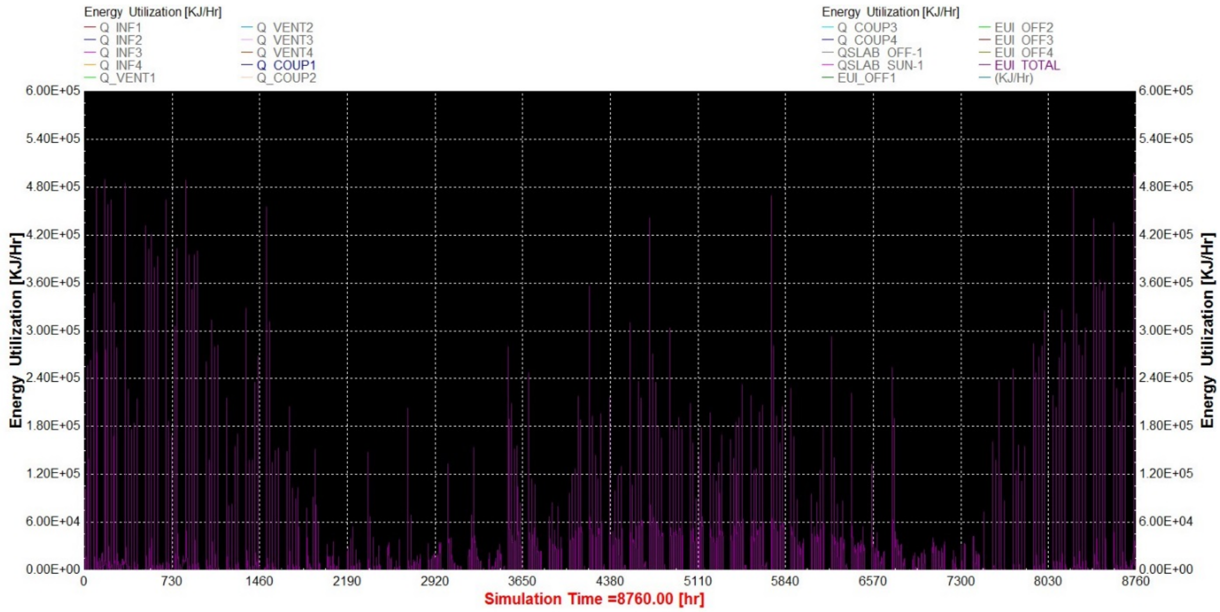
Office Load Intensity *(kJ/hr)*

Run11 G (MV 4-Story NV DSF2 Semi HVAC)



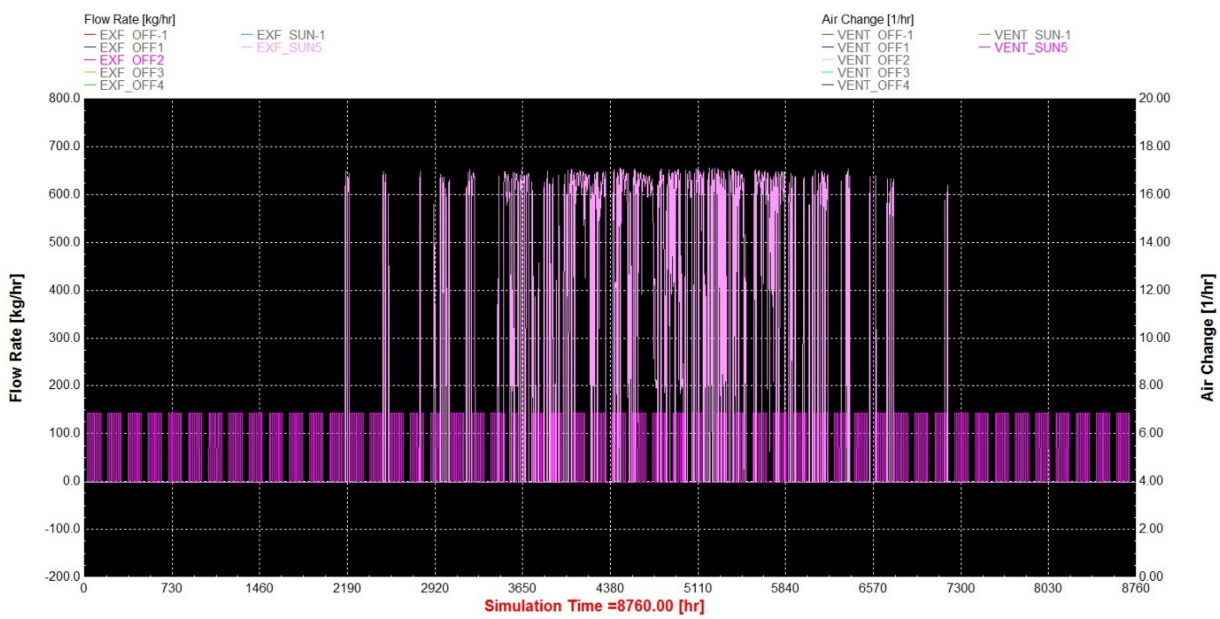
Total Offices Load Intensity *(kJ/hr)*

Run11 G (MV 4-Story NV DSF2 Semi HVAC)



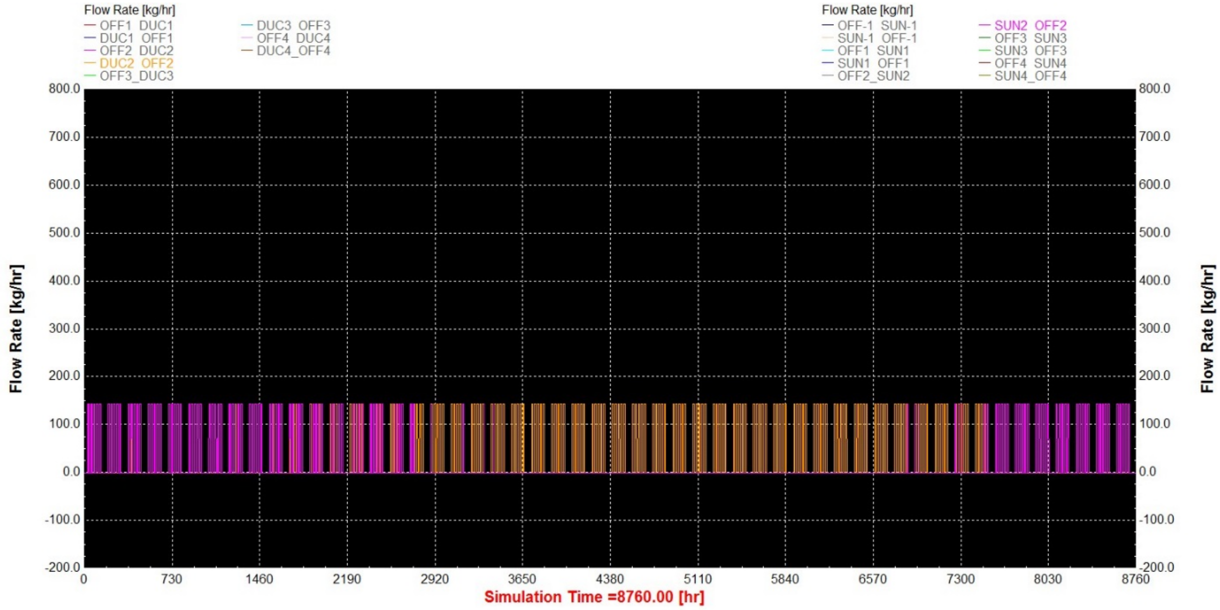
Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run11 G (MV 4-Story NV DSF2 Semi HVAC)



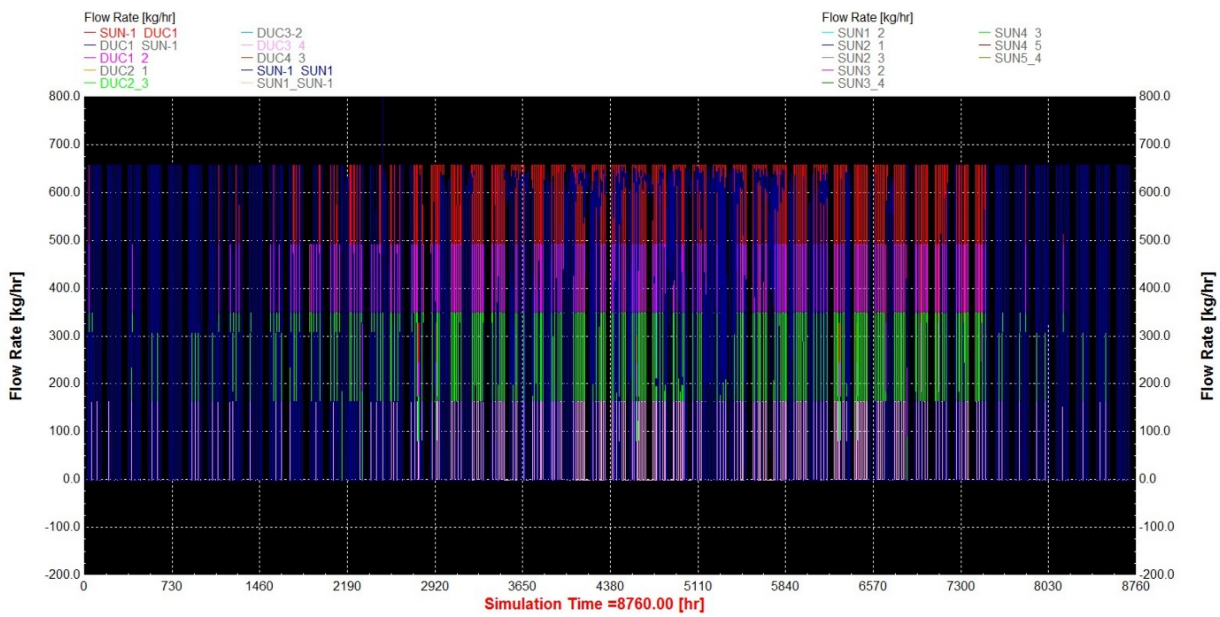
Sunspaces/Ducts-Offices Airflow *(kg/hr or 1/hr)*

Run11 G (MV 4-Story NV DSF2 Semi HVAC)



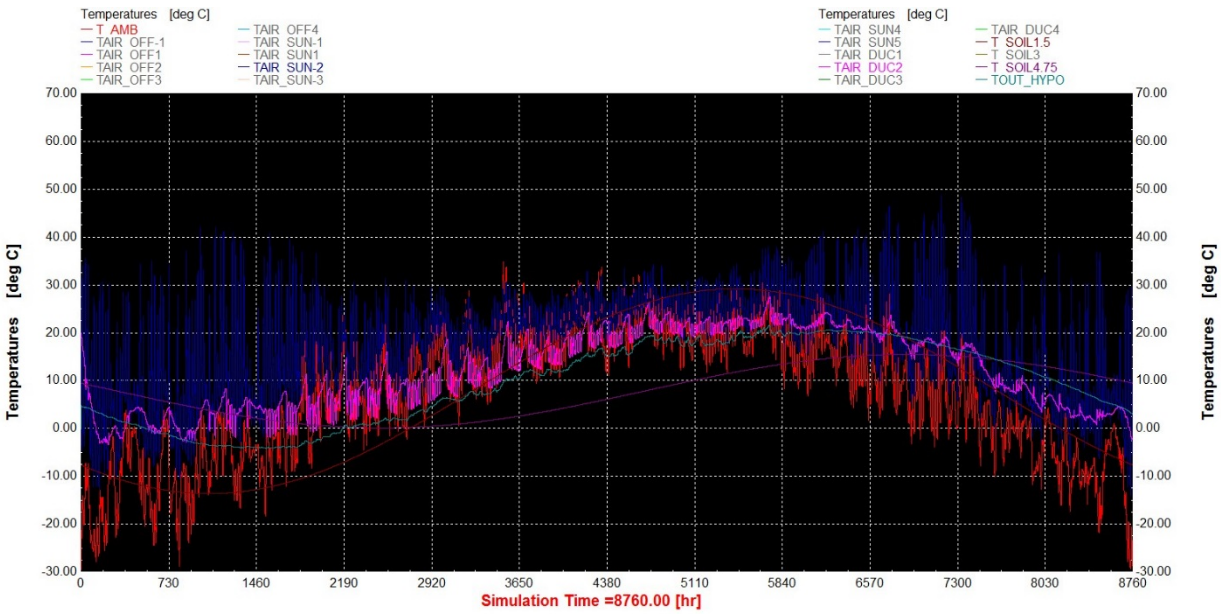
Sunspace/Duct-Sunspace/Duct Airflow *(kg/hr or 1/hr)*

Run11 G (MV 4-Story NV DSF2 Semi HVAC)



Zones Temperature *(°C)*

Run12 G (MV 4-Story NV DSF2 Semi HVAC Hypo)

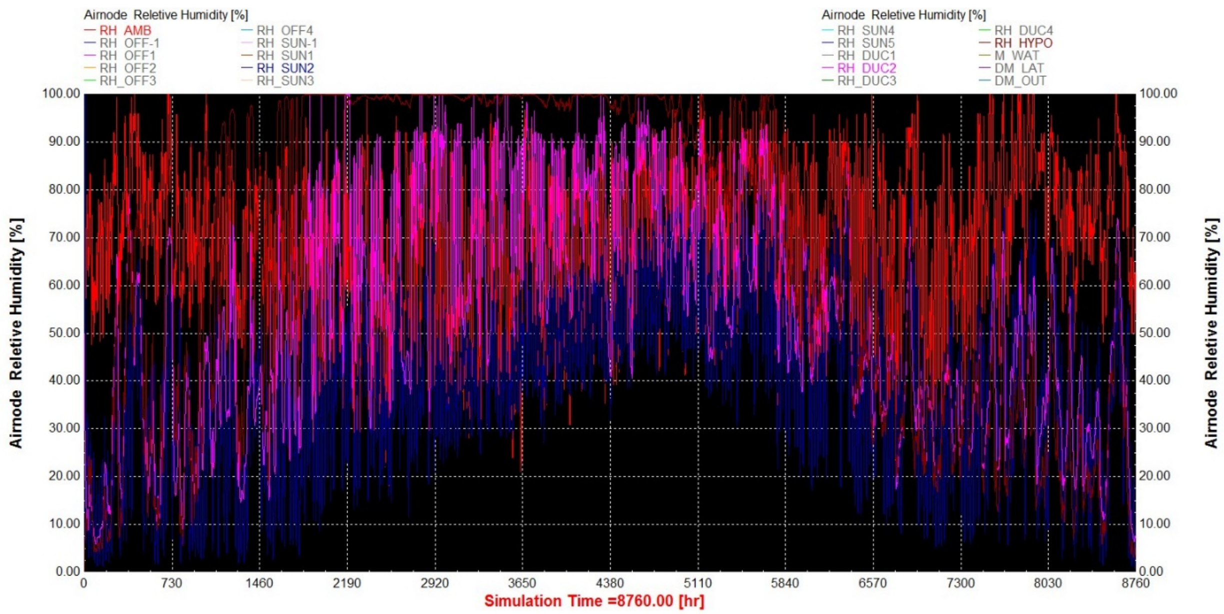


- Zones Temperature Graph Explanation:

This zones temperature graph is affiliated with the Run12 G: the baseline wherein a 2-meter depth, naturally ventilated DSF is attached in front of the south façade primarily functioning as an HVAC contributor with air introduction from both earth-tube system to the DSF and from the DSF into the office zones. This option, therefore, is very similar to the previous option whereas the DSF is now linked into the ground via the air-tubes. By comparing this graph and the previous run, a decrease in LI is observed, endorsing the abilities of the earth-tube systems again in lowering DSF systems' LI specifically in this climate. This alteration in LI is a reduction from 60.97 to 557.42 kwh/m^2 (19.33 to 18.20 kBTU/ft^2). In addition, by comparing this option's LI result (Run12 G) with the baseline (Run4 B), a significant LI decrease is observed.

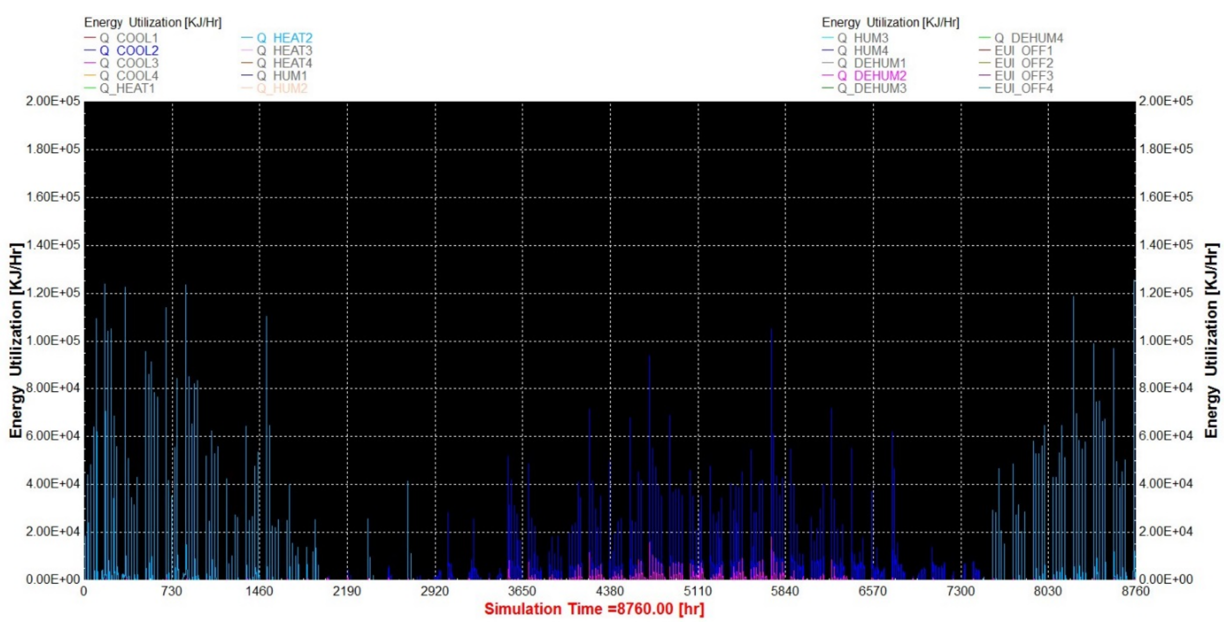
Zones Relative Humidity *(%)*

Run12 G (MV 4-Story NV DSF2 Semi HVAC Hypo)



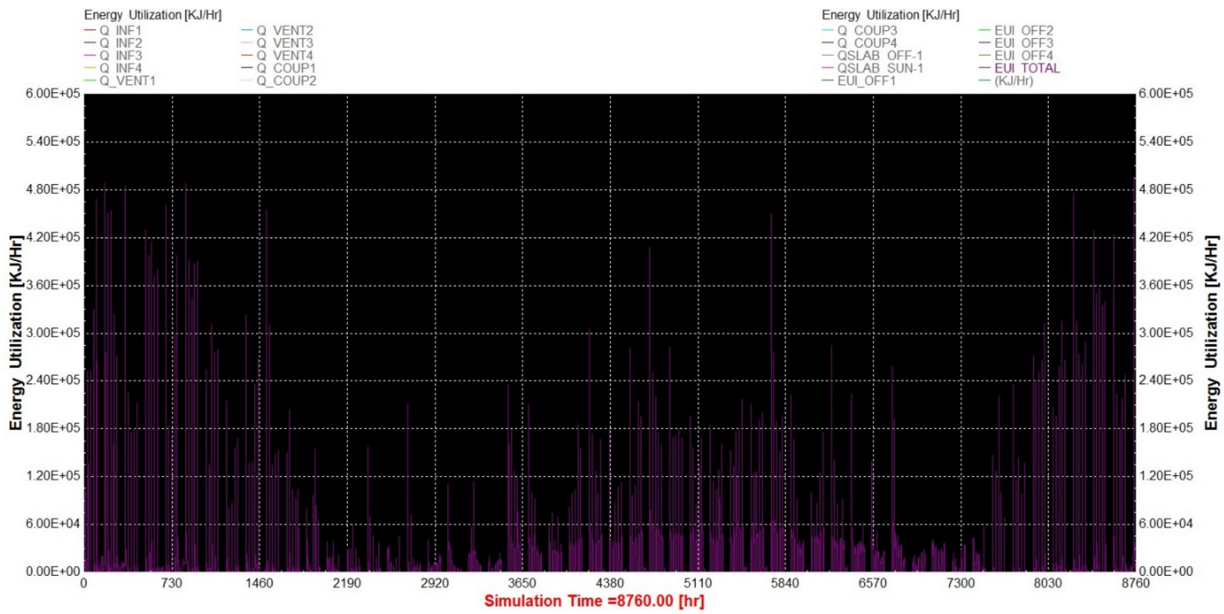
Office Load Intensity *(kJ/hr)*

Run12 G (MV 4-Story NV DSF2 Semi HVAC Hypo)



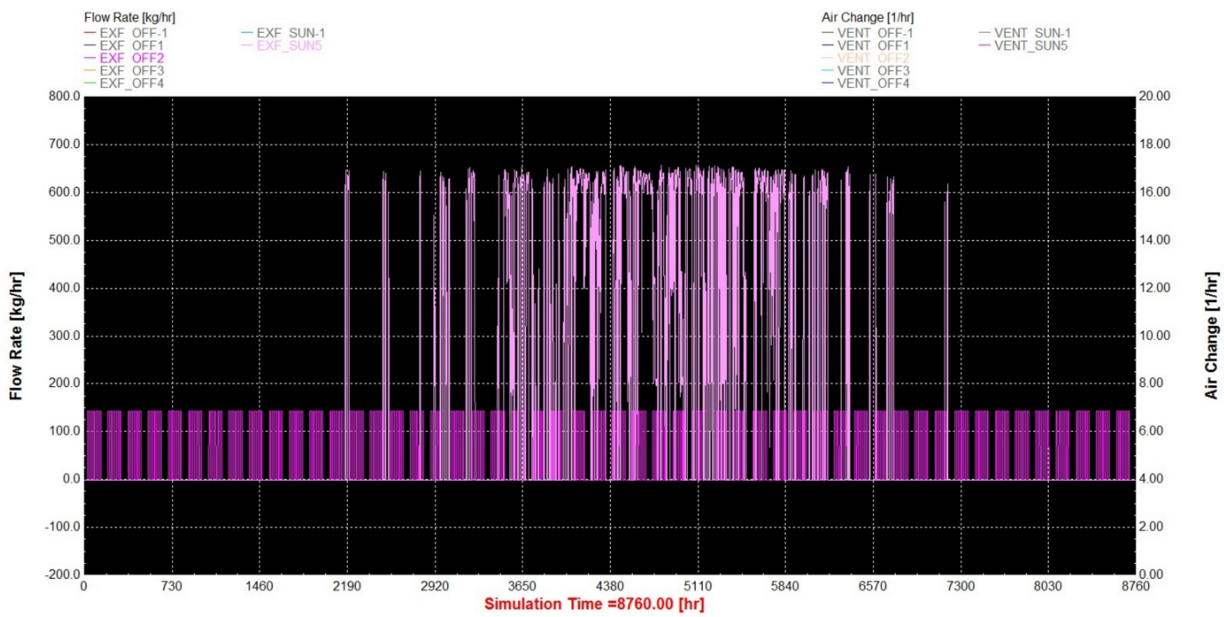
Total Offices Load Intensity *(kJ/hr)*

Run12 G (MV 4-Story NV DSF2 Semi HVAC Hypo)



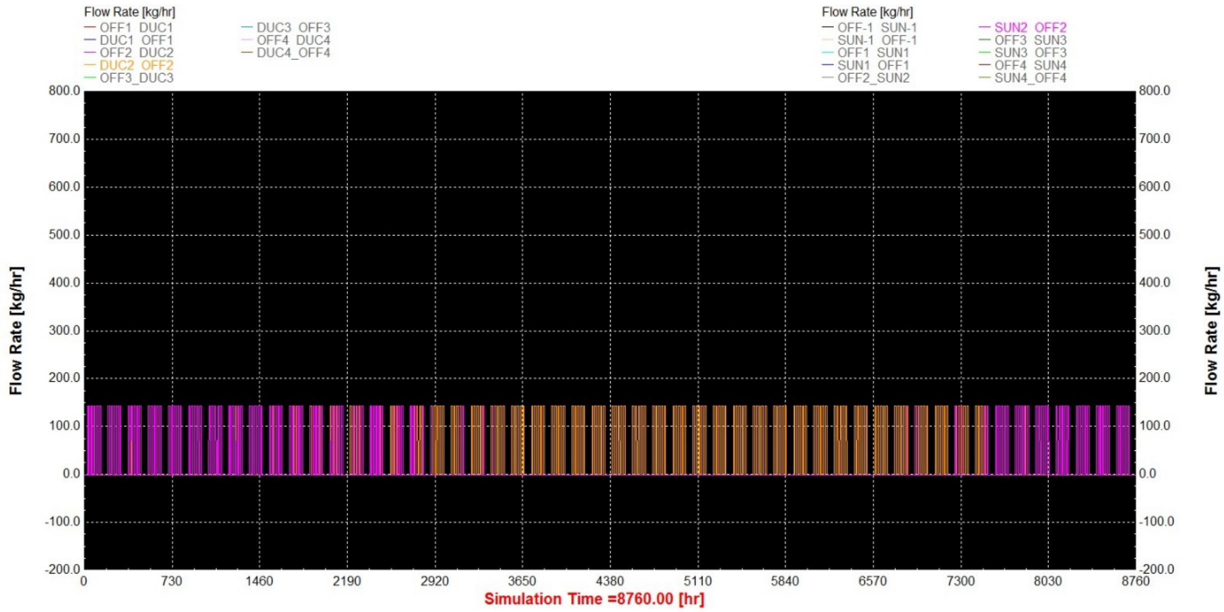
Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run12 G (MV 4-Story NV DSF2 Semi HVAC Hypo)



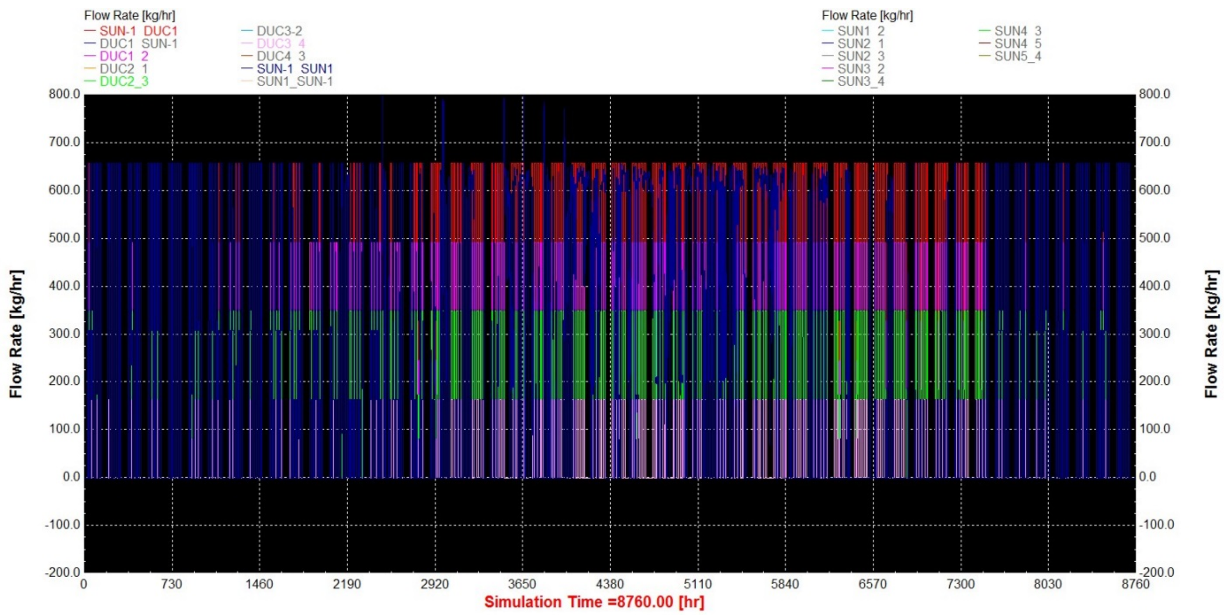
Sunspaces/Ducts-Offices Airflow *(kg/hr or 1/hr)*

Run12 G (MV 4-Story NV DSF2 Semi HVAC Hypo)



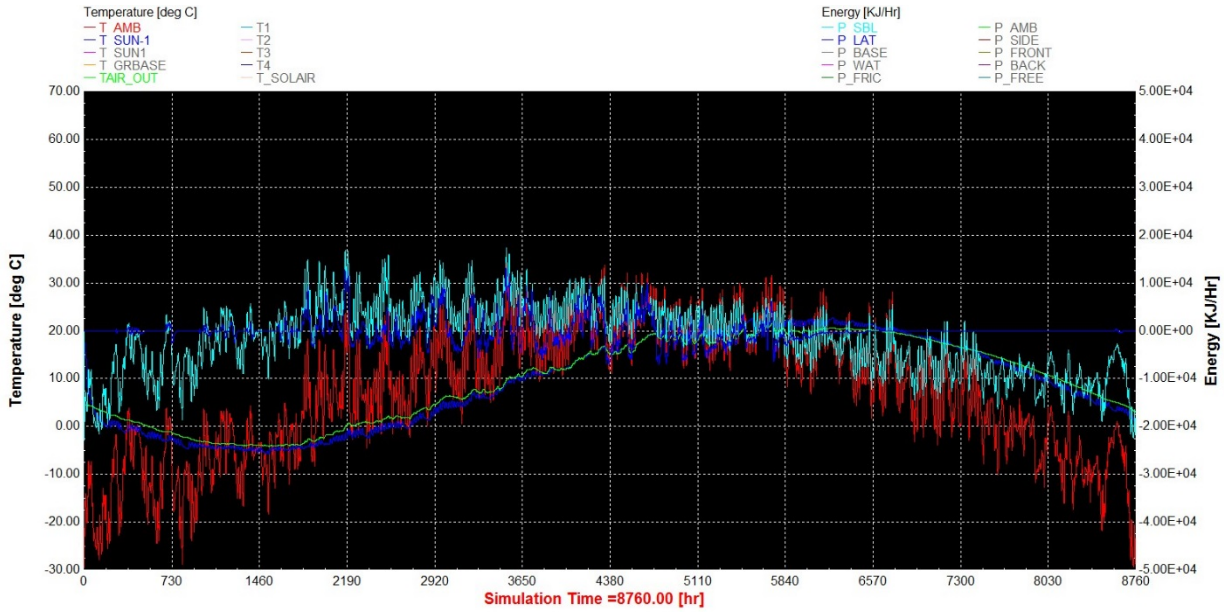
Sunspace/Duct-Sunspace/Duct Airflow *(kg/hr or 1/hr)*

Run12 G (MV 4-Story NV DSF2 Semi HVAC Hypo)



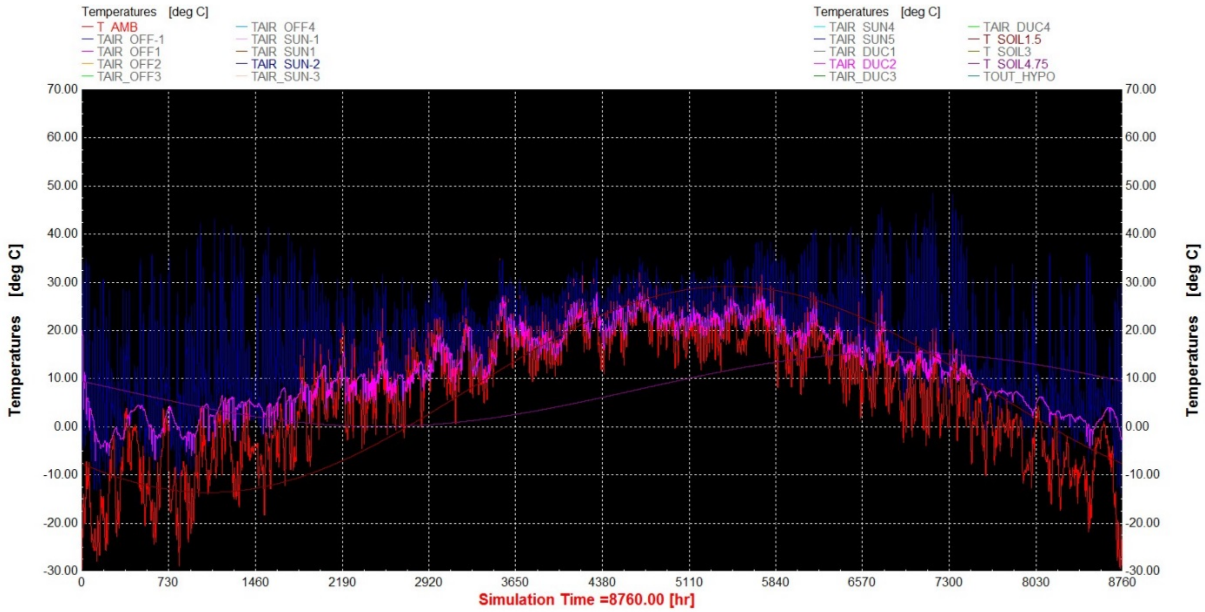
Air-Tubes Temperature and Energy *(°C and kJ/hr)*

Run12 G (MV 4-Story NV DSF2 Semi HVAC Hypo)



Zones Temperature *(°C)*

Run13 H (NC 4-Story NV DSF2 No HVAC)

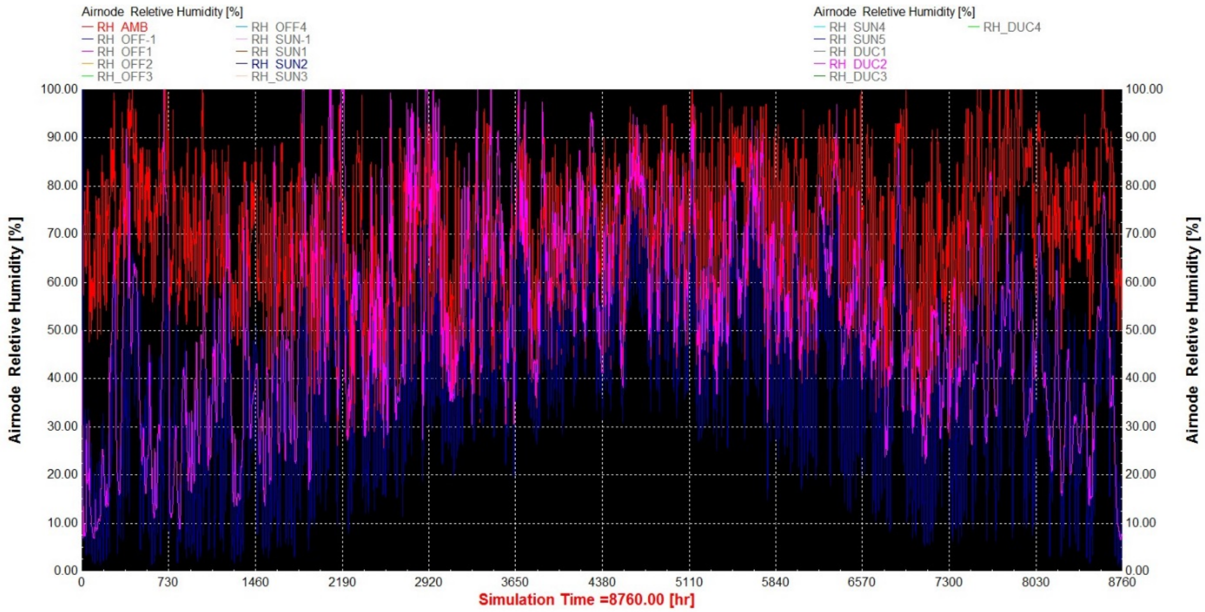


- Zones Temperature Graph Explanation:

The zones temperature graph shown above is related to the Run13 H: the baseline wherein a 2-meter depth, mechanically ventilated DSF is attached in front of the south façade of a naturally conditioned office building. This is primarily functioning as a HVAC contributor with air introduction from both ambient air to the DSF and from the DSF into the office zones. A note on the side is that the airflow in the DSF system in this case is controlled with self-regulating vents/dampers placed in basement sunspace and the top sunspace5. These vents are basically controlling the direction as well as the amount of airflow, to be happening in the same intended direction without any impact on the airflow amount. This option, thus, is similar to the previous options, except the notion that the building is not mechanically ventilated like it was before. Comparing this option's LI result (Run13 H) with the baseline (Run4 B) reveals an LI decrease of 71.57 to 59.99 kwh/m² (22.69 to 19.02 kBTU/ft²).

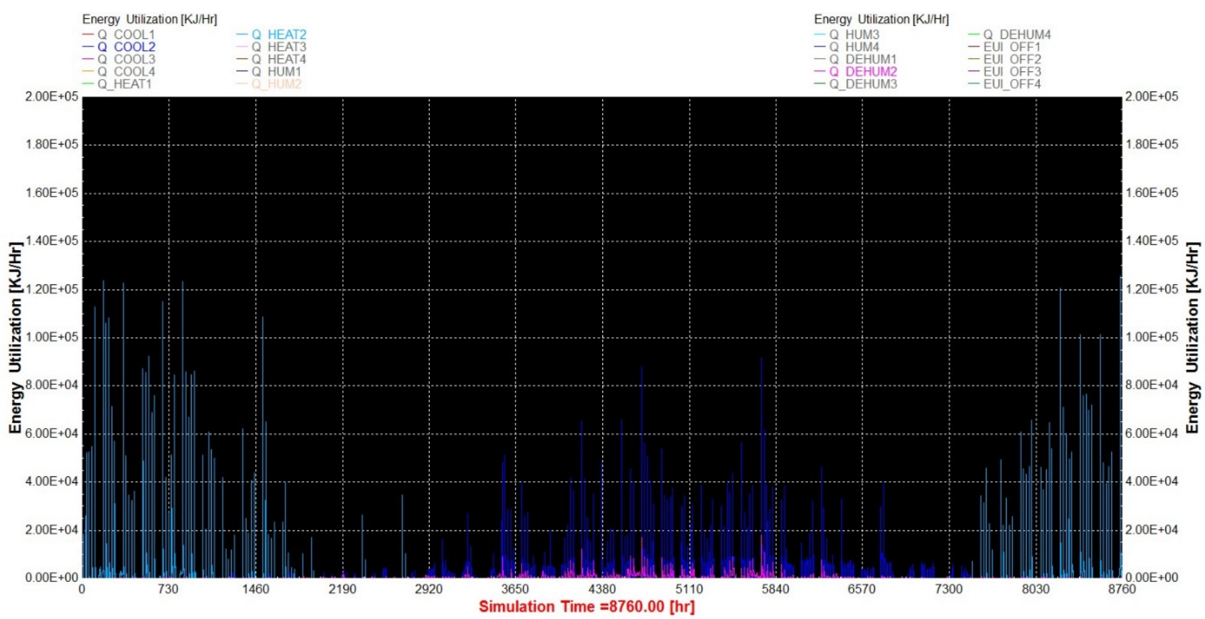
Zones Relative Humidity *(%)*

Run13 H (NC 4-Story NV DSF2 No HVAC)



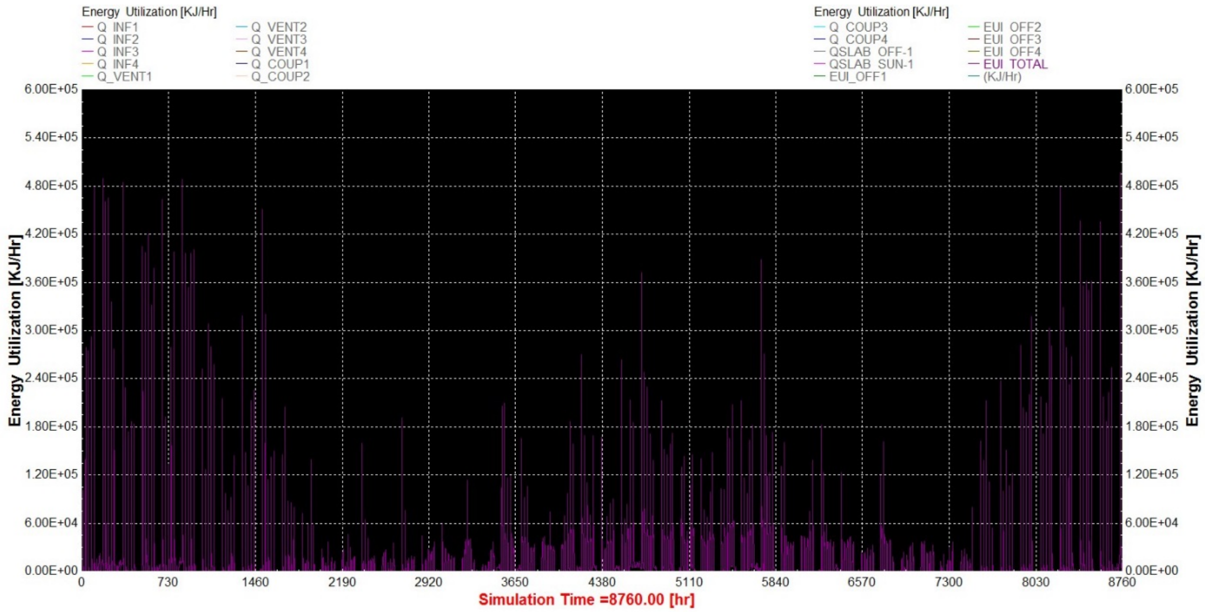
Office Load Intensity *(kJ/hr)*

Run13 H (NC 4-Story NV DSF2 No HVAC)



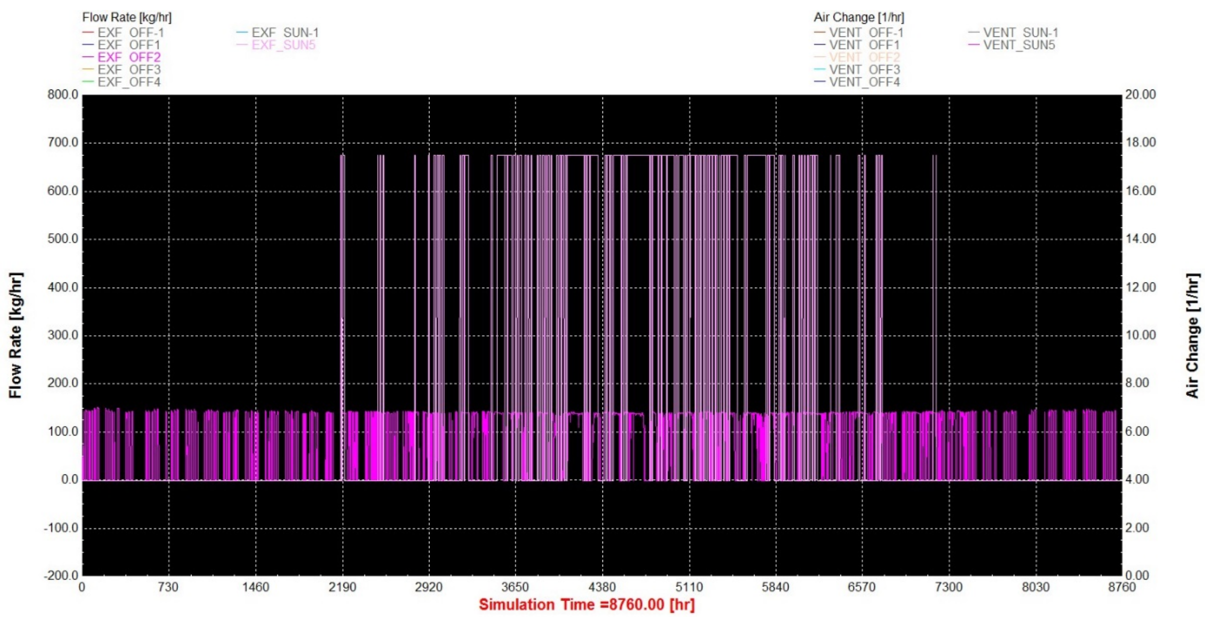
Total Offices Load Intensity *(kJ/hr)*

Run13 H (NC 4-Story NV DSF2 No HVAC)



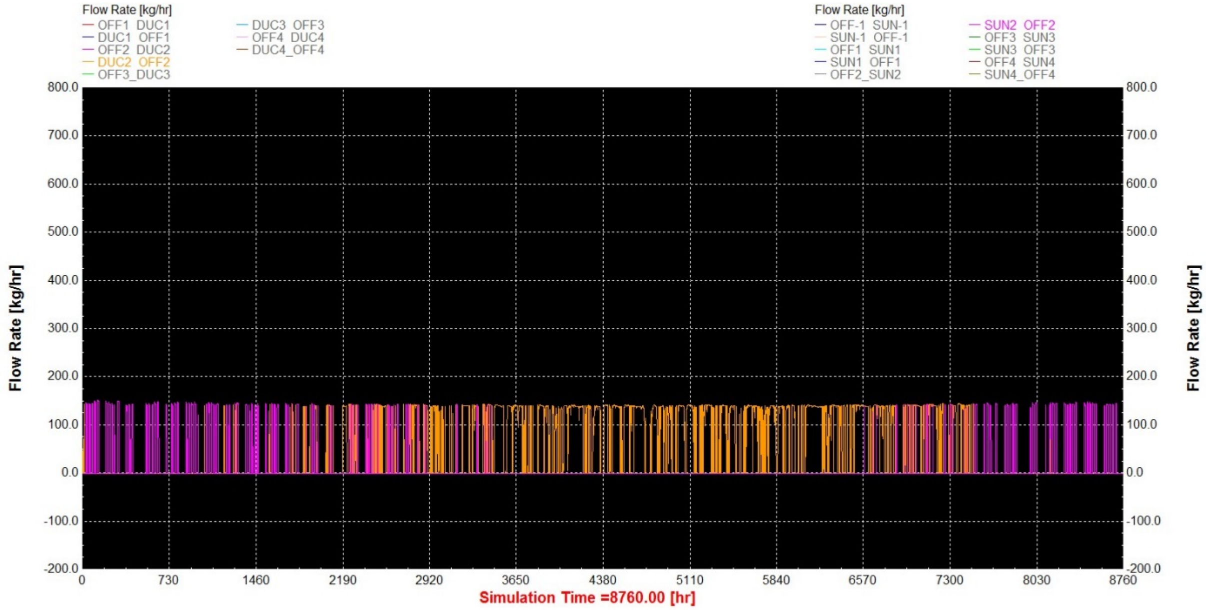
Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run13 H (NC 4-Story NV DSF2 No HVAC)



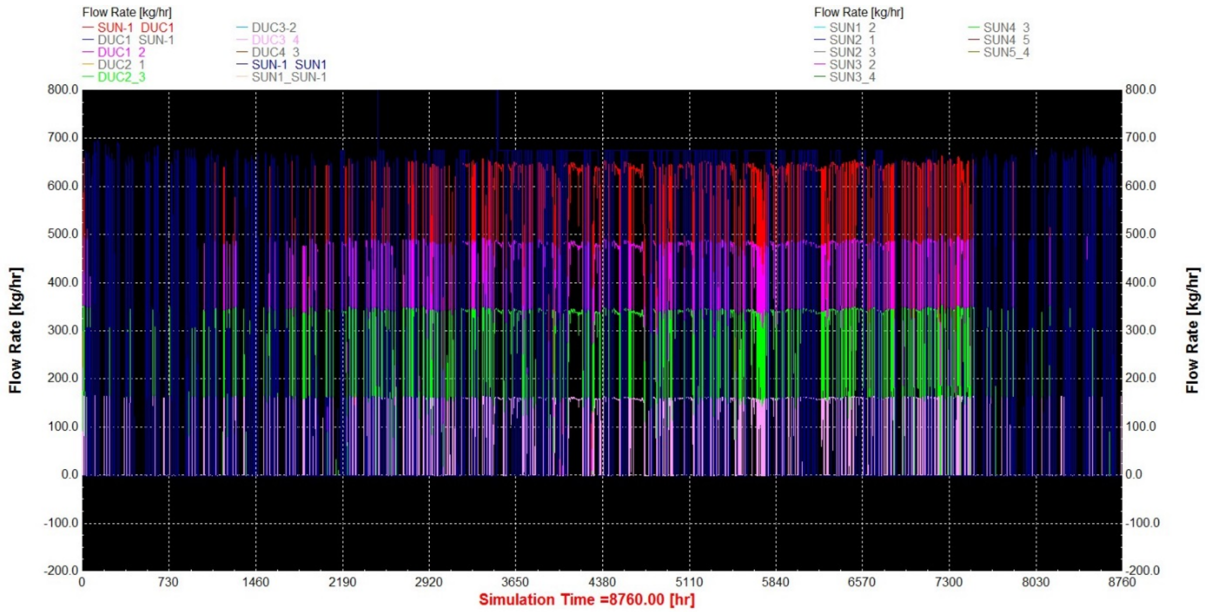
Sunspaces/Ducts-Offices Airflow *(kg/hr or 1/hr)*

Run13 H (NC 4-Story NV DSF2 No HVAC)



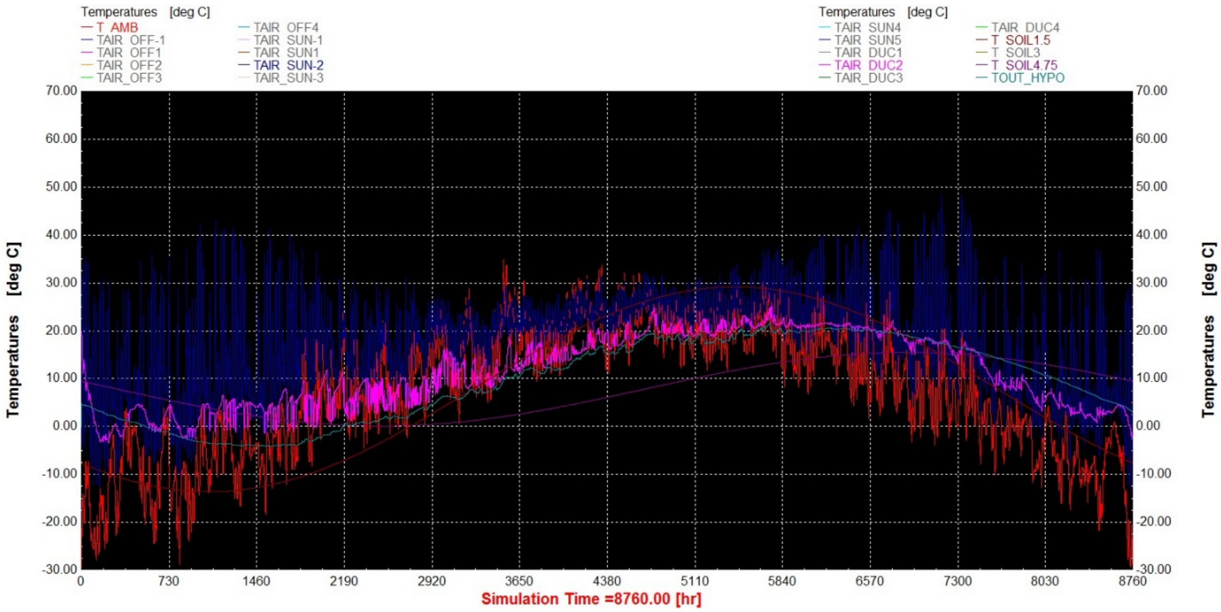
Sunspace/Duct-Sunspace/Duct Airflow *(kg/hr or 1/hr)*

Run13 H (NC 4-Story NV DSF2 No HVAC)



Zones Temperature *(°C)*

Run14 H (NC 4-Story NV DSF2 No HVAC Hypo)

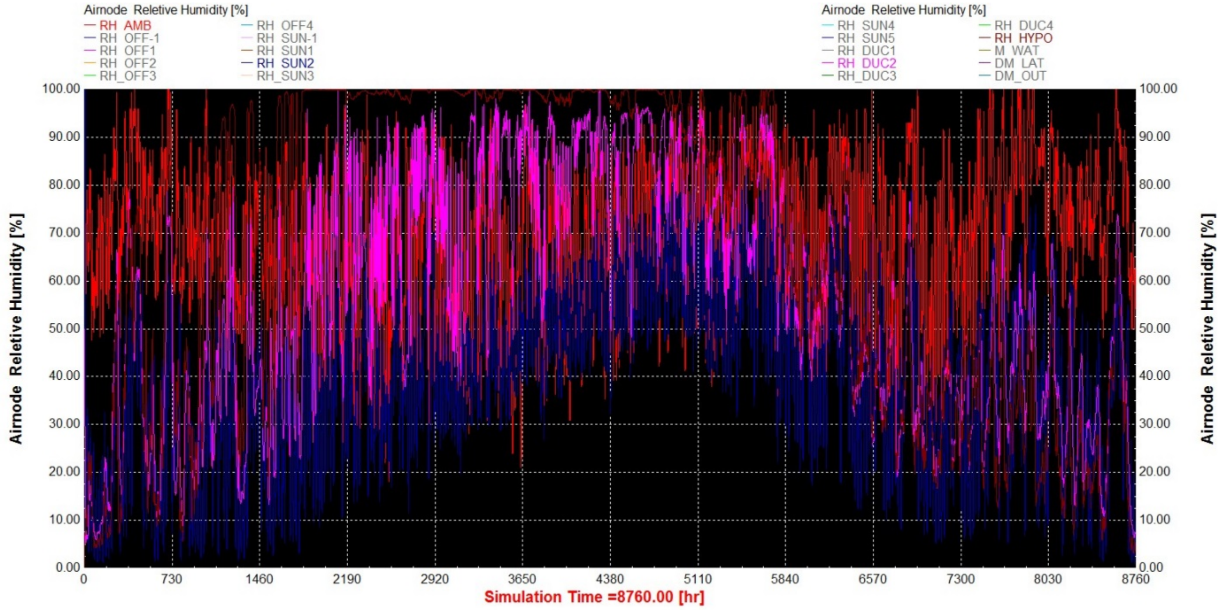


- Zones Temperature Graph Explanation:

The zones temperature graph presented here is related to the Run14 H: the baseline wherein a 2-meter depth, mechanically ventilated DSF is attached in front of the south façade of a naturally conditioned office building. This is primarily functioning as a HVAC contributor with air introduction from both air-tube system to the DSF and from the DSF into the office zones. Essential to note that the airflow in the DSF system in this case is controlled with dampers, the same as the previous option. This option, thus, is similar to previous options except that the DSF system here is linked into the earth via the earth-tube system. An LI decrease of 59.99 to 56.47 kwh/m² (23.72 to 22.30 kBTU/ft²) is witnessed when comparing this option's LI result (Run14 H) with the baseline (Run3 B). In addition, the comparison of this option with the previous option that was without the connection to the earth-tubes demonstrates an LI decrease from 70.35 to 68.86 kwh/m² (19.02 to 17.90 kBTU/ft²).

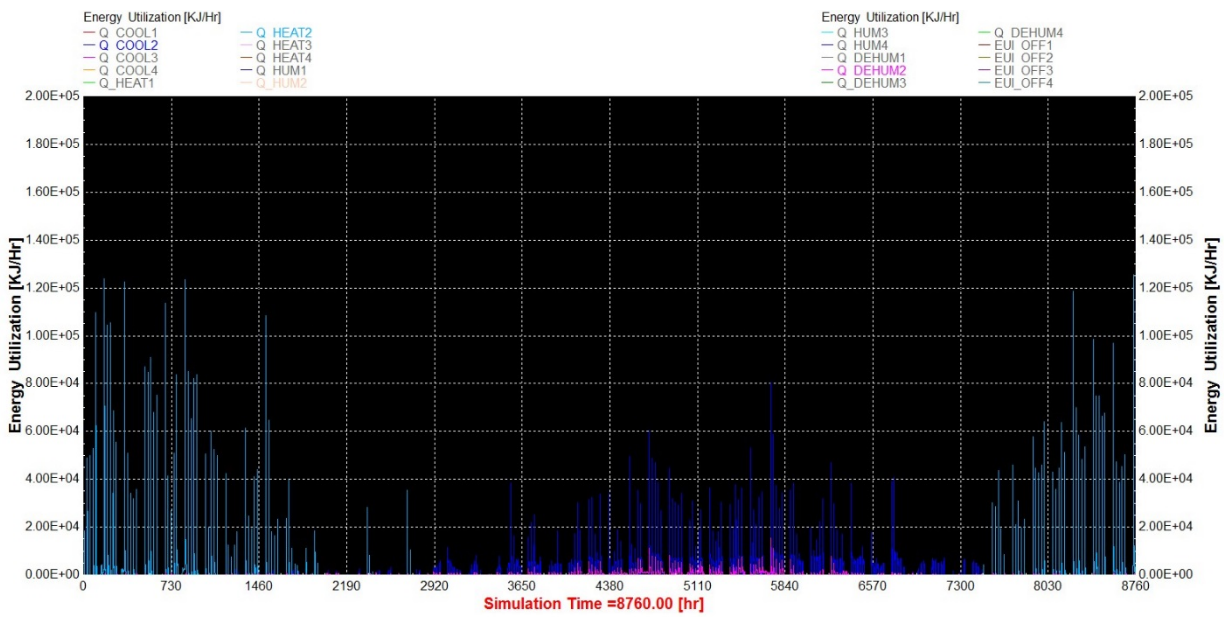
Zones Relative Humidity *(%)*

Run14 H (NC 4-Story NV DSF2 No HVAC Hypo)



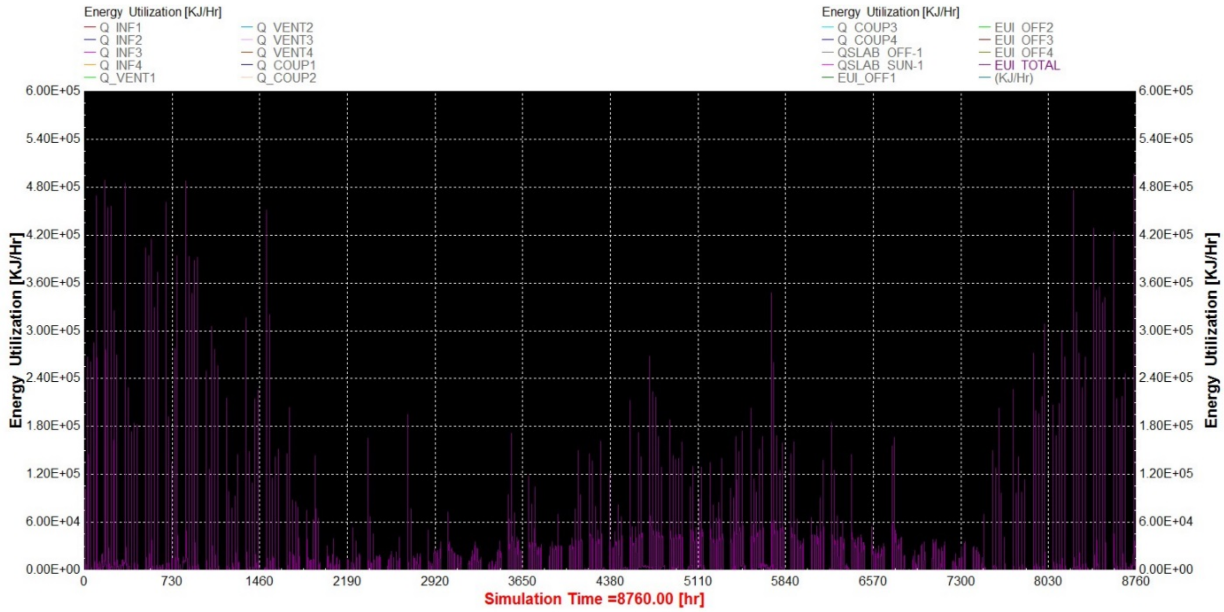
Office Load Intensity *(kJ/hr)*

Run14 H (NC 4-Story NV DSF2 No HVAC Hypo)



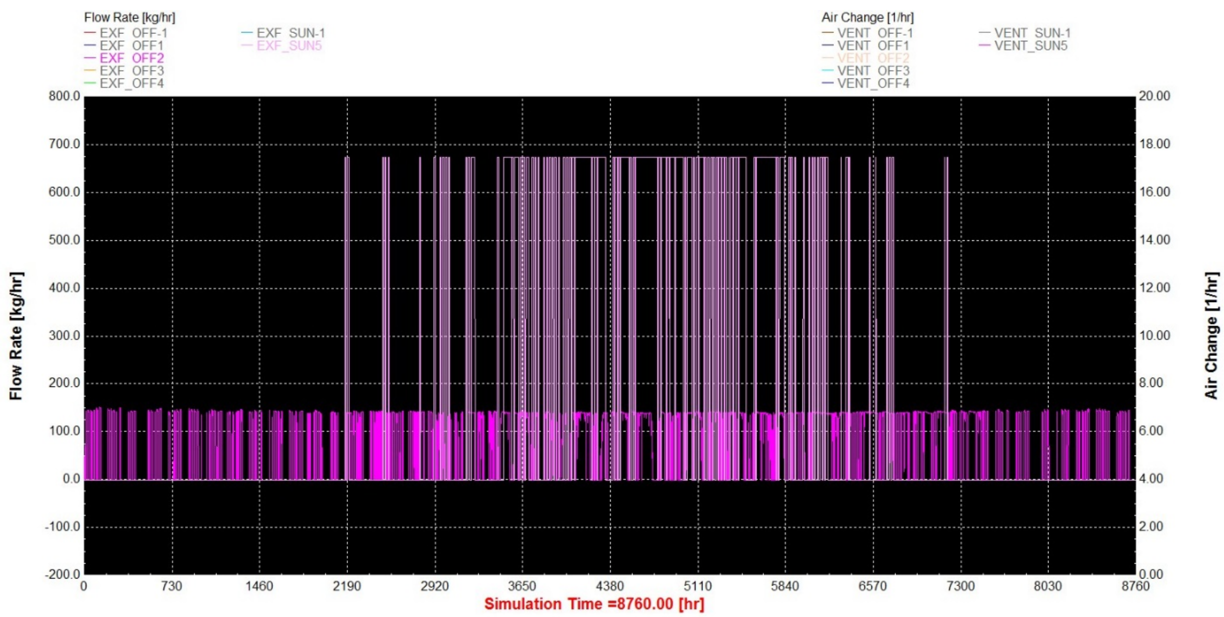
Total Offices Load Intensity *(kJ/hr)*

Run14 H (NC 4-Story NV DSF2 No HVAC Hypo)



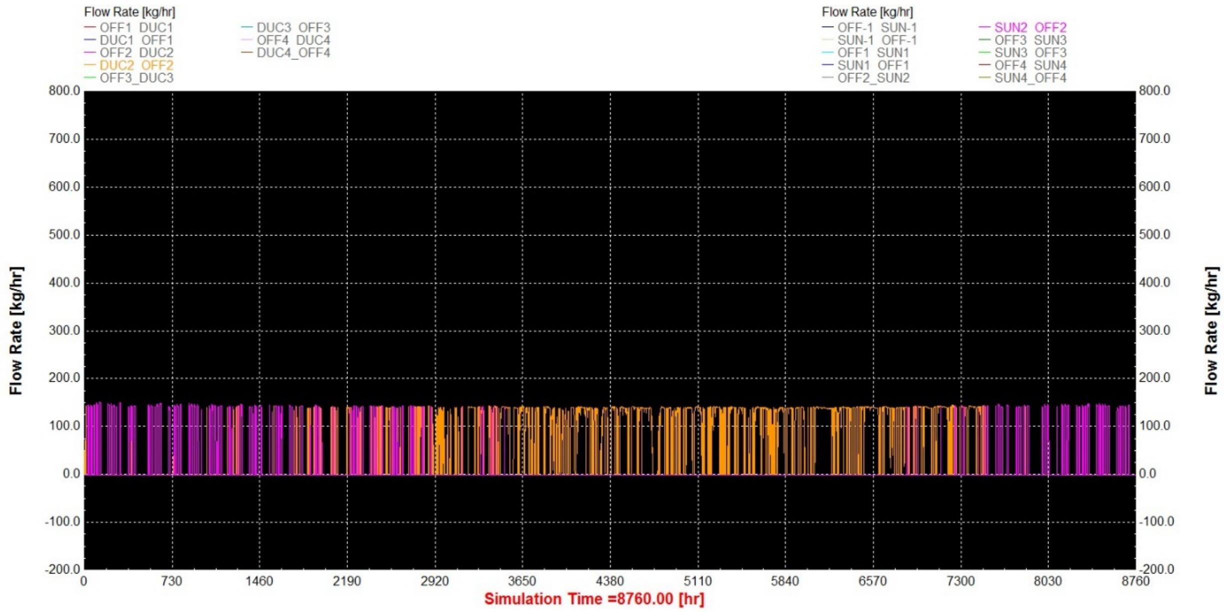
Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run14 H (NC 4-Story NV DSF2 No HVAC Hypo)



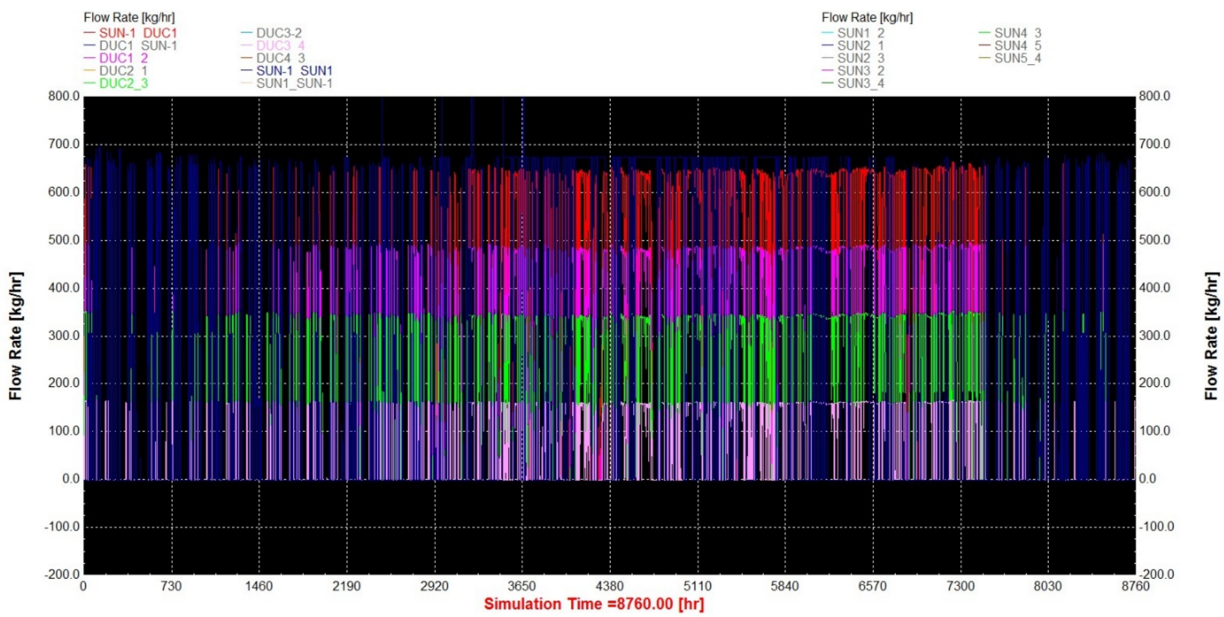
Sunspaces/Ducts-Offices Airflow *(kg/hr or 1/hr)*

Run14 H (NC 4-Story NV DSF2 No HVAC Hypo)



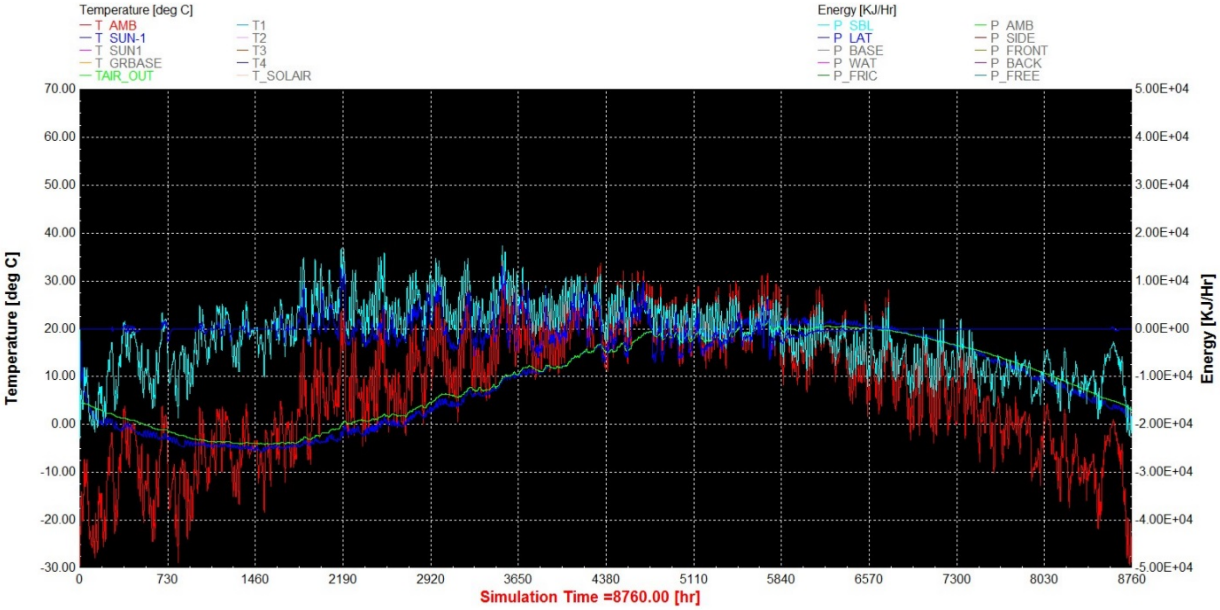
Sunspace/Duct-Sunspace/Duct Airflow *(kg/hr or 1/hr)*

Run14 H (NC 4-Story NV DSF2 No HVAC Hypo)



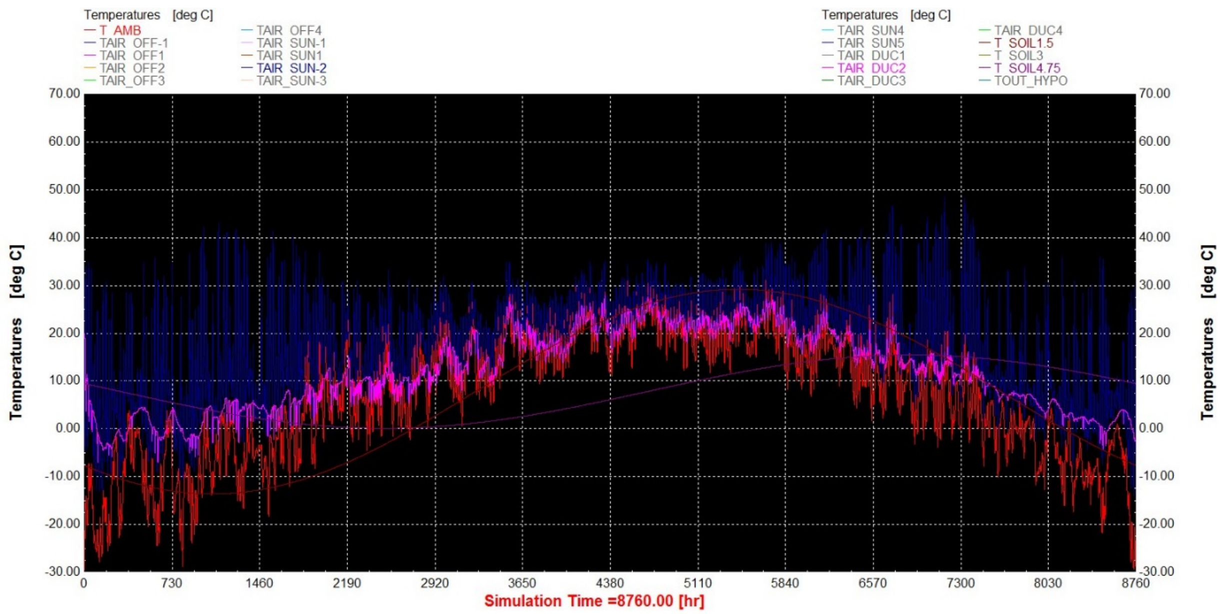
Air-Tubes Temperature and Energy *(°C and kJ/hr)*

Run14 H (NC 4-Story NV DSF2 No HVAC Hypo)



Zones Temperature *(°C)*

Run15 I (NC 4-Story NV DSF2 No HVAC)

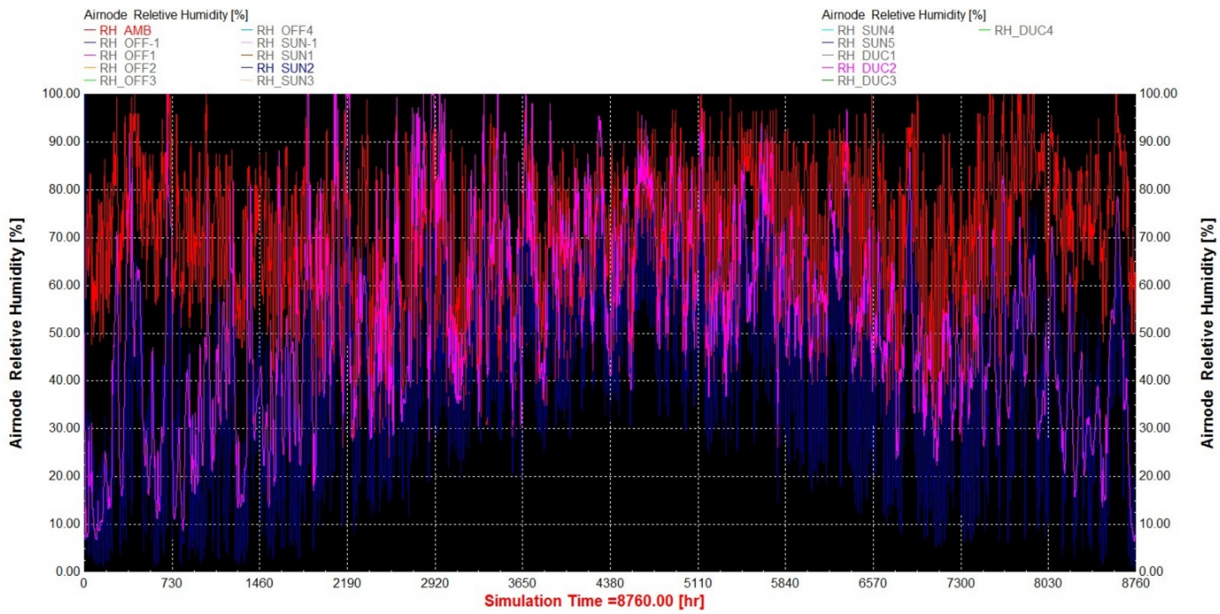


- Zones Temperature Graph Explanation:

This zones temperature graph is associated with the Run15 I: the baseline wherein a 2-meter depth, naturally ventilated DSF is attached in front of the south façade of a naturally conditioned office building. The DSF system primarily functions as an HVAC contributor with air introduction from both ambient air to the DSF and from the DSF into the office zones. A side note is that the airflow in the DSF system in this option is controlled with self-regulating dampers placed in the top sunspace5. These dampers will control both the direction and the amount of airflow to be in the same intended direction and extent. This option, thus, is similar to previous options, with the exception that the DSF is now naturally ventilated. Comparing this option's LI result (Run15 H) with the baseline (Run4 B) indicates a significant LI decrease of 71.57 to 60.13 kwh/m² (22.69 to 19.06 kBTU/ft²).

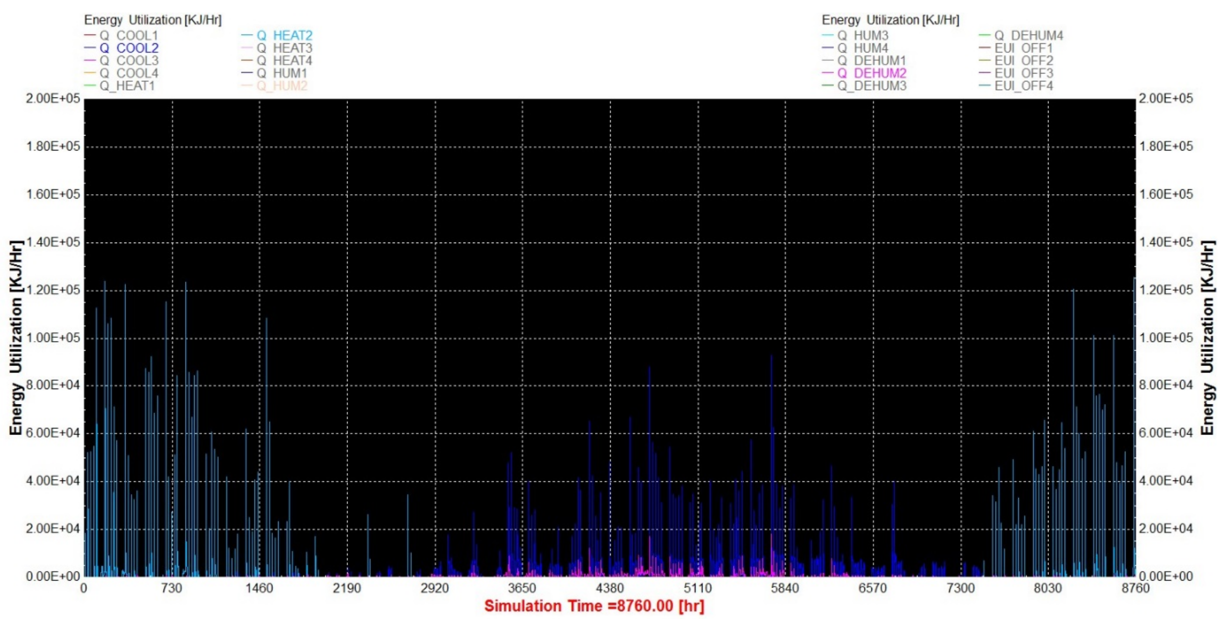
Zones Relative Humidity *(%)*

Run15 I (NC 4-Story NV DSF2 No HVAC)



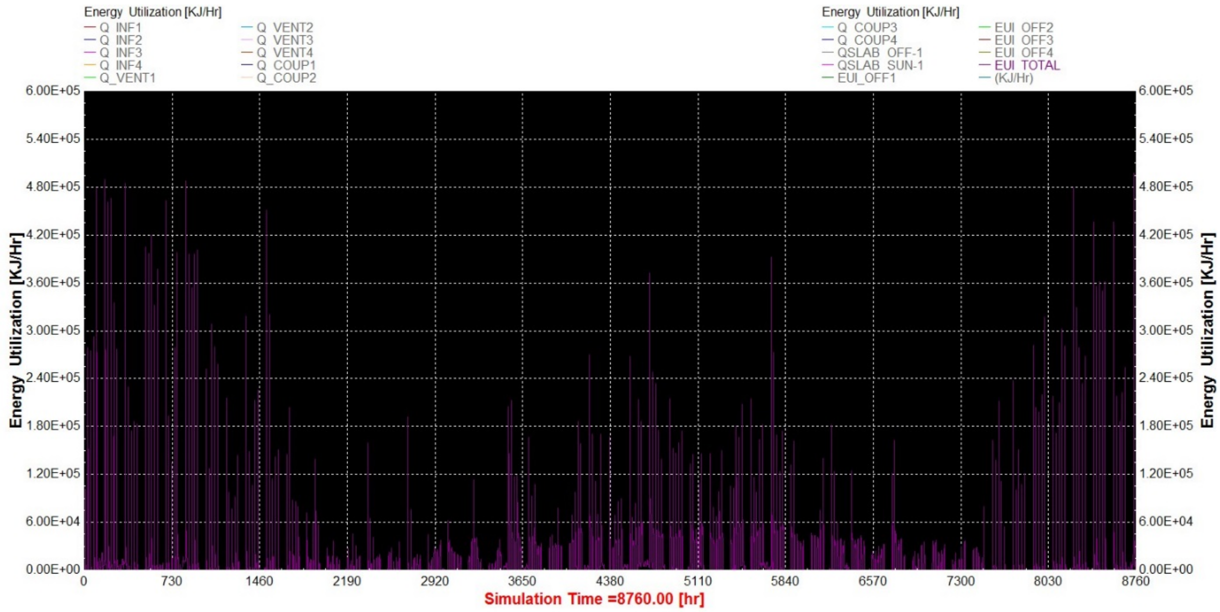
Office Load Intensity *(kJ/hr)*

Run15 I (NC 4-Story NV DSF2 No HVAC)



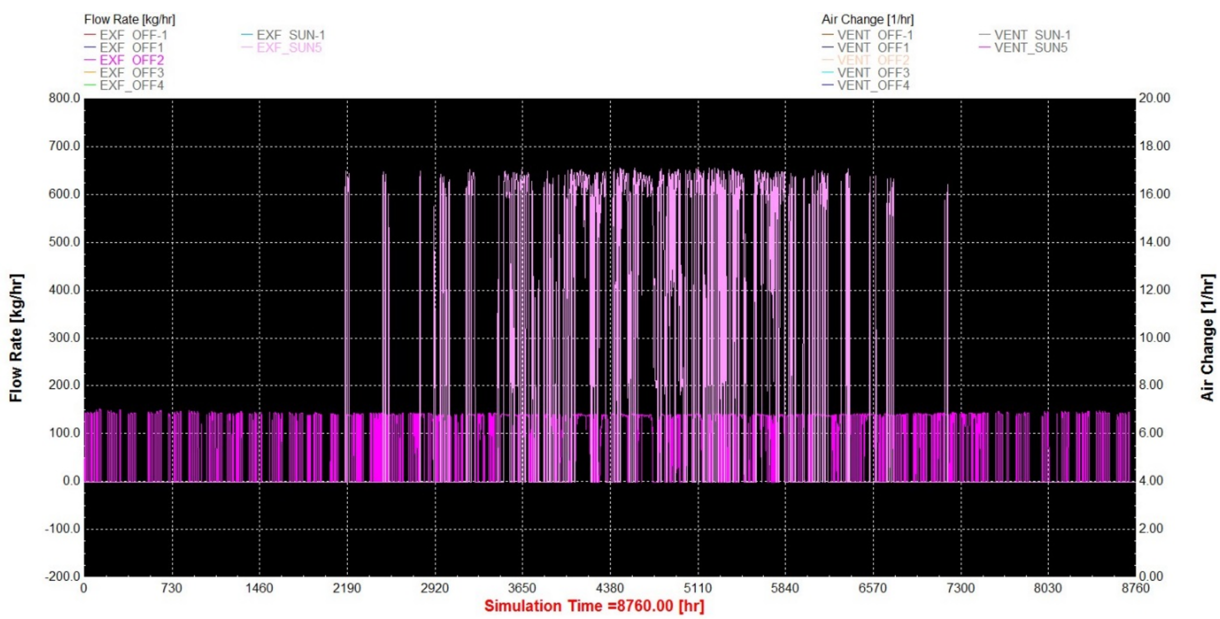
Total Offices Load Intensity *(kJ/hr)*

Run15 I (NC 4-Story NV DSF2 No HVAC)



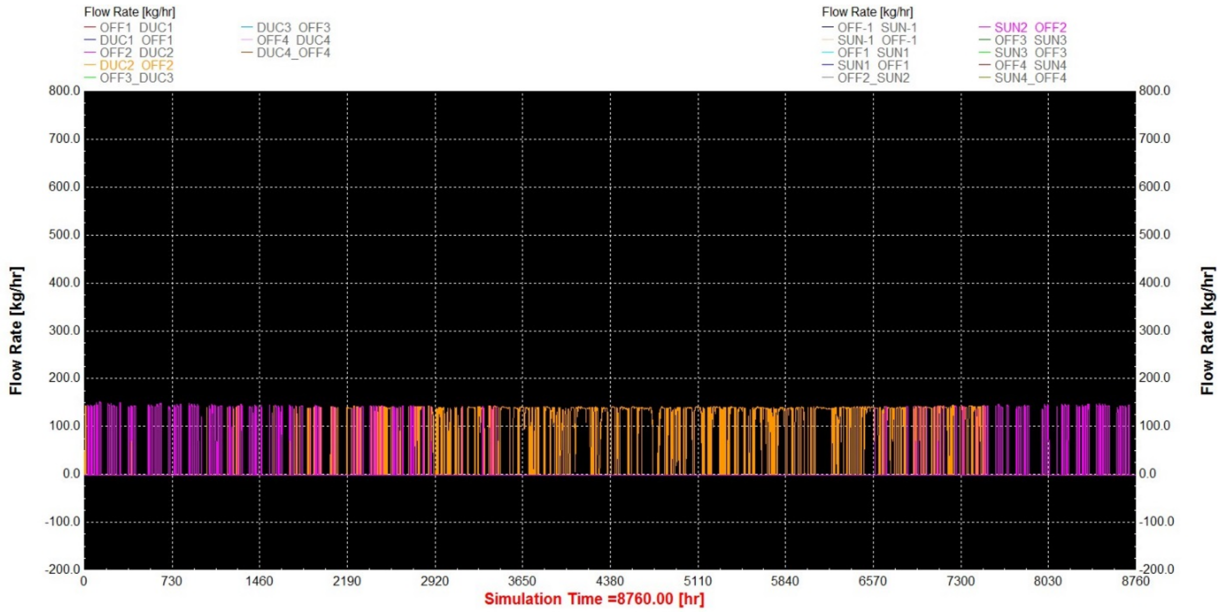
Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run15 I (NC 4-Story NV DSF2 No HVAC)



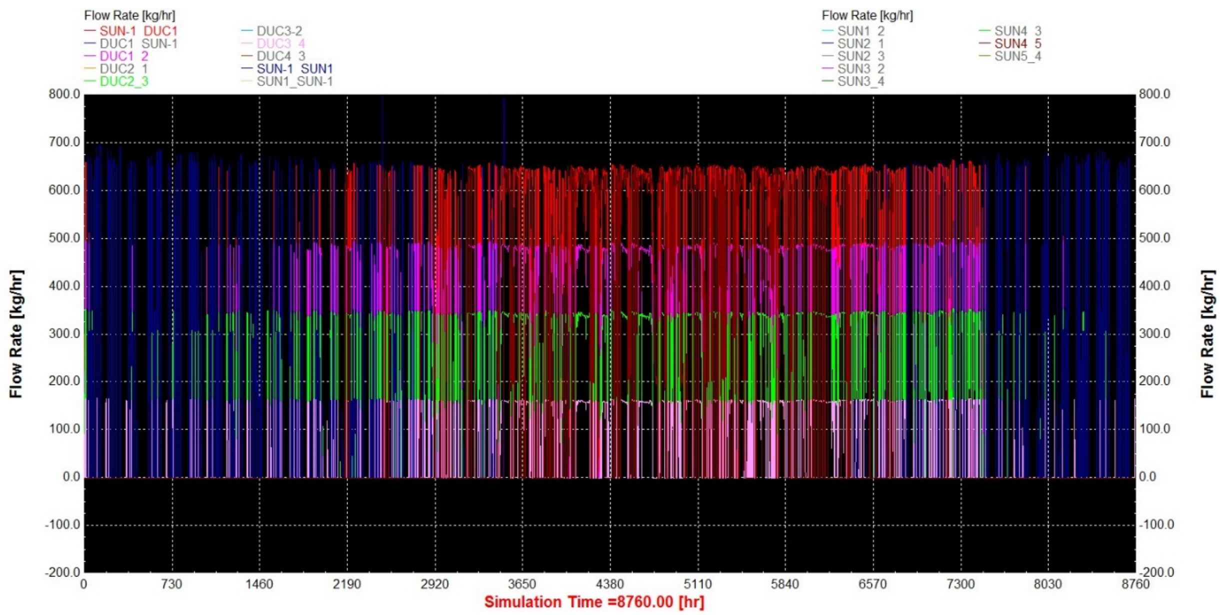
Sunspaces/Ducts-Offices Airflow *(kg/hr or 1/hr)*

Run15 I (NC 4-Story NV DSF2 No HVAC)



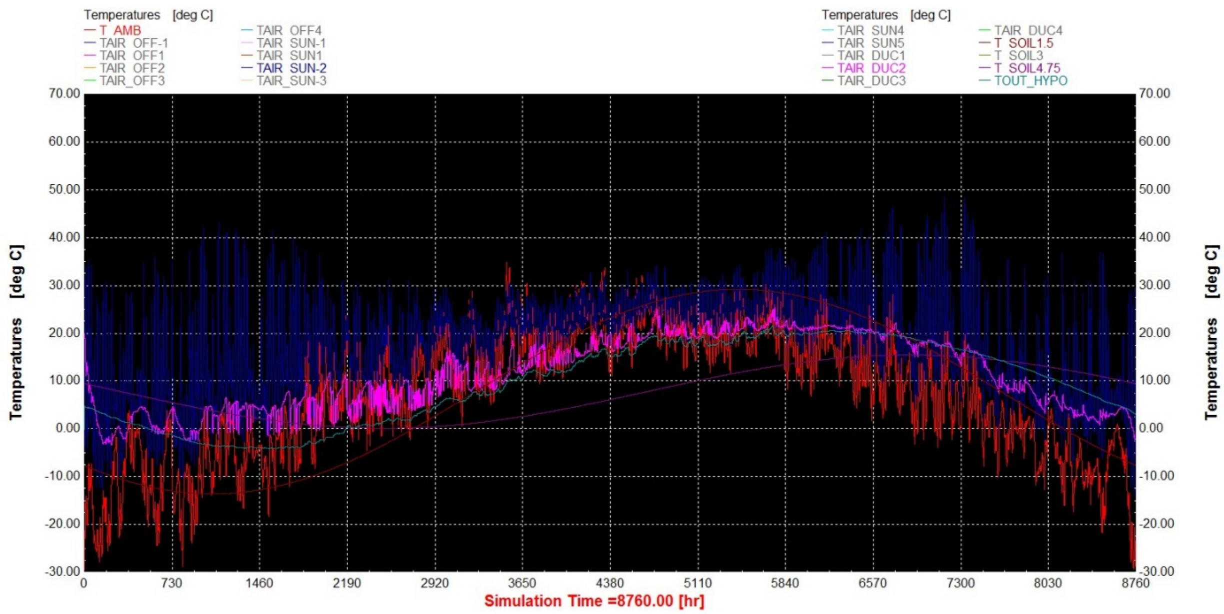
Sunspace/Duct-Sunspace/Duct Airflow *(kg/hr or 1/hr)*

Run15 I (NC 4-Story NV DSF2 No HVAC)



Zones Temperature *(°C)*

Run16 I (NC 4-Story NV DSF2 No HVAC Hypo)

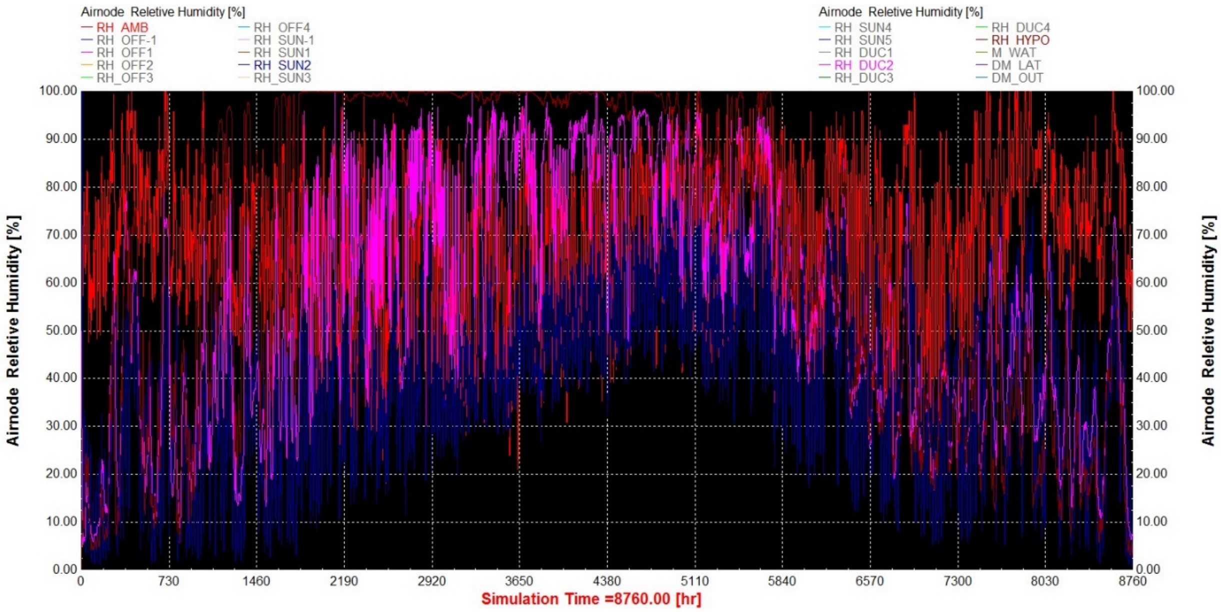


- Zones Temperature Graph Explanation:

This final zones temperature graph is linked with the Run16 I: the baseline wherein a 2-meter depth, naturally ventilated DSF is attached in front of the south façade of a naturally conditioned office building. The DSF system primarily functions as an HVAC contributor with air introduction from both air-tube system to the DSF and from the DSF into the office zones. It should be noted that the airflow in the DSF system in this option is controlled with self-regulating vents placed in the top sunspace5. These vents will control both the direction and the amount of airflow to be in the same intended direction and magnitude. This option, thus, is similar to previous option, except that the DSF system is linked into the earth via earth-tube system. A considerably significant LI decrease from 71.57 to 56.85 kwh/m² (22.69 to 18.02 kBTU/ft²) becomes detectable when comparing this option's LI result (Run16 I) with the baseline (Run4 B). After all, the comparison of this option with the previous option without the connection to the earth-tubes can show an LI decrease from 60.13 to 56.85 kwh/m² (19.06.66 to 18.02 kBTU/ft²).

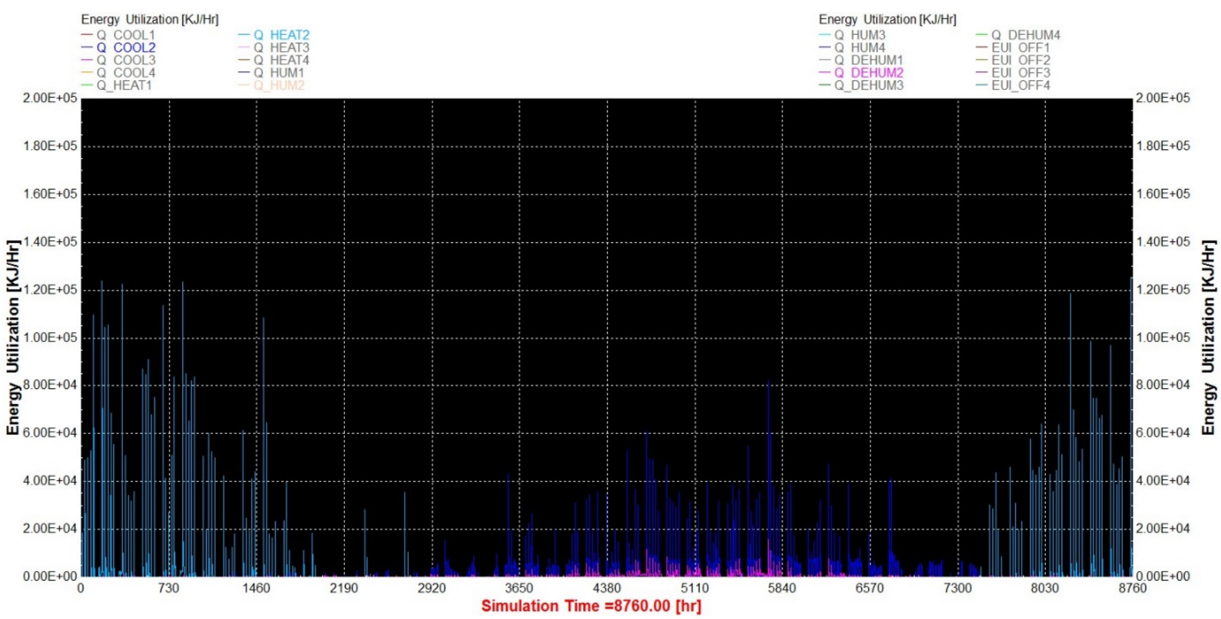
Zones Relative Humidity *(%)*

Run16 I (NC 4-Story NV DSF2 No HVAC Hypo)



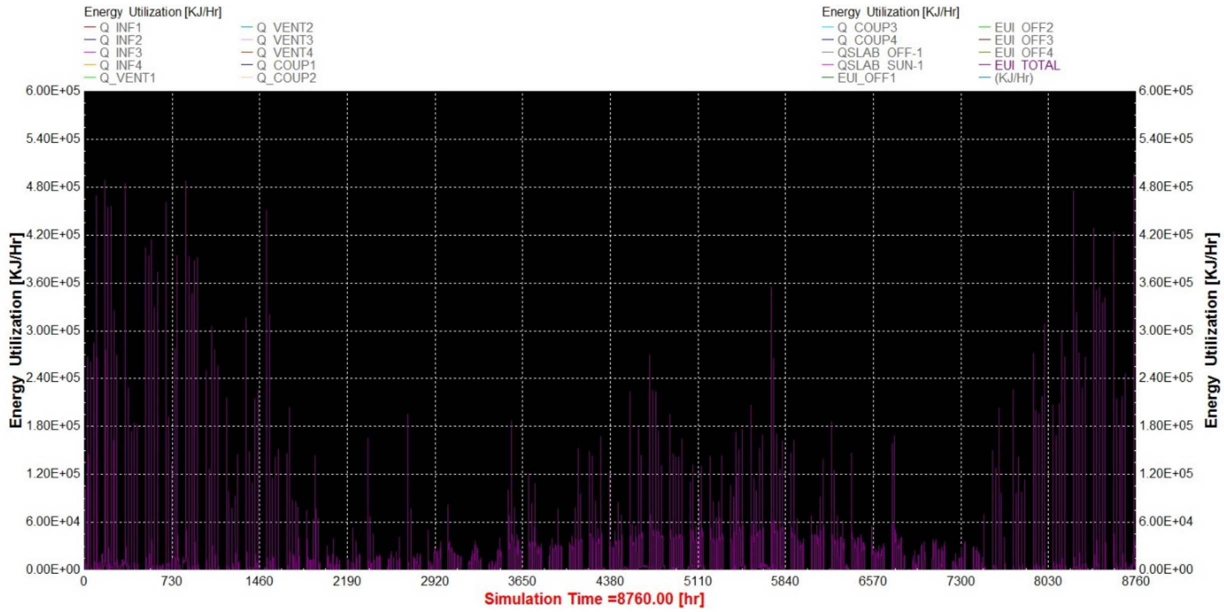
Office Load Intensity *(kJ/hr)*

Run16 I (NC 4-Story NV DSF2 No HVAC Hypo)



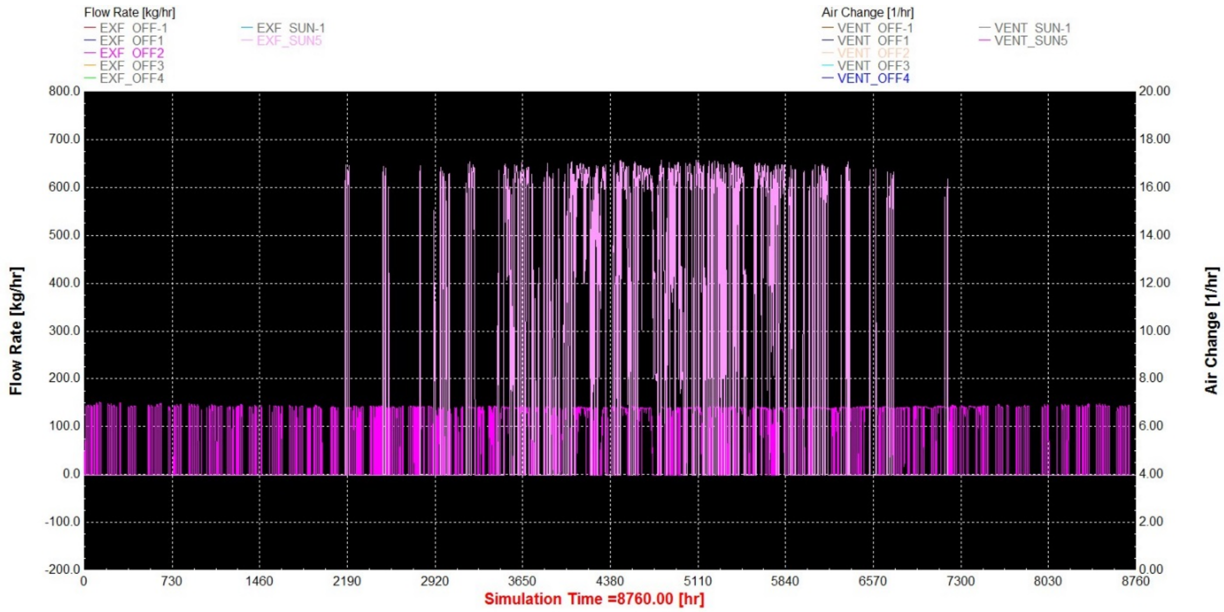
Total Offices Load Intensity *(kJ/hr)*

Run16 I (NC 4-Story NV DSF2 No HVAC Hypo)



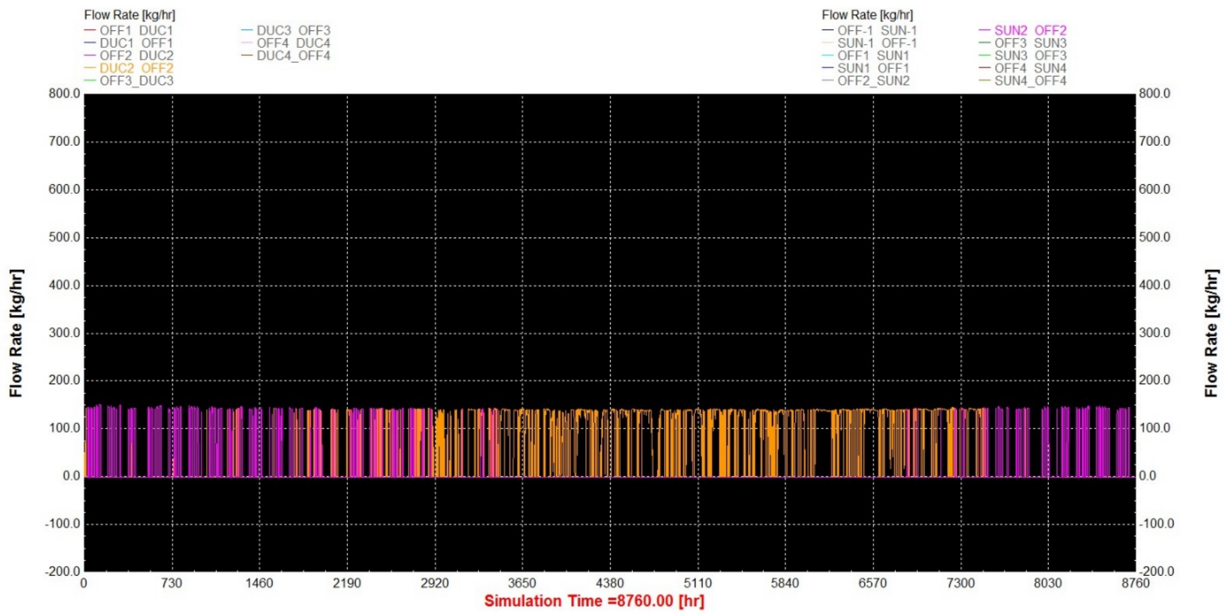
Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run16 I (NC 4-Story NV DSF2 Self No HVAC Hypo)



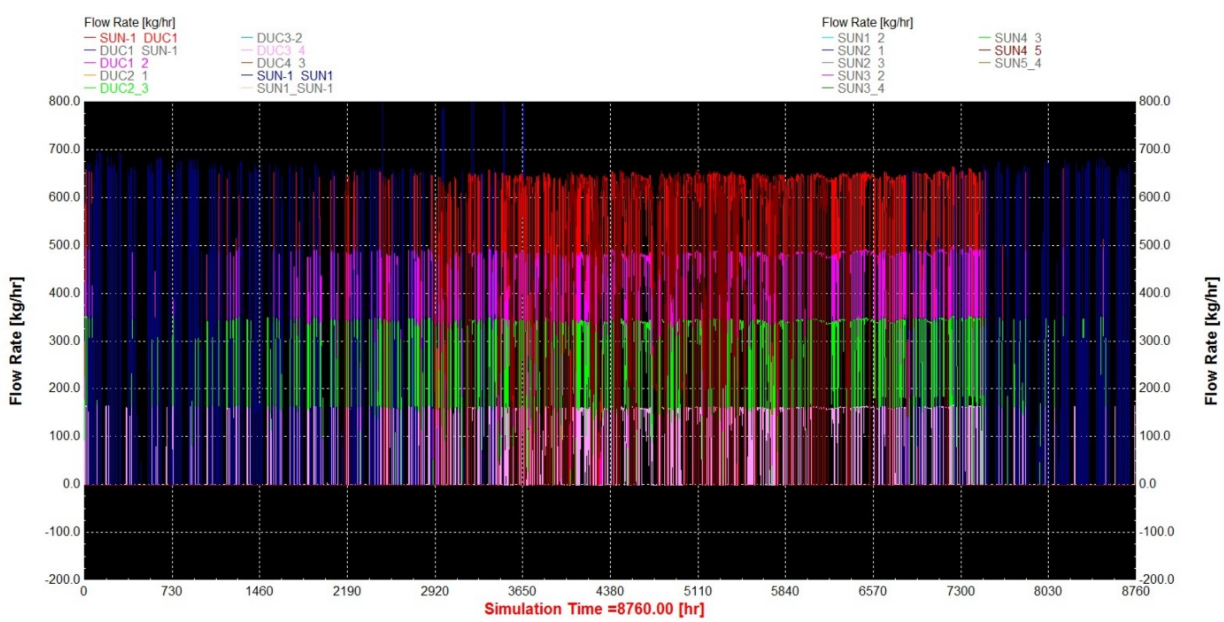
Sunspaces/Ducts-Offices Airflow *(kg/hr or 1/hr)*

Run16 I (NC 4-Story NV DSF2 No HVAC Hypo)



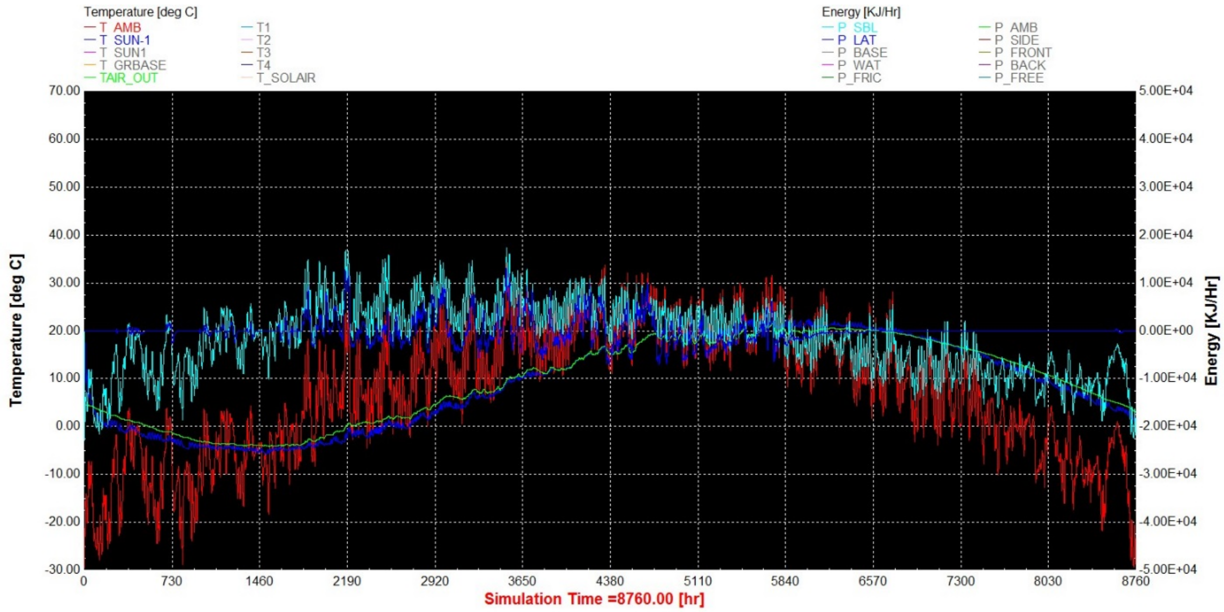
Sunspace/Duct-Sunspace/Duct Airflow *(kg/hr or 1/hr)*

Run16 I (NC 4-Story NV DSF2 No HVAC Hypo)



Air-Tubes Temperature and Energy *(°C and kJ/hr)*

Run16 I (NC 4-Story NV DSF2 No HVAC Hypo)



5.4 Discussion

The previous section presented the complete set of all the graphs for Minneapolis, one of the three research climates, related to the 2-meter DSF depth option. The parameter of total load intensity (LI_TOTAL) is compared for all the runs to specify the best optimized alternative. That is, the exact performance enhancement of each option is added on the right side of the tables in comparison to the baseline, the Run4 B. Run4 is assumed to be the baseline, and in all the other runs, LI is compared to this baseline so that the role of each designed system and its gradual modifications would be delineated. Run4 B is considered as the reference in accordance with ASHRAE's suggested envelope construction type, while mechanically ventilated following ASHRAE's recommended ventilated air for each office's conditioned area and number of people. Due to the notion that all the DSF-integrated options have a passive shading for the DSFs' external single-pane window when hot outside, such consideration is also included for the baseline. This integrated shading is separate from the one proposed for Run3 B. It passively integrates a light-shelf with an overhang. In fact, Run3 B was considered to demonstrate the feasibility of achieving the stated 70% shading, necessarily, without the application of complicated automatic sun tracking solar shading louver systems,

which would demand further expenditure and maintenance. The option of having a shading device integrated with a light-shelf for Run4 B is, hence, repeated for all the three climates to be compared with their baseline, accordingly. This could additionally demonstrate how and to what extents the conventional office building (the baseline) can be enhanced without the integration of a DSF. In comparison to the baseline, the tables below show the best as well as the second best strategies and third options in terms of combinations. In addition, the operating energy cost of HVAC, related to heating, cooling, dehumidification, and humidification, is provided for each option over a 30-year life cycle of building, assuming a 15-cent cost per Kwh. That is worthy to emphasize again that this LI is merely associated with the HVAC energy loads, and the whole EUI of the offices can be estimated by multiplying it by 2, considering the fact that HVAC system accounts for almost 50% of the entire office buildings' LI (Figure 2.3.b).[91]

At the next stage, the "main effects" related to variables such as DSF Integration, DSF Depth, DSF Ventilation Strategy, Building Ventilation Strategy, and Earth-Tubes Integration for the three climates are indicated. Prior to analyzing the results, it is useful to clarify how these numbers should be reflected upon. That is, all the first runs are defined to validate the integrative role of the HVAC system (for Run2 B), the envelope's construction type and the 70% external shading (for Run3 B), the passive shading devices namely the combined overhang and light-shelf (for Run4 B), the enclosed double skin attached to the south façade (for Run5 C), and the same passive external shading that is added to all the other next runs (from Run6 C on). Therefore, the results to be compared to for each variable's evaluation are the Run4 B (the baseline). This is the optimized conventional building without DSF and earth-tubes systems, comparable to the proposed systems in Run7 D, Run 8 E, Run9 F, Run10 F, Run11 G, Run12 G, Run13 H, Run14 H, Run15 I, and Run16 I. For the ease of access as reference, the title descriptions of all of the runs are restated below:

1- Run1 A (4-Story Shoe Box No HVAC)
2- Run2 B (MC 4-Story Full HVAC)
3- Run3 B (MC 4-Story Construction Eshading Full HVAC)
4- Run4 B (MC 4-Story Construction Shading Full HVAC), assumed to be the ***BASELINE***
5- Run5 C (MC 4-Story DSF2 Full HVAC)
6- Run6 C (MC 4-Story DSF2 Shading Full HVAC)
7- Run7 D (MC 4-Story MV DSF2 Full HVAC)

[91] This 2012 statistics shows the energy use in U.S. for commercial buildings by major end-uses. Total number is trillion British thermal units. (Source: U.S. Energy Information Administration (2012), Commercial Buildings Energy Consumption Survey: Energy Usage Summary, Table 5, March 2016.)

8- Run8 E (MC 4-Story NV DSF2 Full HVAC)
9- Run9 F (MV 4-Story MV DSF2 Semi HVAC)
10- Run10 F (MV 4-Story MV DSF2 Semi HVAC Hypo)
11- Run11 G (MV 4-Story NV DSF2 Semi HVAC)
12- Run12 G (MV 4-Story NV DSF2 Semi HVAC Hypo)
13- Run13 H (NC 4-Story MV DSF2 No HVAC)
14- Run14 H (NC 4-Story MV DSF2 No HVAC Hypo)
15- Run15 I (NC 4-Story NV DSF2 No HVAC)
16- Run16 I (NC 4-Story NV DSF2 No HVAC Hypo)

The following tables display the results of the comparison between energy performance of each depth option, of 2, 1, and 0.5 meter, for the three climates of Minneapolis, Atlanta, and Phoenix respectively. Tables are followed by separately stated main effect analysis for each climate.

5.4.1 Minneapolis, 2-meter Depth DSF

Minneapolis Load Intensity Break Down (2m DSF Depth)													
Elements	Load Intensity	Load Intensity	Q_HEAT	Q_COOL	Q_DEHUM	Q_HUM	Q-INF	Q_VENT	Q_COUPL	LI_TOTAL	Vent. Rate	ACH	$/30 Yrs
RUN #	KWH/SM/Yr	KBTU/SF/Yr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	Kg/Hr	1/Hr	$
Run1	0.00	0.00	0	0	0	0	1,412	0	0	0	0.00	0.00	0
Run2	118.50	37.56	13,994	43,709	4,617	14	1,739	3,099	0	62,334	164.32	0.59	170,639
Run3	75.46	23.92	10,633	24,334	4,720	7	1,727	3,036	0	39,695	164.32	0.59	108,665
Run4	71.57	22.69	11,980	20,931	4,728	9	1,683	2,965	0	37,648	164.32	0.59	103,062
Run5	76.95	24.39	8,594	27,294	4,586	4	1,822	3,062	0	40,478	164.32	0.59	110,807
Run6	67.06	21.26	9,968	20,596	4,710	4	1,748	2,985	0	35,278	164.32	0.59	96,573
Minneapolis Comparable Runs (2m DSF Depth)													
Run7	63.39	20.10	8,735	19,889	4,720	4	1,746	0	2,452	33,347	164.30	0.59	91,288
Run8 *	63.53	20.14	8,735	19,962	4,717	4	1,747	0	2,458	33,418	164.30	0.59	91,481
Run9	60.83	19.28	7,270	20,024	4,702	4	1,770	0	1,756	32,000	164.30	0.59	87,599
Run10 #	56.41	17.88	6,865	18,216	4,589	4	1,764	0	1,985	29,673	164.30	0.59	81,229
Run11 *	60.97	19.33	7,270	20,096	4,700	4	1,771	0	1,762	32,070	164.30	0.59	87,792
Run12 #*	57.42	18.20	6,839	18,774	4,588	4	1,768	0	1,912	30,204	164.30	0.59	82,685
Run13 ^	59.99	19.02	6,593	18,546	6,416	3	1,743	0	2,230	31,559	226.72	0.82	86,392
Run14 #^	56.47	17.90	6,304	17,606	5,794	3	1,742	0	2,290	29,707	216.99	0.78	81,323
Run15 *^	60.13	19.06	6,593	18,624	6,411	3	1,744	0	2,238	31,631	226.52	0.82	86,589
Run16 #*^	56.85	18.02	6,303	17,823	5,776	3	1,744	0	2,295	29,905	217.37	0.78	81,866

Options with Linked Earth-Tubes
* Options with Naturally Ventilated (NV) DSF
^ Options with Naturally Ventilated (NV) Bldg

Conventional Buildings Design
Attached SDF as Just a Buffer Zone
Attached SDF as an HVAC Contributer
The above Attached SDF to a NV Building

22.69 kBTU/f² Assumed as Baseline
ASHRAE Suggestion+Passive Shading

Run 10 (21.2 % less than Baseline)
Best Strategy (MV DSF+MV Bldg+Earth-Tubes)

Run 14 (21 % less than Baseline)
2nd Best Strat. (NV DSF+NV Bldg+Earth-Tubes)

19.8 to 21.1 % less than Baseline
Best Combinations (DSF+Shading+Earth-Tubes)

Note1: Typical Office Buildings's EUI is 211 kWh/m²/yr (67 kBTU/ft²/yr) with 60% reduction based on 2030 building challenge, 85 kWh/m²/yr (27 kBTU/ft²/yr).
Note2: In typical Office Buildings, half of the EUI is due to HVAC systems. Therefore, the whole EUI would be around twice as the numbers above. ACH and Vent. Rate are average hourly of airchange & ventilation.
Note3: Q_HEAT is average energy required for heating, Q_COOL for cooling, Q_DEHUM for dehumidification, Q_HUM for humidification, Q_INF for infiltration, Q_VENT for ventilation, and Q_COUPL for coupling.

Table 5.1: Minneapolis Results, 2-meter Depth DSF

The sixteen run results for the table above (Table 5.1) indicate that all the proposed DSF systems (Run7 D to Run16 I) are performing better than the baseline, at the same time that the changes are significant for some alternatives, namely, Run10 F and Run14 H. The best option, in this case, Run10 F that has mechanically ventilated building and DSF with earth-tubes system, is highlighted in darker blue with 21.2% higher efficiency, in a comparison to the baseline. The second best option with 21% higher efficiency is Run14

H that is similar to the Run10 F except that the building is mechanically ventilated. The third best options ranging higher efficiency are related to combinations of DSF and earth-tubes, in general. LI ranging from 19.8 to 21.2 % are compared to a conventional building in accordance with ASHRAE requirements, integrated with a passive external shading (the assumed baseline).

It is also remarkable that the integrated passive shading device proposed in the Run4 B, which is limited to just an overhang in Minneapolis to maximize heat gain during cold seasons, has a relative high efficiency highlighting the impact of a proper shading device integration in lowering LI of a conventional building.

Assuming that the HVAC system accounts for almost 50% of the entire LI in a commercial building, the whole LI of the best proposed option will be 113.7 kwh/m²/yr (36.04 kBTU/ft²/yr). By considering a typical office building's LI that is around 211 kwh/m²/yr (67 kBTU/ft²/yr), it can be implied that the best option's LI is significantly lower, although, it is still higher than the 2030 Building Challenge of 60% reduction in LI (85 kwh/m²/yr or 27 kBTU/ft²/yr). As far as the economic dimension is concerned, the best option can save around $21,833 during a 30-year presumed lifecycle of the office building.

The average air-change of mechanically ventilated options shows a constant rate of 0.59 1/Hr during the occupancy hours while the controlling strategies used for the naturally ventilated options resulted in an average of 0.78 1/Hr clearly with more fluctuation although it closely resembles the options with mechanical equipment's.

5.4.2 Minneapolis, 1m Depth DSF

Minneapolis Load Intensity Break Down (2m DSF Depth)													
Elements	Load Intensity	Load Intensity	Q_HEAT	Q_COOL	Q_DEHUM	Q_HUM	Q-INF	Q_VENT	Q_COUPL	LI_TOTAL	Vent. Rate	ACH	$/30 Yrs
RUN #	KWH/SM/Yr	KBTU/SF/Yr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	Kg/Hr	1/Hr	$
Run1	0.00	0.00	0	0	0	0	1,412	0	0	0	0.00	0.00	0
Run2	118.50	37.56	13,994	43,709	4,617	14	1,739	3,099	0	62,334	164.32	0.59	170,639
Run3	75.46	23.92	10,633	24,334	4,720	7	1,727	3,036	0	39,695	164.32	0.59	108,665
Run4	71.57	22.69	11,980	20,931	4,728	9	1,683	2,965	0	37,648	164.32	0.59	103,062
Run5	76.95	24.39	8,594	27,294	4,586	4	1,822	3,062	0	40,478	164.32	0.59	110,807
Run6	67.06	21.26	9,968	20,596	4,710	4	1,748	2,985	0	35,278	164.32	0.59	96,573
Minneapolis Comparable Runs (2m DSF Depth)													
Run7	63.39	20.10	8,735	19,889	4,720	4	1,746	0	2,452	33,347	164.30	0.59	91,288
Run8 *	63.53	20.14	8,735	19,962	4,717	4	1,747	0	2,458	33,418	164.30	0.59	91,481
Run9	60.83	19.28	7,270	20,024	4,702	4	1,770	0	1,756	32,000	164.30	0.59	87,599
Run10 #	56.41	17.88	6,865	18,216	4,589	4	1,764	0	1,985	29,673	164.30	0.59	81,229
Run11 *	60.97	19.33	7,270	20,096	4,700	4	1,771	0	1,762	32,070	164.30	0.59	87,792
Run12 #*	57.42	18.20	6,839	18,774	4,588	4	1,768	0	1,912	30,204	164.30	0.59	82,685
Run13 ^	59.99	19.02	6,593	18,546	6,416	3	1,743	0	2,230	31,559	226.72	0.82	86,392
Run14 #^	56.47	17.90	6,304	17,606	5,794	3	1,742	0	2,290	29,707	216.99	0.78	81,323
Run15 *^	60.13	19.06	6,593	18,624	6,411	3	1,744	0	2,238	31,631	226.52	0.82	86,589
Run16 #*^	56.85	18.02	6,303	17,823	5,776	3	1,744	0	2,295	29,905	217.37	0.78	81,866

Options with Linked Earth-Tubes
* Options with Naturally Ventilated (NV) DSF
^ Options with Naturally Ventilated (NV) Bldg

Conventional Buildings Design
Attached SDF as Just a Buffer Zone
Attached SDF as an HVAC Contributer
The above Attached SDF to a NV Building

22.69 kBTU/f² Assumed as Baseline
ASHRAE Suggestion+Passive Shading

Run 10 (21.2 % less than Baseline)
Best Strategy (MV DSF+MV Bldg+Earth-Tubes)

Run 14 (21 % less than Baseline)
2nd Best Strat. (NV DSF+NV Bldg+Earth-Tubes)

19.8 to 21.1 % less than Baseline
Best Combinations (DSF+Shading+Earth-Tubes)

Note1: Typical Office Buildings's EUI is 211 kWh/m²/yr (67 kBTU/ft²/yr) with 60% reduction based on 2030 building challenge, 85 kWh/m²/yr (27 kBTU/ft²/yr).

Note2: In typical Office Buildings, half of the EUI is due to HVAC systems. Therefore, the whole EUI would be around twice as the numbers above. ACH and Vent. Rate are average hourly of airchange & ventilation.

Note3: Q_HEAT is average energy required for heating, Q_COOL for cooling, Q_DEHUM for dehumidification, Q_HUM for humidification, Q_INF for infiltration, Q_VENT for ventilation, and Q_COUPL for coupling.

Table 5.2: Minneapolis Results, 1-meter Depth DSF

It is detected in the above table (Table 5.2) that all the proposed, functioning DSF systems are again performing better than the baseline independent of DSF depth. Run10 F is, for a second time, the best option although its efficiency is lowered to 19.3% now. Run14 H with 18.6% higher efficiency is still the best second options. The proposed integrated DSFs in this depth option can primarily have higher efficiency if those are integrated with the earth-tubes system with no exception although the ones without DSF integration still perform better than the baseline up to 13.5%.

The whole LI of the best proposed best option will be 117.24 kwh/m²/yr (37.16 kBTU/ft²/yr), which is considerably lower than a typical office building although it is higher than the 2030 Building Challenge (85 kwh/m²/yr or 27 kBTU/ft²/yr). In terms of economic aspects, the best option can save around $19,866 during a 30-year assumed lifecycle of the office building.

The average air-change of mechanically ventilated is similar to the previous DSF depth of 2m with a constant rate of 0.59 1/Hr while the naturally ventilated options have an average of 0.78 1/Hr.

5.4.3 Minneapolis, 0.5m Depth DSF

Minneapolis Load Intensity Break Down (0.5m DSF Depth)													
Elements	Load Intensity	Load Intensity	Q_HEAT	Q_COOL	Q_DEHUM	Q_HUM	Q-INF	Q_VENT	Q_COUPL	LI_TOTAL	Vent. Rate	ACH	$/30 Yrs
RUN #	KWH/SM/Yr	KBTU/SF/Yr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	Kg/Hr	1/Hr	$
Run1	0.00	0.00	0	0	0	0	1,412	0	0	0	0.00	0.00	0
Run2	118.50	37.56	13,994	43,709	4,617	14	1,739	3,099	0	62,334	164.32	0.59	170,639
Run3	75.46	23.92	10,633	24,334	4,720	7	1,727	3,036	0	39,695	164.32	0.59	108,665
Run4	71.57	22.69	11,980	20,931	4,728	9	1,683	2,965	0	37,648	164.32	0.59	103,062
Run5	84.72	26.86	6,628	33,401	4,532	4	1,868	3,144	0	44,566	164.32	0.59	122,000
Run6	69.44	22.01	7,835	24,037	4,649	4	1,785	3,053	0	36,525	164.32	0.59	99,987
Minneapolis Comparable Runs (0.5m DSF Depth)													
Run7	66.92	21.21	7,130	23,419	4,646	5	1,783	0	2,678	35,199	164.30	0.59	96,359
Run8 *	67.06	21.26	7,130	23,496	4,644	5	1,784	0	2,680	35,275	164.30	0.59	96,564
Run9	65.06	20.62	5,922	23,660	4,635	4	1,807	0	2,051	34,221	164.30	0.59	93,680
Run10 #	59.65	18.91	5,439	21,399	4,536	4	1,801	0	2,324	31,378	164.30	0.59	85,898
Run11 *	65.20	20.67	5,922	23,737	4,633	4	1,807	0	2,053	34,296	164.30	0.59	93,885
Run12 #*	60.89	19.30	5,410	22,084	4,530	4	1,806	0	2,219	32,029	164.30	0.59	87,679
Run13 ^	64.11	20.32	5,337	22,149	6,236	4	1,776	0	2,585	33,726	229.72	0.83	92,325
Run14 #^	60.39	19.14	5,009	21,087	5,669	3	1,777	0	2,613	31,768	217.89	0.78	86,965
Run15 *^	64.25	20.37	5,337	22,226	6,231	4	1,776	0	2,590	33,798	229.61	0.83	92,522
Run16 #*^	60.78	19.27	5,009	21,309	5,654	3	1,779	0	2,620	31,974	218.27	0.79	87,530

Options with Linked Earth-Tubes
* Options with Naturally Ventilated (NV) DSF
^ Options with Naturally Ventilated (NV) Bldg

Conventional Buildings Design
Attached SDF as Just a Buffer Zone
Attached SDF as an HVAC Contributer
The above Attached SDF to a NV Building

22.69 kBTU/f² Assumed as Baseline
ASHRAE Suggestion+Passive Shading

Run 10 (16.7 % less than Baseline)
Best Strategy (MV DSF+MV Bldg+Earth-Tubes)

Run 14 (15.6 % less than Baseline)
2nd Best Strat. (NV DSF+NV Bldg+Earth-Tubes)

14.9 to16.7 % less than Baseline
Best Combinations (DSF+Shading+Earth-Tubes)

Note1: Typical Office Buildings's EUI is 211 kWh/m²/yr (67 kBTU/ft²/yr) with 60% reduction based on 2030 building challenge, 85 kWh/m²/yr (27 kBTU/ft²/yr).

Note2: In typical Office Buildings, half of the EUI is due to HVAC systems. Therefore, the whole EUI would be around twice as the numbers above. ACH and Vent. Rate are average hourly of airchange & ventilation.

Note3: Q_HEAT is average energy required for heating, Q_COOL for cooling, Q_DEHUM for dehumidification, Q_HUM for humidification, Q_INF for infiltration, Q_VENT for ventilation, and Q_COUPL for coupling.

Table 5.3: Minneapolis Results, 0.5-meter Depth DSF

Observations on the above table (Table 5.3) for the DSF's narrow depth of 0.5m suggests that Run10 F is still the best option while its performance is 16,7% higher than baseline. The Run14 H is, yet again, the

best second options with 15.6% higher efficiency. Generally, the proposed integrated DSFs in this option of the 0.5m DSF depth- even the worst option- are substantially performing better than the baseline. All the options in this climate, after all, follow the same pattern in terms of LI performance.

The whole LI of the best proposed option will be 119.30 kwh/m²/yr (37.82 kBTU/ft²/yr), which is once more lower than a typical office building, although, it is obviously higher than the 2030 Building Challenge (85 kwh/m²/yr or 27 kBTU/ft²/yr). As far as economic aspects is concerned, the best option can save around $17,163 during a 30-year presumed lifecycle of this office building. The following section compares all the results for the climate of Minneapolis.

The average air-change of mechanically ventilated is a constant rate of 0.59 1/Hr while the naturally ventilated options have an average of 0.78 1/Hr.

5.4.4 Combined analysis for Minneapolis

The below combined table analysis for Minneapolis highlights the following findings:

- The most energy efficient option for all the alternatives is Run10 F in which a mechanically conditioned office building is integrated with a mechanically ventilated DSF, with a maximum of 21.2% higher performance compared to the baseline for the DSF depth of 2m and minimum of 16.7% for a DSF depth of 0.5m.
- In terms of the most efficient DSF depth in this climate, the 2-meter depth is obviously the ideal option. Yet, the other two depth options are still considerably effective. Generally, the LI has an inverse correlation with the DSF depth; the LI in Minneapolis will be increased by decreasing the DSF's depth.
- In the stated best combinations including the naturally ventilated DSF options, the self-regulating vents in the top sunspace, functioning as a controller for both introduction and exhaustion of the air within the DSF system's cavity, are essential in lowering LI. In fact, the average office zones' air change is evidently higher than the minimum rate by close to 40%.
- These consistent outcomes for the three DSF depths in the climate of Minneapolis suggest that a naturally conditioned building that benefits from a naturally ventilated DSF introducing air into the building zones could be also among the best alternatives.

The comparison between the buffer (Run8 E) and HVAC contributing DSF (Run10 F, for instance) in which the air in the cavity is either just exhausted or used for heating during cold seasons, reveals that air

introduction from cavity to the office zone does have considerable impact on LI of a DSF system up to 11.2%.

- The Run4 B's results associated with the option of an integrated, passive shading device, which just includes and overhang in Minneapolis to have maximum heat gain, has 39.6% higher efficiency than a conventional building that has floor to ceiling glazing without any shading strategy. The results, thus, prove the higher influence of proper shading strategies.
- Compared to the baseline, the proposed integrated DSFs in this climate are further effective with the DSF depth of 2m and relatively the depth of 1m, but most of the options associated with the DSF with depth of 0.5m perform slightly inferior.

Minneapolis Load Intensity Break Down (2m DSF Depth)													
Elements	Load Intensity	Load Intensity	Q_HEAT	Q_COOL	Q_DEHUM	Q_HUM	Q-INF	Q_VENT	Q_COUPL	LI_TOTAL	Vent. Rate	ACH	$/30 Yrs
RUN #	KWH/SM/Yr	KBTU/SF/Yr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	Kg/Hr	1/Hr	$
Run1	0.00	0.00	0	0	0	0	1,412	0	0	0	0.00	0.00	0
Run2	118.50	37.56	13,994	43,709	4,617	14	1,739	3,099	0	62,334	164.32	0.59	170,639
Run3	75.46	23.92	10,633	24,334	4,720	7	1,727	3,036	0	39,695	164.32	0.59	108,665
Run4	71.57	22.69	11,980	20,931	4,728	9	1,683	2,965	0	37,648	164.32	0.59	103,062
Run5	76.95	24.39	8,594	27,294	4,586	4	1,822	3,062	0	40,478	164.32	0.59	110,807
Run6	67.06	21.26	9,968	20,596	4,710	4	1,748	2,985	0	35,278	164.32	0.59	96,573
Minneapolis Comparable Runs (2m DSF Depth)													
Run7	63.39	20.10	8,735	19,889	4,720	4	1,746	0	2,452	33,347	164.30	0.59	91,288
Run8 *	63.53	20.14	8,735	19,962	4,717	4	1,747	0	2,458	33,418	164.30	0.59	91,481
Run9	60.83	19.28	7,270	20,024	4,702	4	1,770	0	1,756	32,000	164.30	0.59	87,599
Run10 #	56.41	17.88	6,865	18,216	4,589	4	1,764	0	1,985	29,673	164.30	0.59	81,229
Run11 *	60.97	19.33	7,270	20,096	4,700	4	1,771	0	1,762	32,070	164.30	0.59	87,792
Run12 #*	57.42	18.20	6,839	18,774	4,588	4	1,768	0	1,912	30,204	164.30	0.59	82,685
Run13 ^	59.99	19.02	6,593	18,546	6,416	3	1,743	0	2,230	31,559	226.72	0.82	86,392
Run14 #^	56.47	17.90	6,304	17,606	5,794	3	1,742	0	2,290	29,707	216.99	0.78	81,323
Run15 *^	60.13	19.06	6,593	18,624	6,411	3	1,744	0	2,238	31,631	226.52	0.82	86,589
Run16 #*^	56.85	18.02	6,303	17,823	5,776	3	1,744	0	2,295	29,905	217.37	0.78	81,866

Note1: Typical Office Buildings's EUI is 211 kWh/m²/yr (67 kBTU/ft²/yr) with 60% reduction based on 2030 building challenge, 85 kWh/m²/yr (27 kBTU/ft²/yr).

Note2: In typical Office Buildings, half of the EUI is due to HVAC systems. Therefore, the whole EUI would be around twice as the numbers above.

Options with Linked Earth-Tubes
* Options with Naturally Ventilated (NV) DSF
^ Options with Naturally Ventilated (NV) Bldg

Conventional Buildings Design
Attached SDF as Just a Buffer Zone
Attached SDF as an HVAC Contributer
The above Attached SDF to a NV Building

22.69 kBTU/f² Assumed as Baseline
ASHRAE Suggestion+Passive Shading

Run 10 (21.2 % less than Baseline)
Best Strategy (MV DSF+MV Bldg+Earth-Tubes)

Run 14 (21 % less than Baseline)
2nd Best Strat. (NV DSF+NV Bldg+Earth-Tubes)

19.8 to 21.1 % less than Baseline
Best Combinations (DSF+Shading+Earth-Tubes)

Minneapolis Load Intensity Break Down (1m DSF Depth)													
Elements	Load Intensity	Load Intensity	Q_HEAT	Q_COOL	Q_DEHUM	Q_HUM	Q-INF	Q_VENT	Q_COUPL	LI_TOTAL	Vent. Rate	ACH	$/30 Yrs
RUN #	KWH/SM/Yr	KBTU/SF/Yr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	Kg/Hr	1/Hr	$
Run1	0.00	0.00	0	0	0	0	1,412	0	0	0	0.00	0.00	0
Run2	118.50	37.56	13,994	43,709	4,617	14	1,739	3,099	0	62,334	164.32	0.59	170,639
Run3	75.46	23.92	10,633	24,334	4,720	7	1,727	3,036	0	39,695	164.32	0.59	108,665
Run4	71.57	22.69	11,980	20,931	4,728	9	1,683	2,965	0	37,648	164.32	0.59	103,062
Run5	80.81	25.62	7,397	30,552	4,554	3	1,848	3,108	0	42,507	164.32	0.59	116,363
Run6	68.04	21.57	8,692	22,423	4,675	4	1,769	3,022	0	35,793	164.32	0.59	97,984
Minneapolis Comparable Runs (1m DSF Depth)													
Run7	65.02	20.61	7,768	21,755	4,677	4	1,767	0	2,580	34,204	164.30	0.59	93,634
Run8 *	65.16	20.66	7,768	21,832	4,674	4	1,767	0	2,584	34,278	164.30	0.59	93,837
Run9	62.84	19.92	6,439	21,948	4,663	4	1,791	0	1,919	33,054	164.30	0.59	90,486
Run10 #	57.77	18.31	5,982	19,846	4,559	4	1,785	0	2,182	30,391	164.30	0.59	83,196
Run11 *	62.98	19.96	6,439	22,024	4,661	4	1,792	0	1,922	33,129	164.30	0.59	90,689
Run12 #*	58.92	18.68	5,953	20,479	4,555	4	1,790	0	2,090	30,992	164.30	0.59	82,685
Run13 ^	61.93	19.63	5,817	20,445	6,313	4	1,762	0	2,429	32,579	228.46	0.82	89,184
Run14 #^	58.23	18.46	5,497	19,406	5,724	3	1,762	0	2,477	30,631	217.39	0.78	83,853
Run15 *^	62.07	19.68	5,817	20,523	6,308	4	1,762	0	2,435	32,652	228.30	0.82	89,384
Run16 #*^	58.62	18.58	5,497	19,627	5,708	3	1,764	0	2,483	30,836	217.76	0.78	84,413

Note1: Typical Office Buildings's EUI is 211 kWh/m²/yr (67 kBTU/ft²/yr) with 60% reduction based on 2030 building challenge, 85 kWh/m²/yr (27 kBTU/ft²/yr).

Note2: In typical Office Buildings, half of the EUI is due to HVAC systems. Therefore, the whole EUI would be around twice as the numbers above.

Options with Linked Earth-Tubes
* Options with Naturally Ventilated (NV) DSF
^ Options with Naturally Ventilated (NV) Bldg

Conventional Buildings Design
Attached SDF as Just a Buffer Zone
Attached SDF as an HVAC Contributer
The above Attached SDF to a NV Building

22.69 kBTU/f² Assumed as Baseline
ASHRAE Suggestion+Passive Shading

Run 10 (19.3 % less than Baseline)
Best Strategy (MV DSF+MV Bldg+Earth-Tubes)

Run 14 (18.6 % less than Baseline)
2nd Best Strat. (NV DSF+NV Bldg+Earth-Tubes)

17.7 to19.3 % less than Baseline
Best Combinations (DSF+Shading+Earth-Tubes)

Minneapolis Load Intensity Break Down (0.5m DSF Depth)													
Elements	Load Intensity	Load Intensity	Q_HEAT	Q_COOL	Q_DEHUM	Q_HUM	Q-INF	Q_VENT	Q_COUPL	LI_TOTAL	Vent. Rate	ACH	$/30 Yrs
RUN #	KWH/SM/Yr	KBTU/SF/Yr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	Kg/Hr	1/Hr	$
Run1	0.00	0.00	0	0	0	0	1,412	0	0	0	0.00	0.00	0
Run2	118.50	37.56	13,994	43,709	4,617	14	1,739	3,099	0	62,334	164.32	0.59	170,639
Run3	75.46	23.92	10,633	24,334	4,720	7	1,727	3,036	0	39,695	164.32	0.59	108,665
Run4	71.57	22.69	11,980	20,931	4,728	9	1,683	2,965	0	37,648	164.32	0.59	103,062
Run5	84.72	26.86	6,628	33,401	4,532	4	1,868	3,144	0	44,566	164.32	0.59	122,000
Run6	69.44	22.01	7,835	24,037	4,649	4	1,785	3,053	0	36,525	164.32	0.59	99,987
Minneapolis Comparable Runs (0.5m DSF Depth)													
Run7	66.92	21.21	7,130	23,419	4,646	5	1,783	0	2,678	35,199	164.30	0.59	96,359
Run8 *	67.06	21.26	7,130	23,496	4,644	5	1,784	0	2,680	35,275	164.30	0.59	96,564
Run9	65.06	20.62	5,922	23,660	4,635	4	1,807	0	2,051	34,221	164.30	0.59	93,680
Run10 #	59.65	18.91	5,439	21,399	4,536	4	1,801	0	2,324	31,378	164.30	0.59	85,898
Run11 *	65.20	20.67	5,922	23,737	4,633	4	1,807	0	2,053	34,296	164.30	0.59	93,885
Run12 #*	60.89	19.30	5,410	22,084	4,530	4	1,806	0	2,219	32,029	164.30	0.59	82,685
Run13 ^	64.11	20.32	5,337	22,149	6,236	4	1,776	0	2,585	33,726	229.72	0.83	92,325
Run14 #^	60.39	19.14	5,009	21,087	5,669	3	1,777	0	2,613	31,768	217.89	0.78	86,965
Run15 *^	64.25	20.37	5,337	22,226	6,231	4	1,776	0	2,590	33,798	229.61	0.83	92,522
Run16 #*^	60.78	19.27	5,009	21,309	5,654	3	1,779	0	2,620	31,974	218.27	0.79	87,530

Note1: Typical Office Buildings's EUI is 211 kWh/m²/yr (67 kBTU/ft²/yr) with 60% reduction based on 2030 building challenge, 85 kWh/m²/yr (27 kBTU/ft²/yr).

Note2: In typical Office Buildings, half of the EUI is due to HVAC systems. Therefore, the whole EUI would be around twice as the numbers above.

Options with Linked Earth-Tubes
* Options with Naturally Ventilated (NV) DSF
^ Options with Naturally Ventilated (NV) Bldg

Conventional Buildings Design
Attached SDF as Just a Buffer Zone
Attached SDF as an HVAC Contributer
The above Attached SDF to a NV Building

22.69 kBTU/f² Assumed as Baseline
ASHRAE Suggestion+Passive Shading

Run 10 (16.7 % less than Baseline)
Best Strategy (MV DSF+MV Bldg+Earth-Tubes)

Run 14 (15.6 % less than Baseline)
2nd Best Strat. (NV DSF+NV Bldg+Earth-Tubes)

14.9 to16.7 % less than Baseline
Best Combinations (DSF+Shading+Earth-Tubes)

Table 5.4: Minneapolis Combined Results

5.4.5 Minneapolis, Variables Main Effects

In this section, the main effect of various variables such as the DSF Integration, DSF Depth, DSF Ventilation Strategy, Building Ventilation Strategy, and Earth-Tubes Integration in the climate of Minneapolis are considered. That is, reinterpreting their general applicability from a broader viewpoint. Each main effect is calculated via applying the Minneapolis results of Run7 D to Run16 I for all the three DSF depths. In order to do this when comparing two variables, the average result for one variable is subtracted from the average of the other. The greater the number, the higher the LI efficiency is expected while the number's sign depends on which variable was considered first. For instance, the main effect of having to not having the DSF (DSF Integration Main Effect) is calculated based on the following formula:

DSF Main Effect = (Run10 + Run12 + Run14 + Run16)/4 - (Run9 + Run11 + Run13 + Run15)/4

In this case, if the outcome is a negative number, it shows that the first variable (having DSF) is more efficient than the second variable (not having DSF). Accordingly, the number indicates to what extents the LI will be impacted. Table 5.5 illustrates the calculated main effect for each stated variable, individually explained in the next page in the order of their effectiveness.

Minneapolis Main Effects (Run 7-16)	Load Intensity	Load Intensity	Q_HEAT	Q_COOL	Q_DEHUM	Q_HUM	Q-INF	Q_VENT	Q_COUPL	LI_TOTAL	Vent. Rate	ACH	$/30 Yrs
	KWH/SM/Yr	KBTU/SF/Yr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	Kg/Hr	1/Hr	$
Having to not Having DSF (baseline)	-10.11	-3.20	-5,576	-197	461	-5	90	-2,965	2,296	-5,317	23	0.08	-14,556
Natural to Mechanical DSF Ventilation	0.39	0.12	-6	215	-6	0	2	0	-14	203	0	0.00	556
Natural to Mechanical Bldg Ventilation	-1.90	-0.60	-1,075	-1,310	1,385	-1	-19	0	240	-1,001	59	0.21	-2,739
Having to not having Earth-Tubes	-4.00	-1.27	-387	-1,362	-352	0	-2	0	127	-2,102	-5	-0.02	-5,754
2 to 1 m DSF Depth	-1.76	-0.56	853	-1,832	57	-1	-20	0	-172	-923	0	0.00	-2,527
2 to 0.5 m DSF Depth	-3.83	-1.21	1,386	-3,501	100	-1	-36	0	-303	-2,015	-1	0.00	-5,516
1 to 0.5 m DSF Depth	-2.08	-0.66	533	-1,668	43	0	-15	0	-131	-1,092	0	0.00	-2,989

Note1: negetive sign means that one can lose when going from the first to the second option.

Note2: Having to not having DSF is a comparison between average of all options with DSF and the baseline.

Table 5.5: Variables Main Effects

5.4.5.1 DSF Integration

DSF system integration is the most effective variable in a cold climate that has relatively hot summers. The main effect from having to not having a DSF system is -10.11 kwh/m²/yr (-3.20 kBTU/ft²/yr), which is equivalent to $14,556 throughout a 30-year life-cycle of the office building. This means that generally having

an integrated DSF system in the climate of Minneapolis is relatively effective. Yet, with a proper integration of a naturally ventilated DSF linked to earth-tubes system, the level of effectiveness increases to 21% equal to 15.10 kwh/m^2/yr (-4.79 kBTU/ft^2/yr), which is equal to $21,739 during a 30-year building life-cycle. The results also specifies the key role of DSF on dropping heating loads as shown by 5,576 KJ/Hr.

5.4.5.2 Earth-Tubes Integration

Integration of an earth-tube system is the next most effective solution among the stated variables to minimize the LI in this climate. In fact, from having to not having the earth-tube system, the main effect is -4 kwh/m^2/yr (-1.27 kBTU/ft^2/yr) equal to $5,754 during the building life-cycle.

5.4.5.3 DSF Depth

The impact of changing 2m depth to 0.5m is the next influential variable in this climatic condition. This is suggesting that although all the three depths assist in lowering LI, the proper design of DSF depth is critical to the practicality of the system where:

- From 2-meter to 0.5-meter depth, the main effect is -3.83 kwh/m^2/yr (-1.21 kBTU/ft^2/yr) equal to $5,516 for 30 years.
- From the 1-meter to 0.5-meter depth, the main effect is -2.08 kwh/m^2/yr (-0.66 kBTU/ft^2/yr) equal to $2,989 for 30 years.
- From 2-meter to 1-meter depth, the main effect is -1.76 kwh/m^2/yr (-1.47 kBTU/ft^2/yr) equal to $2,527 for 30 years.

5.4.5.4 Building Ventilation Strategy

In spite of the fact that the best combination in Minneapolis consists of a mechanically ventilated building with a mechanically ventilated DSF, the results indicates that natural ventilation is more effective in general. I. This is based on the fact that the main effect from naturally to mechanically ventilated building is -1.9 kwh/m^2/yr (-0.6 kBTU/ft^2/yr), equivalent to $2,739 per 30 years. In addition, the average air-change of the building will be increased by 0.21 1/Hr if a naturally ventilated option is designed in this condition.

5.4.5.5 DSF Ventilation Strategy

Similar to the main effect of buildings' ventilation strategy explained above, The DSF ventilation strategy refers to whether the air in the cavity is ventilated naturally, using dampers/self-regulating vents, or mechanically, through the three 110 cfm fans in sunspace 5 on the top of the building. From a naturally to mechanically ventilated DSF, the main effect is +0.39 kwh/m^2/yr (+0.12 kBTU/ft^2/yr). It is equal to $556 more expenditure in 30 years. It should be noticed that the sign is now positive, suggesting that the first variable

(natural ventilation of DSF) actually increases the LI. An important point here is that choosing a naturally ventilated DSF, if controlled properly, could have identical energy performance to a mechanically ventilated DSF whilst it has various other positive impact on buildings' performance.

5.4.5.6 Minneapolis Variables' impacts on Load Intensity

After all, the following figures (Figure 5.1 to 5.4) showcase the impact of each stated variable on LI as a whole and Heating, Cooling, and Dehumidification distinctly. Below are the interpretations:

- The figure related to LI (Figure 5.1) illustrate that the most important variable impacting LI of the proposed model in Minneapolis is *DSF Integration*.
- Figure 5.2 indicates that the most effective variable on heating is again *DSF Integration*.
- As far as cooling is concerned, the most effective variable influencing cooling loads in Minneapolis is *DSF Depth*. More specifically going from 2 to 0.5m depth has the most impact in increasing cooling loads. Simply, wider depths lower cooling loads in Minneapolis (Figure 5.3).
- Although not deastically, but *Building Ventilation Strategy* plays the most significant role on dehumidification loads where wider depth slightly increase dehumidification loads.

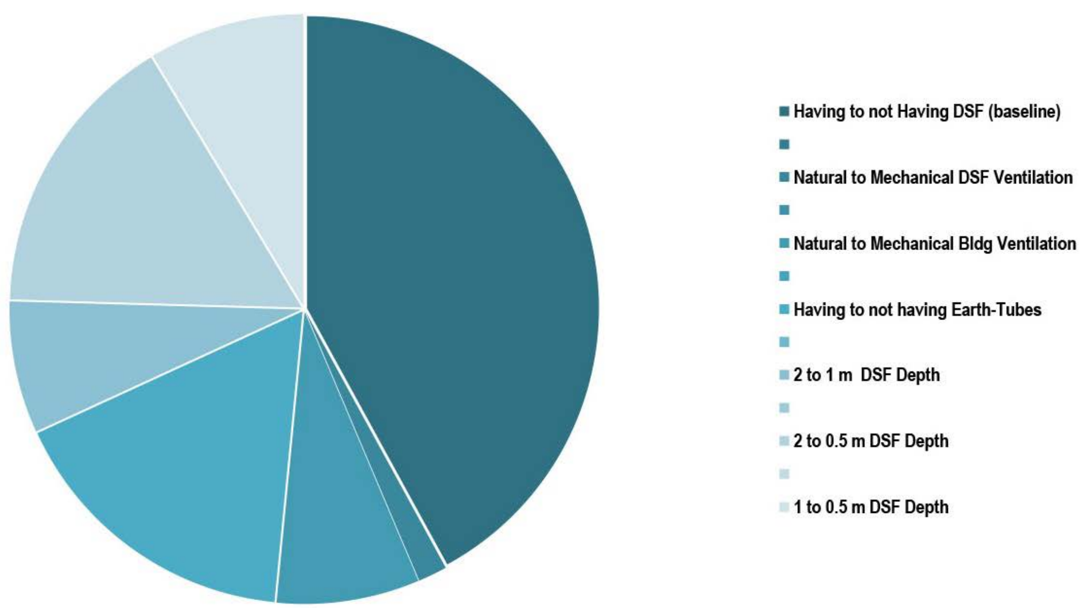


Figure 5.1
Each Variable's Impact on the Total LI for Minneapolis.

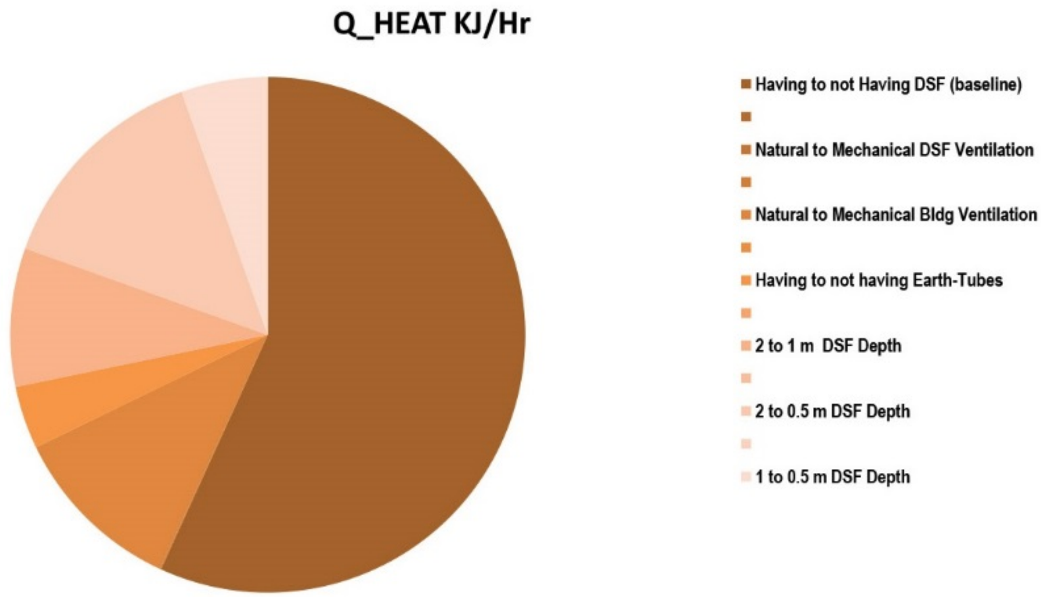


Figure 5.2
Each Variable's Impact on the Total Heating for Minneapolis.

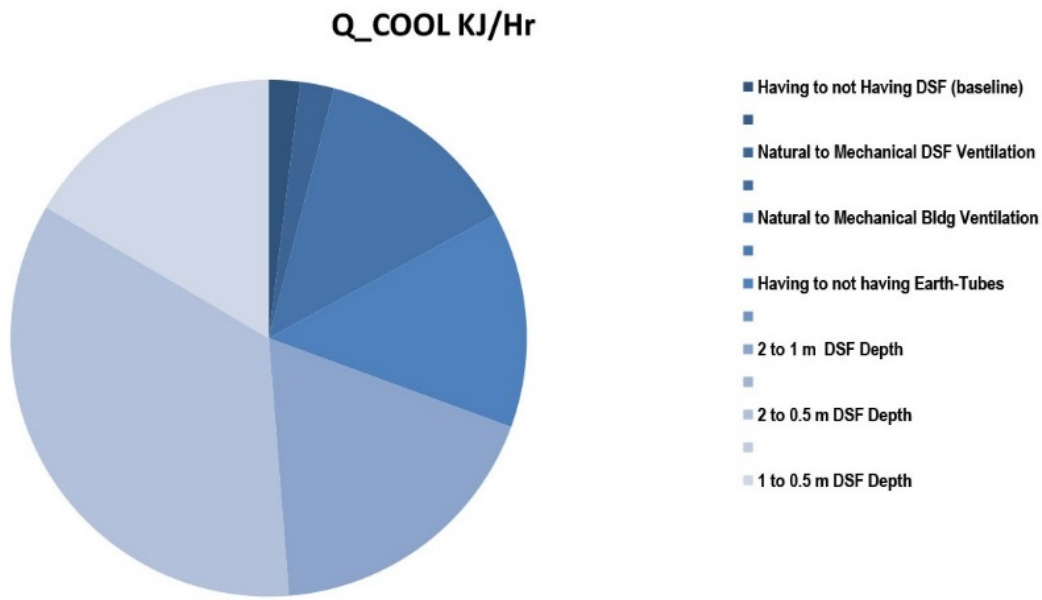


Figure 5.3
Each Variable's Impact on the Total Cooling for Minneapolis.

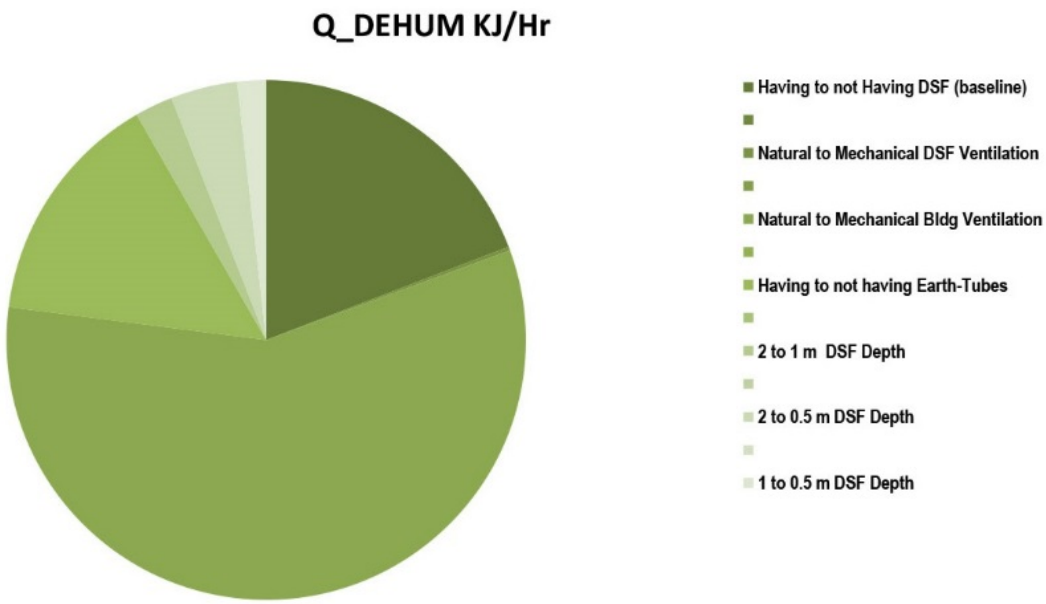


Figure 5.4
Each Variable's Impact on the Total Dehumidification for Minneapolis.

5.4.6 Phoenix, 2-meter Depth DSF

Phoenix Load Intensity Break Down (2m DSF Depth)													
Elements	Load Intensity	Load Intensity	Q_HEAT	Q_COOL	Q_DEHUM	Q_HUM	Q-INF	Q_VENT	Q_COUPL	LI_TOTAL	Vent. Rate	ACH	$/30 Yrs
RUN #	KWH/SM/Yr	KBTU/SF/Yr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	Kg/Hr	1/Hr	$
Run1	0.00	0.00	0	0	0	0	1,412	0	0	0	0.00	0.00	0
Run2	231.50	73.39	81	118,439	3,258	0	1,027	1,738	0	121,777	164.31	0.59	333,365
Run3	109.61	34.75	203	54,181	3,274	1	903	1,648	0	57,660	164.31	0.59	157,843
Run4	104.92	33.26	340	51,561	3,287	1	874	1,603	0	55,189	164.31	0.59	151,080
Run5	130.41	41.34	45	65,297	3,260	0	983	1,677	0	68,602	164.31	0.59	187,797
Run6	106.48	33.75	145	52,590	3,274	0	918	1,641	0	56,009	164.31	0.59	153,324
Phoenix Comparable Runs (2m DSF Depth)													
Run7	104.07	32.99	108	51,301	3,335	0	919	0	1,111	54,744	164.30	0.59	149,862
Run8 *	104.28	33.06	108	51,412	3,335	0	920	0	1,086	54,855	164.30	0.59	150,166
Run9	104.11	33.00	103	51,330	3,333	0	922	0	1,103	54,765	164.30	0.59	149,920
Run10 #	100.64	31.90	97	49,521	3,323	0	921	0	1,114	52,942	164.30	0.59	144,928
Run11 *	104.32	33.07	103	51,440	3,333	0	923	0	1,079	54,876	164.30	0.59	150,224
Run12 #*	102.49	32.49	97	50,489	3,324	0	923	0	1,138	53,910	164.30	0.59	147,579
Run13 ^	98.83	31.33	110	47,639	4,240	0	898	0	1,482	51,990	260.33	0.94	142,321
Run14 #^	100.56	31.88	104	48,471	4,324	0	908	0	1,348	52,898	260.31	0.94	144,809
Run15 *^	99.20	31.45	110	47,826	4,248	0	899	0	1,484	52,184	259.73	0.94	142,854
Run16 #*^	101.56	32.20	104	49,003	4,319	0	910	0	1,347	53,426	261.84	0.94	146,253

Options with Linked Earth-Tubes
* Options with Naturally Ventilated (NV) DSF
^ Options with Naturally Ventilated (NV) Bldg

Conventional Buildings Design
Attached SDF as Just a Buffer Zone
Attached SDF as an HVAC Contributer
The above Attached SDF to a NV Building

33.26 kBTU/f² Assumed as Baseline
ASHRAE Suggestion+Passive Shading

Run 13 (5.8 % less than Baseline)
Best Strategy (MV DSF+MV Bldg)

Run 15 (4.1 % less than Baseline)
2nd Best Strat. (NV DSF+NV Bldg+Earth-Tubes)

4.1 to 5.8 % less than Baseline
Best Combinations (DSF+Shading)+Earth-Tubes

Note1: Typical Office Buildings's EUI is 211 kWh/m²/yr (67 kBTU/ft²/yr) with 60% reduction based on 2030 building challenge, 85 kWh/m²/yr (27 kBTU/ft²/yr).

Note2: In typical Office Buildings, half of the EUI is due to HVAC systems. Therefore, the whole EUI would be around twice as the numbers above. ACH and Vent. Rate are average hourly of airchange & ventilation.

Note3: Q_HEAT is average energy required for heating, Q_COOL for cooling, Q_DEHUM for dehumidification, Q_HUM for humidification, Q_INF for infiltration, Q_VENT for ventilation, and Q_COUPL for coupling.

Table 5.6: Phoenix Results, 2-meter Depth DSF

The table above (Table 5.6) for the sixteen results of the 2-meter DSF depth in the hot climate of Phoenix specifies that all the proposed DSF systems (<u>Run7 D</u> to <u>Run16 I</u>) perform better than the baseline. Yet, for

the first time, results show that the integration of earth-tube system is not necessarily assisting in the system efficiency. The best option, Run13 H with 5.8% efficiency, includes a naturally ventilated building and a mechanically ventilated DSF without integrated earth-tubes system highlighted in darker blue. The second best options (Run15 I) has almost the same performance as the best option (4.1 % efficiency) highlighted in blue. These two options both consist of naturally ventilated buildings integrated with either a naturally or mechanically ventilated DSF.

The integrated passive shading device including the overhang and light-shelf proposed in Run4 B has an incredible efficiency of 55% higher than an ASHRAE-based conventional building without shading strategy, which is by far higher than all the proposed options in all the climates.

With the same assumption that the HVAC system accounts for almost 50% of the entire LI in a commercial building, the whole LI of the best proposed option will be 197.67 kwh/m²/yr (62.66 kBTU/ft²/yr). By considering a typical office building's LI that is around 211 kwh/m²/yr (67 kBTU/ft²/yr), it can be implied that the best option's LI is very close to it, although, it is still higher than the 2030 Building Challenge of 60% reduction in LI (85 kwh/m²/yr or 27 kBTU/ft²/yr). In terms of economic considerations, the best option can save around $8,759 in the presumed 30-year lifecycle of the office building.

5.4.7 Phoenix, 1-meter Depth DSF

Phoenix Load Intensity Break Down (1m DSF Depth)													
Elements	Load Intensity	Load Intensity	Q_HEAT	Q_COOL	Q_DEHUM	Q_HUM	Q-INF	Q_VENT	Q_COUPL	LI_TOTAL	Vent. Rate	ACH	$/30 Yrs
RUN #	KWH/SM/Yr	KBTU/SF/Yr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	Kg/Hr	1/Hr	$
Run1	0.00	0.00	0	0	0	0	1,412	0	0	0	0.00	0.00	0
Run2	231.50	73.39	81	118,439	3,258	0	1,027	1,738	0	121,777	164.31	0.59	333,365
Run3	109.61	34.75	203	54,181	3,274	1	903	1,648	0	57,660	164.31	0.59	157,843
Run4	104.92	33.26	340	51,561	3,287	1	874	1,603	0	55,189	164.31	0.59	151,080
Run5	136.88	43.39	45	68,697	3,259	0	984	1,678	0	72,001	164.31	0.59	197,103
Run6	109.25	34.63	137	54,061	3,271	0	918	1,641	0	57,469	164.31	0.59	157,322
Minneapolis Comparable Runs (1m DSF Depth)													
Run7	106.92	33.89	104	52,807	3,333	0	918	0	1,175	56,244	164.30	0.59	153,969
Run8 *	107.15	33.97	104	52,927	3,333	0	919	0	1,153	56,364	164.30	0.59	154,297
Run9	106.98	33.91	100	52,846	3,331	0	921	0	1,166	56,277	164.30	0.59	154,057
Run10 #	102.68	32.55	93	50,600	3,321	0	920	0	1,184	54,014	164.30	0.59	147,864
Run11 *	107.21	33.99	100	52,966	3,331	0	921	0	1,144	56,396	164.30	0.59	154,385
Run12 #*	104.69	33.19	93	51,659	3,320	0	922	0	1,213	55,072	164.30	0.59	150,761
Run13 ^	100.96	32.00	109	48,782	4,215	0	894	0	1,614	53,106	258.66	0.93	145,378
Run14 #^	103.23	32.72	101	49,869	4,332	0	908	0	1,428	54,301	257.04	0.93	148,649
Run15 *^	101.31	32.12	109	48,960	4,224	0	895	0	1,614	53,293	258.16	0.93	145,889
Run16 #*^	104.21	33.04	101	50,390	4,328	0	909	0	1,432	54,819	258.53	0.93	150,068

Options with Linked Earth-Tubes
* Options with Naturally Ventilated (NV) DSF
^ Options with Naturally Ventilated (NV) Bldg

Conventional Buildings Design
Attached SDF as Just a Buffer Zone
Attached SDF as an HVAC Contributer
The above Attached SDF to a NV Building

33.26 kBTU/f² Assumed as Baseline
ASHRAE Suggestion+Passive Shading

Run 13 (3.8 % less than Baseline)
Best Strategy (MV DSF+MV Bldg)

Run 15 (3.4 % less than Baseline)
2nd Best Strat. (NV DSF+NV Bldg+Earth-Tubes)

2.1 to 3.8 % less than Baseline
Best Combinations (DSF+Shading)+Earth-Tubes

Note1: Typical Office Buildings's EUI is 211 kWh/m²/yr (67 kBTU/ft²/yr) with 60% reduction based on 2030 building challenge, 85 kWh/m²/yr (27 kBTU/ft²/yr).

Note2: In typical Office Buildings, half of the EUI is due to HVAC systems. Therefore, the whole EUI would be around twice as the numbers above. ACH and Vent. Rate are aver 0.0161

Note3: Q_HEAT is average energy required for heating, Q_COOL for cooling, Q_DEHUM for dehumidification, Q_HUM for humidification, Q_INF for infiltration, Q_VENT for ventilation, and Q_COUPL for coupling.

Table 5.7: Phoenix Results, 1-meter Depth DSF

For the first time, the above table (Table 5.7) displays that some of the proposed, functioning DSF systems are performing poorer than the baseline when the DSF depth is narrower to one meter. Among all, Run13 H is still the best option, although, its efficiency is lowered to 3.8% better than the baseline. Run15 I with 3.4% better efficiency are still among the best options. The proposed integrated DSFs in this climate cannot always have higher efficiency even if those are integrated with the earth-tubes system. Ironically, the integrated passive shading device including the overhang and light-shelf proposed in Run4 B has further efficiency in comparison to all the proposed DSF systems in this climate.

The whole LI of the best proposed option is also 201.91 kwh/m²/yr (64 kBTU/ft²/yr), which is still marginally more efficient than a typical office building of 211 kwh/m²/yr (67 kBTU/ft²/yr). Economically, the best option here can help saving around $5,702 in a 30-year assumed lifecycle of the office building.

5.4.8 Phoenix, 0.5-meter Depth DSF

Phoenix Load Intensity Break Down (0.5m DSF Depth)													
Elements	Load Intensity	Load Intensity	Q_HEAT	Q_COOL	Q_DEHUM	Q_HUM	Q-INF	Q_VENT	Q_COUPL	LI_TOTAL	Vent. Rate	ACH	$/30 Yrs
RUN #	KWH/SM/Yr	KBTU/SF/Yr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	Kg/Hr	1/Hr	$
Run1	0.00	0.00	0	0	0	0	1,412	0	0	0	0.00	0.00	0
Run2	231.50	73.39	81	118,439	3,258	0	1,027	1,738	0	121,777	164.31	0.59	333,365
Run3	109.61	34.75	203	54,181	3,274	1	903	1,648	0	57,660	164.31	0.59	157,843
Run4	104.92	33.26	340	51,561	3,287	1	874	1,603	0	55,189	164.31	0.59	151,080
Run5	144.36	45.76	40	72,640	3,258	0	992	1,686	0	75,938	164.31	0.59	207,881
Run6	101.06	32.03	135	49,752	3,271	0	907	1,652	0	53,158	164.31	0.59	145,521
Phoenix Comparable Runs (0.5m DSF Depth)													
Run7	109.01	34.56	105	53,904	3,333	0	916	0	1,233	57,342	164.30	0.59	156,974
Run8 *	109.23	34.63	105	54,022	3,332	0	917	0	1,214	57,460	164.30	0.59	157,297
Run9	109.08	34.58	99	53,952	3,330	0	919	0	1,220	57,381	164.30	0.59	157,082
Run10 #	104.34	33.07	92	51,472	3,319	0	919	0	1,238	54,884	164.30	0.59	150,246
Run11 *	109.31	34.65	99	54,069	3,330	0	920	0	1,201	57,499	164.30	0.59	157,404
Run12 #*	106.44	33.74	92	52,578	3,319	0	921	0	1,270	55,989	164.30	0.59	153,271
Run13 ^	102.74	32.57	110	49,736	4,200	0	891	0	1,705	54,046	257.07	0.93	147,950
Run14 #^	105.29	33.38	100	50,943	4,344	0	908	0	1,487	55,387	254.07	0.91	151,622
Run15 *^	103.08	32.68	110	49,903	4,210	0	892	0	1,703	54,222	256.77	0.92	148,433
Run16 #*^	106.32	33.70	100	51,488	4,341	0	909	0	1,488	55,929	255.83	0.92	153,105

Options with Linked Earth-Tubes
* Options with Naturally Ventilated (NV) DSF
^ Options with Naturally Ventilated (NV) Bldg

Conventional Buildings Design
Attached SDF as Just a Buffer Zone
Attached SDF as an HVAC Contributer
The above Attached SDF to a NV Building
33.26 kBTU/f² Assumed as Baseline
ASHRAE Suggestion+Passive Shading
Run 13 (2.1 % less than Baseline)
Best Strategy (MV DSF+MV Bldg+Earth-Tubes)
Run 15 (1.8 % less than Baseline)
2nd Best Strat. (NV DSF+NV Bldg+Earth-Tubes)
0 to 2.1 % less than Baseline
Best Combinations (DSF+Shading)+Earth-Tubes

Note1: Typical Office Buildings's EUI is 211 kWh/m²/yr (67 kBTU/ft²/yr) with 60% reduction based on 2030 building challenge, 85 kWh/m²/yr (27 kBTU/ft²/yr).

Note2: In typical Office Buildings, half of the EUI is due to HVAC systems. Therefore, the whole EUI would be around twice as the numbers above. ACH and Vent. Rate are average hourly of airchange & ventilation.

Note3: Q_HEAT is average energy required for heating, Q_COOL for cooling, Q_DEHUM for dehumidification, Q_HUM for humidification, Q_INF for infiltration, Q_VENT for ventilation, and Q_COUPL for coupling.

Table 5.8: Phoenix Results, 0.5-meter Depth DSF

The above table (Table 5.8) for the DSF's narrow depth of 0.5m suggests that Run13 H is still the best option, although, its performance is now only 2.1% more efficient than the baseline. The same as the pattern seen for the two previous DSF depths, Run15 I is the best second option with around 1.8% higher efficiency. Accordingly, not all the proposed integrated DSFs in this option of 0.5m DSF depth are performing better

than the baseline. Yet, the integrated passive shading device proposed in the Run4 B still has high efficiency compared to the best option.

The whole LI of the best proposed option will be 205.49 kwh/m²/yr (65.14 kBTU/ft²/yr), which is again marginally better than a typical office building of 211 kwh/m²/yr (67 kBTU/ft²/yr) and clearly worse than the 2030 Building Challenge (85 kwh/m²/yr or 27 kBTU/ft²/yr). The best option in this condition is not economically viable as it just save $3,130 during a 30-year presumed lifecycle of this office building. The following section compares all the results for the climate of Phoenix.

Phoenix Load Intensity Break Down (2m DSF Depth)													
Elements	Load Intensity	Load Intensity	Q_HEAT	Q_COOL	Q_DEHUM	Q_HUM	Q-INF	Q_VENT	Q_COUPL	LI_TOTAL	Vent. Rate	ACH	$/30 Yrs
RUN #	KWH/SM/Yr	KBTU/SF/Yr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	Kg/Hr	1/Hr	$
Run1	0.00	0.00	0	0	0	0	1,412	0	0	0	0.00	0.00	0
Run2	231.50	73.39	81	118,439	3,258	0	1,027	1,738	0	121,777	164.31	0.59	333,365
Run3	109.61	34.75	203	54,181	3,274	1	903	1,648	0	57,660	164.31	0.59	157,843
Run4	104.92	33.26	340	51,561	3,287	1	874	1,603	0	55,189	164.31	0.59	151,080
Run5	130.41	41.34	45	65,297	3,260	0	983	1,677	0	68,602	164.31	0.59	187,797
Run6	106.48	33.75	145	52,590	3,274	0	918	1,641	0	56,009	164.31	0.59	153,324
Phoenix Comparable Runs (2m DSF Depth)													
Run7	104.07	32.99	108	51,301	3,335	0	919	0	1,111	54,744	164.30	0.59	149,862
Run8 *	104.28	33.06	108	51,412	3,335	0	920	0	1,086	54,855	164.30	0.59	150,166
Run9	104.11	33.00	103	51,330	3,333	0	922	0	1,103	54,765	164.30	0.59	149,920
Run10 #	100.64	31.90	97	49,521	3,323	0	921	0	1,114	52,942	164.30	0.59	144,928
Run11 *	104.32	33.07	103	51,440	3,333	0	923	0	1,079	54,876	164.30	0.59	150,224
Run12 #*	102.49	32.49	97	50,489	3,324	0	923	0	1,138	53,910	164.30	0.59	82,685
Run13 ^	98.83	31.33	110	47,639	4,240	0	898	0	1,482	51,990	260.33	0.94	142,321
Run14 #^	100.56	31.88	104	48,471	4,324	0	908	0	1,348	52,898	260.31	0.94	144,809
Run15 *^	99.20	31.45	110	47,826	4,248	0	899	0	1,484	52,184	259.73	0.94	142,854
Run16 #*^	101.56	32.20	104	49,003	4,319	0	910	0	1,347	53,426	261.84	0.94	146,253

Note1: Typical Office Buildings's EUI is 211 kWh/m²/yr (67 kBTU/ft²/yr) with 60% reduction based on 2030 building challenge, 85 kWh/m²/yr (27 kBTU/ft²/yr).

Note2: In typical Office Buildings, half of the EUI is due to HVAC systems. Therefore, the whole EUI would be around twice as the numbers above.

Options with Linked Earth-Tubes
* Options with Naturally Ventilated (NV) DSF
^ Options with Naturally Ventilated (NV) Bldg
Conventional Buildings Design
Attached SDF as Just a Buffer Zone
Attached SDF as an HVAC Contributer
The above Attached SDF to a NV Building

33.26 kBTU/f² Assumed as Baseline
ASHRAE Suggestion+Passive Shading

Run 13 (5.8 % less than Baseline)
Best Strategy (MV DSF+MV Bldg)

Run 15 (4.1 % less than Baseline)
2nd Best Strat. (NV DSF+NV Bldg+Earth-Tubes)

4.1 to 5.8 % less than Baseline
Best Combinations (DSF+Shading)+Earth-Tubes

Phoenix Load Intensity Break Down (1m DSF Depth)													
Elements	Load Intensity	Load Intensity	Q_HEAT	Q_COOL	Q_DEHUM	Q_HUM	Q-INF	Q_VENT	Q_COUPL	LI_TOTAL	Vent. Rate	ACH	$/30 Yrs
RUN #	KWH/SM/Yr	KBTU/SF/Yr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	Kg/Hr	1/Hr	$
Run1	0.00	0.00	0	0	0	0	1,412	0	0	0	0.00	0.00	0
Run2	231.50	73.39	81	118,439	3,258	0	1,027	1,738	0	121,777	164.31	0.59	333,365
Run3	109.61	34.75	203	54,181	3,274	1	903	1,648	0	57,660	164.31	0.59	157,843
Run4	104.92	33.26	340	51,561	3,287	1	874	1,603	0	55,189	164.31	0.59	151,080
Run5	136.88	43.39	45	68,697	3,259	0	984	1,678	0	72,001	164.31	0.59	197,103
Run6	109.25	34.63	137	54,061	3,271	0	918	1,641	0	57,469	164.31	0.59	157,322
Minneapolis Comparable Runs (1m DSF Depth)													
Run7	106.92	33.89	104	52,807	3,333	0	918	0	1,175	56,244	164.30	0.59	153,969
Run8 *	107.15	33.97	104	52,927	3,333	0	919	0	1,153	56,364	164.30	0.59	154,297
Run9	106.98	33.91	100	52,846	3,331	0	921	0	1,166	56,277	164.30	0.59	154,057
Run10 #	102.68	32.55	93	50,600	3,321	0	920	0	1,184	54,014	164.30	0.59	147,864
Run11 *	107.21	33.99	100	52,966	3,331	0	921	0	1,144	56,396	164.30	0.59	154,385
Run12 #*	104.69	33.19	93	51,659	3,320	0	922	0	1,213	55,072	164.30	0.59	150,761
Run13 ^	100.96	32.00	109	48,782	4,215	0	894	0	1,614	53,106	258.66	0.93	145,378
Run14 #^	103.23	32.72	101	49,869	4,332	0	908	0	1,428	54,301	257.04	0.93	148,649
Run15 *^	101.31	32.12	109	48,960	4,224	0	895	0	1,614	53,293	258.16	0.93	145,889
Run16 #*^	104.21	33.04	101	50,390	4,328	0	909	0	1,432	54,819	258.53	0.93	150,068

Note1: Typical Office Buildings's EUI is 211 kWh/m²/yr (67 kBTU/ft²/yr) with 60% reduction based on 2030 building challenge, 85 kWh/m²/yr (27 kBTU/ft²/yr).

Note2: In typical Office Buildings, half of the EUI is due to HVAC systems. Therefore, the whole EUI would be around twice as the numbers above. 0.0161

Options with Linked Earth-Tubes
* Options with Naturally Ventilated (NV) DSF
^ Options with Naturally Ventilated (NV) Bldg
Conventional Buildings Design
Attached SDF as Just a Buffer Zone
Attached SDF as an HVAC Contributer
The above Attached SDF to a NV Building

33.26 kBTU/f² Assumed as Baseline
ASHRAE Suggestion+Passive Shading

Run 13 (3.8 % less than Baseline)
Best Strategy (MV DSF+MV Bldg)

Run 15 (3.4 % less than Baseline)
2nd Best Strat. (NV DSF+NV Bldg+Earth-Tubes)

2.1 to 3.8 % less than Baseline
Best Combinations (DSF+Shading)+Earth-Tubes

Phoenix Load Intensity Break Down (0.5m DSF Depth)													
Elements	Load Intensity	Load Intensity	Q_HEAT	Q_COOL	Q_DEHUM	Q_HUM	Q-INF	Q_VENT	Q_COUPL	LI_TOTAL	Vent. Rate	ACH	$/30 Yrs
RUN #	KWH/SM/Yr	KBTU/SF/Yr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	Kg/Hr	1/Hr	$
Run1	0.00	0.00	0	0	0	0	1,412	0	0	0	0.00	0.00	0
Run2	231.50	73.39	81	118,439	3,258	0	1,027	1,738	0	121,777	164.31	0.59	333,365
Run3	109.61	34.75	203	54,181	3,274	1	903	1,648	0	57,660	164.31	0.59	157,843
Run4	104.92	33.26	340	51,561	3,287	1	874	1,603	0	55,189	164.31	0.59	151,080
Run5	144.36	45.76	40	72,640	3,258	0	992	1,686	0	75,938	164.31	0.59	207,881
Run6	101.06	32.03	135	49,752	3,271	0	907	1,652	0	53,158	164.31	0.59	145,521
Phoenix Comparable Runs (0.5m DSF Depth)													
Run7	109.01	34.56	105	53,904	3,333	0	916	0	1,233	57,342	164.30	0.59	156,974
Run8 *	109.23	34.63	105	54,022	3,332	0	917	0	1,214	57,460	164.30	0.59	157,297
Run9	109.08	34.58	99	53,952	3,330	0	919	0	1,220	57,381	164.30	0.59	157,082
Run10 #	104.34	33.07	92	51,472	3,319	0	919	0	1,238	54,884	164.30	0.59	150,246
Run11 *	109.31	34.65	99	54,069	3,330	0	920	0	1,201	57,499	164.30	0.59	157,404
Run12 #*	106.44	33.74	92	52,578	3,319	0	921	0	1,270	55,989	164.30	0.59	82,685
Run13 ^	102.74	32.57	110	49,736	4,200	0	891	0	1,705	54,046	257.07	0.93	147,950
Run14 #^	105.29	33.38	100	50,943	4,344	0	908	0	1,487	55,387	254.07	0.91	151,622
Run15 *^	103.08	32.68	110	49,903	4,210	0	892	0	1,703	54,222	256.77	0.92	148,433
Run16 #*^	106.32	33.70	100	51,488	4,341	0	909	0	1,488	55,929	255.83	0.92	153,105

Note1: Typical Office Buildings's EUI is 211 kWh/m²/yr (67 kBTU/ft²/yr) with 60% reduction based on 2030 building challenge, 85 kWh/m²/yr (27 kBTU/ft²/yr).

Note2: In typical Office Buildings, half of the EUI is due to HVAC systems. Therefore, the whole EUI would be around twice as the numbers above.

Options with Linked Earth-Tubes
* Options with Naturally Ventilated (NV) DSF
^ Options with Naturally Ventilated (NV) Bldg
Conventional Buildings Design
Attached SDF as Just a Buffer Zone
Attached SDF as an HVAC Contributer
The above Attached SDF to a NV Building

33.26 kBTU/f² Assumed as Baseline
ASHRAE Suggestion+Passive Shading

Run 13 (2.1 % less than Baseline)
Best Strategy (MV DSF+MV Bldg+Earth-Tubes)

Run 15 (1.8 % less than Baseline)
2nd Best Strat. (NV DSF+NV Bldg+Earth-Tubes)

0 to 2.1 % less than Baseline
Best Combinations (DSF+Shading)+Earth-Tubes

Table 5.9: Phoenix Combined Results

5.4.9 Combined analysis for Phoenix

The combined table of Phoenix demonstrates the following findings.

- The integration of earth-tubes is not generally assisting in lowering LI in this climate with the exception of Run10 F, a mechanically ventilated building integrated with a mechanically ventilated DSF linked into the earth via earth-tube system. The efficiency compared to the baseline is very insignificant though.
- The most energy efficient option for all the alternatives is Run13 H, in which a naturally conditioned office building is integrated with a mechanically ventilated DSF. It has a maximum of 5.8% higher efficiency, compared to the baseline for the DSF depth of 2m and a minimum of 2.1% higher efficiency for DSF depths of 0.5m.
- In terms of the most efficient DSF depth in this climate, the 2-meter depth has better performance while the difference is not as significant as the other climates. LI has similarly an inverse correlation with the DSF depth; the LI in Phoenix will be increased by decreasing the DSF's depth.
- In the stated best option of Run13 H, the self-regulating vents in the office zones, functioning as a controller for exhaustion of air, is essential in lowering LI.
- The outcomes are evidently consistent throughout all the options in the climate of Phoenix.
- A buffer DSF system, that does not introduce air from cavity into the office zones, is not lowering LI in this climate except a very insignificant better efficiency with the 2m DSF depths.
- The comparison between the buffer and HVAC-contributing DSF in which the air in the cavity is either just exhausted (Run7 D) or used for heating during cold seasons (Run9 F), indicates that introduction of air from the cavity into the office spaces, does not considerably reduce the LI of the integrated DSFs.
- Run4 B's results associated with the option of an integrated, passive shading device, which include a combined light-shelf and overhang, has 55% higher efficiency than the conventional building in Run2 B underscoring higher impacts of proper shading strategies.
- Compared to a proper passive shading device strategy, the integration of earth-tubes is insignificant in lowering LI in this climate except for the DSF depth of 2m that could further aid after all shading strategies are integrated.

5.4.10 Phoenix, Variables Main Effects

This section reflects on the main effect of various variables in Phoenix, such as the DSF Integration, DSF Depth, DSF Ventilation Strategy, Building Ventilation Strategy, and Earth-Tubes Integration, which reinterprets their general applicability from a broader standpoint. Each main effect is calculated by applying

the results of Run7 D to Run16 I for all three DSF depths (Table 5.10). The table below illustrates the calculated main effect for each variable, individually explained in the following page in the order of their effectiveness.

Phoenix Main Effects (Run 7-16)	Load Intensity	Load Intensity	Q_HEAT	Q_COOL	Q_DEHUM	Q_HUM	Q-INF	Q_VENT	Q_COUPL	LI_TOTAL	Vent. Rate	ACH	$/30 Yrs
	KWH/SM/Yr	KBTU/SF/Yr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	Kg/Hr	1/Hr	$
Having to not Having DSF (baseline)	-0.57	-0.18	-237	-484	420	-1	39	-1,603	1,306	-302	37.55	0.14	-826
Natural to Mechanical DSF Ventilation	0.76	0.24	0	397	1	0	1	0	-3	398	0	0.00	1,090
Natural to Mechanical Bldg Ventilation	-3.44	-1.09	5	-2,766	948	0	-18	0	342	-1,812	94	0.34	-4,960
Having to not having Earth-Tubes	-0.39	-0.12	-7	-247	49	0	7	0	-69	-205	0	0.00	-562
2 to 1 m DSF Depth	-2.53	-0.80	3	-1,337	5	0	2	0	-83	-1,330	1	0.00	-3,640
2 to 0.5 m DSF Depth	-4.48	-1.42	3	-2,364	6	0	3	0	-147	-2,355	2	0.01	-6,447
1 to 0.5 m DSF Depth	-1.95	-0.62	0	-1,026	1	0	2	0	-64	-1,025	1	0.00	-2,807

Note1: negetive sign means that one can lose when going from the first to the second option.

Note2: Having to not having DSF is a comparison between average of all options with DSF and the baseline.

Table 5.10: Phoenix, Variables Main Effects

5.4.10.1 DSF Depth

Similar to Minneapolis and Atlanta, the DSF depth is a highly important variable in LI where the same inverse correlation is also the case in this climate; the 2-meter depth performs better than the 1-meter DSF depth, and the 0.5-meter depth has the least efficiency in general. The following statements would describe each:

- From the 2-meter to 0.5-meter depth, the main effect is -4.48 kwh/m²/yr (-1.42 kBTU/ft²/yr) equal to $6,447 economic saving for 30 years.
- From the 2-meter to 1-meter depth, the main effect is -2.53 kwh/m²/yr (-0.80 kBTU/ft²/yr) equal to $3,640 economic saving for 30 years.
- From the 1-meter to 0.5-meter depth, the main effect is -1.95 kwh/m²/yr (-0.62 kBTU/ft²/yr) equal to $2,807 for economic saving 30 years.

5.4.10.2 Building Ventilation Strategy

In Phoenix, the ventilation strategy of the building zones themselves is the most effective variable after DSF depth where a naturally ventilated building is generally higher efficient especially when it is combined with an appropriate integration of the DSF and earth-tubes systems. This is based on the main effect from naturally to mechanically ventilated building that is -3.44 kwh/m²/yr (-1.09 kBTU/ft²/yr) equivalent to $4,960 saving per 30 years.

5.4.10.3 DSF Ventilation Strategy

The next important variable in Phoenix regarding the proposed system, the DSF ventilation strategy refers to whether the air in the cavity is ventilated naturally or mechanically. From naturally to mechanically ventilated DSF, the main effect is +0.76 kwh/m²/yr (+0.24 kBTU/ft²/yr). It is equal to $1,090 loss in 30 years. Simply put, there is not considerable change in LI if the mechanically ventilated DSF is replaced by a naturally ventilated system that is not integrated with other complimentary solutions. In this situation, the other benefits of a natural ventilation system come to play in choosing an appropriate ventilation strategy.

5.4.10.4 DSF Integration

Next, the DSF system's integration is the most effective variable. The main effect of the DSF integration from being present to not being present is -0.57 kwh/m²/yr (-0.18 kBTU/ft²/yr), resulting in $826 economic saving. This means that having the DSF in the climate of Phoenix will not considerably assist in LI decrease.

5.4.10.4 Earth-Tubes Integration

From having to not having the earth-tubes system, the main effect is -0.39 kwh/m²/yr (-0.12 kBTU/ft²/yr), which is equal to $562 saving in expenditure during the building life-cycle. Obviously, this amount of saving is not comparable to the added cost of an earth-tube system, but it clarifies to what extents the general application of the system helps to reduce LI.

5.4.10.5 Phoenix Variables' impacts on Load Intensity

After all, the following figures (Figure 5.5 to 5.8) showcase the impact of each stated variable on LI as a whole and Heating, Cooling, and Dehumidification distinctly. Below are the interpretations:

- The figure related to LI (Figure 5.5) illustrate that the most important variable impacting LI of the proposed model in Phoenix are *DSF and Earth-Tubes Integration*.
- Figure 5.6 indicates that the most effective variable on heating is again *DSF Integration*.
- As far as cooling is concerned, the most effective variables influencing cooling loads in Phoenix are *Building Ventilation Strategy* and *DSF Depth*. Going from 2 to 0.5m depth impacts cooling loads where narrower depths lower cooling loads in Phoenix (Figure 5.7).
- Although not deastically, but *Building Ventilation Strategy* plays the most significant role on dehumidification loads where wider depth slightly increase dehumidification loads (Figure 5.8).

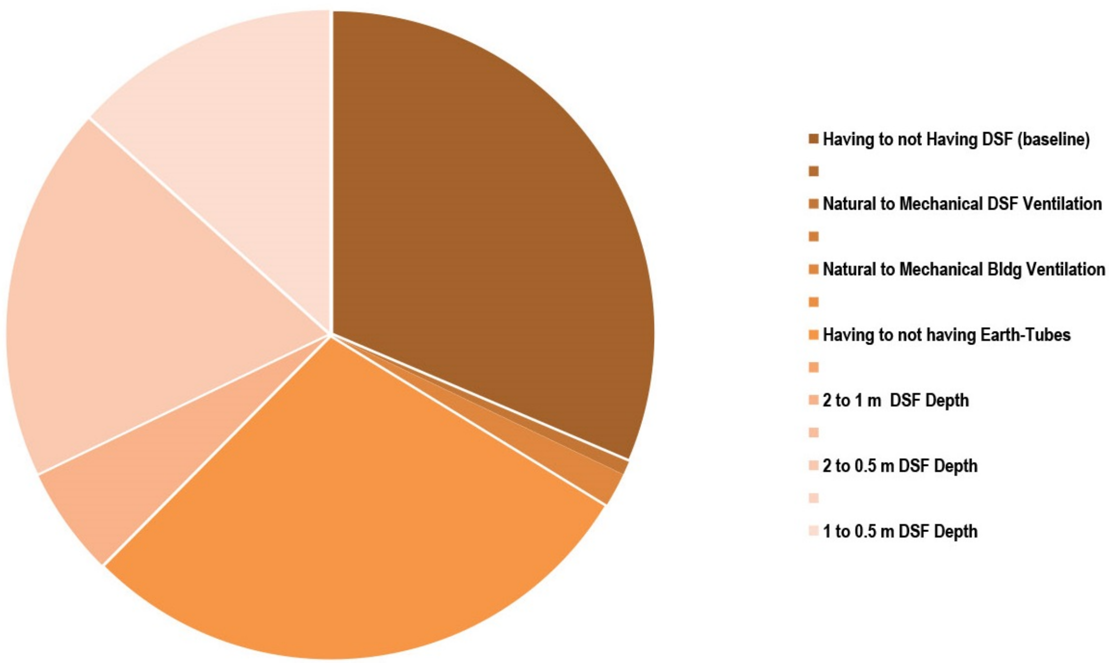


Figure 5.5
Each Variable's Impact on the Total LI for Phoenix.

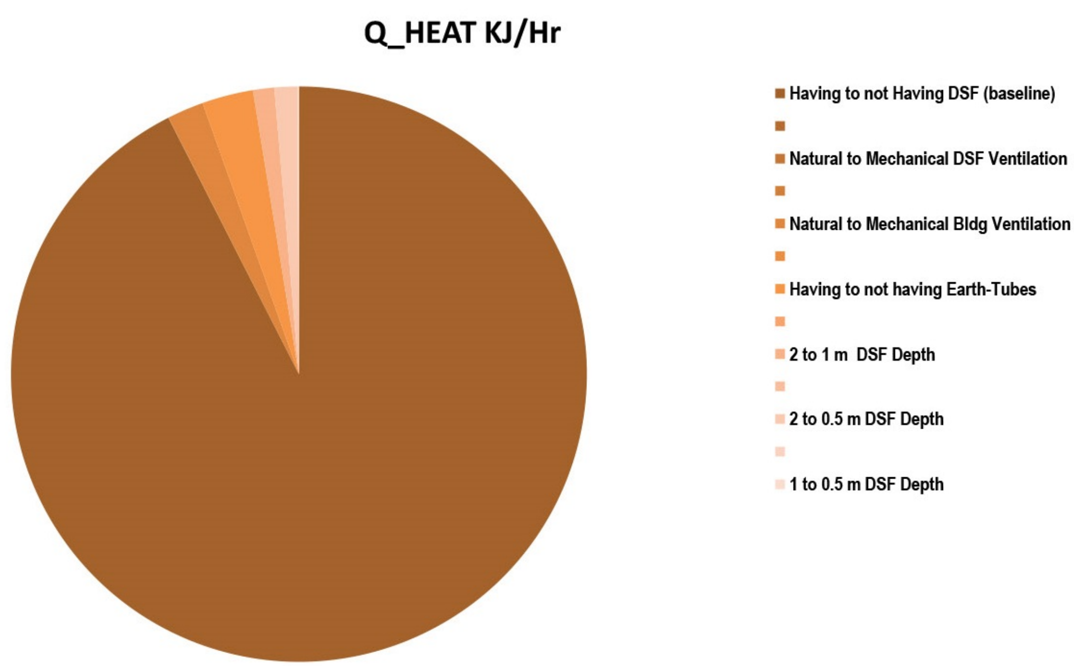


Figure 5.6
Each Variable's Impact on the Total Heating for Phoenix.

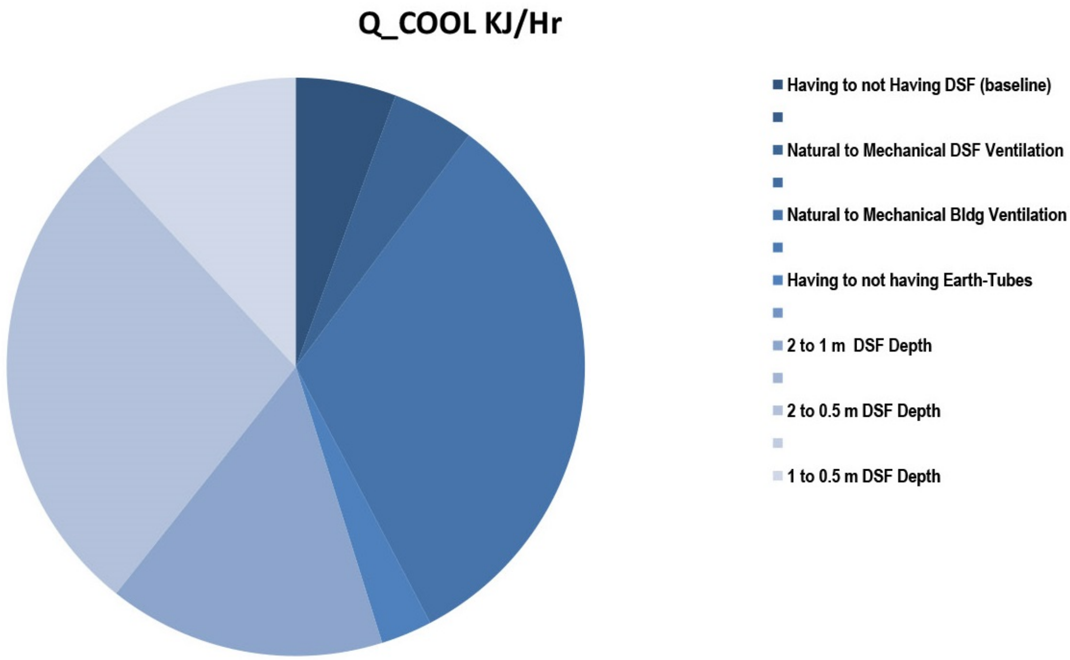


Figure 5.7
Each Variable's Impact on the Total Cooling for Phoenix.

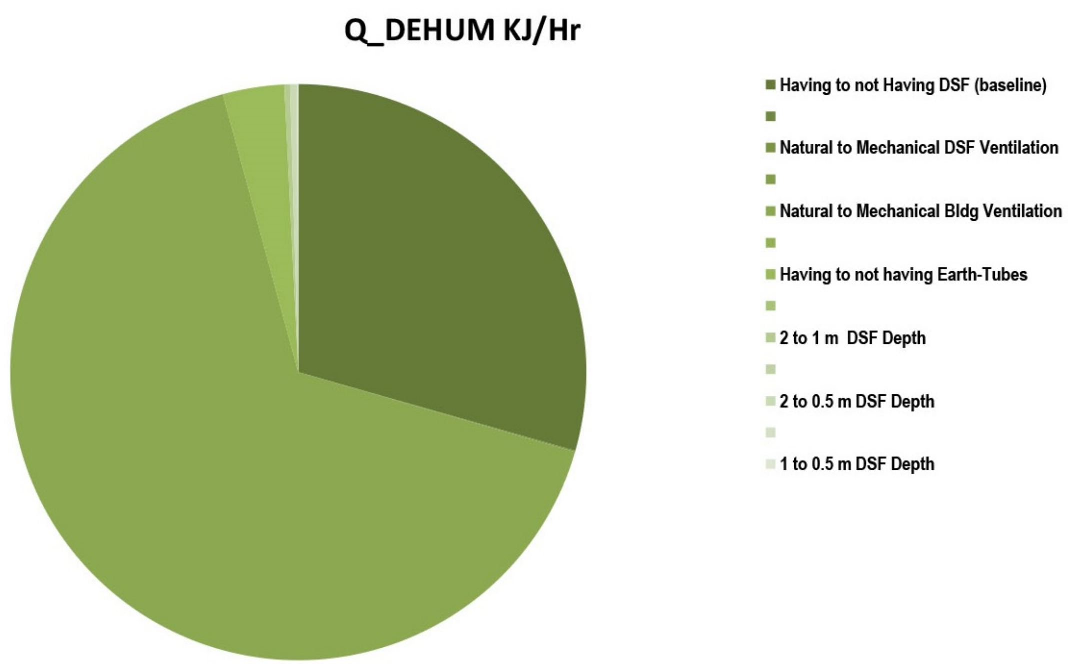


Figure 5.8
Each Variable's Impact on the Total Dehumidification for Phoenix.

5.4.11 Atlanta, 2-meter Depth DSF

Atlanta Load Intensity Break Down (2m DSF Depth)														
Elements	Load Intensity	Load Intensity	Q_HEAT	Q_COOL	Q_DEHUM	Q_HUM	Q-INF	Q_VENT	Q_COUPL	LI_TOTAL	Vent. Rate	ACH	$/30 Yrs
RUN #	KWH/SM/Yr	KBTU/SF/Yr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	Kg/Hr	1/Hr	$
Run1	0.00	0.00	0	0	0	0	1,247	0	0	0	0.00	0.00	0
Run2	147.88	46.88	1,399	67,442	8,945	4	1,155	1,763	0	77,791	164.32	0.59	212,952
Run3	77.65	24.62	3,183	28,132	9,525	7	962	1,563	0	40,847	164.32	0.59	111,818
Run4	74.72	23.69	4,523	25,167	9,610	7	917	1,488	0	39,307	164.32	0.59	107,602
Run5	104.30	33.06	294	45,816	8,756	0	1,226	1,794	0	54,866	164.32	0.59	150,196
Run6	89.14	28.26	474	37,471	8,942	0	1,155	1,735	0	46,888	164.32	0.59	128,356
Atlanta Comparable Runs (2m DSF Depth)													
Run7	80.24	25.44	563	32,569	9,076	0	1,107	0	1,283	42,208	164.30	0.59	115,544
Run8 *	71.91	22.80	3,016	25,309	9,499	3	970	0	1,148	37,826	164.30	0.59	103,549
Run9	71.12	22.54	2,714	25,220	9,472	3	977	0	1,011	37,409	164.30	0.59	102,407
Run10 #	68.06	21.57	2,650	24,016	9,132	3	973	0	1,112	35,801	164.30	0.59	98,005
Run11 *	71.36	22.62	2,714	25,357	9,463	3	978	0	1,011	37,537	164.30	0.59	102,757
Run12 #*	69.30	21.97	2,644	24,691	9,116	3	977	0	1,071	36,454	164.30	0.59	99,792
Run13 ^	71.67	22.72	2,513	24,107	11,077	2	957	0	1,376	37,699	217.09	0.78	103,200
Run14 #^	70.10	22.22	2,479	23,966	10,429	2	958	0	1,328	36,875	212.98	0.77	100,946
Run15 *^	71.92	22.80	2,513	24,277	11,043	2	958	0	1,386	37,834	216.75	0.78	103,571
Run16 #*^	70.61	22.38	2,479	24,267	10,396	2	960	0	1,338	37,144	213.55	0.77	101,680

Note1: Typical Office Buildings's EUI is 211 kWh/m²/yr (67 kBTU/ft²/yr) with 60% reduction based on 2030 building challenge, 85 kWh/m²/yr (27 kBTU/ft²/yr).

Note2: In typical Office Buildings, half of the EUI is due to HVAC systems. Therefore, the whole EUI would be around twice as the numbers above. ACH and Vent. Rate are average hourly of airchange & ventilation.

Note3: Q_HEAT is average energy required for heating, Q_COOL for cooling, Q_DEHUM for dehumidification, Q_HUM for humidification, Q_INF for infiltration, Q_VENT for ventilation, and Q_COUPL for coupling.

Options with Linked Earth-Tubes
* Options with Naturally Ventilated (NV) DSF
^ Options with Naturally Ventilated (NV) Bldg

Conventional Buildings Design
Attached SDF as Just a Buffer Zone
Attached SDF as an HVAC Contributer
The above Attached SDF to a NV Building

23.69 kBTU/f² Assumed as Baseline
ASHRAE Suggestion+Passive Shading

Run 10 (8.9 % less than Baseline)
Best Strategy (MV DSF+MV Bldg+Earth-Tubes)

Run 14 (6.1 % less than Baseline)
2nd Best Strat. (NV DSF+NV Bldg+Earth-Tubes)

5.5 to 8.9 % less than Baseline
Best Combinations (DSF+Shading+Earth-Tubes)

Table 5.11: Atlanta Results, 2-meter Depth DSF

In this climate, all the proposed 2-meter DSF systems are more efficient than the baseline except Run7 D shown in (Table 5.11). The same as the climate of Minneapolis, the best option is Run10 F that have mechanically ventilated building and DSF without earth-tubes system, highlighted in darker blue, with 8.9% higher efficiency in comparison to the baseline. The second best option is Run14 H with 6.1% higher efficiency. The proposed integrated DSFs in this condition, thus, considerably minimize LI ranging from 5.5 to 8.9%. Air-change average is also higher than the minimum required rate for naturally ventilated options.

It is also notable that this climate has the integrated passive shading device including the overhang and light-shelf proposed as the maximum heat gain was not the goal in this more moderate climatic condition. This is stressing the importance of the impact of a well-drafted shading device integration in lowering the LI of a conventional building.

After all, assuming that the HVAC system accounts for almost 50% of the entire LI in a commercial building, the whole LI of the best proposed option will be 136.12 kwh/m²/yr (43.14 kBTU/ft²/yr). By considering a typical office building's EUI that is around 211 kwh/m²/yr (67 kBTU/ft²/yr), it can be implied that the best option's LI is significantly lower, although, it is still higher than the 2030 Building Challenge. The best option can save around $9,597 during the 30-year presumed lifecycle of the office building.

5.4.12 Atlanta, 1-meter Depth DSF

Atlanta Load Intensity Break Down (1m DSF Depth)													
Elements	Load Intensity	Load Intensity	Q_HEAT	Q_COOL	Q_DEHUM	Q_HUM	Q-INF	Q_VENT	Q_COUPL	LI_TOTAL	Vent. Rate	ACH	$/30 Yrs
RUN #	KWH/SM/Yr	KBTU/SF/Yr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	Kg/Hr	1/Hr	$
Run1	0.00	0.00	0	0	0	0	1,247	0	0	0	0.00	0.00	0
Run2	147.88	46.88	1,399	67,442	8,945	4	1,155	1,763	0	77,791	164.32	0.59	212,952
Run3	77.65	24.62	3,183	28,132	9,525	7	962	1,563	0	40,847	164.32	0.59	111,818
Run4	74.72	23.69	4,523	25,167	9,610	7	917	1,488	0	39,307	164.32	0.59	107,602
Run5	89.18	28.27	1,991	35,816	9,099	4	1,062	1,633	0	46,910	164.32	0.59	128,417
Run6	75.75	24.01	3,338	27,073	9,435	4	972	1,537	0	39,849	164.32	0.59	109,087
Atlanta Comparable Runs (1m DSF Depth)													
Run7	73.22	23.21	2,763	26,287	9,460	4	975	0	1,205	38,514	164.30	0.59	105,432
Run8 *	73.28	23.23	2,855	26,225	9,464	4	973	0	1,201	38,548	164.30	0.59	105,525
Run9	72.50	22.98	2,540	26,153	9,441	4	980	0	1,063	38,137	164.30	0.59	104,401
Run10 #	68.89	21.84	2,462	24,667	9,106	4	976	0	1,190	36,238	164.30	0.59	99,201
Run11 *	72.75	23.06	2,539	26,294	9,431	4	981	0	1,062	38,269	164.30	0.59	104,761
Run12 #*	70.28	22.28	2,454	25,425	9,088	4	980	0	1,140	36,971	164.30	0.59	101,207
Run13 ^	73.03	23.15	2,345	24,985	11,084	3	960	0	1,443	38,417	217.91	0.78	105,167
Run14 #^	71.39	22.63	2,302	24,839	10,409	2	962	0	1,366	37,553	212.41	0.76	102,801
Run15 *^	73.29	23.23	2,345	25,151	11,055	3	961	0	1,451	38,554	217.68	0.78	105,542
Run16 #*^	71.91	22.80	2,302	25,145	10,380	2	963	0	1,376	37,829	212.95	0.77	103,557

Options with Linked Earth-Tubes
* Options with Naturally Ventilated (NV) DSF
^ Options with Naturally Ventilated (NV) Bldg

Conventional Buildings Design
Attached SDF as Just a Buffer Zone
Attached SDF as an HVAC Contributer
The above Attached SDF to a NV Building

23.69 kBTU/f² Assumed as Baseline
ASHRAE Suggestion+Passive Shading

Run 10 (7.8 % less than Baseline)
Best Strategy (MV DSF+MV Bldg+Earth-Tubes)

Run 14 (4.5 % less than Baseline)
2nd Best Strat. (NV DSF+NV Bldg+Earth-Tubes)

3.8 to7.8 % less than Baseline
Best Combinations (DSF+Shading+Earth-Tubes)

Note1: Typical Office Buildings's EUI is 211 kWh/m²/yr (67 kBTU/ft²/yr) with 60% reduction based on 2030 building challenge, 85 kWh/m²/yr (27 kBTU/ft²/yr).
Note2: In typical Office Buildings, half of the EUI is due to HVAC systems. Therefore, the whole EUI would be around twice as the numbers above. ACH and Vent. Rate are average hourly of airchange & ventilation.
Note3: Q_HEAT is average energy required for heating, Q_COOL for cooling, Q_DEHUM for dehumidification, Q_HUM for humidification, Q_INF for infiltration, Q_VENT for ventilation, and Q_COUPL for coupling.

Table 5.12: Atlanta Results, 1-meter Depth DSF

Identified in the above table for Atlanta (Table 5.12), all the proposed 1-meter DSF systems are more efficient than the baseline following the same pattern as the previous DSF option of 2m. The best option, Run10 F is highlighted in darker blue with 7.8% higher efficiency, in a comparison to the baseline. Similar to the DSF depth of 2m, the second best option is Run12 G with 4.5% efficiency instead of Run14 H seen in Minneapolis.

The integrated passive shading device in this option (Run4 B) demonstrates an efficiency of around 50% over a conventional building without any shading strategy.

Accordingly, the whole LI of the best proposed option will be 137.78 kwh/m²/yr (43.68 kBTU/ft²/yr), which is considerably lower than a typical office building, although, still higher than the 2030 Building Challenge. Financially, the best option can save around $8,401 during the 30-year assumed lifecycle of the office building.

5.4.13 Atlanta, 0.5-meter Depth DSF

Atlanta Load Intensity Break Down (0.5m DSF Depth)													
Elements	Load Intensity	Load Intensity	Q_HEAT	Q_COOL	Q_DEHUM	Q_HUM	Q-INF	Q_VENT	Q_COUPL	LI_TOTAL	Vent. Rate	ACH	$/30 Yrs
RUN #	KWH/SM/Yr	KBTU/SF/Yr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	Kg/Hr	1/Hr	$
Run1	0.00	0.00	0	0	0	0	1,247	0	0	0	0.00	0.00	0
Run2	147.88	46.88	1,399	67,442	8,945	4	1,155	1,763	0	77,791	164.32	0.59	212,952
Run3	77.65	24.62	3,183	28,132	9,525	7	962	1,563	0	40,847	164.32	0.59	111,818
Run4	74.72	23.69	4,523	25,167	9,610	7	917	1,488	0	39,307	164.32	0.59	107,602
Run5	92.24	29.24	1,879	37,552	9,082	4	1,066	1,643	0	48,518	164.32	0.59	132,819
Run6	76.71	24.32	3,182	27,748	9,417	5	973	1,543	0	40,352	164.32	0.59	110,465
Atlanta Comparable Runs (0.5m DSF Depth)													
Run7	74.15	23.51	2,764	26,786	9,451	4	972	0	1,247	39,006	164.30	0.59	106,778
Run8 *	74.40	23.59	2,764	26,929	9,442	4	974	0	1,246	39,139	164.30	0.59	107,143
Run9	73.63	23.34	2,436	26,870	9,420	4	982	0	1,101	38,730	164.30	0.59	106,024
Run10 #	69.65	22.08	2,349	25,197	9,088	4	978	0	1,246	36,639	164.30	0.59	100,298
Run11 *	73.88	23.42	2,436	27,012	9,411	4	983	0	1,100	38,863	164.30	0.59	106,388
Run12 #*	71.14	22.55	2,341	26,006	9,069	4	982	0	1,190	37,421	164.30	0.59	102,439
Run13 ^	74.19	23.52	2,243	25,688	11,095	2	961	0	1,483	39,028	217.98	0.78	106,840
Run14 #^	72.49	22.98	2,194	25,539	10,395	2	964	0	1,386	38,131	211.66	0.76	104,382
Run15 *^	74.46	23.60	2,243	25,850	11,072	2	962	0	1,490	39,167	217.86	0.78	107,219
Run16 #*^	73.02	23.15	2,194	25,845	10,370	2	965	0	1,397	38,410	212.16	0.76	105,148

Note1: Typical Office Buildings's EUI is 211 kWh/m²/yr (67 kBTU/ft²/yr) with 60% reduction based on 2030 building challenge, 85 kWh/m²/yr (27 kBTU/ft²/yr).

Note2: In typical Office Buildings, half of the EUI is due to HVAC systems. Therefore, the whole EUI would be around twice as the numbers above. ACH and Vent. Rate are average hourly of airchange & ventilation.

Note3: Q_HEAT is average energy required for heating, Q_COOL for cooling, Q_DEHUM for dehumidification, Q_HUM for humidification, Q_INF for infiltration, Q_VENT for ventilation, and Q_COUPL for coupling.

Options with Linked Earth-Tubes
* Options with Naturally Ventilated (NV) DSF
^ Options with Naturally Ventilated (NV) Bldg

Conventional Buildings Design
Attached SDF as Just a Buffer Zone
Attached SDF as an HVAC Contributer
The above Attached SDF to a NV Building

23.69 kBTU/f² Assumed as Baseline
ASHRAE Suggestion+Passive Shading

Run 10 (6.8 % less than Baseline)
Best Strategy (MV DSF+MV Bldg+Earth-Tubes)

Run 14 (3 % less than Baseline)
2nd Best Strat. (NV DSF+NV Bldg+Earth-Tubes)

2.3 to 6.8 % less than Baseline
Best Combinations (DSF+Shading+Earth-Tubes)

Table 5.13: Atlanta Results, 0.5-meter Depth DSF

Observations on the above Atlanta table (Table 5.13) reveals that all the proposed 0.5-meter DSF systems are, yet again, performing more efficient than the baseline although the difference is not very significant. Similar to the DSF depth of 2 and 1m, the best option is the <u>Run10 F</u> where the second best option is <u>Run12 G</u> with around 6.8 and 3% higher efficiency respectively.

The whole EUI of the best proposed option is assumed to be around 139.3 kwh/m²/yr (44.16 kBTU/ft²/yr), which is considerably lower than a typical office building still higher than the 2030 Building Challenge. In terms of economic aspects, the best option can save around $7,304 during a 30-year assumed lifecycle of the office building.

The following page compares all the three DSF depths' results for the climate of Atlanta.

Atlanta Load Intensity Break Down (2m DSF Depth)													
Elements	Load Intensity	Load Intensity	Q_HEAT	Q_COOL	Q_DEHUM	Q_HUM	Q-INF	Q_VENT	Q_COUPL	LI_TOTAL	Vent. Rate	ACH	$/30 Yrs
RUN #	KWH/SM/Yr	KBTU/SF/Yr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	Kg/Hr	1/Hr	$
Run1	0.00	0.00	0	0	0	0	1,247	0	0	0	0.00	0.00	0
Run2	147.88	46.88	1,399	67,442	8,945	4	1,155	1,763	0	77,791	164.32	0.59	212,952
Run3	77.65	24.62	3,183	28,132	9,525	7	962	1,563	0	40,847	164.32	0.59	111,818
Run4	74.72	23.69	4,523	25,167	9,610	7	917	1,488	0	39,307	164.32	0.59	107,602
Run5	104.30	33.06	294	45,816	8,756	0	1,226	1,794	0	54,866	164.32	0.59	150,196
Run6	89.14	28.26	474	37,471	8,942	0	1,155	1,735	0	46,888	164.32	0.59	128,356
Atlanta Comparable Runs (2m DSF Depth)													
Run7	80.24	25.44	563	32,569	9,076	0	1,107	0	1,283	42,208	164.30	0.59	115,544
Run8 *	71.91	22.80	3,016	25,309	9,499	3	970	0	1,148	37,826	164.30	0.59	103,549
Run9	71.12	22.54	2,714	25,220	9,472	3	977	0	1,011	37,409	164.30	0.59	102,407
Run10 #	68.06	21.57	2,650	24,016	9,132	3	973	0	1,112	35,801	164.30	0.59	98,005
Run11 *	71.36	22.62	2,714	25,357	9,463	3	978	0	1,011	37,537	164.30	0.59	102,757
Run12 #*	69.30	21.97	2,644	24,691	9,116	3	977	0	1,071	36,454	164.30	0.59	82,685
Run13 ^	71.67	22.72	2,513	24,107	11,077	2	957	0	1,376	37,699	217.09	0.78	103,200
Run14 #^	70.10	22.22	2,479	23,966	10,429	2	958	0	1,328	36,875	212.98	0.77	100,946
Run15 *^	71.92	22.80	2,513	24,277	11,043	2	958	0	1,386	37,834	216.75	0.78	103,571
Run16 #*^	70.61	22.38	2,479	24,267	10,396	2	960	0	1,338	37,144	213.55	0.77	101,680

Note1: Typical Office Buildings's EUI is 211 kWh/m^2/yr (67 kBTU/ft^2/yr) with 60% reduction based on 2030 building challenge, 85 kWh/m^2/yr (27 kBTU/ft^2/yr).

Note2: In typical Office Buildings, half of the EUI is due to HVAC systems. Therefore, the whole EUI would be around twice as the numbers above.

Options with Linked Earth-Tubes
* Options with Naturally Ventilated (NV) DSF
^ Options with Naturally Ventilated (NV) Bldg
Conventional Buildings Design
Attached SDF as Just a Buffer Zone
Attached SDF as an HVAC Contributer
The above Attached SDF to a NV Building

23.69 kBTU/f^2 Assumed as Baseline
ASHRAE Suggestion+Passive Shading

Run 10 (8.9 % less than Baseline)
Best Strategy (MV DSF+MV Bldg+Earth-Tubes)

Run 14 (6.1 % less than Baseline)
2nd Best Strat. (NV DSF+NV Bldg+Earth-Tubes)

5.5 to 8.9 % less than Baseline
Best Combinations (DSF+Shading+Earth-Tubes)

Atlanta Load Intensity Break Down (1m DSF Depth)													
Elements	Load Intensity	Load Intensity	Q_HEAT	Q_COOL	Q_DEHUM	Q_HUM	Q-INF	Q_VENT	Q_COUPL	LI_TOTAL	Vent. Rate	ACH	$/30 Yrs
RUN #	KWH/SM/Yr	KBTU/SF/Yr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	Kg/Hr	1/Hr	$
Run1	0.00	0.00	0	0	0	0	1,247	0	0	0	0.00	0.00	0
Run2	147.88	46.88	1,399	67,442	8,945	4	1,155	1,763	0	77,791	164.32	0.59	212,952
Run3	77.65	24.62	3,183	28,132	9,525	7	962	1,563	0	40,847	164.32	0.59	111,818
Run4	74.72	23.69	4,523	25,167	9,610	7	917	1,488	0	39,307	164.32	0.59	107,602
Run5	89.18	28.27	1,991	35,816	9,099	4	1,062	1,633	0	46,910	164.32	0.59	128,417
Run6	75.75	24.01	3,338	27,073	9,435	4	972	1,537	0	39,849	164.32	0.59	109,087
Atlanta Comparable Runs (1m DSF Depth)													
Run7	73.22	23.21	2,763	26,287	9,460	4	975	0	1,205	38,514	164.30	0.59	105,432
Run8 *	73.28	23.23	2,855	26,225	9,464	4	973	0	1,201	38,548	164.30	0.59	105,525
Run9	72.50	22.98	2,540	26,153	9,441	4	980	0	1,063	38,137	164.30	0.59	104,401
Run10 #	68.89	21.84	2,462	24,667	9,106	4	976	0	1,190	36,238	164.30	0.59	99,201
Run11 *	72.75	23.06	2,539	26,294	9,431	4	981	0	1,062	38,269	164.30	0.59	104,761
Run12 #*	70.28	22.28	2,454	25,425	9,088	4	980	0	1,140	36,971	164.30	0.59	82,685
Run13 ^	73.03	23.15	2,345	24,985	11,084	3	960	0	1,443	38,417	217.91	0.78	105,167
Run14 #^	71.39	22.63	2,302	24,839	10,409	2	962	0	1,366	37,553	212.41	0.76	102,801
Run15 *^	73.29	23.23	2,345	25,151	11,055	3	961	0	1,451	38,554	217.68	0.78	105,542
Run16 #*^	71.91	22.80	2,302	25,145	10,380	2	963	0	1,376	37,829	212.95	0.77	103,557

Note1: Typical Office Buildings's EUI is 211 kWh/m^2/yr (67 kBTU/ft^2/yr) with 60% reduction based on 2030 building challenge, 85 kWh/m^2/yr (27 kBTU/ft^2/yr).

Note2: In typical Office Buildings, half of the EUI is due to HVAC systems. Therefore, the whole EUI would be around twice as the numbers above.

Options with Linked Earth-Tubes
* Options with Naturally Ventilated (NV) DSF
^ Options with Naturally Ventilated (NV) Bldg
Conventional Buildings Design
Attached SDF as Just a Buffer Zone
Attached SDF as an HVAC Contributer
The above Attached SDF to a NV Building

23.69 kBTU/f^2 Assumed as Baseline
ASHRAE Suggestion+Passive Shading

Run 10 (7.8 % less than Baseline)
Best Strategy (MV DSF+MV Bldg+Earth-Tubes)

Run 14 (4.5 % less than Baseline)
2nd Best Strat. (NV DSF+NV Bldg+Earth-Tubes)

3.8 to7.8 % less than Baseline
Best Combinations (DSF+Shading+Earth-Tubes)

Atlanta Load Intensity Break Down (0.5m DSF Depth)													
Elements	Load Intensity	Load Intensity	Q_HEAT	Q_COOL	Q_DEHUM	Q_HUM	Q-INF	Q_VENT	Q_COUPL	LI_TOTAL	Vent. Rate	ACH	$/30 Yrs
RUN #	KWH/SM/Yr	KBTU/SF/Yr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	Kg/Hr	1/Hr	$
Run1	0.00	0.00	0	0	0	0	1,247	0	0	0	0.00	0.00	0
Run2	147.88	46.88	1,399	67,442	8,945	4	1,155	1,763	0	77,791	164.32	0.59	212,952
Run3	77.65	24.62	3,183	28,132	9,525	7	962	1,563	0	40,847	164.32	0.59	111,818
Run4	74.72	23.69	4,523	25,167	9,610	7	917	1,488	0	39,307	164.32	0.59	107,602
Run5	92.24	29.24	1,879	37,552	9,082	4	1,066	1,643	0	48,518	164.32	0.59	132,819
Run6	76.71	24.32	3,182	27,748	9,417	5	973	1,543	0	40,352	164.32	0.59	110,465
Atlanta Comparable Runs (0.5m DSF Depth)													
Run7	74.15	23.51	2,764	26,786	9,451	4	972	0	1,247	39,006	164.30	0.59	106,778
Run8 *	74.40	23.59	2,764	26,929	9,442	4	974	0	1,246	39,139	164.30	0.59	107,143
Run9	73.63	23.34	2,436	26,870	9,420	4	982	0	1,101	38,730	164.30	0.59	106,024
Run10 #	69.65	22.08	2,349	25,197	9,088	4	978	0	1,246	36,639	164.30	0.59	100,298
Run11 *	73.88	23.42	2,436	27,012	9,411	4	983	0	1,100	38,863	164.30	0.59	106,388
Run12 #*	71.14	22.55	2,341	26,006	9,069	4	982	0	1,190	37,421	164.30	0.59	82,685
Run13 ^	74.19	23.52	2,243	25,688	11,095	2	961	0	1,483	39,028	217.98	0.78	106,840
Run14 #^	72.49	22.98	2,194	25,539	10,395	2	964	0	1,386	38,131	211.66	0.76	104,382
Run15 *^	74.46	23.60	2,243	25,850	11,072	2	962	0	1,490	39,167	217.86	0.78	107,219
Run16 #*^	73.02	23.15	2,194	25,845	10,370	2	965	0	1,397	38,410	212.16	0.76	105,148

Note1: Typical Office Buildings's EUI is 211 kWh/m^2/yr (67 kBTU/ft^2/yr) with 60% reduction based on 2030 building challenge, 85 kWh/m^2/yr (27 kBTU/ft^2/yr).

Note2: In typical Office Buildings, half of the EUI is due to HVAC systems. Therefore, the whole EUI would be around twice as the numbers above.

Options with Linked Earth-Tubes
* Options with Naturally Ventilated (NV) DSF
^ Options with Naturally Ventilated (NV) Bldg
Conventional Buildings Design
Attached SDF as Just a Buffer Zone
Attached SDF as an HVAC Contributer
The above Attached SDF to a NV Building

23.69 kBTU/f^2 Assumed as Baseline
ASHRAE Suggestion+Passive Shading

Run 10 (6.8 % less than Baseline)
Best Strategy (MV DSF+MV Bldg+Earth-Tubes)

Run 14 (3 % less than Baseline)
2nd Best Strat. (NV DSF+NV Bldg+Earth-Tubes)

2.3 to 6.8 % less than Baseline
Best Combinations (DSF+Shading+Earth-Tubes)

Table 5.14: Atlanta Combined Results

5.4.14 Combined analysis for Phoenix

The combined table analysis of Atlanta exhibits the following findings:

- Similar to the Minneapolis climate, the most energy efficient option for all the alternatives is Run10 F in which a mechanically conditioned office building is integrated with a mechanically ventilated DSF. This is performing up to 8.9% higher efficiency compared to the baseline for the DSF depth of 2m and marginally lower values for a DSF depth of 0.5m in comparison to the baseline.
- As far as the most efficient DSF depth in this climate is concerned, the 2-meter depth is again the ideal option while all the other options are still performing better. The LI has, yet again, an inverse correlation with the DSF depth; the LI in Atlanta increases by reducing the DSF's depth.
- In the stated best option of Run10 F, the self-regulating damper in the top sunspace, functioning as a controller for both introduction and exhaustion of the air within the DSF system's cavity, is essential in lowering LI.
- These consistent outcomes for the three DSF depths in the climate of Atlanta suggest that a naturally conditioned building that uses a mechanically ventilated DSF as an HVAC-contributing system with air introduction to offices could also be among the best alternatives, namely Run14 H.
- The comparison between the buffer and HVAC-contributing DSF, in which the air in the cavity is either just exhausted (Run7 D) or used for heating during cold seasons (Run9 F), indicates that the introduction of air from the cavity into the office spaces does not always reduce the LI of the integrated DSF system.
- Run12 G and Run14 H in which the DSF is either ventilated mechanically or naturally are both among the best options with all the DSF's depth while the best option employs a mechanically ventilated approach for the DSF.
- Run4 B's results, associated with the option of an integrated, passive shading device including a combined light-shelf and overhang, has relatively identical performance as most of the best options in this clime showcasing the higher influence of proper shading strategies.
- Compared to a proper passive shading device strategy, the integration of earth-tubes is not equally significant in lowering LI in this climate.

5.4.15 Atlanta, Variables Main Effects

This section reflects on the main effect of several variables in Atlanta, namely, the DSF Integration, DSF Depth, DSF Ventilation Strategy, Building Ventilation Strategy, and Earth-Tubes Integration reinterpreting their general applicability from a broader viewpoint. Each of their main effects is calculated using Atlanta

results from Run7 D to Run16 I for all the three DSF depths (Table 5.15). The table below demonstrates the calculated main effect for each of the stated variables, independently explained in the next page in the order of their effectiveness.

AtlantaMain Effects (Run 7-16)	Load Intensity	Load Intensity	Q_HEAT	Q_COOL	Q_DEHUM	Q_HUM	Q-INF	Q_VENT	Q_COUPL	LI_TOTAL	Vent. Rate	ACH	$/30 Yrs
	KWH/SM/Yr	KBTU/SF/Yr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	KJ/Hr	Kg/Hr	1/Hr	$
Having to not Having DSF (baseline)	-2.46	-0.78	-2,084	522	271	-4	58	-1,488	1,248	-1,295	20.29	0.07	-3,545
Natural to Mechanical DSF Ventilation	-0.05	-0.02	168	-207	11	0	-8	0	-15	-28	0	0.00	-77
Natural to Mechanical Bldg Ventilation	0.13	0.04	-154	-1,196	1,421	-1	-24	0	256	70	51	0.18	191
Having to not having Earth-Tubes	-2.25	-0.71	-61	-614	-507	0	0	0	14	-1,182	-2	-0.01	-3,235
2 to 1 m DSF Depth	-0.43	-0.14	-62	-139	-22	-1	10	0	-43	-224	0	0.00	-614
2 to 0.5 m DSF Depth	-1.47	-0.47	32	-794	-11	-1	9	0	-82	-775	0	0.00	-2,121
1 to 0.5 m DSF Depth	-1.05	-0.33	94	-655	11	0	-1	0	-39	-550	0	0.00	-1,506

Note1: negetive sign means that one can lose when going from the first to the second option.

Note2: Having to not having DSF is a comparison between average of all options with DSF and the baseline.

Table 5.15: Atlanta, Variables Main Effects

5.4.15.1 DSF Integration

Similar to Minneapolis, the DSF system integration is the most effective variable. The main effect of DSF Integration from existence to non-existence is -2.46 kwh/m²/yr (-0.78 kBTU/ft²/yr), resulting in $3,545 economic saving. This means that having the DSF in the climate of Atlanta will assist in the LI decrease as the most effective variable..

5.4.15.4 Earth-Tubes integration

From having to not having the earth-tubes system, the main effect in Atlanta is -2.25 kwh/m²/yr (-0.71 kBTU/ft²/yr), which is equal to $3,235 savings in expenditure during a building life-cycle. This is clarifying to what extents the general application of the system helps to reduce LI.

5.4.15.1 DSF Depth

Similarly in Minneapolis and Phoenix, the DSF depth is an important variable in LI where the same inverse correlation is also the case in this climate; the 2-meter depth performs slightly better than 1-meter DSF depth, and the 0.5-meter depth has the least efficiency in general. Yet, the energy performance is not drastically diverse. The followings describe each:

- From 2-meter to 0.5-meter Depth, the main effect is -1.47 kwh/m²/yr (-0.47 kBTU/ft²/yr) equal to $2,121 economic saving for 30 years.
- 1-meter to 0.5-meter Depth, the main effect is -1.05 kwh/m²/yr (-0.33 kBTU/ft²/yr) equal to $1,506 for economic saving for 30 years.
- From 2-meter to 1-meter Depth, the main effect is -0.43 kwh/m²/yr (-0.14 kBTU/ft²/yr) equal to $614 economic saving for 30 years.

5.4.15.3 Building and DSF Ventilation Strategy

In Atlanta, the ventilation strategy of the building zones themselves and the DSF are less among less effective variables provided that all the other strategies are appropriately integrated. This is based on the main effect from naturally to mechanically ventilated DSF that is -0.05 kwh/m²/yr (-0.02 kBTU/ft²/yr) equivalent to $77 saving per 30 years. The same situation exists for building ventilation where the main effect is +0.13 kwh/m²/yr (+0.04 kBTU/ft²/yr) going from naturally to mechanically ventilated building. This also indicates that natural ventilation could be efficiently applied without destructive impact on LI. In other words, there is not considerable change in LI if the mechanically ventilated DSF is replaced by a naturally ventilated system.

5.4.15.4 Atlanta Variables' impacts on Load Intensity

After all, the following figures (Figure 5.9 to 5.12) showcase the impact of each stated variable on LI as a whole and Heating, Cooling, and Dehumidification distinctly. Below is the explanation:

- The figure related to LI (Figure 5.9) illustrate that the most important variables impacting LI of the proposed model in Atlanta are *DSF and Earth-Tube System Integration*.
- Figure 5.10 shows that the most effective variable on heating is again *DSF Integration*.
- In terms of cooling, the most effective variable influencing cooling loads in Atlanta is *Building Ventilation Strategy*. Then, *DSF Depth;* More specifically going from 2 to 0.5m depth has the most impact in increasing cooling loads, which means norrower depths slightly lower cooling loads in Atlanta (Figure 5.11).
- Although not deastically, but *Building Ventilation Strategy* plays the most significant role on dehumidification loads where wider depth slightly increase dehumidification loads (Figure 5.12).

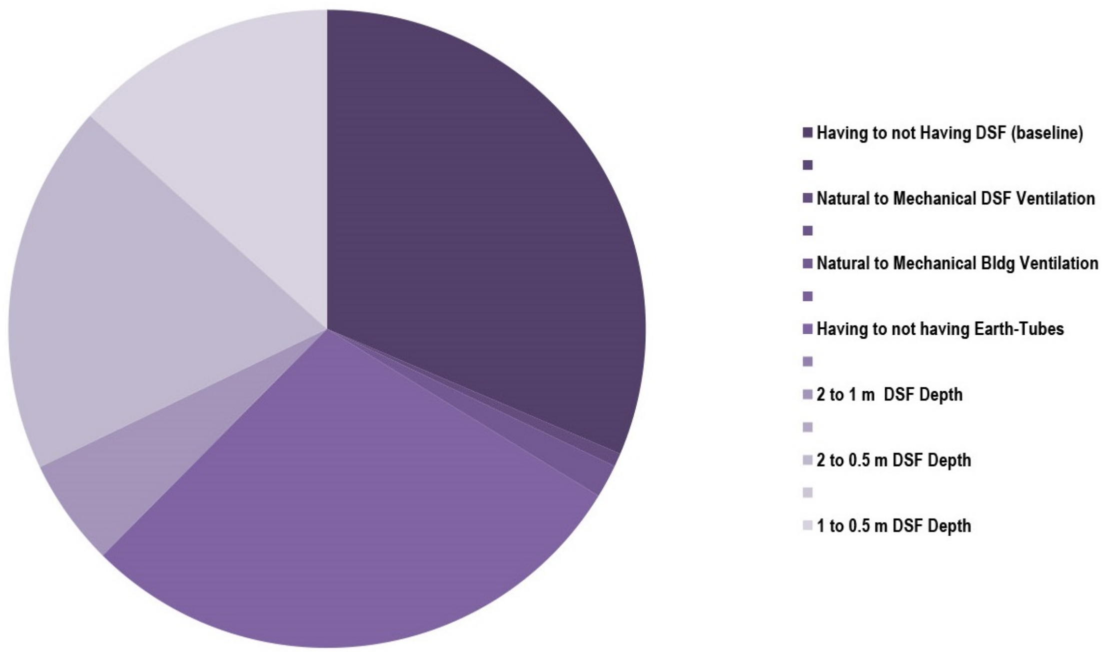


Figure 5.9
Each Variable's Impact on the Total LI for Atlanta.

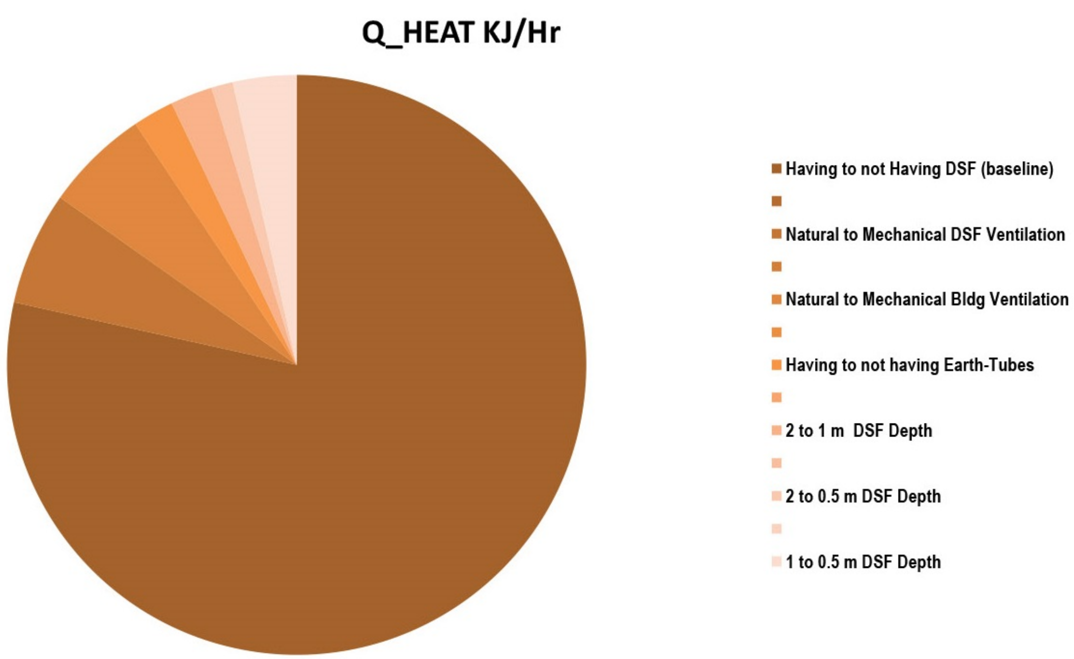


Figure 5.10
Each Variable's Impact on the Total Heating for Atlanta.

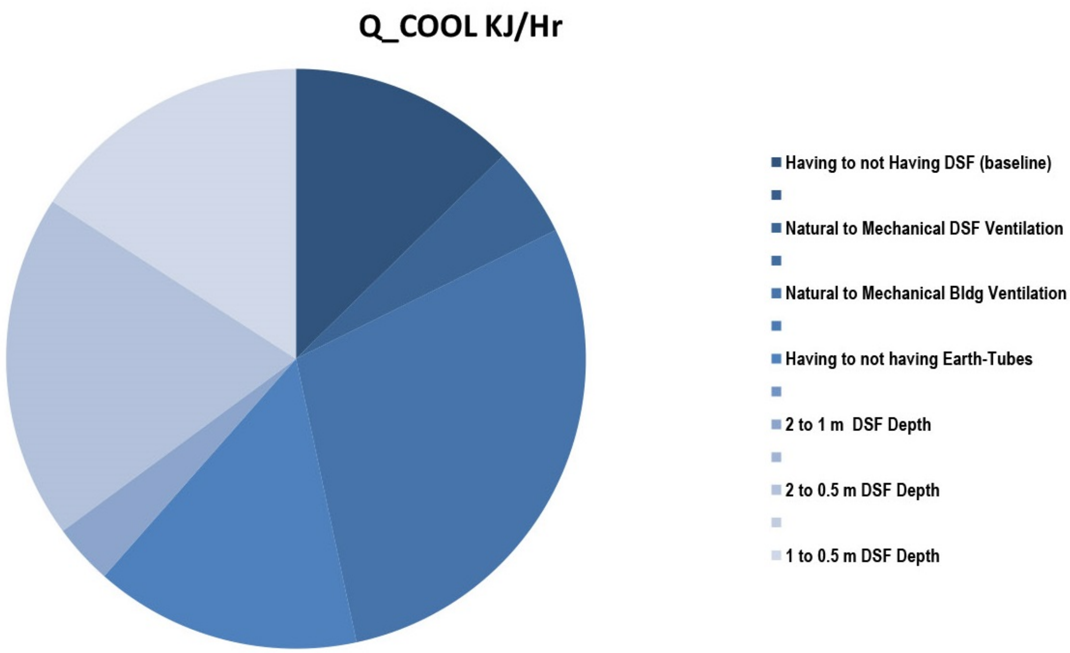


Figure 5.11
Each Variable's Impact on the Total Cooling for Atlanta.

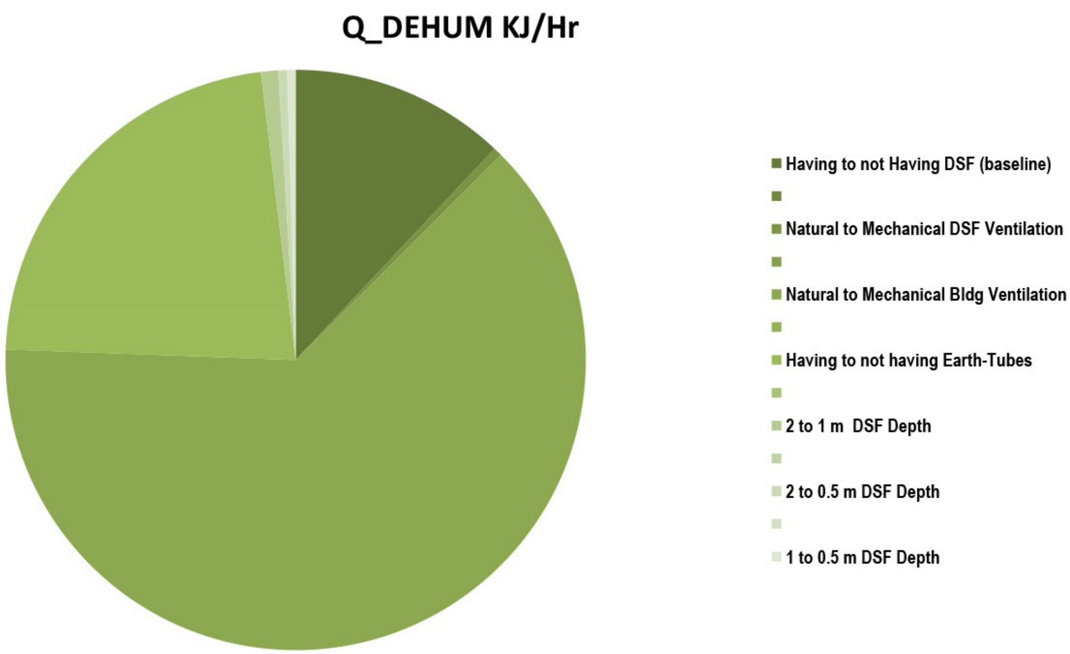


Figure 5.12
Each Variable's Impact on the Total Dehumidification for Atlanta.

5.4 Findings on DSFs Overheating Issue

Based on DSF literature studies, the main disadvantage of this system is recognized to be overheating during hot seasons and maintenance and construction costs. To sum up, acoustic insulation, thermal insulation, energy saving and reduced environmental impacts, transparency, natural ventilation, low U-value, and protection of shading and reflecting devices are main benefits of DSFs, while the higher construction cost, overheating, reducing square footage, additional maintenance, increased construction weight, and glare are the main drawbacks of DSFs (Poirazis, 2004, pp.179-182). Hoseggen et al. (2008) also assert that, from the economic standpoints, energy savings associated with the use of DSFs do not defend the additional costs related to their construction; therefore, choosing them as options must be done for other reasons than economy.[92]

Now that the results for each climate were presented and the <u>Run16 I</u> with 2-meter DSF depth has been identified as the optimized design for the proposed integrated system, the following research hypothesis can to be reconsidered based on the optimized option's performance:

In a non-residential building, an optimized double-skin facade linked into the earth would eliminate the issue of overheating in hot seasons; therefore, it would minimize its Load Intensity (LI) to an extent that can make it a practical solution.

In addressing the hypothesis, an additional investigation on the optimized options' temperature graphs from all the three climates of Minneapolis, Atlanta, and Phoenix, respectively, will be beneficial (Figure 5.13, Figure 5.14, and Figure 5.15).

[92] R. Høseggen, B. J. Wachenfeldt, and S. O. Hanssen (2008). Building Simulation as an Assisting Tool in Decision Making: Case Study: With or Without a Double-Skin Facade?. *Energy and Buildings, 40(5)*, 821-827.

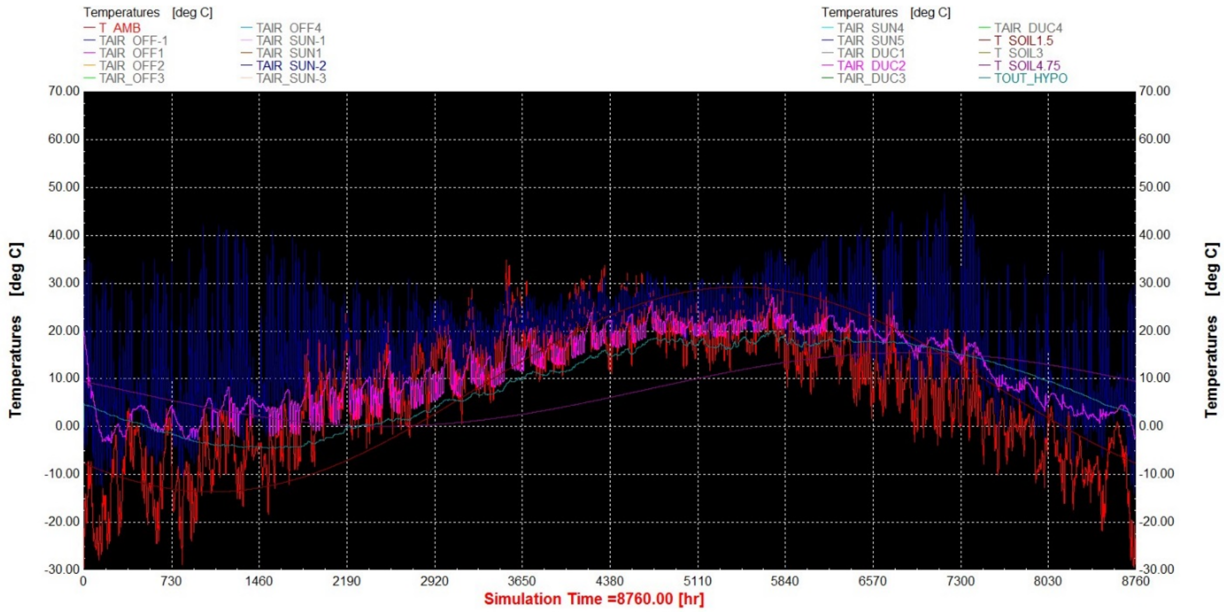


Figure 5.13
RUN10 F: The Optimized Option’s Temperature Graph for Minneapolis

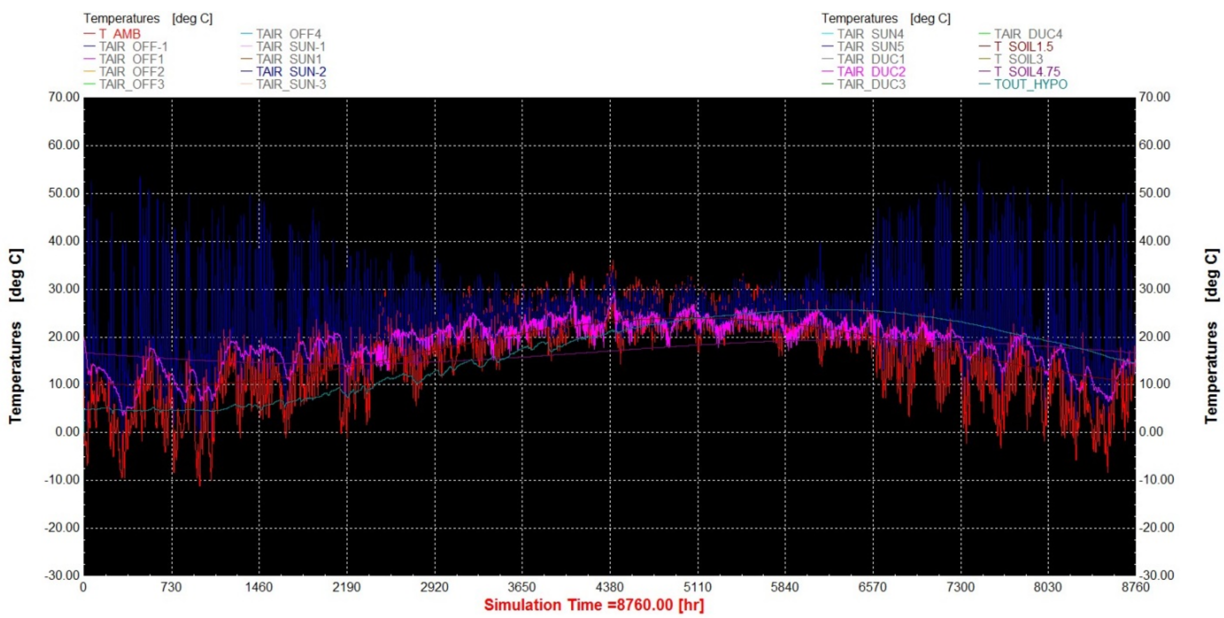


Figure 5.14
RUN10 F: The Optimized Option’s Temperature Graph for Atlanta

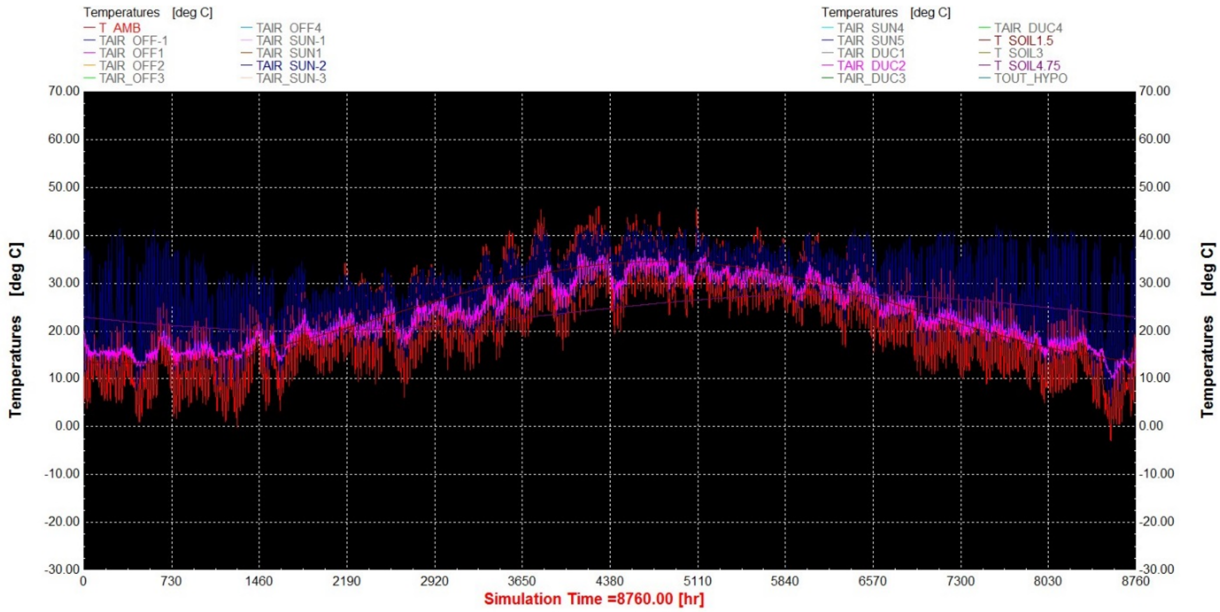


Figure 5.15
RUN13 H: The Optimized Option's Temperature Graph for Phoenix

The temperature graphs of sunspaces2 in all three climates are shown in blue (TAIR_SUN2) compared to the ambient air temperature in red (T_AMB). It is clearly noticeable that the issue of overheating during hot seasons, namely, May, June, July, and August are not considerable and it is almost resolved in all the three climates specifically in the hot climate of Phoenix. Now, the question is whether this level of efficiency is sufficient to rationalize the construction cost of an integrated DSF with earth-tubes system. By looking at the energy efficiency of these three optimized options, ranging from 5.8 to 11 to 21.2% higher than the baseline, it implies that energy efficiency should not be the main design drive to propose these systems unless the practicality of the system is examined in relation to all the other forces. Yet, the other constructive high-performance aspects of a DSF system can come to play towards an informed decision. This, in fact, supports Hoseggen et al's statement on previous pages related to the economic performance of DSFs.

5.6 Summary and Transition to Chapter VI

This chapter explored the results of the sixteen proposed runs, extracted from TRNSYS. Explorations were based on four different traits, starting from the very simple shoe-box zone, in Run1 A, to the most sophisticated system, in Run16 I. As the first trait, 104 graphs associated with the sixteen runs for

Minneapolis and their DSF depth of 2m were individually examined. This was done in a step-by-step fashion in order to help in profoundly understanding any modification to the systems and also be able to methodologically validate the process of LI analysis in the data collection process. In the second trait, the LI results for each of the sixteen options for three different DSF depths situated in three dissimilar climatic conditions were presented. These were compared to assess the best possible option, coupled with understanding the roles that each variable has played in optimizing the LI of the integrated systems. The third trait has looked into the LI of the three DSF depths in conjunction with the three climates, presented and elaborated to specifically grasp the role of climate in relation to the DSF depths. In forth trait, finally, forty LI results for each climate were presented and evaluated by calculating the main effect for each of the following variables: the DSF Integration, DSF Depth, DSF Ventilation Strategy, Building Ventilation Strategy, and Earth-Tubes integration. This process has particularly been revealing inferences related to the generalizability of the proposed DSF options, and how and to what extents the various examined options could offer practicality in application. Looking at these results more holistically and from a broader viewpoint can lead to a more all-inclusive comprehension of such integrated building systems. These holistic elaborations are offered in the next, final conclusion chapter of the dissertation.

Chapter VI: Interpretations and Conclusions

6.1 Restatement of Research Questions (Hypotheses)

It was hitherto deliberated that, in architectural design, the integration of an ecological perspective is key to reaching high-performance architectural design solutions. On the one hand, along this line, the dissertation recognized the position on the essence and careful consideration of energy as a crucial concern. On the other hand, it cherished Double-Skin Facades, valued as inclusive systems that are able to address various aspects of ecological design. It was also conversed as a disadvantage that DSFs economic remunerations have been debated. The dissertation's focus, therefore, has become the examination of ways to optimize the Load Intensity of DSFs, as result the EUI. Then, it was hypothesized that, by connecting a DSF into the earth, a building's energy demands would be reduced, hence, its economic performance would be improved:

> *In a non-residential building, an optimized double-skin facade linked into the earth would eliminate the issue of overheating in hot seasons; therefore, it would minimize its Load Intensity (LI) to an extent that can make it a practical solution.*

The hypothesis specified above was examined by designing a system that has combined a naturally-ventilated DSF, inspired by the concept of the vernacular passive solution of the Persian Wind-Catchers. The system was then enhanced by being linked into the earth, applying the ancient concept of Hypocausts, developed by Romans. The combined system was modeled with a coupled-procedure application of the TRNSYS (Figure 6.1) and CONTAM software (Figure 6.2) to simulate patterns of airflow and its influence on the energy performance of a commercial building. The following sections illustrate the results extracted from the softwares' coupled process. As a recap previously listed foundations, results were based on the following sixteen design options for the three different depths of 0.5,1, and 2 meters and in three distinct climatic conditions of Minneapolis, Phoenix, and Atlanta, as listed below:

1- Run1 A (4-Story Shoe Box No HVAC)
2- Run2 B (MC 4-Story Full HVAC)
3- Run3 B (MC 4-Story Construction Eshading Full HVAC)
4- Run4 B (MC 4-Story Construction Shading Full HVAC), assumed to be the <u>*BASELINE*</u>
5- Run5 C (MC 4-Story DSF2 Full HVAC)
6- Run6 C (MC 4-Story DSF2 Shading Full HVAC)
7- Run7 D (MC 4-Story MV DSF2 Full HVAC)
8- Run8 E (MC 4-Story NV DSF2 Full HVAC)
9- Run9 F (MV 4-Story MV DSF2 Semi HVAC)
10- Run10 F (MV 4-Story MV DSF2 Semi HVAC Hypo)
11- Run11 G (MV 4-Story NV DSF2 Semi HVAC)
12- Run12 G (MV 4-Story NV DSF2 Semi HVAC Hypo)
13- Run13 H (NC 4-Story MV DSF2 No HVAC)

14- Run14 H (NC 4-Story MV DSF2 No HVAC Hypo)
15- Run15 I (NC 4-Story NV DSF2 No HVAC)
16- Run16 I (NC 4-Story NV DSF2 No HVAC Hypo)

Due to high quantities of stemmed graphs, the sixteen simulation run results were then presented only for the DSF depth of 2m in Minneapolis and all other simulation runs are placed in the Appendix H and I sections. The first four runs were representative of conventional buildings common in a single climate. The second four runs were representative of a buffer type DSF for which there is no air introduction to offices. The last eight runs were based on a DSF that contributes to HVAC system via the introduction of air to offices for each of the three indicated climates, of Minneapolis, Phoenix, and Atlanta, and also for each of the three DSFs' depth, of 0.5, 1, and 2 meters.

At the next stage, the results of the sixteen proposed runs extracted from TRNSYS were explored based on four different traits, starting from the very simple shoe-box zone, in Run1 A, to the most sophisticated system, in Run16 I. As the first trait, runs for Minneapolis and their DSF depth of 2m were individually examined in a step-by-step manner. In the second trait, the LI results for three different DSF depths situated in three dissimilar climatic conditions were presented to assess the best possible option. The roles that each variable has played in optimizing the LI of the integrated systems were also examined. The third trait evaluated LI of the three DSF depths in combination with the three climates. After all, within the forth trait, results for each climate were presented and evaluated by calculating the main effect for each variables of the DSF Integration, DSF Depth, DSF Ventilation Strategy, Building Ventilation Strategy, Earth-Tubes integration, and climate. This process particularly revealed implications related to the generalizability of the proposed DSF options, and how and to what extents the various examined options could offer practicality in application. Looking at these results more holistically and from a broader viewpoint can lead to a more all-inclusive comprehension of such integrated building systems. These holistic elaborations are offered in the next section of this final chapter.

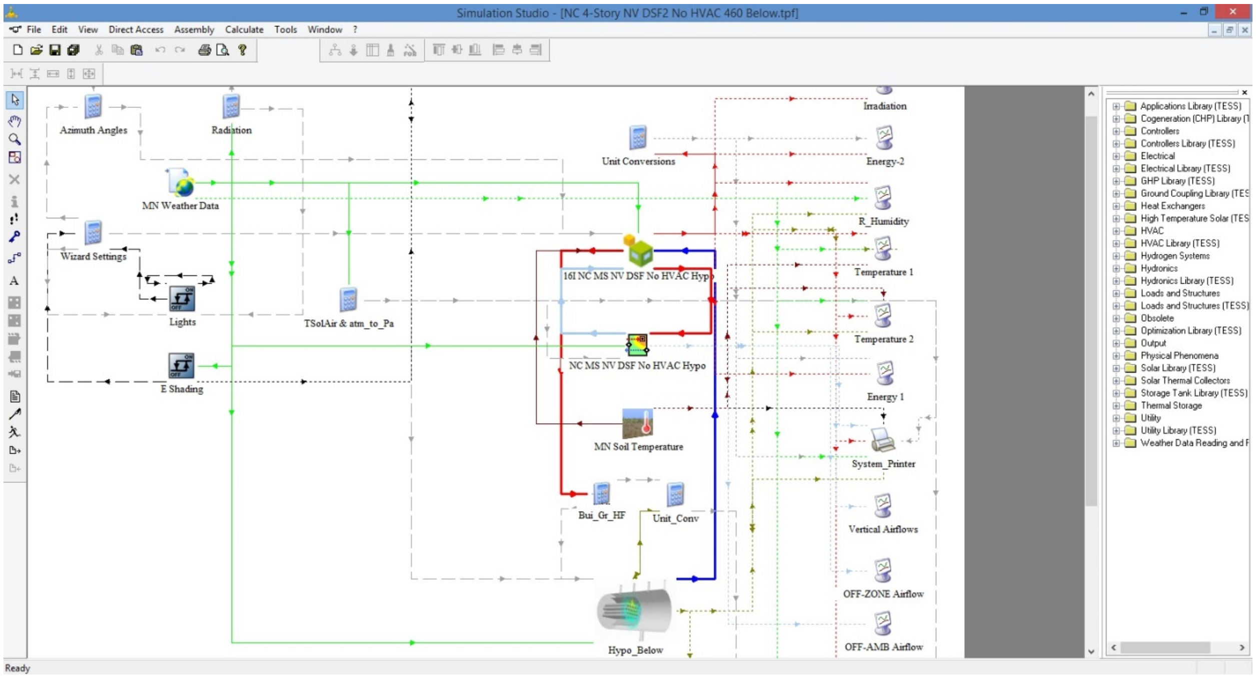


Figure 6.1
Coupled TRNSYS and CONTAM Software

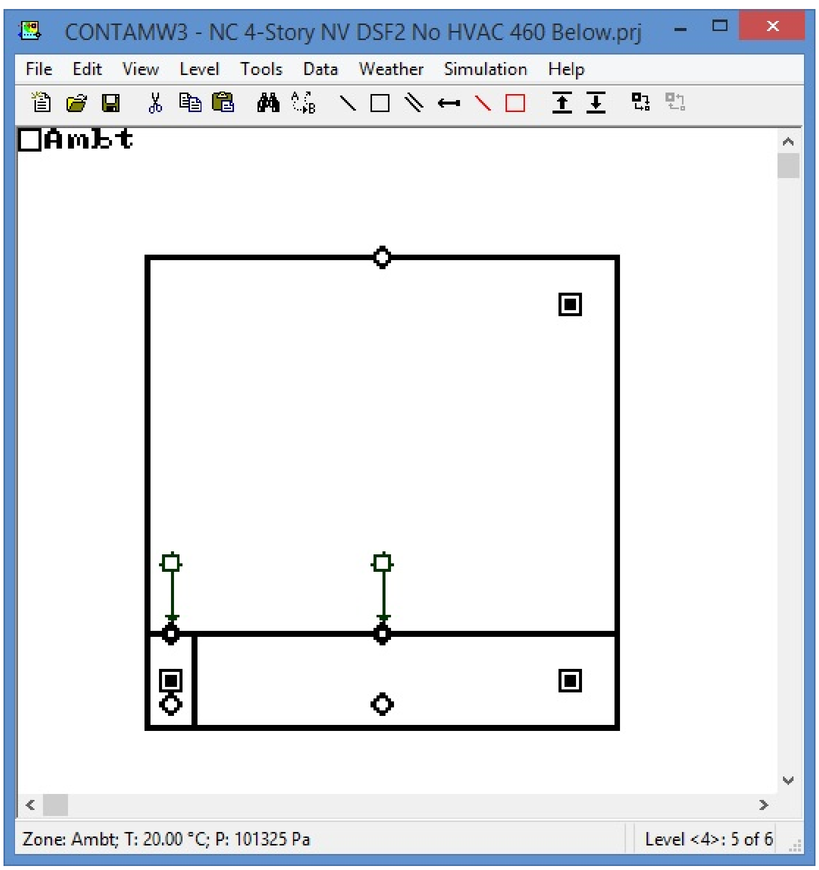


Figure 6.2
CONTAM Software

6.2 Interpretations and Conclusions

The following accounts for each of the studied variables, which are put in the order of their actual effectiveness, are the conclusion outcomes of this dissertation research. The combined main effects analysis for each climate is graphically presented in the diagram below (Figure 6.3). This is a way in summarizing the research conclusions, followed by their interpretations.

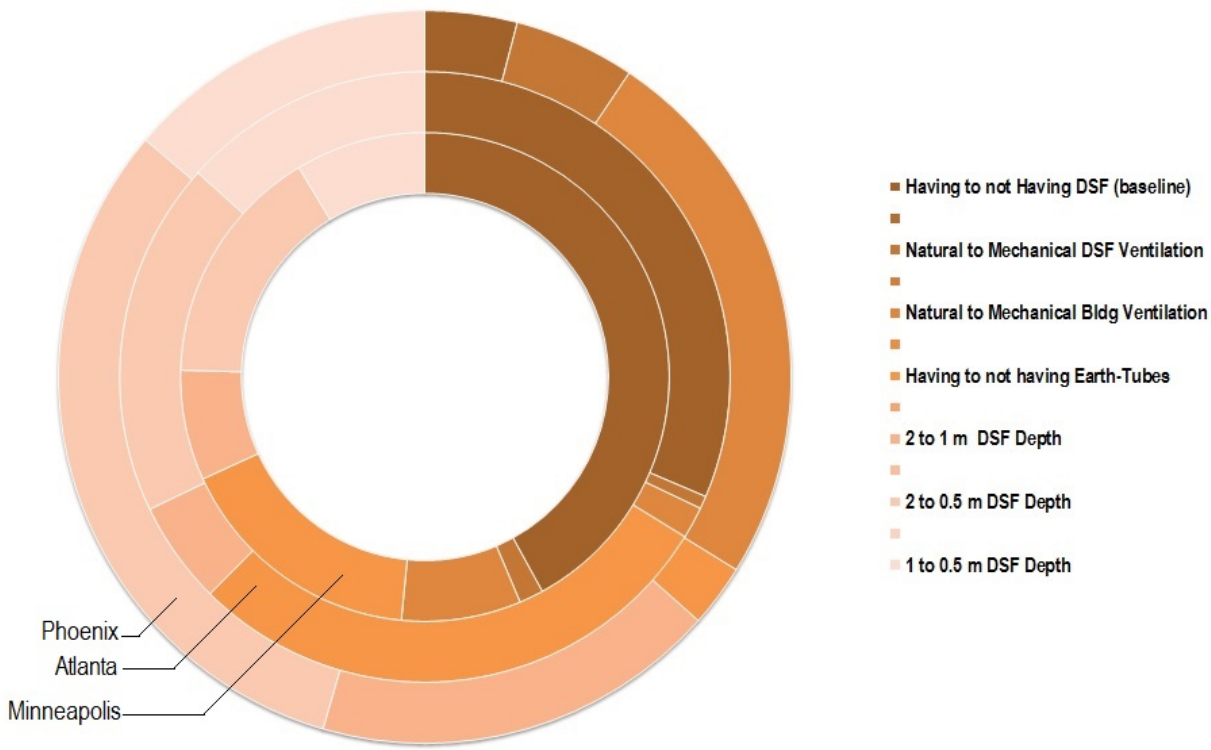


Figure 6.3
Summary of Dissertation Research Conclusions Illustrating each Variable's Impact on Load Intensity (LI)

6.2.1 DSF Integration

- The integration of a DSF system with an optimum depth into a non-residential building always enhances a building's energy performance independent of its location.
- The significance of a properly designed DSF system is interrelated to variables such as climate, DSF depth, or building ventilation strategy while the DSF ventilation strategy does not obstruct it.
- Air temperature and relative humidity in a DSF's cavity are always higher and lower than the outside air, respectively unless other strategies are integrated namely shading strategies.
- If properly designed, an integrated DSF system is capable of pre-conditioning the air in cavity throughout

the course of a year in spite of the findings in DSF literature about its overheating issue in hot seasons.

- DSF systems are more effective in cold climates, moderate climates, and hot climates respectively. It is due to fact that DSFs are primarily capable of reducing heating loads drastically. This research, thus, indorses the literature findings regarding the DSF's insignificant effect on EUI in hot climates.

- Among the studied variables, DSF integration has the highest impact on heating load in an integrated DSF system.

6.2.2 Buildings Ventilation Strategy

- LI in an integrated DSF system is primarily linked to the building ventilation strategy where cooling loads can be lowered due to both air movement making occupants feel cooler and the potential of higher air-change.

- The ventilation strategy has the highest impact on LI in a hot climate while a cold climate with hot summers is next. It has slight impact on a DSF system in a more moderate climatic condition.

- The effectiveness of a naturally ventilated building with a DSF system is tightly associated to the controlling strategies for restraining air introduction in cold seasons and maximizing it during hot seasons. A self-regulating vent for instance, can both control the airflow amount and direction, eliminating the unpredictability inherent to natural ventilation, which is a function of various factors such as wind characteristics or air paths' size and height.

- A comparison between the buffer and HVAC-contributing DSF revealed that the air introduction from the cavity into the office zone does have considerable impacts on the LI of a DSF system.

- Among the studies variables, cooling loads are primarily impacted by building ventilation strategies followed by DSF depth.

- Buildings ventilation strategies in an integrated DSF system can considerably reduce dehumidification loads in all studied climatic conditions.

6.2.3 DSF Depth

- Depth of a DSF has an inverse correlation with a building's LI, as result EUI; the LI in all the studied climates was increased by decreasing the DSF's depth. Yet, its impact on heating and cooling is the product of climate it is located in.

- DSF depths are more important in extreme hot or cold climatic condition as opposed to moderate climates.

- Airflow velocity is a product of a DSF depth for naturally ventilated systems as the air in the cavity has

more time to be preheated during the cold seasons before it is introduced into zones for ventilation purposes in an HVAC-contributing system.

- If properly designed, a depth of 2m is always a more practical solution for a DSF system in all climatic condition provide that relevant controlling strategies are integrated.

6.2.4 Earth-Tubes Integration

-The integration of an earth-tubes system into a DSF system always increases the system's energy performance provided that optimum DSF depth of 2m is designed.

- The air-tube system's integration into buildings with DSF has higher constructive impact on buildings' LI in cold climates in comparison to moderate and hot climates where it has very low impact.

6.2.5 DSF Ventilation Strategy

- DSF ventilation strategy does not have substantial impact on LI suggesting that natural forces of wind and buoyancy even in extreme climatic condition could sufficiently ventilate a DSF system.

6.2.6 Passive Shading Strategies

- In contrast to some other studies on DSFs suggesting that the integration of a DSF system will always increase cooling loads, a DSF system can considerably lower cooling loads on conditions that appropriate shading devices, construction types, DSF depths, and ventilation strategies are implemented.

- A passive shading strategy that combines a simple overhang and light-shelf can even performs better than an automatic shading device, which provides 70% shading in hot seasons without any negative impact on heat gain during cold seasons.

6.2.7 Climate

- Climate is it the key factor in considering DSFs practicality. While climatic condition itself cannot be changed or optimized, a profound understanding of its characteristics, how or to what extents it could impact LI, assists in making informed decisions.

- The impact of other variable such as DSF depth, ventilation strategies for both DSFs and buildings, and earth-tube system integration considerably changes by change of climatic condition.

6.2.8 Evaluation significance

- This research could be seen as a tangible example in which an initially proposed concept that was

assumed to drastically increase a system's performance was evidently challenged by taking an evaluative-based programming approach throughout the process.

- This process has explicitly showcased how an early hypnotized design solution can perform differently from what is known in the literature, highlighting the importance of evaluation throughout the process.

6.3 Generalizations, Limitations, and Implications

Study outcomes suggest additional emphasis, especially throughout the course of architectural education, on the role and the need for systematic communication of scientific dimensions related to buildings. This should not be seen in opposition, but as a companion to the artistic breadths of architectural design. In the realm of design practice, study outcomes advocate that, in order to best take up an integrated design process, it deems essential that design team members gain/bring in detailed scientific knowledge also on the fully technical sides of building systems. Both basic and advanced knowledge in such domains can help in bringing initial creative solutions into fruition. Another lesson-learned would also propose for architecture to perceive the built environment components, not as singular, added-on matters, but, as the essential parts of interrelating systems. In addition, the research process has elaborately showcased how an early theorized design solution can still perform otherwise, different from what had been known or read in the literature. This, again, is a means to highlight the importance of evaluation and an assessment-based mindset throughout the process. A major challenge and limitation of the study and research design was its higher dependency on operating in the computer software environment. This greater reliance made the data generation more challenging for the researcher to be in full control of the process. This also brought in the weights of repeating the same process a number of times, with the intentions of troubleshooting and satisfying methodological triangulation demands. Impacts of such issues became more central to the research process when deadlines should be precisely met. At this final stage, the research offer a number of future prospects. In fact, possibilities that the integrated design solution of a

DSF combined with earth-tubes can offer is now more intriguing than before. Promises still remain to enhance the performance of this integrated design solution, specifically, where it is united with the earth. In addition, research studies on comparisons between construction and maintenance costs of a DSF, as compared to a conventional building, are promising, bringing resourceful information to the design process.

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APPENDICES

Appendix A: Acceptable Approximation for Operative Temperature

The assumption that operative temperature equals air temperature is acceptable when these four conditions exist:

1. There is no radiant and/or radiant panel heating or radiant panel cooling system;

2. The average U-factor of the outside window/wall is determined by the following equation:

$$U_W < \frac{50}{t_{d,i} - t_{d,e}} \qquad \text{(SI)}$$

$$U_W < \frac{15.8}{t_{d,i} - t_{d,e}} \qquad \text{(IP)}$$

Where,

Uw = average U-factor of window/wall, W/m2 ·K (Btu/h·ft2 ·°F)

td,i = internal design temperature, °C (°F)

td,e = external design temperature, °C (°F);

3. Window solar heat gain coefficients (SHGC) are less than 0.48; and

4. There is no major heat generating equipment in the space.

Appendix B: Calculation of Operative Temperature Based on Air and Mean-Radiant Temperature”

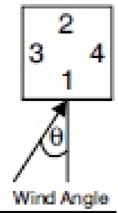
In most practical cases where the relative air speed is small (< 0.2 m/s, 40 fpm) or where the difference between mean radiant and air temperature is small (< 4°C, 7°F), the operative temperature can be calculated with sufficient approximation as the mean value of air temperature and mean radiant temperature. For higher precision and other environments, the following formula may be used:

$$t_{op} = A\, t_a + (1 - A)\, t_r$$

where
t_{op} = operative temperature,
t_a = air temperature,
t_r = mean radiant temperature, and
the value of A can be found from the values below as a function of the relative air speed, v_r.

$\boldsymbol{v_r}$	< 0.2 m/s (<40 fpm)	0.2 to 0.6 m/s (40 to 120 fpm)	0.6 to 1.0 m/s (120 to 200 fpm) ~~m/s)~~
A	0.5	0.6	0.7

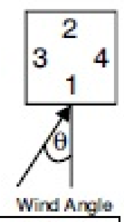
Appendix C: Wind Pressure Coefficient Based on AIVC Ventilation Handbook



Low-rise buildings (up to 3 storeys)
Length to width ratio: 1:1
Shielding condition: Exposed

Wind speed reference level: Building height

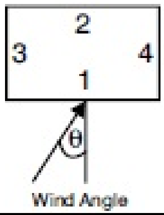
Location		Wind Angle							
		0°	45°	90°	135°	180°	225°	270°	315°
Face 1		0.7	0.35	-0.5	-0.4	-0.2	-0.4	-0.5	0.35
Face 2		-0.2	-0.4	-0.5	0.35	0.7	0.35	-0.5	-0.4
Face 3		-0.5	0.35	0.7	0.35	-0.5	-0.4	-0.2	-0.4
Face 4		-0.5	-0.4	-0.2	-0.4	-0.5	0.35	0.7	0.35
Roof (<10° pitch)	Front	-0.8	-0.7	-0.6	-0.5	-0.4	-0.5	-0.6	-0.7
	Rear	-0.4	-0.5	-0.6	-0.7	-0.8	-0.7	-0.6	-0.5
Average		-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6
Roof (11-30° pitch)	Front	-0.4	-0.5	-0.6	-0.5	-0.4	-0.5	-0.6	-0.5
	Rear	-0.4	-0.5	-0.6	-0.5	-0.4	-0.5	-0.6	-0.5
Average		-0.4	-0.5	-0.6	-0.5	-0.4	-0.5	-0.6	-0.5
Roof (>30° pitch)	Front	0.3	-0.4	-0.6	-0.4	-0.5	-0.4	-0.6	-0.4
	Rear	-0.5	-0.4	-0.6	-0.4	0.3	-0.4	-0.6	-0.4
Average		-0.1	-0.4	-0.6	-0.4	-0.1	-0.4	-0.6	-0.4



Low-rise buildings (up to 3 storeys)
Length to width ratio: 1:1
Shielding condition: Surrounded by obstructions equivalent to half the height of the building
Wind speed reference level: Building height

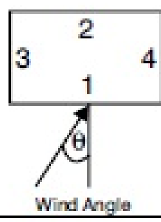
Location		Wind Angle							
		0°	45°	90°	135°	180°	225°	270°	315°
Face 1		0.4	0.1	-0.3	-0.35	-0.2	-0.35	-0.3	0.1
Face 2		-0.2	-0.35	-0.3	0.1	0.4	0.1	-0.3	-0.35
Face 3		-0.3	0.1	0.4	0.1	-0.3	-0.35	-0.2	-0.35
Face 4		-0.3	-0.35	-0.2	-0.35	-0.3	0.1	0.4	0.1
Roof (<10° pitch)	Front	-0.6	-0.5	-0.4	-0.5	-0.6	-0.5	-0.4	-0.5
	Rear	-0.6	-0.5	-0.4	-0.5	-0.6	-0.5	-0.4	-0.5
Average		-0.6	-0.5	-0.4	-0.5	-0.6	-0.5	-0.4	-0.5
Roof (11-30° pitch)	Front	-0.35	-0.45	-0.55	-0.45	-0.35	-0.45	-0.55	-0.45
	Rear	-0.35	-0.45	-0.55	-0.45	-0.35	-0.45	-0.55	-0.45
Average		-0.35	-0.45	-0.55	-0.45	-0.35	-0.45	-0.55	-0.45
Roof (>30° pitch)	Front	0.3	-0.5	-0.6	-0.5	-0.5	-0.5	-0.6	-0.5
	Rear	-0.5	-0.5	-0.6	-0.5	0.3	-0.5	-0.6	-0.5
Average		-0.1	-0.5	-0.6	-0.5	-0.1	-0.5	-0.6	-0.5

Low-rise buildings (up to 3 storeys)
Length to width ratio: 2:1
Shielding condition: Surrounded by obstructions equivalent to half the height of the building
Wind speed reference level: Building height



Location		Wind Angle							
		0°	45°	90°	135°	180°	225°	270°	315°
Face 1		0.25	0.06	-0.35	-0.6	-0.5	-0.6	-0.35	0.06
Face 2		-0.5	-0.6	-0.35	0.06	0.25	0.06	-0.35	-0.6
Face 3		-0.6	0.2	0.4	0.2	-0.6	-0.5	-0.3	-0.5
Face 4		-0.6	-0.5	-0.3	-0.5	-0.6	0.5	0.4	0.2
Roof	Front	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6
(<10° pitch)	Rear	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6
Average		-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6
Roof	Front	-0.6	-0.6	-0.55	-0.55	-0.45	-0.55	-0.55	-0.6
(11-30° pitch)	Rear	-0.45	-0.55	-0.55	-0.6	-0.6	-0.6	-0.55	-0.55
Average		-0.5	-0.6	-0.55	-0.6	-0.5	-0.6	-0.55	-0.6
Roof	Front	0.15	-0.08	-0.4	-0.75	-0.6	-0.75	-0.4	-0.08
(>30° pitch)	Rear	-0.6	-0.75	-0.4	-0.08	0.15	-0.08	-0.4	-0.75
Average		-0.2	-0.4	-0.4	-0.4	-0.2	-0.4	-0.4	-0.4

Low-rise buildings (up to 3 storeys)
Length to width ratio: 2:1
Shielding condition: Surrounded by obstructions equal to the height of the building
Wind speed reference level: Building height



Location		Wind Angle							
		0°	45°	90°	135°	180°	225°	270°	315°
Face 1		0.06	-0.12	-0.2	-0.38	-0.3	-0.38	-0.2	0.12
Face 2		-0.3	-0.38	-0.2	-0.12	0.06	-0.12	-0.2	-0.38
Face 3		-0.3	0.15	0.18	0.15	-0.3	-0.32	-0.2	-0.32
Face 4		-0.3	-0.32	-0.2	-0.32	-0.3	0.15	0.18	0.15
Roof	Front	-0.49	-0.46	-0.41	-0.46	-0.49	-0.46	-0.41	-0.46
(<10° pitch	Rear	-0.49	-0.46	-0.41	-0.46	-0.49	-0.46	-0.41	-0.46
Average		-0.49	-0.46	-0.41	-0.46	-0.49	-0.46	-0.41	-0.46
Roof	Front	-0.49	-0.46	-0.41	-0.46	-0.4	-0.46	-0.41	-0.46
(11-30° pitch)	Rear	-0.4	-0.46	-0.41	-0.46	-0.49	-0.46	-0.41	-0.46
Average		-0.45	-0.46	-0.41	-0.46	-0.45	-0.46	-0.41	-0.46
Roof	Front	0.06	-0.15	-0.23	-0.6	-0.42	-0.6	-0.23	-0.15
(>30° pitch)	Rear	-0.42	-0.6	-0.23	-0.15	-0.06	-0.15	-0.23	-0.6
Average		-0.18	-0.4	-0.23	-0.4	-0.18	-0.4	-0.23	-0.4

Appendix D: TRNSYS .Bui File for Run16 I, 2-meter DSF Depth in Minneapolis

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* TRNBuild 2.0.208
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****
* BUILDING DESCRIPTIONS FILE TRNSYS
* FOR BUILDING: C:\Users\Payman\Desktop\CONTAM TRNSYS Files\08.06.2017\Post Done\Minneapolis\DSF_2\Run16 I (NC 4-Story NV DSF2 Self No HVAC Hypo)\NC 4-Story NV DSF2 No HVAC 460 Below.b17
* GET BY WORKING WITH TRNBuild 1.0 for Windows
****
****
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****
*
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* C o m m e n t s
*---

----
*#C Originally created by TRNSIDF Version 1.57
*#C
*#C

```
*#C -----------------------------------------------------------------------------------------------------s
*#C  Total floor areas generated by importing Trnsys3d file
*#C ----
*#C  BUILDING                              520  m^2
*#C ----
*#C  ZONE            2_11                         80   m^2
*#C  AIRNODE  2_11                          80   m^2
*#C ----
*#C  ZONE            2_12                          2   m^2
*#C  AIRNODE  2_12                           2   m^2
*#C ----
*#C  ZONE            2_13                         18   m^2
*#C  AIRNODE  2_13                          18   m^2
*#C ----
*#C  ZONE            3_9                           2   m^2
*#C  AIRNODE  3_9                            2   m^2
*#C ----
*#C  ZONE            3_8                          80   m^2
*#C  AIRNODE  3_8                           80   m^2
*#C ----
*#C  ZONE            3_10                         18   m^2
*#C  AIRNODE  3_10                          18   m^2
*#C ----
*#C  ZONE            1_14                         80   m^2
*#C  AIRNODE  1_14                          80   m^2
*#C ----
*#C  ZONE            1_15                         20   m^2
*#C  AIRNODE  1_15                          20   m^2
*#C ----
*#C  ZONE            4_6                           2   m^2
*#C  AIRNODE  4_6                            2   m^2
```

```
*#C ----
*#C  ZONE               4_7                        18   m^2
*#C  AIRNODE  4_7                     18   m^2
*#C ----
*#C  ZONE               4_5                        80   m^2
*#C  AIRNODE  4_5                     80   m^2
*#C ----
*#C  ZONE               5_3                         2   m^2
*#C  AIRNODE  5_3                      2   m^2
*#C ----
*#C  ZONE               5_2                        80   m^2
*#C  AIRNODE  5_2                     80   m^2
*#C ----
*#C  ZONE               5_4                        18   m^2
*#C  AIRNODE  5_4                     18   m^2
*#C ----
*#C  ZONE               6_1                        20   m^2
*#C  AIRNODE  6_1                     20   m^2
*#C ----------------------------------------------------------------------------------------------------------e
*----------------------------------------------------------------------------------------------------------------------------------------
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* P r o j e c t
*----------------------------------------------------------------------------------------------------------------------------------------
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--------------------------------------------------------------------------------------------------------------------
*+++ PROJECT
*+++ TITLE=MC 4-STORY NV DSF2 SHADING NO HVAC 460 BELOW
*+++ DESCRIPTION=MULTY-STORY TYPE
*+++ CREATED=PAYMAN SADEGHI
*+++ ADDRESS=MINNESOTA
```

```
*+++ CITY=MINNEAPOLIS
*+++ SWITCH=UNDEFINED
*------------------------------------------------------------------------------------------------------------------------------------------
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------------------------------------------------------------------------------------------------------------------
* P r o p e r t i e s
*------------------------------------------------------------------------------------------------------------------------------------------
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------------------------------------------------------------------------------------------------------------------
PROPERTIES
 DENSITY=1.204 : CAPACITY=1.012 : PRESSURE=101325.000 : HVAPOR=2454.0 : SIGMA=2.041e-007 :
RTEMP=281.01
*--- alpha calculation -------------------
 KFLOORUP=7.2 : EFLOORUP=0.31 : KFLOORDOWN=3.888 : EFLOORDOWN=0.31
 KCEILUP=7.2 : ECEILUP=0.31 : KCEILDOWN=3.888 : ECEILDOWN=0.31
 KVERTICAL=5.76 : EVERTICAL=0.3
*
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TYPES
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*-----------------------------------------------------------------------------------------------------------------------------
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* L a y e r s
*-----------------------------------------------------------------------------------------------------------------------------
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LAYER DUMMY_TRNSYS3D
 RESISTANCE=      0.1
LAYER PLASTERBOA
 CONDUCTIVITY=  0.576 : CAPACITY=   0.84 : DENSITY=    950
LAYER FBRGLS_ASHRAE
 CONDUCTIVITY=  0.144 : CAPACITY=   0.84 : DENSITY=     12
LAYER WD_SIDN_ASHRA
 CONDUCTIVITY=  0.504 : CAPACITY=    0.9 : DENSITY=    530
LAYER TMBR_FLR_ASHR
 CONDUCTIVITY=  0.504 : CAPACITY=    1.2 : DENSITY=    650
LAYER INS_FLR_ASH
 RESISTANCE=    6.965
LAYER RFDCK_ASHRAE
 CONDUCTIVITY=  0.504 : CAPACITY=    0.9 : DENSITY=    530
LAYER CONC_SLAB
 CONDUCTIVITY=  4.068 : CAPACITY=      1 : DENSITY=   1400
LAYER INS_FLR_ASH_900
 RESISTANCE=    6.993
LAYER BEECH_OAK
 CONDUCTIVITY=   0.72 : CAPACITY=      2 : DENSITY=    800
LAYER BLOCK_M_SW
 CONDUCTIVITY=   0.72 : CAPACITY=      1 : DENSITY=    300
LAYER 8INCHCOM
 CONDUCTIVITY=  2.596 : CAPACITY=  0.837 : DENSITY= 1922.2
```

```
LAYER STONE_MASS
 CONDUCTIVITY=   3.56 : CAPACITY=      1 : DENSITY=   1500
LAYER 4INCHCOM
 CONDUCTIVITY=  2.596 : CAPACITY=  0.837 : DENSITY= 1922.2
*-------------------------------------------------------------------------------------------------------------------------------------------
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* I n p u t s
*-------------------------------------------------------------------------------------------------------------------------------------------
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INPUTS TGROUND TBOUNDARY BRIGHT SHADE_CLOSE SHADE_OPEN MAX_ISHADE MAX_ESHADE MIX_5_4_6_1 INFIL_6_1 MIX_5_3_5_2 MIX_5_4_5_2 INFIL_5_2 MIX_5_2_5_3 MIX_4_6_5_3 MIX_6_1_5_4 MIX_5_2_5_4 MIX_4_7_5_4 MIX_4_6_4_5 MIX_4_7_4_5 INFIL_4_5 MIX_5_3_4_6 MIX_4_5_4_6 MIX_3_9_4_6 MIX_5_4_4_7 MIX_4_5_4_7 MIX_3_10_4_7 MIX_3_9_3_8 MIX_3_10_3_8 INFIL_3_8 MIX_4_6_3_9 MIX_3_8_3_9 MIX_2_12_3_9 MIX_4_7_3_10 MIX_3_8_3_10 ;
 MIX_2_13_3_10 MIX_2_12_2_11 MIX_2_13_2_11 INFIL_2_11 MIX_3_9_2_12 MIX_2_11_2_12 MIX_1_15_2_12 MIX_3_10_2_13 MIX_2_11_2_13 MIX_1_15_2_13 MIX_1_15_1_14 INFIL_1_14 MIX_2_12_1_15 MIX_2_13_1_15 MIX_1_14_1_15 INFIL_1_15 TAIR_IN RH_IN T_GRBASE
*-------------------------------------------------------------------------------------------------------------------------------------------
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---------------------------------------------------------------------------------------------------------------------
* S c h e d u l e s
*-------------------------------------------------------------------------------------------------------------------------------------------
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---------------------------------------------------------------------------------------------------------------------
SCHEDULE WORKDAY
 HOURS =0.000 8.000 18.000 24.0
 VALUES=0 1. 0 0
SCHEDULE WEEKEND
 HOURS =0.000 1.000 24.0
```

```
 VALUES=0 0 0
SCHEDULE WORKLIGHT
 HOURS =0.000 8.000 18.000 24.0
 VALUES=0 1. 0 0
SCHEDULE DAYNIGHT
 HOURS =0.000 6.000 18.000 24.0
 VALUES=0 1. 0 0
SCHEDULE USE
 DAYS=1 2 3 4 5 6 7
 HOURLY=WORKDAY WORKDAY WORKDAY WORKDAY WORKDAY WEEKEND WEEKEND
SCHEDULE LIGHT
 DAYS=1 2 3 4 5 6 7
 HOURLY=WORKLIGHT WORKLIGHT WORKLIGHT WORKLIGHT WORKLIGHT WEEKEND WEEKEND
SCHEDULE SETOFF
 DAYS=1 2 3 4 5 6 7
 HOURLY=DAYNIGHT DAYNIGHT DAYNIGHT DAYNIGHT DAYNIGHT WEEKEND WEEKEND
*-----------------------------------------------------------------------------------------------------------------------------------------------
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---------------------------------------------------------------------------------------------------------------------
* W a l l s
*-----------------------------------------------------------------------------------------------------------------------------------------------
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---------------------------------------------------------------------------------------------------------------------
WALL BND_WALL
 LAYERS   = PLASTERBOA FBRGLS_ASHRAE PLASTERBOA
 THICKNESS= 0.012     0.066       0.012
 ABS-FRONT= 0.6   : ABS-BACK= 0.6
 EPS-FRONT= 0.9   : EPS-BACK= 0.9
 HFRONT   = 11 : HBACK= 11
WALL EXT_WALL
 LAYERS   = PLASTERBOA FBRGLS_ASHRAE WD_SIDN_ASHRA
```

```
 THICKNESS= 0.012     0.066        0.009
 ABS-FRONT= 0.6   : ABS-BACK= 0.6
 EPS-FRONT= 0.9   : EPS-BACK= 0.9
 HFRONT   = 11 : HBACK= 64
WALL EXT_ROOF
 LAYERS   = PLASTERBOA FBRGLS_ASHRAE RFDCK_ASHRAE
 THICKNESS= 0.01      0.112        0.019
 ABS-FRONT= 0.6   : ABS-BACK= 0.6
 EPS-FRONT= 0.9   : EPS-BACK= 0.9
 HFRONT   = 11 : HBACK= 64
WALL EXT_FLOOR
 LAYERS   = TMBR_FLR_ASHR FBRGLS_ASHRAE
 THICKNESS= 0.03         0.04
 ABS-FRONT= 0.6   : ABS-BACK= 0.6
 EPS-FRONT= 0.9   : EPS-BACK= 0.9
 HFRONT   = 11 : HBACK= 11
WALL BND_CEILING
 LAYERS   = CONC_SLAB
 THICKNESS= 0.08
 ABS-FRONT= 0.6   : ABS-BACK= 0.6
 EPS-FRONT= 0.9   : EPS-BACK= 0.9
 HFRONT   = 11 : HBACK= 11
WALL BND_FLOOR
 LAYERS   = TMBR_FLR_ASHR FBRGLS_ASHRAE
 THICKNESS= 0.03         0.04
 ABS-FRONT= 0.6   : ABS-BACK= 0.6
 EPS-FRONT= 0.9   : EPS-BACK= 0.9
 HFRONT   = 11 : HBACK= 11
WALL GROUND_FLOOR
 LAYERS   = CONC_SLAB FBRGLS_ASHRAE
 THICKNESS= 0.08      0.04
```

```
 ABS-FRONT= 0.6   : ABS-BACK= 0.6
 EPS-FRONT= 0.9   : EPS-BACK= 0.9
 HFRONT   = 11 : HBACK= 0.001
WALL ADJ_WALL
 LAYERS   = PLASTERBOA FBRGLS_ASHRAE PLASTERBOA
 THICKNESS= 0.012      0.066         0.012
 ABS-FRONT= 0.6   : ABS-BACK= 0.6
 EPS-FRONT= 0.9   : EPS-BACK= 0.9
 HFRONT   = 11 : HBACK= 11
WALL ADJ_CEILING
 LAYERS   = CONC_SLAB
 THICKNESS= 0.08
 ABS-FRONT= 0.6   : ABS-BACK= 0.6
 EPS-FRONT= 0.9   : EPS-BACK= 0.9
 HFRONT   = 11 : HBACK= 11
WALL ADJ_CEILING_A
 LAYERS   = CONC_SLAB FBRGLS_ASHRAE PLASTERBOA
 THICKNESS= 0.08      0.054         0.012
 ABS-FRONT= 0.6   : ABS-BACK= 0.6
 EPS-FRONT= 0.9   : EPS-BACK= 0.9
 HFRONT   = 11 : HBACK= 11
WALL EXT_ROOF_A
 LAYERS   = PLASTERBOA FBRGLS_ASHRAE RFDCK_ASHRAE
 THICKNESS= 0.01       0.25          0.019
 ABS-FRONT= 0.6   : ABS-BACK= 0.6
 EPS-FRONT= 0.9   : EPS-BACK= 0.9
 HFRONT   = 11 : HBACK= 64
WALL EXT_ROOF_PH
 LAYERS   = PLASTERBOA FBRGLS_ASHRAE RFDCK_ASHRAE
 THICKNESS= 0.01       0.25          0.019
 ABS-FRONT= 0.6   : ABS-BACK= 0.6
```

```
 EPS-FRONT= 0.9   : EPS-BACK= 0.9
 HFRONT   = 11 : HBACK= 64
WALL EXT_ROOF_M
 LAYERS   = PLASTERBOA FBRGLS_ASHRAE RFDCK_ASHRAE
 THICKNESS= 0.01       0.32         0.019
 ABS-FRONT= 0.6   : ABS-BACK= 0.6
 EPS-FRONT= 0.9   : EPS-BACK= 0.9
 HFRONT   = 11 : HBACK= 64
WALL BND_WALL_A
 LAYERS   = PLASTERBOA 8INCHCOM
 THICKNESS= 0.012      0.2
 ABS-FRONT= 0.6   : ABS-BACK= 0.6
 EPS-FRONT= 0.9   : EPS-BACK= 0.9
 HFRONT   = 11 : HBACK= 11
WALL BND_WALL_M
 LAYERS   = PLASTERBOA FBRGLS_ASHRAE 8INCHCOM
 THICKNESS= 0.012      0.056        0.2
 ABS-FRONT= 0.6   : ABS-BACK= 0.6
 EPS-FRONT= 0.9   : EPS-BACK= 0.9
 HFRONT   = 11 : HBACK= 11
WALL EXT_WALL_A
 LAYERS   = PLASTERBOA FBRGLS_ASHRAE 8INCHCOM
 THICKNESS= 0.012      0.026        0.2
 ABS-FRONT= 0.6   : ABS-BACK= 0.6
 EPS-FRONT= 0.9   : EPS-BACK= 0.9
 HFRONT   = 11 : HBACK= 64
WALL EXT_WALL_PH
 LAYERS   = PLASTERBOA FBRGLS_ASHRAE 8INCHCOM
 THICKNESS= 0.012      0.026        0.2
 ABS-FRONT= 0.6   : ABS-BACK= 0.6
 EPS-FRONT= 0.9   : EPS-BACK= 0.9
```

```
 HFRONT   = 11 : HBACK= 64
WALL EXT_WALL_M
 LAYERS   = PLASTERBOA FBRGLS_ASHRAE 8INCHCOM
 THICKNESS= 0.012      0.068         0.2
 ABS-FRONT= 0.6   : ABS-BACK= 0.6
 EPS-FRONT= 0.9   : EPS-BACK= 0.9
 HFRONT   = 11 : HBACK= 64
WALL ADJ_CEILING_PH
 LAYERS   = CONC_SLAB FBRGLS_ASHRAE PLASTERBOA
 THICKNESS= 0.08      0.054         0.012
 ABS-FRONT= 0.6   : ABS-BACK= 0.6
 EPS-FRONT= 0.9   : EPS-BACK= 0.9
 HFRONT   = 11 : HBACK= 11
WALL ADJ_CEILING_M
 LAYERS   = CONC_SLAB FBRGLS_ASHRAE PLASTERBOA
 THICKNESS= 0.08      0.128         0.012
 ABS-FRONT= 0.6   : ABS-BACK= 0.6
 EPS-FRONT= 0.9   : EPS-BACK= 0.9
 HFRONT   = 11 : HBACK= 11
WALL ADJ_WALL_A
 LAYERS   = 4INCHCOM FBRGLS_ASHRAE 4INCHCOM
 THICKNESS= 0.1      0.066         0.1
 ABS-FRONT= 0.6   : ABS-BACK= 0.6
 EPS-FRONT= 0.9   : EPS-BACK= 0.9
 HFRONT   = 11 : HBACK= 11
WALL ADJ_WALL_M
 LAYERS   = 4INCHCOM FBRGLS_ASHRAE 4INCHCOM
 THICKNESS= 0.1      0.066         0.1
 ABS-FRONT= 0.6   : ABS-BACK= 0.6
 EPS-FRONT= 0.9   : EPS-BACK= 0.9
 HFRONT   = 11 : HBACK= 11
```

```
WALL ADJ_WALL_PH
 LAYERS   = 4INCHCOM FBRGLS_ASHRAE 4INCHCOM
 THICKNESS= 0.1      0.066        0.1
 ABS-FRONT= 0.6   : ABS-BACK= 0.6
 EPS-FRONT= 0.9   : EPS-BACK= 0.9
 HFRONT   = 11 : HBACK= 11
WALL BND_WALL_PH
 LAYERS   = PLASTERBOA 8INCHCOM
 THICKNESS= 0.012      0.2
 ABS-FRONT= 0.6   : ABS-BACK= 0.6
 EPS-FRONT= 0.9   : EPS-BACK= 0.9
 HFRONT   = 11 : HBACK= 11
WALL GRND_FLOOR_A
 LAYERS   = CONC_SLAB
 THICKNESS= 0.1
 ABS-FRONT= 0.6   : ABS-BACK= 0.6
 EPS-FRONT= 0.9   : EPS-BACK= 0.9
 HFRONT   = 11 : HBACK= 0.001
WALL GRND_FLOOR_PH
 LAYERS   = CONC_SLAB
 THICKNESS= 0.1
 ABS-FRONT= 0.6   : ABS-BACK= 0.6
 EPS-FRONT= 0.9   : EPS-BACK= 0.9
 HFRONT   = 11 : HBACK= 0.001
WALL GRND_FLOOR_M
 LAYERS   = CONC_SLAB FBRGLS_ASHRAE
 THICKNESS= 0.1       0.01
 ABS-FRONT= 0.6   : ABS-BACK= 0.6
 EPS-FRONT= 0.9   : EPS-BACK= 0.9
 HFRONT   = 11 : HBACK= 0.001
```

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* W i n d o w s

*--

WINDOW EXT_WINDOW1

WINID=6001 : HINSIDE=11 : HOUTSIDE=64 : SLOPE=90 : SPACID=0 : WWID=0 : WHEIG=0 : FFRAME=0.3 : UFRAME=10.9091 : ABSFRAME=0.6 : RISHADE=0 : RESHADE=0 : REFLISHADE=0.5 : REFLOSHADE=0.5 : CCISHADE=0.5 : EPSFRAME=0.9 : EPSISHADE=0.9 : ITSHADECLOSE=0 : ITSHADEOPEN=0

WINDOW EXT_WINDOW2

WINID=6001 : HINSIDE=11 : HOUTSIDE=64 : SLOPE=90 : SPACID=0 : WWID=0 : WHEIG=0 : FFRAME=0.3 : UFRAME=10.9091 : ABSFRAME=0.6 : RISHADE=0 : RESHADE=0 : REFLISHADE=0.5 : REFLOSHADE=0.5 : CCISHADE=0.5 : EPSFRAME=0.9 : EPSISHADE=0.9 : ITSHADECLOSE=0 : ITSHADEOPEN=0

WINDOW ADJ_WINDOW

WINID=7003 : HINSIDE=11 : HOUTSIDE=64 : SLOPE=90 : SPACID=0 : WWID=0 : WHEIG=0 : FFRAME=0.3 : UFRAME=10.9091 : ABSFRAME=0.6 : RISHADE=0 : RESHADE=0 : REFLISHADE=0.5 : REFLOSHADE=0.5 : CCISHADE=0.5 : EPSFRAME=0.9 : EPSISHADE=0.9 : ITSHADECLOSE=0 : ITSHADEOPEN=0

WINDOW ADJ_WINDOW2

WINID=6001 : HINSIDE=11 : HOUTSIDE=64 : SLOPE=90 : SPACID=0 : WWID=0 : WHEIG=0 : FFRAME=0.3 : UFRAME=10.9091 : ABSFRAME=0.6 : RISHADE=0 : RESHADE=0 : REFLISHADE=0.5 : REFLOSHADE=0.5 : CCISHADE=0.5 : EPSFRAME=0.9 : EPSISHADE=0.9 : ITSHADECLOSE=0 : ITSHADEOPEN=0

WINDOW ADJ_WINDOW_PH

WINID=7003 : HINSIDE=11 : HOUTSIDE=64 : SLOPE=90 : SPACID=0 : WWID=0 : WHEIG=0 : FFRAME=0.3 : UFRAME=10.9091 : ABSFRAME=0.6 : RISHADE=0 : RESHADE=0 : REFLISHADE=0.5 :

REFLOSHADE=0.5 : CCISHADE=0.5 : EPSFRAME=0.9 : EPSISHADE=0.9 : ITSHADECLOSE=0 : ITSHADEOPEN=0

WINDOW ADJ_WINDOW_A

WINID=7003 : HINSIDE=11 : HOUTSIDE=64 : SLOPE=90 : SPACID=0 : WWID=0 : WHEIG=0 : FFRAME=0.3 : UFRAME=10.9091 : ABSFRAME=0.6 : RISHADE=0 : RESHADE=0 : REFLISHADE=0.5 : REFLOSHADE=0.5 : CCISHADE=0.5 : EPSFRAME=0.9 : EPSISHADE=0.9 : ITSHADECLOSE=0 : ITSHADEOPEN=0

WINDOW ADJ_WINDOW_M

WINID=7002 : HINSIDE=11 : HOUTSIDE=64 : SLOPE=90 : SPACID=0 : WWID=0 : WHEIG=0 : FFRAME=0.3 : UFRAME=10.9091 : ABSFRAME=0.6 : RISHADE=0 : RESHADE=0 : REFLISHADE=0.5 : REFLOSHADE=0.5 : CCISHADE=0.5 : EPSFRAME=0.9 : EPSISHADE=0.9 : ITSHADECLOSE=0 : ITSHADEOPEN=0

WINDOW SINGLE_DSF

WINID=1001 : HINSIDE=11 : HOUTSIDE=64 : SLOPE=90 : SPACID=1 : WWID=0.77 : WHEIG=1.08 : FFRAME=0.15 : UFRAME=8.17 : ABSFRAME=0.6 : RISHADE=0 : RESHADE=0 : REFLISHADE=0.5 : REFLOSHADE=0.5 : CCISHADE=0.5 : EPSFRAME=0.9 : EPSISHADE=0.9 : ITSHADECLOSE=0 : ITSHADEOPEN=0

WINDOW EXT_WINDOW_A

WINID=7003 : HINSIDE=11 : HOUTSIDE=64 : SLOPE=90 : SPACID=0 : WWID=0 : WHEIG=0 : FFRAME=0.3 : UFRAME=10.9091 : ABSFRAME=0.6 : RISHADE=0 : RESHADE=0 : REFLISHADE=0.5 : REFLOSHADE=0.5 : CCISHADE=0.5 : EPSFRAME=0.9 : EPSISHADE=0.9 : ITSHADECLOSE=0 : ITSHADEOPEN=0

WINDOW EXT_WINDOW_M

WINID=7002 : HINSIDE=11 : HOUTSIDE=64 : SLOPE=90 : SPACID=0 : WWID=0 : WHEIG=0 : FFRAME=0.3 : UFRAME=10.9091 : ABSFRAME=0.6 : RISHADE=0 : RESHADE=0 : REFLISHADE=0.5 : REFLOSHADE=0.5 : CCISHADE=0.5 : EPSFRAME=0.9 : EPSISHADE=0.9 : ITSHADECLOSE=0 : ITSHADEOPEN=0

WINDOW EXT_WINDOW_PH

WINID=7003 : HINSIDE=11 : HOUTSIDE=64 : SLOPE=90 : SPACID=0 : WWID=0 : WHEIG=0 : FFRAME=0.3 : UFRAME=10.9091 : ABSFRAME=0.6 : RISHADE=0 : RESHADE=0 : REFLISHADE=0.5 :

REFLOSHADE=0.5 : CCISHADE=0.5 : EPSFRAME=0.9 : EPSISHADE=0.9 : ITSHADECLOSE=0 : ITSHADEOPEN=0

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* D e f a u l t G a i n s

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GAIN PERS_ISO04

CONVECTIVE=180 : RADIATIVE=90 : HUMIDITY=0.11

GAIN COMPUTER03

CONVECTIVE=420 : RADIATIVE=84 : HUMIDITY=0

GAIN LIGHT02_01

CONVECTIVE=INPUT 1152*BRIGHT : RADIATIVE=INPUT 1728*BRIGHT : HUMIDITY=0

GAIN LIGHT02_05

CONVECTIVE=INPUT 1152*BRIGHT : RADIATIVE=INPUT 1728*BRIGHT : HUMIDITY=0

GAIN LIGHT02_07

CONVECTIVE=INPUT 1152*BRIGHT : RADIATIVE=INPUT 1728*BRIGHT : HUMIDITY=0

GAIN LIGHT02_11

CONVECTIVE=INPUT 1152*BRIGHT : RADIATIVE=INPUT 1728*BRIGHT : HUMIDITY=0

GAIN LIGHT02_13

CONVECTIVE=INPUT 1152*BRIGHT : RADIATIVE=INPUT 1728*BRIGHT : HUMIDITY=0

*---

* O t h e r G a i n s

*---

GAIN PRINTER

```
 CONVECTIVE=522 : RADIATIVE=276 : HUMIDITY=0
*-----------------------------------------------------------------------------------------------------------------------------------------------
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-----------------------------------------------------------------------------------------------------------------------
* C o m f o r t
*-----------------------------------------------------------------------------------------------------------------------------------------------
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COMFORT COMF_OFFICE
 CLOTHING=1 : MET=1.2 : WORK=0 : VELOCITY=0.1
*-----------------------------------------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------------
* I n f i l t r a t i o n
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-----------------------------------------------------------------------------------------------------------------------
INFILTRATION INFIL_OFFICE
 AIRCHANGE=0.1
*-----------------------------------------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------------
* V e n t i l a t i o n
*-----------------------------------------------------------------------------------------------------------------------------------------------
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-----------------------------------------------------------------------------------------------------------------------
VENTILATION OFF1_VENTILATION
 TEMPERATURE=OUTSIDE
 AIRCHANGE=INPUT 1*INFIL_2_11
 HUMIDITY=OUTSIDE
VENTILATION OFF2_VENTILATION
```

```
 TEMPERATURE=OUTSIDE
 AIRCHANGE=INPUT 1*INFIL_3_8
 HUMIDITY=OUTSIDE
VENTILATION OFF_1_VENTILATION
 TEMPERATURE=OUTSIDE
 AIRCHANGE=INPUT 1*INFIL_1_14
 HUMIDITY=OUTSIDE
VENTILATION SUN_1_VENTILATION
 TEMPERATURE=INPUT 1*TAIR_IN
 AIRCHANGE=INPUT 1*INFIL_1_15
 HUMIDITY=INPUT 1*RH_IN
VENTILATION OFF3_VENTILATION
 TEMPERATURE=OUTSIDE
 AIRCHANGE=INPUT 1*INFIL_4_5
 HUMIDITY=OUTSIDE
VENTILATION OFF4_VENTILATION
 TEMPERATURE=OUTSIDE
 AIRCHANGE=INPUT 1*INFIL_5_2
 HUMIDITY=OUTSIDE
VENTILATION SUN_1_HYPO
 TEMPERATURE=INPUT 1*TAIR_IN
 AIRFLOW=674
 HUMIDITY=INPUT 1*RH_IN
*----------------------------------------------------------------------------------------------------------------------------------------------------
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* C o o l i n g
*----------------------------------------------------------------------------------------------------------------------------------------------------
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------------------------------------------------------------------------------------------------------------------------
COOLING COOL_OFFICE
```

```
 ON=SCHEDULE -11*USE+35
 POWER=999999999
 HUMIDITY=50
*-----------------------------------------------------------------------------------------------------------------------------------
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--------------------------------------------------------------------------------------------------------------
* H e a t i n g
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--------------------------------------------------------------------------------------------------------------
HEATING HEAT_OFFICE
 ON=SCHEDULE 10*USE+10
 POWER=999999999
 HUMIDITY=0
 RRAD=0
*
*-----------------------------------------------------------------------------------------------------------------------------------
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* Z o n e s
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--------------------------------------------------------------------------------------------------------------
ZONES 2_11 2_12 2_13 3_9 3_8 3_10 1_14 1_15 4_6 4_7 4_5 5_3 5_2 5_4 6_1
*-----------------------------------------------------------------------------------------------------------------------------------
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* O r i e n t a t i o n s
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```
HEMISPHERE NORTHERN
ORIENTATIONS H_0_0 S_0_90 W_90_90 N_180_90 E_270_90
INTERNAL_CALCULATION H_0_0 S_0_90 W_90_90 N_180_90 E_270_90
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BUILDING
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* Z o n e  2_11  /  A i r n o d e  2_11
*------------------------------------------------------------------------------------------------------------------------------------------------------------
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-----------------------------------------------------------------------------------------------------------------------------
ZONE 2_11
RADIATIONMODE
 BEAM=DETAILED : DIFFUSE=DETAILED : LONGWAVE=DETAILED : GEOMODE=3D_DATA :
FSOLAIR=0.4
AIRNODE 2_11
WALL  =EXT_WALL_M : SURF=  1 : AREA=       24 : EXTERNAL : ORI=E_270_90 : FSKY=0.5
WALL  =ADJ_CEILING_M : SURF=  2 : AREA=       80 : ADJACENT=3_8 : ADJ_SURF=32 : FRONT
WALL  =EXT_WALL_M : SURF=  3 : AREA=       30 : EXTERNAL : ORI=N_180_90 : FSKY=0.5
```

WALL =EXT_WALL_M : SURF= 4 : AREA= 24 : EXTERNAL : ORI=W_90_90 : FSKY=0.5

WALL =ADJ_CEILING_M : SURF= 5 : AREA= 80 : ADJACENT=1_14 : ADJ_SURF=47 : BACK

WALL =ADJ_WALL_M : SURF= 6 : AREA= 3 : ADJACENT=2_12 : ADJ_SURF=11 : FRONT : COUPL=INPUT 1*MIX_2_12_2_11

WALL =ADJ_WALL_M : SURF= 7 : AREA= 3.78 : ADJACENT=2_13 : ADJ_SURF=16 : FRONT : COUPL=INPUT 1*MIX_2_13_2_11

WINDOW=ADJ_WINDOW_M : SURF= 8 : AREA= 23.22 : ADJACENT=2_13 : ADJ_SURF=21 : FRONT : ORI=S_0_90

REGIME

GAIN = PERS_ISO04 : SCALE= SCHEDULE 6*USE : GEOPOS= 0

GAIN = COMPUTER03 : SCALE= SCHEDULE 6*USE : GEOPOS= 0

GAIN = LIGHT02_01 : SCALE= INPUT 1*BRIGHT : GEOPOS= 0

GAIN = PRINTER : SCALE= SCHEDULE 2*USE : GEOPOS= 0

COMFORT = COMF_OFFICE : COMFID= 1 : MRT= INTERNAL : GEOPOS= 0

INFILTRATION= INFIL_OFFICE

COOLING = COOL_OFFICE

HEATING = HEAT_OFFICE

CAPACITANCE = 2880 : VOLUME= 240 : TINITIAL= 20 : PHINITIAL= 50 : WCAPR= 1

*---

* Z o n e 2_12 / A i r n o d e 2_12

*---

ZONE 2_12

RADIATIONMODE

BEAM=STANDARD : DIFFUSE=STANDARD : LONGWAVE=STANDARD : GEOMODE=3D_DATA : FSOLAIR=0

AIRNODE 2_12

WALL =ADJ_CEILING_M : SURF= 9 : AREA= 2 : ADJACENT=1_15 : ADJ_SURF=54 : BACK : COUPL=INPUT 1*MIX_1_15_2_12

WALL =ADJ_CEILING_M : SURF= 10 : AREA= 2 : ADJACENT=3_9 : ADJ_SURF=24 : FRONT : COUPL=INPUT 1*MIX_3_9_2_12

WALL =ADJ_WALL_M : SURF= 11 : AREA= 3 : ADJACENT=2_11 : ADJ_SURF=6 : BACK : COUPL=INPUT 1*MIX_2_11_2_12

WALL =EXT_WALL_M : SURF= 12 : AREA= 6 : EXTERNAL : ORI=W_90_90 : FSKY=0.5

WALL =ADJ_WALL_M : SURF= 13 : AREA= 6 : ADJACENT=2_13 : ADJ_SURF=18 : FRONT

WALL =EXT_WALL_M : SURF= 14 : AREA= 3 : EXTERNAL : ORI=S_0_90 : FSKY=0.5

REGIME

INFILTRATION= INFIL_OFFICE

CAPACITANCE = 7.2 : VOLUME= 6 : TINITIAL= 20 : PHINITIAL= 50 : WCAPR= 1

*---

* Zone 2_13 / Airnode 2_13

*---

ZONE 2_13

RADIATIONMODE

BEAM=STANDARD : DIFFUSE=STANDARD : LONGWAVE=STANDARD : GEOMODE=3D_DATA : FSOLAIR=0

AIRNODE 2_13

WALL =ADJ_CEILING_M : SURF= 15 : AREA= 18 : ADJACENT=1_15 : ADJ_SURF=51 : BACK : COUPL=INPUT 1*MIX_1_15_2_13

WALL =ADJ_WALL_M : SURF= 16 : AREA= 3.78 : ADJACENT=2_11 : ADJ_SURF=7 : BACK : COUPL=INPUT 1*MIX_2_11_2_13

WINDOW=ADJ_WINDOW_M : SURF= 21 : AREA= 23.22 : ADJACENT=2_11 : ADJ_SURF=8 : BACK : ORI=N_180_90

WALL =ADJ_CEILING_M : SURF= 17 : AREA= 18 : ADJACENT=3_10 : ADJ_SURF=42 : FRONT : COUPL=INPUT 1*MIX_3_10_2_13

WALL =ADJ_WALL_M : SURF= 18 : AREA= 6 : ADJACENT=2_12 : ADJ_SURF=13 : BACK

WALL =EXT_WALL_M : SURF= 19 : AREA= 6 : EXTERNAL : ORI=E_270_90 : FSKY=0.5

WALL =EXT_WALL_M : SURF= 20 : AREA= 3.78 : EXTERNAL : ORI=S_0_90 : FSKY=0.5

WINDOW=SINGLE_DSF : SURF= 22 : AREA= 23.22 : EXTERNAL : ORI=S_0_90 : FSKY=0.5 : ESHADE=INPUT 1*MAX_ESHADE

REGIME

INFILTRATION= INFIL_OFFICE

CAPACITANCE = 64.8 : VOLUME= 54 : TINITIAL= 20 : PHINITIAL= 50 : WCAPR= 1

*--

* Z o n e 3_9 / A i r n o d e 3_9

*--

ZONE 3_9

RADIATIONMODE

BEAM=STANDARD : DIFFUSE=STANDARD : LONGWAVE=STANDARD : GEOMODE=3D_DATA : FSOLAIR=0

AIRNODE 3_9

WALL =ADJ_WALL_M : SURF= 23 : AREA= 3 : ADJACENT=3_8 : ADJ_SURF=33 : FRONT : COUPL=INPUT 1*MIX_3_8_3_9

WALL =ADJ_CEILING_M : SURF= 24 : AREA= 2 : ADJACENT=2_12 : ADJ_SURF=10 : BACK : COUPL=INPUT 1*MIX_2_12_3_9

WALL =EXT_WALL_M : SURF= 25 : AREA= 3 : EXTERNAL : ORI=S_0_90 : FSKY=0.5

WALL =EXT_WALL_M : SURF= 26 : AREA= 6 : EXTERNAL : ORI=W_90_90 : FSKY=0.5

WALL =ADJ_CEILING_M : SURF= 27 : AREA= 2 : ADJACENT=4_6 : ADJ_SURF=61 : FRONT : COUPL=INPUT 1*MIX_4_6_3_9

WALL =ADJ_WALL_M : SURF= 28 : AREA= 6 : ADJACENT=3_10 : ADJ_SURF=37 : FRONT

REGIME
INFILTRATION= INFIL_OFFICE
CAPACITANCE = 7.2 : VOLUME= 6 : TINITIAL= 20 : PHINITIAL= 50 : WCAPR= 1
*--
* Zone 3_8 / Airnode 3_8
*--
ZONE 3_8
RADIATIONMODE
BEAM=DETAILED : DIFFUSE=DETAILED : LONGWAVE=DETAILED : GEOMODE=3D_DATA : FSOLAIR=0.4
AIRNODE 3_8
WALL =EXT_WALL_M : SURF= 29 : AREA= 24 : EXTERNAL : ORI=E_270_90 : FSKY=0.5
WALL =EXT_WALL_M : SURF= 30 : AREA= 30 : EXTERNAL : ORI=N_180_90 : FSKY=0.5
WALL =ADJ_WALL_M : SURF= 31 : AREA= 3.78 : ADJACENT=3_10 : ADJ_SURF=39 : FRONT : COUPL=INPUT 1*MIX_3_10_3_8
WINDOW=ADJ_WINDOW_M : SURF= 36 : AREA= 23.22 : ADJACENT=3_10 : ADJ_SURF=43 : FRONT : ORI=S_0_90
WALL =ADJ_CEILING_M : SURF= 32 : AREA= 80 : ADJACENT=2_11 : ADJ_SURF=2 : BACK
WALL =ADJ_WALL_M : SURF= 33 : AREA= 3 : ADJACENT=3_9 : ADJ_SURF=23 : BACK : COUPL=INPUT 1*MIX_3_9_3_8
WALL =EXT_WALL_M : SURF= 34 : AREA= 24 : EXTERNAL : ORI=W_90_90 : FSKY=0.5
WALL =ADJ_CEILING_M : SURF= 35 : AREA= 80 : ADJACENT=4_5 : ADJ_SURF=78 : FRONT
REGIME
GAIN = PERS_ISO04 : SCALE= SCHEDULE 4*USE : GEOPOS= 0
GAIN = COMPUTER03 : SCALE= SCHEDULE 4*USE : GEOPOS= 0
GAIN = LIGHT02_05 : SCALE= INPUT 1*BRIGHT : GEOPOS= 0
GAIN = PRINTER : SCALE= SCHEDULE 2*USE : GEOPOS= 0

COMFORT = COMF_OFFICE : COMFID= 2 : MRT= INTERNAL : GEOPOS= 0

INFILTRATION= INFIL_OFFICE

COOLING = COOL_OFFICE

HEATING = HEAT_OFFICE

CAPACITANCE = 2880 : VOLUME= 240 : TINITIAL= 20 : PHINITIAL= 50 : WCAPR= 1

*---

* Z o n e 3_10 / A i r n o d e 3_10

*---

ZONE 3_10

RADIATIONMODE

BEAM=STANDARD : DIFFUSE=STANDARD : LONGWAVE=STANDARD : GEOMODE=3D_DATA : FSOLAIR=0

AIRNODE 3_10

WALL =ADJ_WALL_M : SURF= 37 : AREA= 6 : ADJACENT=3_9 : ADJ_SURF=28 : BACK

WALL =EXT_WALL_M : SURF= 38 : AREA= 6 : EXTERNAL : ORI=E_270_90 : FSKY=0.5

WALL =ADJ_WALL_M : SURF= 39 : AREA= 3.78 : ADJACENT=3_8 : ADJ_SURF=31 : BACK : COUPL=INPUT 1*MIX_3_8_3_10

WINDOW=ADJ_WINDOW_M : SURF= 43 : AREA= 23.22 : ADJACENT=3_8 : ADJ_SURF=36 : BACK : ORI=N_180_90

WALL =ADJ_CEILING_M : SURF= 40 : AREA= 18 : ADJACENT=4_7 : ADJ_SURF=67 : FRONT : COUPL=INPUT 1*MIX_4_7_3_10

WALL =EXT_WALL_M : SURF= 41 : AREA= 3.78 : EXTERNAL : ORI=S_0_90 : FSKY=0.5

WINDOW=SINGLE_DSF : SURF= 44 : AREA= 23.22 : EXTERNAL : ORI=S_0_90 : FSKY=0.5 : ESHADE=INPUT 1*MAX_ESHADE

WALL =ADJ_CEILING_M : SURF= 42 : AREA= 18 : ADJACENT=2_13 : ADJ_SURF=17 : BACK : COUPL=INPUT 1*MIX_2_13_3_10

REGIME

INFILTRATION= INFIL_OFFICE

CAPACITANCE = 64.8 : VOLUME= 54 : TINITIAL= 20 : PHINITIAL= 50 : WCAPR= 1

*---

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* Z o n e 1_14 / A i r n o d e 1_14

*---

ZONE 1_14

RADIATIONMODE

BEAM=DETAILED : DIFFUSE=DETAILED : LONGWAVE=DETAILED : GEOMODE=3D_DATA : FSOLAIR=0.4

AIRNODE 1_14

WALL =ADJ_WALL_M : SURF= 45 : AREA= 30 : ADJACENT=1_15 : ADJ_SURF=57 : FRONT : COUPL=INPUT 1*MIX_1_15_1_14

WALL =BND_WALL_M : SURF= 46 : AREA= 24 : BOUNDARY=INPUT 1*TBOUNDARY

WALL =ADJ_CEILING_M : SURF= 47 : AREA= 80 : ADJACENT=2_11 : ADJ_SURF=5 : FRONT

WALL =BND_WALL_M : SURF= 48 : AREA= 24 : BOUNDARY=INPUT 1*TBOUNDARY

WALL =GRND_FLOOR_M : SURF= 49 : AREA= 80 : BOUNDARY=INPUT 1*TGROUND

WALL =BND_WALL_M : SURF= 50 : AREA= 30 : BOUNDARY=INPUT 1*TBOUNDARY

REGIME

GAIN = LIGHT02_07 : SCALE= INPUT 1*BRIGHT : GEOPOS= 0

INFILTRATION= INFIL_OFFICE

CAPACITANCE = 2880 : VOLUME= 240 : TINITIAL= 20 : PHINITIAL= 50 : WCAPR= 1

*---

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* Z o n e 1_15 / A i r n o d e 1_15

*---

ZONE 1_15
RADIATIONMODE
BEAM=STANDARD : DIFFUSE=STANDARD : LONGWAVE=STANDARD : GEOMODE=3D_DATA : FSOLAIR=0
AIRNODE 1_15
WALL =ADJ_CEILING_M : SURF= 51 : AREA= 18 : ADJACENT=2_13 : ADJ_SURF=15 : FRONT : COUPL=INPUT 1*MIX_2_13_1_15
WALL =BND_WALL_M : SURF= 52 : AREA= 6 : BOUNDARY=INPUT 1*TBOUNDARY
WALL =BND_WALL_M : SURF= 53 : AREA= 6 : BOUNDARY=INPUT 1*TBOUNDARY
WALL =ADJ_CEILING_M : SURF= 54 : AREA= 2 : ADJACENT=2_12 : ADJ_SURF=9 : FRONT : COUPL=INPUT 1*MIX_2_12_1_15
WALL =BND_WALL_M : SURF= 55 : AREA= 30 : BOUNDARY=INPUT 1*TBOUNDARY
WALL =GRND_FLOOR_M : SURF= 56 : AREA= 20 : BOUNDARY=INPUT 1*TGROUND
WALL =ADJ_WALL_M : SURF= 57 : AREA= 30 : ADJACENT=1_14 : ADJ_SURF=45 : BACK : COUPL=INPUT 1*MIX_1_14_1_15
REGIME
INFILTRATION= INFIL_OFFICE
VENTILATION = SUN_1_VENTILATION
CAPACITANCE = 72 : VOLUME= 60 : TINITIAL= 20 : PHINITIAL= 50 : WCAPR= 1
*---

----
* Zone 4_6 / Airnode 4_6
*---

ZONE 4_6
RADIATIONMODE

BEAM=STANDARD : DIFFUSE=STANDARD : LONGWAVE=STANDARD : GEOMODE=3D_DATA : FSOLAIR=0

AIRNODE 4_6

WALL =ADJ_WALL_M : SURF= 58 : AREA= 6 : ADJACENT=4_7 : ADJ_SURF=66 : FRONT

WALL =ADJ_CEILING_M : SURF= 59 : AREA= 2 : ADJACENT=5_3 : ADJ_SURF=82 : FRONT : COUPL=INPUT 1*MIX_5_3_4_6

WALL =EXT_WALL_M : SURF= 60 : AREA= 3 : EXTERNAL : ORI=S_0_90 : FSKY=0.5

WALL =ADJ_CEILING_M : SURF= 61 : AREA= 2 : ADJACENT=3_9 : ADJ_SURF=27 : BACK : COUPL=INPUT 1*MIX_3_9_4_6

WALL =ADJ_WALL_M : SURF= 62 : AREA= 3 : ADJACENT=4_5 : ADJ_SURF=76 : FRONT : COUPL=INPUT 1*MIX_4_5_4_6

WALL =EXT_WALL_M : SURF= 63 : AREA= 6 : EXTERNAL : ORI=W_90_90 : FSKY=0.5

REGIME

INFILTRATION= INFIL_OFFICE

CAPACITANCE = 7.2 : VOLUME= 6 : TINITIAL= 20 : PHINITIAL= 50 : WCAPR= 1

*---

* Z o n e 4_7 / A i r n o d e 4_7

*---

ZONE 4_7

RADIATIONMODE

BEAM=STANDARD : DIFFUSE=STANDARD : LONGWAVE=STANDARD : GEOMODE=3D_DATA : FSOLAIR=0

AIRNODE 4_7

WALL =ADJ_WALL_M : SURF= 64 : AREA= 3.78 : ADJACENT=4_5 : ADJ_SURF=72 : FRONT : COUPL=INPUT 1*MIX_4_5_4_7

WINDOW=ADJ_WINDOW_M : SURF= 71 : AREA= 23.22 : ADJACENT=4_5 : ADJ_SURF=79 : FRONT : ORI=N_180_90

WALL =ADJ_CEILING_M : SURF= 65 : AREA= 18 : ADJACENT=5_4 : ADJ_SURF=94 : FRONT : COUPL=INPUT 1*MIX_5_4_4_7

WALL =ADJ_WALL_M : SURF= 66 : AREA= 6 : ADJACENT=4_6 : ADJ_SURF=58 : BACK

WALL =ADJ_CEILING_M : SURF= 67 : AREA= 18 : ADJACENT=3_10 : ADJ_SURF=40 : BACK : COUPL=INPUT 1*MIX_3_10_4_7

WALL =EXT_WALL_M : SURF= 68 : AREA= 6 : EXTERNAL : ORI=E_270_90 : FSKY=0.5

WALL =EXT_WALL_M : SURF= 69 : AREA= 3.78 : EXTERNAL : ORI=S_0_90 : FSKY=0.5

WINDOW=SINGLE_DSF : SURF= 70 : AREA= 23.22 : EXTERNAL : ORI=S_0_90 : FSKY=0.5 : ESHADE=INPUT 1*MAX_ESHADE

REGIME

INFILTRATION= INFIL_OFFICE

CAPACITANCE = 64.8 : VOLUME= 54 : TINITIAL= 20 : PHINITIAL= 50 : WCAPR= 1

*---

* Z o n e 4_5 / A i r n o d e 4_5

*---

ZONE 4_5

RADIATIONMODE

BEAM=DETAILED : DIFFUSE=DETAILED : LONGWAVE=DETAILED : GEOMODE=3D_DATA : FSOLAIR=0.4

AIRNODE 4_5

WALL =ADJ_WALL_M : SURF= 72 : AREA= 3.78 : ADJACENT=4_7 : ADJ_SURF=64 : BACK : COUPL=INPUT 1*MIX_4_7_4_5

WINDOW=ADJ_WINDOW_M : SURF= 79 : AREA= 23.22 : ADJACENT=4_7 : ADJ_SURF=71 : BACK : ORI=S_0_90

WALL =ADJ_CEILING_M : SURF= 73 : AREA= 80 : ADJACENT=5_2 : ADJ_SURF=87 : FRONT

WALL =EXT_WALL_M : SURF= 74 : AREA= 30 : EXTERNAL : ORI=N_180_90 : FSKY=0.5

WALL =EXT_WALL_M : SURF= 75 : AREA= 24 : EXTERNAL : ORI=W_90_90 : FSKY=0.5

WALL =ADJ_WALL_M : SURF= 76 : AREA= 3 : ADJACENT=4_6 : ADJ_SURF=62 : BACK : COUPL=INPUT 1*MIX_4_6_4_5

WALL =EXT_WALL_M : SURF= 77 : AREA= 24 : EXTERNAL : ORI=E_270_90 : FSKY=0.5

WALL =ADJ_CEILING_M : SURF= 78 : AREA= 80 : ADJACENT=3_8 : ADJ_SURF=35 : BACK

REGIME

GAIN = PERS_ISO04 : SCALE= SCHEDULE 8*USE : GEOPOS= 0

GAIN = COMPUTER03 : SCALE= SCHEDULE 8*USE : GEOPOS= 0

GAIN = LIGHT02_11 : SCALE= INPUT 1*BRIGHT : GEOPOS= 0

GAIN = PRINTER : SCALE= SCHEDULE 2*USE : GEOPOS= 0

COMFORT = COMF_OFFICE : COMFID= 3 : MRT= INTERNAL : GEOPOS= 0

INFILTRATION= INFIL_OFFICE

COOLING = COOL_OFFICE

HEATING = HEAT_OFFICE

CAPACITANCE = 2880 : VOLUME= 240 : TINITIAL= 20 : PHINITIAL= 50 : WCAPR= 1

*--

* Z o n e 5_3 / A i r n o d e 5_3

*--

ZONE 5_3

RADIATIONMODE

BEAM=STANDARD : DIFFUSE=STANDARD : LONGWAVE=STANDARD : GEOMODE=3D_DATA : FSOLAIR=0

AIRNODE 5_3

WALL =EXT_WALL_M : SURF= 80 : AREA= 6 : EXTERNAL : ORI=W_90_90 : FSKY=0.5

WALL =EXT_WALL_M : SURF= 81 : AREA= 3 : EXTERNAL : ORI=S_0_90 : FSKY=0.5

WALL =ADJ_CEILING_M : SURF= 82 : AREA= 2 : ADJACENT=4_6 : ADJ_SURF=59 : BACK : COUPL=INPUT 1*MIX_4_6_5_3

WALL =ADJ_WALL_M : SURF= 83 : AREA= 3 : ADJACENT=5_2 : ADJ_SURF=86 : FRONT : COUPL=INPUT 1*MIX_5_2_5_3
WALL =ADJ_WALL_M : SURF= 84 : AREA= 6 : ADJACENT=5_4 : ADJ_SURF=97 : FRONT
WALL =ADJ_CEILING_M : SURF= 85 : AREA= 2 : ADJACENT=6_1 : ADJ_SURF=103 : FRONT
REGIME
INFILTRATION= INFIL_OFFICE
CAPACITANCE = 7.2 : VOLUME= 6 : TINITIAL= 20 : PHINITIAL= 50 : WCAPR= 1
*--

* Zone 5_2 / Airnode 5_2
*--

ZONE 5_2
RADIATIONMODE
BEAM=DETAILED : DIFFUSE=DETAILED : LONGWAVE=DETAILED : GEOMODE=3D_DATA : FSOLAIR=0.4
AIRNODE 5_2
WALL =ADJ_WALL_M : SURF= 86 : AREA= 3 : ADJACENT=5_3 : ADJ_SURF=83 : BACK : COUPL=INPUT 1*MIX_5_3_5_2
WALL =ADJ_CEILING_M : SURF= 87 : AREA= 80 : ADJACENT=4_5 : ADJ_SURF=73 : BACK
WALL =ADJ_WALL_M : SURF= 88 : AREA= 3.78 : ADJACENT=5_4 : ADJ_SURF=96 : FRONT : COUPL=INPUT 1*MIX_5_4_5_2
WINDOW=ADJ_WINDOW_M : SURF= 93 : AREA= 23.22 : ADJACENT=5_4 : ADJ_SURF=100 : FRONT : ORI=S_0_90
WALL =EXT_WALL_M : SURF= 89 : AREA= 30 : EXTERNAL : ORI=N_180_90 : FSKY=0.5
WALL =EXT_WALL_M : SURF= 90 : AREA= 24 : EXTERNAL : ORI=E_270_90 : FSKY=0.5
WALL =EXT_WALL_M : SURF= 91 : AREA= 24 : EXTERNAL : ORI=W_90_90 : FSKY=0.5
WALL =EXT_ROOF_M : SURF= 92 : AREA= 80 : EXTERNAL : ORI=H_0_0 : FSKY=1
REGIME

GAIN = PERS_ISO04 : SCALE= SCHEDULE 6*USE : GEOPOS= 0
GAIN = COMPUTER03 : SCALE= SCHEDULE 6*USE : GEOPOS= 0
GAIN = LIGHT02_13 : SCALE= INPUT 1*BRIGHT : GEOPOS= 0
GAIN = PRINTER : SCALE= SCHEDULE 2*USE : GEOPOS= 0
COMFORT = COMF_OFFICE : COMFID= 4 : MRT= INTERNAL : GEOPOS= 0
INFILTRATION= INFIL_OFFICE
COOLING = COOL_OFFICE
HEATING = HEAT_OFFICE
CAPACITANCE = 2880 : VOLUME= 240 : TINITIAL= 20 : PHINITIAL= 50 : WCAPR= 1
*---

* Z o n e 5_4 / A i r n o d e 5_4
*---

ZONE 5_4
RADIATIONMODE
BEAM=STANDARD : DIFFUSE=STANDARD : LONGWAVE=STANDARD : GEOMODE=3D_DATA : FSOLAIR=0
AIRNODE 5_4
WALL =ADJ_CEILING_M : SURF= 94 : AREA= 18 : ADJACENT=4_7 : ADJ_SURF=65 : BACK : COUPL=INPUT 1*MIX_4_7_5_4
WALL =ADJ_CEILING_M : SURF= 95 : AREA= 18 : ADJACENT=6_1 : ADJ_SURF=102 : FRONT : COUPL=INPUT 1*MIX_6_1_5_4
WALL =ADJ_WALL_M : SURF= 96 : AREA= 3.78 : ADJACENT=5_2 : ADJ_SURF=88 : BACK : COUPL=INPUT 1*MIX_5_2_5_4
WINDOW=ADJ_WINDOW_M : SURF=100 : AREA= 23.22 : ADJACENT=5_2 : ADJ_SURF=93 : BACK : ORI=N_180_90
WALL =ADJ_WALL_M : SURF= 97 : AREA= 6 : ADJACENT=5_3 : ADJ_SURF=84 : BACK
WALL =EXT_WALL_M : SURF= 98 : AREA= 3.78 : EXTERNAL : ORI=S_0_90 : FSKY=0.5

WINDOW=SINGLE_DSF : SURF=101 : AREA= 23.22 : EXTERNAL : ORI=S_0_90 : FSKY=0.5 : ESHADE=INPUT 1*MAX_ESHADE
WALL =EXT_WALL_M : SURF= 99 : AREA= 6 : EXTERNAL : ORI=E_270_90 : FSKY=0.5
REGIME
INFILTRATION= INFIL_OFFICE
CAPACITANCE = 64.8 : VOLUME= 54 : TINITIAL= 20 : PHINITIAL= 50 : WCAPR= 1
*---
* Z o n e 6_1 / A i r n o d e 6_1
*---
ZONE 6_1
RADIATIONMODE
BEAM=STANDARD : DIFFUSE=STANDARD : LONGWAVE=STANDARD : GEOMODE=3D_DATA : FSOLAIR=0
AIRNODE 6_1
WALL =ADJ_CEILING_M : SURF=102 : AREA= 18 : ADJACENT=5_4 : ADJ_SURF=95 : BACK : COUPL=INPUT 1*MIX_5_4_6_1
WALL =ADJ_CEILING_M : SURF=103 : AREA= 2 : ADJACENT=5_3 : ADJ_SURF=85 : BACK
WALL =EXT_WALL_M : SURF=104 : AREA= 30 : EXTERNAL : ORI=N_180_90 : FSKY=0.5
WALL =EXT_WALL_M : SURF=105 : AREA= 6 : EXTERNAL : ORI=W_90_90 : FSKY=0.5
WALL =EXT_ROOF_M : SURF=106 : AREA= 20 : EXTERNAL : ORI=H_0_0 : FSKY=1
WALL =EXT_WALL_M : SURF=107 : AREA= 6.78 : EXTERNAL : ORI=S_0_90 : FSKY=0.5
WINDOW=SINGLE_DSF : SURF=109 : AREA= 23.22 : EXTERNAL : ORI=S_0_90 : FSKY=0.5
WALL =EXT_WALL_M : SURF=108 : AREA= 6 : EXTERNAL : ORI=E_270_90 : FSKY=0.5
REGIME
INFILTRATION= INFIL_OFFICE
CAPACITANCE = 72 : VOLUME= 60 : TINITIAL= 20 : PHINITIAL= 50 : WCAPR= 1

*---

* O u t p u t s

*---

OUTPUTS

TRANSFER : TIMEBASE=1.000

AIRNODES = 2_11

NTYPES = 1 : TAIR - air temperature of airnode

= 9 : RELHUM - relativ humidity of airnode air

= 30 : QHEAT - sensible heating demand of airnode (positive values)

= 31 : QCOOL - sensible cooling demand of airnode (positive values)

= 98 : QDEHUM - latent energy demand of airnode by dehumidification (positive values)

= 99 : QHUM - latent energy demand of airnode by humidification (positive values)

= 4 : QINF - sensible infiltration energy gain of airnode

= 5 : QVENT - sensible ventilation energy gain of airnode

= 6 : QCOUP - sensible coupling energy gain of airnode

AIRNODES = 2_12

NTYPES = 1 : TAIR - air temperature of airnode

= 9 : RELHUM - relativ humidity of airnode air

AIRNODES = 2_13

NTYPES = 1 : TAIR - air temperature of airnode

= 9 : RELHUM - relativ humidity of airnode air

= 101 : SURF = 22, : OSHADB - Total external shading factor of window for direct radiation incl. geomtric shading

= 119 : SURF = 22, : SHADCNTRL - shading control signal of radiation depending control (0 or 1, 0 if not used)

AIRNODES = 3_9

NTYPES = 1 : TAIR - air temperature of airnode

= 9 : RELHUM - relativ humidity of airnode air

AIRNODES = 3_8

NTYPES = 1 : TAIR - air temperature of airnode

= 9 : RELHUM - relativ humidity of airnode air

= 30 : QHEAT - sensible heating demand of airnode (positive values)

= 31 : QCOOL - sensible cooling demand of airnode (positive values)

= 98 : QDEHUM - latent energy demand of airnode by dehumidification (positive values)

= 99 : QHUM - latent energy demand of airnode by humidification (positive values)

= 4 : QINF - sensible infiltration energy gain of airnode

= 5 : QVENT - sensible ventilation energy gain of airnode

= 6 : QCOUP - sensible coupling energy gain of airnode

AIRNODES = 3_10

NTYPES = 1 : TAIR - air temperature of airnode

= 9 : RELHUM - relativ humidity of airnode air

= 101 : SURF = 44, : OSHADB - Total external shading factor of window for direct radiation incl. geomtric shading

= 119 : SURF = 44, : SHADCNTRL - shading control signal of radiation depending control (0 or 1, 0 if not used)

AIRNODES = 1_14

NTYPES = 1 : TAIR - air temperature of airnode

= 9 : RELHUM - relativ humidity of airnode air

= 20 : SURF = 49, : QCOMO - energy to the outside surface incl. conv. to the air and l-wave radiation to other surfaces or Tsky

AIRNODES = 1_15

NTYPES = 1 : TAIR - air temperature of airnode

= 9 : RELHUM - relativ humidity of airnode air

= 20 : SURF = 56, : QCOMO - energy to the outside surface incl. conv. to the air and l-wave radiation to other surfaces or Tsky

= 28 : SCHEDULE = USE, : - - values of all schedules

AIRNODES = 4_6

NTYPES = 1 : TAIR - air temperature of airnode

= 9 : RELHUM - relativ humidity of airnode air

AIRNODES = 4_7

NTYPES = 1 : TAIR - air temperature of airnode

= 9 : RELHUM - relativ humidity of airnode air

= 101 : SURF = 70, : OSHADB - Total external shading factor of window for direct radiation incl. geomtric shading

= 119 : SURF = 70, : SHADCNTRL - shading control signal of radiation depending control (0 or 1, 0 if not used)

AIRNODES = 4_5

NTYPES = 1 : TAIR - air temperature of airnode

= 9 : RELHUM - relativ humidity of airnode air

= 30 : QHEAT - sensible heating demand of airnode (positive values)

= 31 : QCOOL - sensible cooling demand of airnode (positive values)

= 98 : QDEHUM - latent energy demand of airnode by dehumidification (positive values)

= 99 : QHUM - latent energy demand of airnode by humidification (positive values)

= 4 : QINF - sensible infiltration energy gain of airnode

= 5 : QVENT - sensible ventilation energy gain of airnode

= 6 : QCOUP - sensible coupling energy gain of airnode

AIRNODES = 5_3

NTYPES = 1 : TAIR - air temperature of airnode

= 9 : RELHUM - relativ humidity of airnode air

AIRNODES = 5_2

NTYPES = 1 : TAIR - air temperature of airnode

= 9 : RELHUM - relativ humidity of airnode air

= 30 : QHEAT - sensible heating demand of airnode (positive values)

= 31 : QCOOL - sensible cooling demand of airnode (positive values)

= 98 : QDEHUM - latent energy demand of airnode by dehumidification (positive values)

= 99 : QHUM - latent energy demand of airnode by humidification (positive values)

= 4 : QINF - sensible infiltration energy gain of airnode

= 5 : QVENT - sensible ventilation energy gain of airnode

= 6 : QCOUP - sensible coupling energy gain of airnode

AIRNODES = 5_4
NTYPES =   1 : TAIR - air temperature of airnode
=   9 : RELHUM - relativ humidity of airnode air
= 101 : SURF = 101,   : OSHADB - Total external shading factor of window for direct radiation incl. geomtric shading
= 119 : SURF = 101, : SHADCNTRL - shading control signal of radiation depending control (0 or 1, 0 if not used)
AIRNODES = 6_1
NTYPES =   1 : TAIR - air temperature of airnode
=   9 : RELHUM - relativ humidity of airnode air
*---

----
* E n d
*---

END

_EXTENSION_WINPOOL_START_
WINDOW 4.1 DOE-2 Data File : Multi Band Calculation
Unit System : SI
Name   : TRNSYS 15 WINDOW LIB
Desc   : LowSHGC,Ar, gray 1.3 50/40
Window ID   : 3101
Tilt   : 90.0
Glazings   : 2
Frame   : 11   2.270
Spacer   : 1 Class1   2.330 -0.010   0.138
Total Height: 1639.7 mm
Total Width : 1239.3 mm

Glass Height: 1500.0 mm

Glass Width : 1100.0 mm

Mullion : None

Gap Thick Cond dCond Vis dVis Dens dDens Pr dPr

1 Argon 16.0 0.01620 5.000 2.110 6.300 1.780 -0.0060 0.680 0.00066

2 0 0 0 0 0 0 0 0 0

3 0 0 0 0 0 0 0 0 0

4 0 0 0 0 0 0 0 0 0

5 0 0 0 0 0 0 0 0 0

Angle 0 10 20 30 40 50 60 70 80 90 Hemis

Tsol 0.316 0.318 0.313 0.306 0.296 0.279 0.243 0.176 0.079 0.000 0.260

Abs1 0.448 0.453 0.460 0.463 0.462 0.461 0.466 0.456 0.355 0.001 0.450

Abs2 0.064 0.064 0.065 0.065 0.067 0.067 0.065 0.056 0.040 0.000 0.062

Abs3 0 0 0 0 0 0 0 0 0 0 0

Abs4 0 0 0 0 0 0 0 0 0 0 0

Abs5 0 0 0 0 0 0 0 0 0 0 0

Abs6 0 0 0 0 0 0 0 0 0 0 0

Rfsol 0.172 0.165 0.163 0.166 0.176 0.193 0.227 0.312 0.526 0.999 0.217

Rbsol 0.226 0.221 0.219 0.220 0.227 0.242 0.281 0.375 0.575 1.000 0.271

Tvis 0.504 0.507 0.500 0.490 0.478 0.452 0.396 0.288 0.134 0.000 0.421

Rfvis 0.099 0.092 0.090 0.092 0.104 0.125 0.165 0.262 0.496 0.999 0.153

Rbvis 0.154 0.148 0.146 0.150 0.164 0.191 0.252 0.389 0.647 1.000 0.229

SHGC 0.397 0.400 0.395 0.389 0.380 0.363 0.325 0.251 0.134 0.000 0.340

SC: 0.38

Layer ID# 9028 9026 0 0 0 0

Tir 0.000 0.000 0 0 0 0

Emis F 0.840 0.838 0 0 0 0

Emis B 0.100 0.838 0 0 0 0

Thickness(mm) 6.0 6.0 0 0 0 0

Cond(W/m2-C) 150.0 150.0 0 0 0 0

Spectral File None None None None None None

Overall and Center of Glass Ig U-values (W/m2-C)

Outdoor Temperature -17.8 C 15.6 C 26.7 C 37.8 C

Solar WdSpd hcout hrout hin

(W/m2) (m/s) (W/m2-C)

0 0.00 12.25 3.24 7.59 1.45 1.45 1.19 1.19 1.22 1.22 1.34 1.34

0 6.71 25.47 3.21 7.61 1.52 1.52 1.23 1.23 1.26 1.26 1.39 1.39

783 0.00 12.25 3.65 7.17 1.35 1.35 1.32 1.32 1.45 1.45 1.61 1.61

783 6.71 25.47 3.44 5.99 1.43 1.43 1.32 1.32 1.38 1.38 1.56 1.56

Window 5.2 v5.2.17 DOE-2 Data File : Multi Band Calculation

Unit System : SI

Name : DOE-2 WINDOW LIB

Desc : ASH140 DBLE - MOD

Window ID : 6001

Tilt : 90.0

Glazings : 2

Frame : 2 Al w/break 5.680

Spacer : 1 Class1 2.330 -0.010 0.138

Total Height: 1500.0 mm

Total Width : 1200.0 mm

Glass Height: 1385.7 mm

Glass Width : 1085.7 mm

Mullion : None

Gap Thick Cond dCond Vis dVis Dens dDens Pr dPr

1 Air 13.0 0.02407 7.760 1.722 4.940 1.292 -0.0046 0.720 -0.0002

2 0 0 0 0 0 0 0 0 0

3 0 0 0 0 0 0 0 0 0

4 0 0 0 0 0 0 0 0 0

5 0 0 0 0 0 0 0 0 0

Angle 0 10 20 30 40 50 60 70 80 90 Hemis

Tsol 0.747 0.747 0.745 0.740 0.730 0.707 0.652 0.517 0.263 0.000 0.652

Abs1 0.064 0.065 0.066 0.068 0.071 0.075 0.080 0.086 0.094 0.000 0.080

Abs2 0.052 0.053 0.053 0.055 0.057 0.058 0.059 0.054 0.041 0.000 0.059

Abs3 0 0 0 0 0 0 0 0 0 0 0

Abs4 0 0 0 0 0 0 0 0 0 0 0

Abs5 0 0 0 0 0 0 0 0 0 0 0

Abs6 0 0 0 0 0 0 0 0 0 0 0

Rfsol 0.136 0.136 0.136 0.137 0.143 0.160 0.210 0.343 0.602 1.000 0.210

Rbsol 0.136 0.136 0.136 0.137 0.143 0.160 0.210 0.343 0.602 1.000 0.210

Tvis 0.747 0.747 0.745 0.740 0.730 0.707 0.652 0.517 0.263 0.000 0.652

Rfvis 0.136 0.136 0.136 0.137 0.143 0.160 0.210 0.343 0.602 1.000 0.210

Rbvis 0.136 0.136 0.136 0.137 0.143 0.160 0.210 0.343 0.602 1.000 0.210

SHGC 0.789 0.789 0.787 0.782 0.769 0.739 0.668 0.519 0.267 0.000 0.688

SC: 0.81

Layer ID# 9991 9991 0 0 0 0

Tir 0.000 0.000 0 0 0 0

Emis F 0.840 0.840 0 0 0 0

Emis B 0.840 0.840 0 0 0 0

Thickness(mm) 3.2 3.2 0 0 0 0

Cond(W/m2-K) 333.9 333.9 0 0 0 0

Spectral File None None None None None None

Overall and Center of Glass Ig U-values (W/m2-K)

Outdoor Temperature -17.8 C 15.6 C 26.7 C 37.8 C

Solar WdSpd hcout hrout hin

(W/m2) (m/s) (W/m2-K)

0 0.00 4.00 3.39 2.43 2.12 2.12 2.24 2.24 2.32 2.32 2.49 2.49

0 6.71 30.84 3.23 2.58 2.72 2.72 2.80 2.80 2.89 2.89 3.13 3.13

783 0.00 4.00 3.52 2.03 2.12 2.12 2.24 2.24 2.32 2.32 2.49 2.49

783 6.71 30.84 3.27 2.39 2.72 2.72 2.80 2.80 2.89 2.89 3.13 3.13

Window 5.2 v5.2.17 DOE-2 Data File : Multi Band Calculation

Unit System : SI

Name : DOE-2 WINDOW LIB

Desc : code requiremen

Window ID : 7002

Tilt : 90.0

Glazings : 2

Frame : 11 CodMin1040 10.500

Spacer : 1 Class1 2.330 -0.010 0.138

Total Height: 1500.0 mm

Total Width : 1200.0 mm

Glass Height: 1385.7 mm

Glass Width : 1085.7 mm

Mullion : None

Gap	Thick	Cond	dCond	Vis	dVis	Dens	dDens	Pr	dPr
1 Air	12.0	0.02407	7.760	1.722	4.940	1.292	-0.0046	0.720	-0.0002
2	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0

Angle	0	10	20	30	40	50	60	70	80	90	Hemis
Tsol	0.319	0.323	0.315	0.305	0.295	0.276	0.236	0.164	0.074	0.000	0.257
Abs1	0.255	0.258	0.265	0.271	0.272	0.276	0.288	0.298	0.247	0.001	0.272
Abs2	0.065	0.067	0.071	0.073	0.074	0.075	0.079	0.077	0.052	0.000	0.072
Abs3	0	0	0	0	0	0	0	0	0	0	0
Abs4	0	0	0	0	0	0	0	0	0	0	0
Abs5	0	0	0	0	0	0	0	0	0	0	0
Abs6	0	0	0	0	0	0	0	0	0	0	0
Rfsol	0.360	0.353	0.349	0.351	0.359	0.373	0.397	0.460	0.627	0.999	0.388
Rbsol	0.415	0.408	0.404	0.406	0.414	0.427	0.449	0.506	0.659	0.999	0.439
Tvis	0.604	0.611	0.595	0.577	0.557	0.521	0.443	0.305	0.134	0.000	0.485
Rfvis	0.219	0.208	0.204	0.207	0.220	0.241	0.275	0.361	0.566	0.999	0.262
Rbvis	0.223	0.212	0.208	0.210	0.223	0.244	0.279	0.364	0.569	0.999	0.265
SHGC	0.392	0.396	0.392	0.385	0.375	0.357	0.321	0.249	0.135	0.000	0.336

SC: 0.46

Layer ID# 926 924 0 0 0 0

Tir 0.000 0.000 0 0 0 0

Emis F 0.840 0.034 0 0 0 0

Emis B 0.035 0.840 0 0 0 0

Thickness(mm) 4.6 2.2 0 0 0 0

Cond(W/m2-K) 216.3 452.5 0 0 0 0

Spectral File CMFTIR_5.AFG CMFTIR_2.AFG None None None None

Overall and Center of Glass Ig U-values (W/m2-K)

Outdoor Temperature -17.8 C 15.6 C 26.7 C 37.8 C

Solar WdSpd hcout hrout hin

(W/m2) (m/s) (W/m2-K)

0 0.00 4.00 3.31 2.19 1.36 1.36 1.36 1.36 1.39 1.39 1.45 1.45

0 6.71 30.84 3.21 2.29 1.64 1.64 1.55 1.55 1.58 1.58 1.64 1.64

783 0.00 4.00 3.76 1.79 1.36 1.36 1.36 1.36 1.39 1.39 1.45 1.45

783 6.71 30.84 3.32 1.60 1.64 1.64 1.55 1.55 1.58 1.58 1.64 1.64

WINDOW 5.2 TRNSYS 15 Data File : Multi Band Calculation

Unit System : SI

Name : TRNSYS 15 WINDOW LIB

Desc : code requiremen

Window ID : 7003

Tilt : 90.0

Glazings : 2

Frame : 10 CodMinGT40 9.500

Spacer : 1 Class1 2.330 -0.010 0.138

Total Height: 1500.0 mm

Total Width : 1200.0 mm

Glass Height: 1400.0 mm

Glass Width : 1100.0 mm

Mullion : None

Gap Thick Cond dCond Vis dVis Dens dDens Pr dPr

1 Air 12.0 0.02407 7.760 1.722 4.940 1.292 -0.0046 0.720 -0.0002

2	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0

Angle	0	10	20	30	40	50	60	70	80	90	Hemis
Tsol	0.107	0.109	0.106	0.103	0.099	0.093	0.079	0.054	0.024	0.000	0.086
Abs1	0.636	0.641	0.646	0.648	0.644	0.637	0.627	0.587	0.433	0.001	0.615
Abs2	0.136	0.138	0.138	0.136	0.133	0.128	0.118	0.096	0.053	0.000	0.121
Abs3	0	0	0	0	0	0	0	0	0	0	0
Abs4	0	0	0	0	0	0	0	0	0	0	0
Abs5	0	0	0	0	0	0	0	0	0	0	0
Abs6	0	0	0	0	0	0	0	0	0	0	0
Rfsol	0.121	0.112	0.110	0.113	0.124	0.142	0.176	0.263	0.490	0.999	0.167
Rbsol	0.528	0.523	0.522	0.524	0.530	0.540	0.558	0.606	0.728	0.999	0.549
Tvis	0.285	0.288	0.281	0.272	0.262	0.245	0.208	0.143	0.062	0.000	0.228
Rfvis	0.103	0.092	0.089	0.092	0.105	0.127	0.164	0.258	0.492	0.999	0.152
Rbvis	0.175	0.167	0.165	0.168	0.180	0.198	0.232	0.317	0.531	0.999	0.221
SHGC	0.230	0.233	0.230	0.227	0.221	0.211	0.190	0.148	0.081	0.000	0.198

SC: 0.30

Layer ID#	940	776	0	0	0	0
Tir	0.000	0.000	0	0	0	0
Emis F	0.840	0.840	0	0	0	0
Emis B	0.032	0.032	0	0	0	0
Thickness(mm)	5.6	5.8	0	0	0	0
Cond(W/m2-K)	177.3	171.9	0	0	0	0
Spectral File	ES672_6.AFG	ESB5.AFG	None	None	None	None

Overall and Center of Glass Ig U-values (W/m2-K)

Outdoor Temperature -17.8 C 15.6 C 26.7 C 37.8 C

Solar WdSpd hcout hrout hin

(W/m2) (m/s) (W/m2-K)

0 0.00 4.00 3.28 2.58 1.04 1.04 0.91 0.91 0.86 0.86 1.03 1.03

0	6.71	30.84	3.20	2.65	1.19	1.19	1.00	1.00	0.94	0.94	1.13	1.13
783	0.00	4.00	4.49	3.01	1.04	1.04	0.91	0.91	0.86	0.86	1.03	1.03
783	6.71	30.84	3.50	2.39	1.19	1.19	1.00	1.00	0.94	0.94	1.13	1.13

WINDOW 4.1 DOE-2 Data File : Multi Band Calculation

Unit System : SI

Name : TRNSYS15 WINDOW LIB

Desc : FLOAT_6

Window ID : 11003

Tilt : 90.0

Glazings : 1

Frame : 8 TRNSYS WIN - 1 2.270

Spacer : 5 Class5 0.000 1.000 0.000

Total Height: 1600.0 mm

Total Width : 1250.0 mm

Glass Height: 1460.3 mm

Glass Width : 1110.3 mm

Mullion : None

Gap	Thick	Cond	dCond	Vis	dVis	Dens	dDens	Pr	dPr
1	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0

Angle	0	10	20	30	40	50	60	70	80	90	Hemis
Tsol	0.790	0.789	0.786	0.781	0.770	0.747	0.699	0.591	0.355	0.000	0.707
Abs1	0.140	0.141	0.143	0.148	0.153	0.160	0.166	0.169	0.160	0.000	0.154
Abs2	0	0	0	0	0	0	0	0	0	0	0
Abs3	0	0	0	0	0	0	0	0	0	0	0
Abs4	0	0	0	0	0	0	0	0	0	0	0
Abs5	0	0	0	0	0	0	0	0	0	0	0
Abs6	0	0	0	0	0	0	0	0	0	0	0

Rfsol 0.070 0.070 0.070 0.072 0.077 0.093 0.135 0.240 0.485 1.000 0.128

Rbsol 0.070 0.070 0.070 0.072 0.077 0.093 0.135 0.240 0.485 1.000 0.128

Tvis 0.885 0.885 0.884 0.881 0.873 0.854 0.806 0.689 0.428 0.000 0.807

Rfvis 0.080 0.080 0.080 0.082 0.088 0.106 0.152 0.267 0.528 1.000 0.144

Rbvis 0.080 0.080 0.080 0.082 0.088 0.106 0.152 0.267 0.528 1.000 0.144

SHGC 0.827 0.826 0.824 0.820 0.810 0.789 0.743 0.636 0.397 0.000 0.748

SC: 0.81

Layer ID# 4048 0 0 0 0 0

Tir 0.000 0 0 0 0 0

Emis F 0.840 0 0 0 0 0

Emis B 0.840 0 0 0 0 0

Thickness(mm) 6.0 0 0 0 0 0

Cond(W/m2-C) 150.0 0 0 0 0 0

Spectral File None None None None None None

Overall and Center of Glass Ig U-values (W/m2-C)

Outdoor Temperature -17.8 C 15.6 C 26.7 C 37.8 C

Solar WdSpd hcout hrout hin

(W/m2) (m/s) (W/m2-C)

0 0.00 12.25 3.42 8.22 5.20 5.20 4.89 4.89 4.88 4.88 5.46 5.46

0 6.71 25.47 3.33 8.29 6.17 6.17 5.65 5.65 5.61 5.61 6.36 6.36

783 0.00 12.25 3.51 8.13 5.18 5.18 4.60 4.60 5.27 5.27 5.64 5.64

783 6.71 25.47 3.39 8.24 6.15 6.15 5.28 5.28 5.96 5.96 6.52 6.52

WINDOW 4.1 DOE-2 Data File : Multi Band Calculation

Unit System : SI

Name : TRNSYS15 WINDOW LIB

Desc : Pilk. 3-ple INFRASTOP Brilliant5025+OPTITHERM S #5 6/12/6/12/4

Window ID : 12015

Tilt : 90.0

Glazings : 3

Frame : 11 TRNSYS WIN - 1 2.270

Spacer : 1 Class1 2.330 -0.010 0.138

Total Height: 1600.0 mm

Total Width : 1250.0 mm

Glass Height: 1460.3 mm

Glass Width : 1110.3 mm

Mullion : None

Gap	Thick	Cond	dCond	Vis	dVis	Dens	dDens	Pr	dPr
1 Argon	12.0	0.01620	5.000	2.110	6.300	1.780	-0.0060	0.680	0.00066
2 Argon	12.0	0.01620	5.000	2.110	6.300	1.780	-0.0060	0.680	0.00066
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0

Angle	0	10	20	30	40	50	60	70	80	90	Hemis
Tsol	0.177	0.177	0.175	0.173	0.170	0.166	0.154	0.123	0.058	0.000	0.155
Abs1	0.445	0.446	0.447	0.448	0.449	0.450	0.449	0.444	0.403	0.000	0.441
Abs2	0.031	0.031	0.032	0.033	0.034	0.037	0.041	0.048	0.048	0.000	0.037
Abs3	0.017	0.017	0.018	0.018	0.018	0.018	0.019	0.019	0.012	0.000	0.018
Abs4	0	0	0	0	0	0	0	0	0	0	0
Abs5	0	0	0	0	0	0	0	0	0	0	0
Abs6	0	0	0	0	0	0	0	0	0	0	0
Rfsol	0.329	0.329	0.329	0.328	0.328	0.329	0.336	0.365	0.479	1.000	0.340
Rbsol	0.351	0.350	0.348	0.347	0.351	0.362	0.397	0.489	0.680	1.000	0.390
Tvis	0.436	0.438	0.433	0.427	0.415	0.391	0.337	0.236	0.095	0.000	0.361
Rfvis	0.191	0.191	0.191	0.192	0.198	0.215	0.258	0.355	0.545	1.000	0.244
Rbvis	0.192	0.228	0.227	0.230	0.239	0.265	0.327	0.458	0.679	1.000	0.302
SHGC	0.222	0.222	0.221	0.220	0.218	0.215	0.206	0.178	0.105	0.000	0.203

SC: 0.24

Layer ID#	4064	4046	4070	0	0	0
Tir	0.000	0.000	0.000	0	0	0
Emis F	0.840	0.840	0.040	0	0	0
Emis B	0.020	0.840	0.840	0	0	0
Thickness(mm)	6.0	4.0	4.0	0	0	0

Cond(W/m2-C) 150.0 225.0 225.0 0 0 0

Spectral File None None None None None None

Overall and Center of Glass Ig U-values (W/m2-C)

Outdoor Temperature -17.8 C 15.6 C 26.7 C 37.8 C

Solar WdSpd hcout hrout hin

(W/m2) (m/s) (W/m2-C)

0 0.00 12.25 3.20 7.20 0.66 0.66 0.67 0.67 0.69 0.69 0.71 0.71

0 6.71 25.47 3.19 7.21 0.67 0.67 0.68 0.68 0.70 0.70 0.72 0.72

783 0.00 12.25 3.64 6.98 0.69 0.69 0.72 0.72 0.74 0.74 0.76 0.76

783 6.71 25.47 3.43 6.59 0.69 0.69 0.72 0.72 0.74 0.74 0.76 0.76

WINDOW 4.1 DOE-2 Data File : Multi Band Calculation

Unit System : SI

Name : TRNSYS15 WINDOW LIB

Desc : Saint Gobain CLIMATOP SOLAR KR 4/10/4/10/4

Window ID : 13006

Tilt : 90.0

Glazings : 3

Frame : 11 TRNSYS WIN - 1 2.270

Spacer : 1 Class1 2.330 -0.010 0.138

Total Height: 1600.0 mm

Total Width : 1250.0 mm

Glass Height: 1460.3 mm

Glass Width : 1110.3 mm

Mullion : None

Gap Thick Cond dCond Vis dVis Dens dDens Pr dPr

1 Krypton 10.0 0.00860 2.800 2.280 7.500 3.740 -0.0137 0.660 0.00002

2 Krypton 10.0 0.00860 2.800 2.280 7.500 3.740 -0.0137 0.660 0.00002

3 0 0 0 0 0 0 0 0 0

4 0 0 0 0 0 0 0 0 0

5 0 0 0 0 0 0 0 0 0

Angle 0 10 20 30 40 50 60 70 80 90 Hemis

Tsol 0.456 0.456 0.450 0.445 0.437 0.415 0.359 0.250 0.111 0.000 0.380
Abs1 0.149 0.150 0.153 0.155 0.155 0.157 0.163 0.168 0.140 0.000 0.155
Abs2 0.013 0.014 0.014 0.014 0.015 0.015 0.016 0.016 0.016 0.000 0.015
Abs3 0.128 0.128 0.129 0.129 0.127 0.123 0.112 0.088 0.046 0.000 0.114
Abs4 0 0 0 0 0 0 0 0 0 0 0
Abs5 0 0 0 0 0 0 0 0 0 0 0
Abs6 0 0 0 0 0 0 0 0 0 0 0
Rfsol 0.254 0.253 0.254 0.257 0.266 0.290 0.351 0.477 0.688 1.000 0.326
Rbsol 0.287 0.286 0.286 0.289 0.297 0.318 0.372 0.487 0.687 1.000 0.350
Tvis 0.741 0.741 0.732 0.723 0.709 0.671 0.574 0.393 0.170 0.000 0.614
Rfvis 0.158 0.157 0.158 0.163 0.177 0.212 0.296 0.458 0.696 1.000 0.256
Rbvis 0.158 0.157 0.158 0.163 0.177 0.212 0.296 0.458 0.696 1.000 0.256
SHGC 0.585 0.585 0.581 0.575 0.566 0.540 0.474 0.344 0.164 0.000 0.497
SC: 0.58
Layer ID# 9936 4054 9937 0 0 0
Tir 0.000 0.000 0.000 0 0 0
Emis F 0.840 0.840 0.040 0 0 0
Emis B 0.040 0.840 0.840 0 0 0
Thickness(mm) 4.0 4.0 4.0 0 0 0
Cond(W/m2-C) 225.0 225.0 225.0 0 0 0
Spectral File None None None None None None
Overall and Center of Glass Ig U-values (W/m2-C)
Outdoor Temperature -17.8 C 15.6 C 26.7 C 37.8 C
Solar WdSpd hcout hrout hin
(W/m2) (m/s) (W/m2-C)
0 0.00 12.25 3.20 7.12 0.56 0.56 0.50 0.50 0.52 0.52 0.54 0.54
0 6.71 25.47 3.19 7.13 0.58 0.58 0.51 0.51 0.52 0.52 0.54 0.54
783 0.00 12.25 3.35 8.21 0.61 0.61 0.55 0.55 0.55 0.55 0.57 0.57
783 6.71 25.47 3.27 8.17 0.64 0.64 0.56 0.56 0.56 0.56 0.57 0.57
WINDOW 4.1 TRNSYS 15 Data File : Multi Band Calculation
Unit System : SI

Name : TRNSYS 15 WINDOW LIB

Desc : Single

Window ID : 1001

Tilt : 90.0

Glazings : 1

Frame : 1 Al no break 10.790

Spacer : 1 Class1 2.330 -0.010 0.138

Total Height: 1219.2 mm

Total Width : 914.4 mm

Glass Height: 1104.9 mm

Glass Width : 800.1 mm

Mullion : None

Gap	Thick	Cond	dCond	Vis	dVis	Dens	dDens	Pr	dPr
1	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0

Angle	0	10	20	30	40	50	60	70	80	90	Hemis
Tsol	0.850	0.850	0.848	0.844	0.835	0.814	0.766	0.652	0.399	0.000	0.770
Abs1	0.075	0.076	0.077	0.080	0.083	0.087	0.091	0.093	0.092	0.000	0.084
Abs2	0	0	0	0	0	0	0	0	0	0	0
Abs3	0	0	0	0	0	0	0	0	0	0	0
Abs4	0	0	0	0	0	0	0	0	0	0	0
Abs5	0	0	0	0	0	0	0	0	0	0	0
Abs6	0	0	0	0	0	0	0	0	0	0	0
Rfsol	0.075	0.074	0.075	0.076	0.082	0.099	0.144	0.255	0.509	1.000	0.136
Rbsol	0.075	0.074	0.075	0.076	0.082	0.099	0.144	0.255	0.509	1.000	0.136
Tvis	0.901	0.901	0.900	0.897	0.890	0.871	0.824	0.706	0.441	0.000	0.823
Rfvis	0.081	0.081	0.082	0.083	0.090	0.108	0.155	0.271	0.536	1.000	0.146
Rbvis	0.081	0.081	0.082	0.083	0.090	0.108	0.155	0.271	0.536	1.000	0.146

SHGC 0.870 0.870 0.868 0.865 0.857 0.837 0.790 0.677 0.423 0.000 0.792

SC: 0.94

Layer ID#   1   0   0   0   0   0

Tir   0.000   0   0   0   0   0

Emis F   0.840   0   0   0   0   0

Emis B   0.840   0   0   0   0   0

Thickness(mm)   2.5   0   0   0   0   0

Cond(W/m2-C   ) 360.0   0   0   0   0   0

Spectral File   None   None   None   None   None   None

Overall and Center of Glass Ig U-values (W/m2-C)

Outdoor Temperature   -17.8 C   15.6 C   26.7 C   37.8 C

Solar   WdSpd hcout hrout hin

(W/m2)   (m/s)   (W/m2-C)

0   0.00 12.25 3.43 8.23 5.32 5.32 4.99 4.99 4.98 4.98 5.59 5.59

0   6.71 25.47 3.34 8.30 6.33 6.33 5.79 5.79 5.74 5.74 6.54 6.54

783   0.00 12.25 3.47 8.18 5.30 5.30 4.76 4.76 5.24 5.24 5.70 5.70

783   6.71 25.47 3.37 8.28 6.32 6.32 5.64 5.64 5.96 5.96 6.63 6.63

*** END OF LIBRARY ***

****

*WinID   Description   Design   U-Value g-value T-sol Rf-sol T-vis

****

3101   LowSHGC,Ar, gray 1.3 50/40   6/16/6   1.26 0.397 0.316 0.172 0.504

6001   ASH140 DBLE - MOD   3.2/13/3.2   2.89 0.789 0.747 0.136 0.747

7002   code requiremen   4.6/12/2.2   1.58 0.392 0.319 0.36 0.604

7003   code requiremen   5.6/12/5.8   0.94 0.23 0.107 0.121 0.285

11003   FLOAT_6   6   5.61 0.827 0.79 0.07 0.885

12015   Pilk. 3-ple INFRASTOP Brilliant5025+OPTITHERM S #5 6/12/6/12/4   6/12/4/12/4   0.7   0.222
0.177 0.329 0.436

13006   Saint Gobain CLIMATOP SOLAR KR 4/10/4/10/4 4/10/4/10/4   0.52 0.585 0.456 0.254 0.741

1001   Single   2.5   5.74 0.87 0.85 0.075 0.901

_EXTENSION_WINPOOL_END_

_EXTENSION_BuildingGeometry_START_
vertex 1 10.000000000000 0.000000000000 3.000000000000
vertex 2 10.000000000000 0.000000000000 0.000000000000
vertex 3 10.000000000000 8.000000000000 0.000000000000
vertex 4 10.000000000000 8.000000000000 3.000000000000
vertex 5 0.000000000000 8.000000000000 3.000000000000
vertex 6 0.000000000000 0.000000000000 3.000000000000
vertex 7 0.000000000000 8.000000000000 0.000000000000
vertex 8 0.000000000000 0.000000000000 0.000000000000
vertex 9 1.000000000000 0.000000000000 0.000000000000
vertex 10 1.000000000000 0.000000000000 3.000000000000
vertex 11 1.200000000000 0.000000000000 2.800000000000
vertex 12 1.200000000000 0.000000000000 0.100000000000
vertex 13 9.800000000000 0.000000000000 0.100000000000
vertex 14 9.800000000000 0.000000000000 2.800000000000
vertex 15 1.000000000000 -2.000000000000 0.000000000000
vertex 16 0.000000000000 -2.000000000000 0.000000000000
vertex 17 0.000000000000 -2.000000000000 3.000000000000
vertex 18 1.000000000000 -2.000000000000 3.000000000000
vertex 19 10.000000000000 -2.000000000000 0.000000000000
vertex 20 10.000000000000 -2.000000000000 3.000000000000
vertex 21 1.200000000000 -2.000000000000 2.800000000000
vertex 22 1.200000000000 -2.000000000000 0.100000000000
vertex 23 9.800000000000 -2.000000000000 0.100000000000
vertex 24 9.800000000000 -2.000000000000 2.800000000000
vertex 25 1.000000000000 0.000000000000 6.000000000000
vertex 26 0.000000000000 0.000000000000 6.000000000000
vertex 27 0.000000000000 -2.000000000000 6.000000000000
vertex 28 1.000000000000 -2.000000000000 6.000000000000
vertex 29 10.000000000000 0.000000000000 6.000000000000

vertex 30 10.000000000000 8.000000000000 6.000000000000

vertex 31 0.000000000000 8.000000000000 6.000000000000

vertex 32 1.200000000000 0.000000000000 5.800000000000

vertex 33 1.200000000000 0.000000000000 3.100000000000

vertex 34 9.800000000000 0.000000000000 3.100000000000

vertex 35 9.800000000000 0.000000000000 5.800000000000

vertex 36 10.000000000000 -2.000000000000 6.000000000000

vertex 37 1.200000000000 -2.000000000000 5.800000000000

vertex 38 1.200000000000 -2.000000000000 3.100000000000

vertex 39 9.800000000000 -2.000000000000 3.100000000000

vertex 40 9.800000000000 -2.000000000000 5.800000000000

vertex 41 0.000000000000 0.000000000000 -3.000000000000

vertex 42 10.000000000000 0.000000000000 -3.000000000000

vertex 43 0.000000000000 8.000000000000 -3.000000000000

vertex 44 10.000000000000 8.000000000000 -3.000000000000

vertex 45 10.000000000000 -2.000000000000 -3.000000000000

vertex 46 0.000000000000 -2.000000000000 -3.000000000000

vertex 47 1.000000000000 -2.000000000000 9.000000000000

vertex 48 1.000000000000 0.000000000000 9.000000000000

vertex 49 0.000000000000 0.000000000000 9.000000000000

vertex 50 0.000000000000 -2.000000000000 9.000000000000

vertex 51 10.000000000000 0.000000000000 9.000000000000

vertex 52 9.800000000000 0.000000000000 8.800000000000

vertex 53 9.800000000000 0.000000000000 6.100000000000

vertex 54 1.200000000000 0.000000000000 6.100000000000

vertex 55 1.200000000000 0.000000000000 8.800000000000

vertex 56 10.000000000000 -2.000000000000 9.000000000000

vertex 57 1.200000000000 -2.000000000000 8.800000000000

vertex 58 1.200000000000 -2.000000000000 6.100000000000

vertex 59 9.800000000000 -2.000000000000 6.100000000000

vertex 60 9.800000000000 -2.000000000000 8.800000000000

vertex 61 0.000000000000 8.000000000000 9.000000000000

vertex 62 10.000000000000 8.000000000000 9.000000000000

vertex 63 0.000000000000 0.000000000000 12.000000000000

vertex 64 0.000000000000 -2.000000000000 12.000000000000

vertex 65 1.000000000000 -2.000000000000 12.000000000000

vertex 66 1.000000000000 0.000000000000 12.000000000000

vertex 67 10.000000000000 0.000000000000 12.000000000000

vertex 68 1.200000000000 0.000000000000 11.800000000000

vertex 69 1.200000000000 0.000000000000 9.100000000000

vertex 70 9.800000000000 0.000000000000 9.100000000000

vertex 71 9.800000000000 0.000000000000 11.800000000000

vertex 72 10.000000000000 8.000000000000 12.000000000000

vertex 73 0.000000000000 8.000000000000 12.000000000000

vertex 74 10.000000000000 -2.000000000000 12.000000000000

vertex 75 1.200000000000 -2.000000000000 11.800000000000

vertex 76 1.200000000000 -2.000000000000 9.100000000000

vertex 77 9.800000000000 -2.000000000000 9.100000000000

vertex 78 9.800000000000 -2.000000000000 11.800000000000

vertex 79 10.000000000000 0.000000000000 15.000000000000

vertex 80 0.000000000000 0.000000000000 15.000000000000

vertex 81 0.000000000000 -2.000000000000 15.000000000000

vertex 82 10.000000000000 -2.000000000000 15.000000000000

vertex 83 1.200000000000 -2.000000000000 14.800000000000

vertex 84 1.200000000000 -2.000000000000 12.100000000000

vertex 85 9.800000000000 -2.000000000000 12.100000000000

vertex 86 9.800000000000 -2.000000000000 14.800000000000

zone 2_11

wall 1 1 2 3 4

wall 2 5 6 1 4

wall 3 4 3 7 5

wall 4 5 7 8 6

wall 5 3 2 8 7

wall 6 6 8 9 10

wall 7 10 9 2 1

window 8 11 12 13 14

zone 2_12

wall 9 9 15 16 8

wall 10 6 17 18 10

wall 11 10 9 8 6

wall 12 6 8 16 17

wall 13 18 15 9 10

wall 14 17 16 15 18

zone 2_13

wall 15 2 19 15 9

wall 16 1 2 9 10

window 21 14 13 12 11

wall 17 10 18 20 1

wall 18 10 9 15 18

wall 19 20 19 2 1

wall 20 18 15 19 20

window 22 21 22 23 24

zone 3_9

wall 23 25 10 6 26

wall 24 10 18 17 6

wall 25 27 17 18 28

wall 26 26 6 17 27

wall 27 26 27 28 25

wall 28 28 18 10 25

zone 3_8

wall 29 29 1 4 30

wall 30 30 4 5 31

wall 31 25 10 1 29

window 36 32 33 34 35

wall 32 4 1 6 5

wall 33 26 6 10 25

wall 34 31 5 6 26

wall 35 31 26 29 30

zone 3_10

wall 37 25 10 18 28

wall 38 36 20 1 29

wall 39 29 1 10 25

window 43 35 34 33 32

wall 40 25 28 36 29

wall 41 28 18 20 36

window 44 37 38 39 40

wall 42 1 20 18 10

zone 1_14

wall 45 8 41 42 2

wall 46 7 43 41 8

wall 47 7 8 2 3

wall 48 2 42 44 3

wall 49 44 42 41 43

wall 50 3 44 43 7

zone 1_15

wall 51 9 15 19 2

wall 52 19 45 42 2

wall 53 8 41 46 16

wall 54 8 16 15 9

wall 55 16 46 45 19

wall 56 42 45 46 41

wall 57 2 42 41 8

zone 4_6

wall 58 47 28 25 48

wall 59 49 50 47 48

wall 60 50 27 28 47

wall 61 25 28 27 26

wall 62 48 25 26 49

wall 63 49 26 27 50

zone 4_7

wall 64 51 29 25 48

window 71 52 53 54 55

wall 65 48 47 56 51

wall 66 48 25 28 47

wall 67 29 36 28 25

wall 68 56 36 29 51

wall 69 47 28 36 56

window 70 57 58 59 60

zone 4_5

wall 72 48 25 29 51

window 79 55 54 53 52

wall 73 61 49 51 62

wall 74 62 30 31 61

wall 75 61 31 26 49

wall 76 49 26 25 48

wall 77 51 29 30 62

wall 78 30 29 26 31

zone 5_3

wall 80 63 49 50 64

wall 81 64 50 47 65

wall 82 48 47 50 49

wall 83 66 48 49 63

wall 84 65 47 48 66

wall 85 63 64 65 66

zone 5_2

wall 86 63 49 48 66

wall 87 62 51 49 61

wall 88 66 48 51 67

window 93 68 69 70 71

wall 89 72 62 61 73

wall 90 67 51 62 72

wall 91 73 61 49 63

wall 92 73 63 67 72

zone 5_4

wall 94 51 56 47 48

wall 95 66 65 74 67

wall 96 67 51 48 66

window 100 71 70 69 68

wall 97 66 48 47 65

wall 98 65 47 56 74

window 101 75 76 77 78

wall 99 74 56 51 67

zone 6_1

wall 102 67 74 65 66

wall 103 66 65 64 63

wall 104 79 67 63 80

wall 105 80 63 64 81

wall 106 80 81 82 79

wall 107 81 64 74 82

window 109 83 84 85 86

wall 108 82 74 67 79

_EXTENSION_BuildingGeometry_END_

_EXTENSION_VirtualSurfaceGeometry_START_

_EXTENSION_VirtualSurfaceGeometry_END_

_EXTENSION_ExternalShadingGeometry_START_

_EXTENSION_ExternalShadingGeometry_END_

_EXTENSION_GeoPositionGeometry_START_

_EXTENSION_GeoPositionGeometry_END_

_EXTENSION_VAMPARAMS_START_

_EXTENSION_VAMPARAMS_END_

Appendix E: TRNSYS .par File (Earth-Tubes Assumptions for Run16 I, 2-meter DSF Depth in Minneapolis)

```
************************************************
* TYPE 61 SUPPLIED PARAMETERS
*================================================
* Nmod,Nsec,Nsoil,Nsurf,NI,NJ,NK [-]:
  1    3    2     2     24 23 10

* DX [m]:
  1.0000E+00  1.0000E+00
  1.0000E+00  1.0000E+00  1.0000E+00  1.0000E+00
  1.0000E+00  1.0000E+00  1.0000E+00  1.0000E+00
  1.0000E+00  1.0000E+00  1.0000E+00  1.0000E+00
  1.0000E+00  1.0000E+00  1.0000E+00  1.0000E+00
  1.0000E+00  1.0000E+00  1.0000E+00  1.0000E+00
  1.0000E+00  1.0000E+00

* DY [m]:
  1.0000E+00  1.0000E+00
  0.7500E+00  0.5000E+00  0.5000E+00  0.5000E+00
  0.5000E+00  0.5000E+00  0.5000E+00  0.5000E+00
  0.5000E+00  0.5000E+00  0.5000E+00  0.5000E+00
  0.5000E+00  0.5000E+00  0.5000E+00  0.5000E+00
  0.5000E+00  0.5000E+00  0.7500E+00
  1.0000E+00  1.0000E+00

* DZ [m]:
  1.0000E+00  1.0000E+00  1.0000E+00  0.5000E+00
  0.5000E+00  0.5000E+00  0.5000E+00  0.5000E+00
  0.5000E+00  0.5000E+00
```

* TypSec [-]:

```
1 1 2 2 2 2 2 2 2 2 2 2 3 3 3 3 3 3 3 3 3 3 1 1
```

* TypSoil for front surface [-]:

```
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
```

* TypSoil for sec# 1 (through front ambient only) [-]:

```
  2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
0 1 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 1 0
0 1 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 1 0
0 1 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 1 0
0 1 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 1 0
0 1 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 1 0
0 1 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 1 0
0 1 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 1 0
0 1 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 1 0
0 1 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 1 0
0 1 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 1 0
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
```

* TypSoil for sec# 2 (through entire tubes and basement office and sunspace) [-]:

```
   2  2  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  2  2
0  1  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  1  0
0  1  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  1  0
0  1  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  1  0
0  1  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  1  0
0  1  2  2  0  2  2  2  0  2  2  2  0  2  2  2  0  2  2  2  0  2  2  1  0
0  1  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  1  0
0  1  2  2  2  2  0  2  2  2  0  2  2  2  0  2  2  2  0  2  2  2  2  1  0
0  1  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  1  0
0  1  2  2  0  2  2  2  0  2  2  2  0  2  2  2  0  2  2  2  0  2  2  1  0
0  1  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  1  0
   0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
```

* TypSoil for sec# 3 (through entire tubes and ambient) [-]:

```
   2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2
0  1  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  1  0
0  1  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  1  0
0  1  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  1  0
0  1  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  1  0
0  1  2  2  0  2  2  2  0  2  2  2  0  2  2  2  0  2  2  2  0  2  2  1  0
0  1  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  1  0
0  1  2  2  2  2  0  2  2  2  0  2  2  2  0  2  2  2  0  2  2  2  2  1  0
0  1  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  1  0
0  1  2  2  0  2  2  2  0  2  2  2  0  2  2  2  0  2  2  2  0  2  2  1  0
0  1  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  1  0
   0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
```

* TypSoil for rear surface [-]:

```
   0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
   0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
   0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
```

```
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

* PosInf [-]:
 1 1 1 24 23 10

* Kair0 [kJ/K m2] ,Kair1 [(kJ/K m2)/(m/s)]:
 0.7000E+01 0.1400E+02

* LamSoil [kJ/K m], CvSoil [kJ/K m3]:
 0.7200E+01 0.1000E+04
 0.5400E+01 0.1000E+04

* LamTub [kJ/K m], CvTub [kJ/K m3]:
 0.7200E+01 0.1000E+04

* ThTub [m], CtubCor [-], Cfric [-]:
 5.0000E-02 0.8862+00 1.0000E-02

* TypWatFlow [-], Vwat [m/h]:
 1 1 1
 0.0000E+00 0.0000E+00 0.0000E+00

* NiniSoil,NiniWat [-]:
 1 1
```

```
* TiniSoil [degC], PosIniSoil [-]:
  0.5000E+01  3   3   4   22   21   10

* ThIniWat [m], PosIniWat [-]:
  0.0000E+00

* Nopt [-]:
  17

* TypOpt [-], PosOpt [-]:
  107   3   3   4  12  21   4 !Pfree
  107   1   1   1   1   1   1 !Pfix
  103   3   3   1   3  21   10 !Pfront
  104  22   3   1  22  21   10 !Pback
  105   3   3   1  22   3   10 !Pside
  202   3   3   4  22  21   10 !Pwat
  203   3   3   4  22  21   10 !Pfric
  204   3   3   1  22  21   10 !Pin
   22   3   3   4  22  21   10 !PinHt
  109   3   3   1  22  21   10 !PinHs
    5   3   3   4  22  21   10 !Mwat
    6   3   3   4  22  21   10 !dMlat
    9  22   3   4  22  21   10 !dMout
    1   6   3   4   6  21   10 !T1
    1  10   3   4  10  21   10 !T2
    1  14   3   4  14  21   10 !T3
    1  18   3   4  18  21   10 !T4
*************************************************
```

Appendix F: ContamW 3.2 0 .prj File (Assumptions for Run16 I, 2-meter DSF Depth in Minneapolis)

```
! rows cols ud uf    T   uT     N     wH  u  Ao    a
    58   66  0  0 293.150 2    0.00 10.00 0 0.600 0.280
!  scale     us  orgRow  orgCol  invYaxis showGeom
 5.000e-001   0       5       5     0        0
! Ta       Pb      Ws    Wd    rh  day u..
293.150 101325.0  0.000   0.0 0.000 1 2 0 0 1 ! steady simulation
293.150 101325.0  1.000 270.0 0.000 1 2 0 0 1 ! wind pressure test
C:\Users\Payman\Desktop\Dissertation Materials\Modelling\CONTAM\Weather
Files\USA_MN_Minneapolis-St.Paul.Intl.AP.wth ! weather file
null ! no contaminant file
null ! no continuous values file
null ! no discrete values file
null ! no WPC file
null ! no EWC file
WPC description
!  Xref    Yref    Zref   angle u
```

```
   0.000   0.000   0.000   0.00 0

! epsP epsS  tShift  dStart dEnd wp mf wpctrig

  0.01 0.01 00:00:00   1/1   1/1  0  0  0

! latd  longtd   tznr  altd  Tgrnd u..

 40.00  -90.00  -6.00     0 283.15 2 0

!sim_af afcalc afmaxi afrcnvg afacnvg afrelax uac Pbldg uPb

     1      1     30  1e-005  1e-006    0.75   0 50.00   0

!   slae rs aflmaxi aflcnvg aflinit Tadj

      0   1    100  1e-006      1    0

!sim_mf slae rs maxi   relcnvg   abscnvg relax gamma ucc

    0            30 1.00e-004 1.00e-015 1.250         0 ! (cyclic)

          0   1  100 1.00e-006 1.00e-015 1.100 1.000   0 ! (non-trace)

          0   1  100 1.00e-006 1.00e-015 1.100 1.000   0 ! (trace)

          0   1  100 1.00e-006 1.00e-015 1.100         0 ! (cvode)

!mf_solver sim_1dz sim_1dd   celldx  sim_vjt udx

     0        1       0    1.00e-001    0     0

!cvode    rcnvg     acnvg    dtmax

   0    1.00e-006 1.00e-013   0.00
```

```
!tsdens relax tsmaxi cnvgSS densZP stackD dodMdt
   0    0.75    20     1      0      0       0
!date_st time_st  date_0 time_0   date_1 time_1    t_step   t_list   t_scrn
  Jan01 00:00:00  Jan01 00:00:00  Dec31 24:00:00  00:05:00 00:05:00 01:00:00
!restart  date  time
    0    Jan01 00:00:00
!list doDlg pfsave zfsave zcsave
   1     1      1      1       0
!vol ach -bw cbw exp -bw age -bw
  0   0   0   0   0   0   0   0
!rzf rzm rz1 csm srf log
  0   0   0   1   1   1
!bcx dcx pfq zfq zcq
  0   0   0   0   0
! 0  1  2  3  4  5  6  7  8  9  10 11 12 13 14 15 <- extra[]
  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
2 ! rvals:
1.2041 9.8055
```

```
!valZ valD valC
   0    0    0
!cfd  cfdcnvg   var zref  maxi dtcmo
  0  1.00e-002   0   0    1000   1
-999
0 ! contaminants:
0 ! species:
-999
6 ! levels plus icon data:
! #  refHt   delHt  ni  u  name
  1  -3.000   3.000 14 0 0 <-1>
!icn col row  #
 186  15   2   4
 171  15   3   4
 179  15   4   4
  14   5   5   0
  25  15   5  25
  15  25   5   0
```

5 23 7 14

18 5 21 0

23 6 21 26

20 25 21 0

5 23 23 15

17 5 25 0

23 15 25 27

16 25 25 0

2 0.000 3.000 25 0 0 <1>

!icn col row #

14 5 5 0

25 15 5 20

15 25 5 0

5 23 7 11

186 6 18 4

186 12 18 4

170 13 18 4

178 14 18 4

185 15 18 5

171 6 19 4

171 15 19 5

179 6 20 4

179 15 20 5

18 5 21 0

23 6 21 21

19 7 21 0

23 15 21 22

20 25 21 0

5 6 23 12

5 23 23 13

25 6 24 23

25 15 24 24

17 5 25 0

21 7 25 0

16 25 25 0

3 3.000 3.000 22 0 0 <2>

!icn col row #

14	5	5	0
25	15	5	15
15	25	5	0
5	23	7	8
186	6	18	4
186	15	18	5
171	6	19	4
171	15	19	5
179	6	20	4
179	15	20	5
18	5	21	0
23	6	21	16
19	7	21	0
23	15	21	17
20	25	21	0
5	6	23	9
5	23	23	10

```
  25   6  24  18

  25  15  24  19

  17   5  25   0

  21   7  25   0

  16  25  25   0

   4   6.000   3.000 22 0 0 <3>

!icn col row  #

  14   5   5   0

  25  15   5  10

  15  25   5   0

   5  23   7   5

 186   6  18   4

 186  15  18   5

 171   6  19   4

 171  15  19   5

 179   6  20   4

 179  15  20   5

  18   5  21   0
```

23 6 21 11

19 7 21 0

23 15 21 12

20 25 21 0

5 6 23 6

5 23 23 7

25 6 24 13

25 15 24 14

17 5 25 0

21 7 25 0

16 25 25 0

5 9.000 3.000 22 0 0 <4>

!icn col row #

14 5 5 0

25 15 5 5

15 25 5 0

5 23 7 2

186 6 18 4

186 15 18 5

171 6 19 4

171 15 19 5

179 6 20 4

179 15 20 5

18 5 21 0

23 6 21 6

19 7 21 0

23 15 21 7

20 25 21 0

5 6 23 3

5 23 23 4

25 6 24 8

25 15 24 9

17 5 25 0

21 7 25 0

16 25 25 0

6 12.000 3.000 26 0 0 <5>

!icn col row #

185 15 12 1

171 15 13 1

179 15 14 1

7 9 15 -1

184 10 15 2

178 11 15 2

185 12 15 3

170 13 15 3

178 14 15 3

185 15 15 4

171 15 16 4

179 15 20 4

14 5 21 0

23 15 21 1

15 25 21 0

186 2 23 4

170 3 23 4

```
178   4  23   4
 23   5  23   2
  5  23  23   1
 23  25  23   3
180  26  23   4
186  28  23   4
 25  15  24   4
 17   5  25   0
 16  25  25   0
-999
2 ! day-schedules:
! # npts shap utyp ucnv name
 1    4    0    1    0 Weekdays

00:00:00 0
08:00:00 1
18:00:00 0
24:00:00 0
```

2 2 0 1 0 Weekends

00:00:00 0

24:00:00 0

-999

2 ! week-schedules:

! # utyp ucnv name

1 1 0 ClosedPath

2 2 2 2 2 2 2 2 2 2 2 2

2 1 0 Occupancy

The same schedule defined in Type-56 as "USE"

2 1 1 1 1 1 2 2 2 2 2 2

-999

1 ! wind pressure profiles:

1 13 2 AIVC

Wind from North Based on AIVC graph (Clockwise from North)

0.0 0.700

30.0 0.500

60.0 0.200

90.0 -0.600

120.0 -0.500

150.0 -0.300

180.0 -0.200

210.0 -0.300

240.0 -0.500

270.0 -0.600

300.0 0.200

330.0 0.500

360.0 0.700

-999

0 ! kinetic reactions:

-999

0 ! filter elements:

-999

0 ! filters:

-999

0 ! source/sink elements:

-999

31 ! flow elements:

1 27 dor_door AmbientInlet1

0.0253253 1.76494 0.5 0.01 0.2 8 0.78 0 0 0

2 27 dor_pl2 AmbientInlet2

0.00633132 0.882469 0.5 0.0444444 0.2 8 0.78 0 0

3 23 srv_jwa BackdraftDuct

0.566337 0.5 0.0001 1 0

4 27 dor_pl2 BasementInlet

0.00633132 0.882469 0.5 0.0444444 0.2 8 0.78 0 0

5 27 dor_door BasementInlet1

0.0253253 1.76494 0.5 0.01 0.2 8 0.78 0 0 0

6 23 plr_bdf DuctBackdraft

Measurements indicate a flow exponent of 0.6 to 0.7 for typical openin

1.7377e-006 0.01 0.7 1e-005 0.7

7 30 fan_cmf DuctVent

Sum of the four office vents during the scheduled Occupancy

0.187761 8

8 24 dor_door DuctVent1

4.056e-005 0.0110309 0.5 0.01 0.1 0.1 0.78 0 0 0

9 24 dor_pl2 DuctVent2

1.014e-005 0.00551543 0.5 0.0222222 0.1 0.1 0.78 0 0

10 25 plr_orfc FloorGril

0.0548087 1.35765 0.5 1.6 1.4273 0.6 30 0 0

11 27 dor_door GroundOutlet

0.079872 1.76494 0.5 0.01 1.6 1 0.78 0 0 0

12 25 plr_shaft Shaft

0.0251468 6.48663 0.504958 3 2 6 0.1 0 0 0 0

13 23 srv_jwa Sun5_Duct

0.0660726 0.5 0.0001 1 0

14 23 plr_bdf SunBackdraft

Flow exponents vary from 0.5 for large openings where the flow is domi

1.7377e-006 0.01 0.7 1e-005 0.7

15 25 plr_orfc SunSpaceIn

0.0548087 1.35765 0.5 1.6 1.4273 0.6 30 0 0

16 27 dor_door SunspaceInlet

0.021632 0.882469 0.5 0.01 0.4 2 0.78 0 0 0

17 23 plr_orfc SunspaceOut1

0.0193777 0.678823 0.5 0.8 1.00925 0.6 30 0 0

18 25 plr_orfc SunspaceOut2

0.216649 3.39411 0.5 4 2.25676 0.6 30 0 0

19 23 srv_jwa Sunspace_Self

0.0519142 0.5 0.0001 1 0

20 27 dor_door UndergroundInle

0.021632 0.882469 0.5 0.01 0.4 2 0.78 0 0 0

21 30 fan_cmf VentFan1

Ventilation rate Defined in Type-56 for 6people of office1

0.0456389 8

22 30 fan_cmf VentFan2

Ventilation rate Defined in Type-56 for 6people of office2

0.0397778 8

23 30 fan_cmf VentFan3

Ventilation rate Defined in Type-56 for 6people of office3

0.0515 8

24 30 fan_cmf VentFan4

Ventilation rate Defined in Type-56 for 6people of office1

0.0456389 8

25 29 fan_cmf VentFan5

0.0625099 1

26 23 plr_orfc VentIn

0.00085638 0.0848528 0.5 0.1 0.356825 0.6 30 0 0

27 25 plr_orfc VentOut

0.0193777 0.678823 0.5 0.8 1.00925 0.6 30 0 0

28 27 dor_door WinterExhale

0.0288427 0.882469 0.5 0.01 0.8 1 0.78 0 0 0

29 30 fan_cmf WinterFan

To suck air into duct 5 otherwise there wouldnt be any inlet air

 0.222222 8

30 27 dor_door WinterInhale

 0.0253253 1.76494 0.5 0.01 0.2 8 0.78 0 0 0

31 23 srv_jwa test

 5.66337 0.5 0.0001 1 0

-999

0 ! duct elements:

-999

0 ! control super elements:

-999

5 ! control nodes:

! # typ seq f n c1 c2 name

  1 set   1 0 0   0   0 <none>

Constant value

 18

  2 sns   2 0 0   0   0 <none>

zone sensor - Temperature [K]

0 1 0 0 -1 1 1   0.000   0.000   0.000 0 none

3 log   3 1 1   2   0 T-AMB

Report input - Temperature of Ambient

273.15 1 1 T_amb °C

4 lbs   4 0 2   3   1 Sun5Exhaust

Lower band switch

2

5 inv   5 0 1   4   0 NotSun5Exhust

NOT (or invert) input

-999

0 ! simple AHS:

-999

15 ! zones:

! Z# f s# c# k# l# relHt   Vol T0 P0 name clr u[4] axs cdvf <cdvf name> cfd <cfd name> <1D data:>

1 3   0   0   0   6   0.000   60 298.15 0 Sunspace5 -1 0 2 0 0 0 0 0

2 3   0   0   0   5   0.000   240 293.15 0 Office4 -1 0 2 0 0 0 0 0

```
   3  3   0   0   0   5   0.000     6 293.15 0 Duct4 -1 0 2 0 0 0 0 0
   4  3   0   0   0   5   0.000    54 297.15 0 Sunspace4 -1 0 2 0 0 0 0 0
   5  3   0   0   0   4   0.000   240 293.15 0 Office3 -1 0 2 0 0 0 0 0
   6  3   0   0   0   4   0.000     6 293.15 0 Duct3 -1 0 2 0 0 0 0 0
   7  3   0   0   0   4   0.000    54 296.15 0 Sunspace3 -1 0 2 0 0 0 0 0
   8  3   0   0   0   3   0.000   240 293.15 0 Office2 -1 0 2 0 0 0 0 0
   9  3   0   0   0   3   0.000     6 293.15 0 Duct2 -1 0 2 0 0 0 0 0
  10  3   0   0   0   3   0.000    54 295.15 0 Sunspace2 -1 0 2 0 0 0 0 0
  11  3   0   0   0   2   0.000   240 293.15 0 Office1 -1 0 2 0 0 0 0 0
  12  3   0   0   0   2   0.000     6 293.15 0 Duct1 -1 0 2 0 0 0 0 0
  13  3   0   0   0   2   0.000    54 294.15 0 Sunspace1 -1 0 2 0 0 0 0 0
  14  3   0   0   0   1   0.000   240 293.15 0 Office-1 -1 0 2 0 0 0 0 0
  15  3   0   0   0   1   0.000    60 293.15 0 Sunspace-1 -1 0 2 0 0 0 0 0
-999
0 ! initial zone concentrations:
-999
27 ! flow paths:
! P#    f  n#  m#  e#  f#  w#  a#  s#  c#  l#    X       Y      relHt  mult wPset wPmod wazm Fahs Xmax Xmin icn
dir u[4] cdvf <cdvf name> cfd <cfd data[4]>
```

1 1 1 -1 19 0 1 0 0 4 6 0.000 0.000 2.800 1 0 0.36 0 0 0 0 23 1 0 0 0 0 0 0

2 1 1 -1 19 0 1 0 0 4 6 0.000 0.000 2.800 1 0 0.36 270 0 0 0 23 5 0 0 0 0 0 0

3 1 1 -1 19 0 1 0 0 4 6 0.000 0.000 2.800 1 0 0.36 90 0 0 0 23 2 0 0 0 0 0 0

4 0 4 1 10 0 0 0 0 0 6 0.000 0.000 0.000 1 0 0 -1 0 0 0 25 3 0 0 0 0 0 0

5 1 2 -1 27 0 1 0 0 0 5 0.000 0.000 2.800 1 0 0.36 0 0 0 0 25 1 0 0 0 0 0 0

6 0 3 2 6 0 0 0 0 4 5 0.000 0.000 0.300 1 0 0 -1 0 0 0 23 1 0 0 0 0 0 0

7 0 4 2 14 0 0 0 0 5 5 0.000 0.000 2.800 1 0 0 -1 0 0 0 23 1 0 0 0 0 0 0

8 0 6 3 12 0 0 0 0 0 5 0.000 0.000 0.000 1 0 0 -1 0 0 0 25 3 0 0 0 0 0 0

9 0 7 4 10 0 0 0 0 0 5 0.000 0.000 0.000 1 0 0 -1 0 0 0 25 3 0 0 0 0 0 0

10 1 5 -1 27 0 1 0 0 0 4 0.000 0.000 2.800 1 0 0.36 0 0 0 0 25 1 0 0 0 0 0 0

11 0 6 5 6 0 0 0 0 4 4 0.000 0.000 0.300 1 0 0 -1 0 0 0 23 1 0 0 0 0 0 0

12 0 7 5 14 0 0 0 0 5 4 0.000 0.000 2.800 1 0 0 -1 0 0 0 23 1 0 0 0 0 0 0

13 0 9 6 12 0 0 0 0 0 4 0.000 0.000 0.000 1 0 0 -1 0 0 0 25 3 0 0 0 0 0 0

14 0 10 7 10 0 0 0 0 0 4 0.000 0.000 0.000 1 0 0 -1 0 0 0 25 3 0 0 0 0 0 0

15 1 8 -1 27 0 1 0 0 0 3 0.000 0.000 2.800 1 0 0.36 0 0 0 0 25 1 0 0 0 0 0 0

16 0 9 8 6 0 0 0 0 4 3 0.000 0.000 0.300 1 0 0 -1 0 0 0 23 1 0 0 0 0 0 0

17 0 10 8 14 0 0 0 0 5 3 0.000 0.000 2.800 1 0 0 -1 0 0 0 23 1 0 0 0 0 0 0

18 0 12 9 12 0 0 0 0 0 3 0.000 0.000 0.000 1 0 0 -1 0 0 0 25 3 0 0 0 0 0 0

19 0 13 10 10 0 0 0 0 0 3 0.000 0.000 0.000 1 0 0 -1 0 0 0 25 3 0 0 0 0 0 0

20 1 11 -1 27 0 1 0 0 0 2 0.000 0.000 2.800 1 0 0.36 0 0 0 0 25 1 0 0 0 0 0 0

21 0 12 11 6 0 0 0 0 4 2 0.000 0.000 0.300 1 0 0 -1 0 0 0 23 1 0 0 0 0 0 0

22 0 13 11 14 0 0 0 0 5 2 0.000 0.000 2.800 1 0 0 -1 0 0 0 23 1 0 0 0 0 0 0

23 0 15 12 12 0 0 0 0 0 2 0.000 0.000 0.000 1 0 0 -1 0 0 0 25 3 0 0 0 0 0 0

24 0 15 13 10 0 0 0 0 0 2 0.000 0.000 0.000 1 0 0 -1 0 0 0 25 3 0 0 0 0 0 0

25 1 14 -1 27 0 1 0 0 4 1 0.000 0.000 2.800 1 0 0.36 180 0 0 0 25 1 0 0 0 0 0 0

26 0 15 14 6 0 0 0 0 0 1 0.000 0.000 0.300 1 0 0 -1 0 0 0 23 1 0 0 0 0 0 0

27 1 -1 15 19 0 1 0 0 0 1 0.000 0.000 2.800 3 0 0.36 180 0 0 0 23 1 0 0 0 0 0 0

-999

0 ! duct junctions:

-999

0 ! initial junction concentrations:

-999

0 ! duct segments:

-999

0 ! source/sinks:

-999

```
1 ! occupancy schedules:

1 4 0 Occupancy

8-18 Weekdays

 00:00:00 0   0.000   0.000   0.000

 08:00:00 14   0.000   0.000   0.000

 18:00:00 14   0.000   0.000   0.000

 24:00:00 14   0.000   0.000   0.000

-999

0 ! exposures:

-999

0 ! annotations:

-999

* end project file.
```

5.4. Mathematical Description of Type 56

The general case, which does not include the simplified model of the heating and cooling equipment, is presented first. If separate equipment components are used, they can be coupled to the airnodes as either internal convective gains or ventilation gains. Following this, the simplified method of providing heating and cooling equipment within the TYPE 56 component is described. Another section will cover the use of a simulation timestep that is not equal to the timebase on which the wall transfer function relationships are based. Finally, descriptions of the optical and thermal window model, the way in which solar and internal radiation are distributed within each zone, the moisture balance calculations and the integrated model for thermo-active walls are given.

5.4.1. Thermal Zone /Airnode

The building model in TYPE 56 is an energy balance model. Since version 17 a zone may have more than one airnode. The thermal capacity of the air volume and capacities which are closely connected with the air node (furniture, for example). Thus the node capacity is a separate input in addition to the volume.

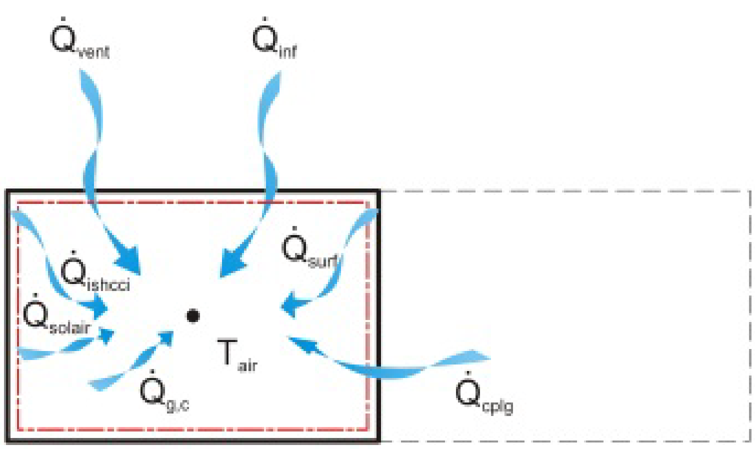


Figure 5.4.1-1: Heat balance on the air node

5.4.1.1. *Convective Heat Flux to the Air Node*

$$\dot{Q}_i = \dot{Q}_{surf,i} + \dot{Q}_{inf,i} + \dot{Q}_{vent,i} + \dot{Q}_{g,c,i} + \dot{Q}_{cplg,i} + \dot{Q}_{solair,i} + \dot{Q}_{ISHCCI,i} \qquad \text{Eq. 5.4.1-1}$$

Where

$\dot{Q}_{surf,i}$ is the convective gain from surfaces

$\dot{Q}_{inf,i}$ is the infiltration gains (air flow from outside only), given by

$$\dot{Q}_{inf,i} = \dot{V} \cdot \rho \cdot c_p \left(T_{outside,i} - T_{air}\right) \qquad \text{Eq. 5.4.1-2}$$

$\dot{Q}_{vent,i}$ is the ventilation gains (air flow from a user-defined source, like an HVAC system, given by

$$\dot{Q}_{vent,i} = \dot{V} \cdot \rho \cdot c_p \left(T_{ventilation,i} - T_{air}\right) \qquad \text{Eq. 5.4.1-3}$$

$\dot{Q}_{g,c,i}$ is the internal convective gains (by people, equipment, illumination, radiators, etc.), and

$\dot{Q}_{cplg,i}$ is the gains due to (connective) air flow from airnode I or boundary condition, given by

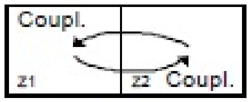
$$\dot{Q}_{cplg,i} = \dot{V} \cdot \rho \cdot c_p \left(T_{zone,i} - T_{air}\right) \qquad \text{Eq. 5.4.1-4}$$

$\dot{Q}_{solair,i}$ the fraction of solar radiation entering an airnode through external windows which is immediately transferred as a convective gain to the internal air (see 5.4.1.9)

$\dot{Q}_{ISHCCI,i}$ is the absorbed solar radiation on all internal shading devices of zone and directly transferred as a convective gain to the internal air

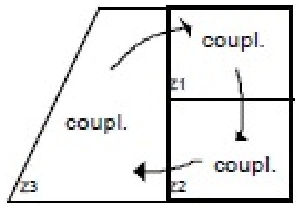
5.4.1.2. *Coupling*

The coupling statement allows the definition an air mass flow a airnode receives from another airnode, considered as a heat flow from or to the air node. The statement does not automatically define the air flow back to the adjacent airnode as would occur in an interzonal air exchange. To consider this return flow, the corresponding coupling must be defined in the adjacent airnode to receive the same air flow in return. The reason for this convention is to allow the user to describe cross ventilation or a ventilation circle within 3 or more airnodes (e.g., thermosyphon through a 2 story winter-garden,).



interzonal airchange

cross ventilation



Ventilation circle

Note: There is no air balance check in TYPE 56. The user can empty or overload a airnode by couplings. Be sure that the specified air flows into a airnode by coupling, ventilation, and infiltration are physically meaningful.

5.4.1.3. *Radiative Heat Flows (only) to the Walls and Windows*

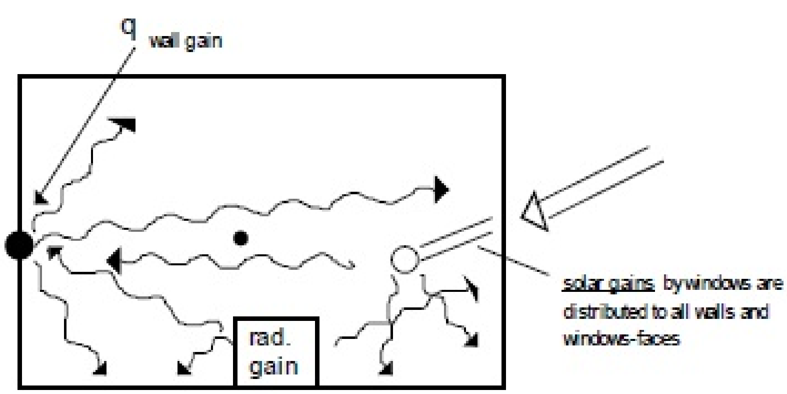


Figure 5.4.1-2: Radiative energy flows considering one wall with its surface temperature node.

$$\dot{Q}_{r,w_i} = \dot{Q}_{g,r,l,w_i} + \dot{Q}_{sol,w_i} + \dot{Q}_{long,w_i} + \dot{Q}_{wall-gain} \qquad \text{Eq. 5.4.1-5}$$

where $\dot{Q}_{r,w_i}$ is the radiative gains for the wall surface temperature node, $\dot{Q}_{g,r,i,w_i}$ is the radiative airnode internal gains received by wall, $\dot{Q}_{sol,w_i}$ is the solar gains through zone windows received by walls, $\dot{Q}_{long,w_i}$ is the longwave radiation exchange between this wall and all other walls and windows (ε_i =1), and $\dot{Q}_{wall-gain}$ is the user-specified heat flow to the wall or window surface. All of these quantities are given in kJ/h.

5.4.1.4. *Integration of Walls and Windows*

Figure 5.4.1-3 shows the heat fluxes and temperatures that characterize the thermal behavior of any wall or window. The nomenclature used in this figure is defined as follows:

$S_{s,i}$	Radiation heat flux absorbed at the inside surface (solar and radiative gains)
$S_{s,o}$	Radiation heat flux absorbed at the outside surface (solar gains)
$\dot{q}_{r,s,i}$	Net radiative heat transfer with all other surfaces within the zone
$\dot{q}_{r,s,o}$	Net radiative heat transfer with all surfaces in view of the outside surface
$\dot{q}_{w,g,i}$	User defined heat flux to the wall or window surface
$\dot{q}_{s,i}$	Conduction heat flux from the wall at the inside surface
$\dot{q}_{s,o}$	Into the wall at the outside surface
$\dot{q}_{c,s,i}$	Convection heat flux from the inside surface to the air
$\dot{q}_{c,s,o}$	Convection heat flux to the outside surface from the boundary/ambient
$T_{s,i}$	Inside surface temperature
$T_{s,o}$	Outside surface temperature

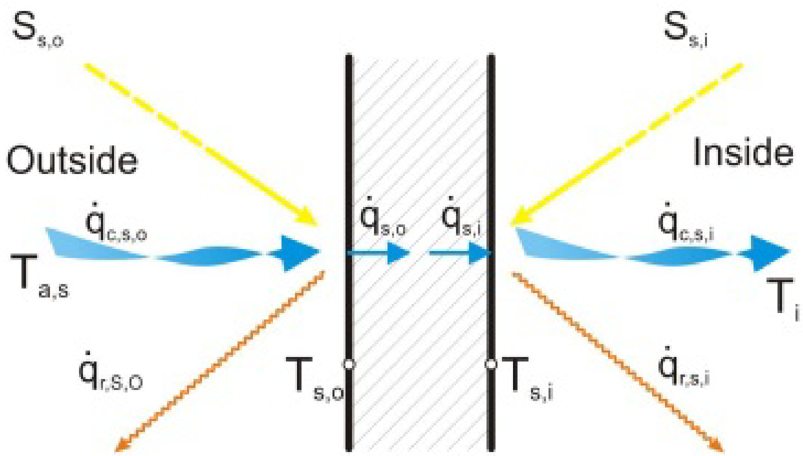


Figure 5.4.1-3: Surface Heat Fluxes and Temperatures

The walls are modeled according to the transfer function relationships of Mitalas and Arseneault [1,2,6] defined from surface to surface. For any wall, the heat conduction at the surfaces are:

$$\dot{q}_{s,i} = \sum_{k=0}^{n_{b_s}} b_s^k T_{s,o}^k - \sum_{k=0}^{n_{c_s}} c_s^k T_{s,i}^k - \sum_{k=1}^{n_{d_s}} d_s^k \dot{q}_{s,i}^k \qquad \text{Eq. 5.4.1-6}$$

$$\dot{q}_{s,0} = \sum_{k=0}^{n_{a_s}} a_s^k T_{s,o}^k - \sum_{k=0}^{n_{b_s}} b_s^k T_{s,i}^k - \sum_{k=1}^{n_{d_s}} d_s^k \dot{q}_{s,0}^k \qquad \text{Eq. 5.4.1-7}$$

These time series equations in terms of surface temperatures and heat fluxes are evaluated at equal time intervals. The superscript k refers to the term in the time series. The current time is k=0, the previous time is for k=1, etc. The time-base on which these calculations are based is specified by the user within the TRNBUILD description. The coefficients of the time series (a's, b's, c's, and d's) are determined within the TRNBUILD program using the z-transfer function routines of reference [2].

A window is thermally considered as an external wall with no thermal mass, partially transparent to solar, but opaque to long-wave internal gains. Long-wave absorption is considered to occur only at the surfaces. In the energy balance calculation of the TYPE 56, the window is described as a 2-node model shown in Figure 5.4.1-4. The detailed optical and thermal window model is described in Section 5.4.2. Eq. 5.4.1-6 to Eq. 5.4.1-33 are valid for a window with:

$$a_s^o = b_s^o = c_s^o = d_s^o = U_{g,s}$$

$a_s^k = b_s^k = c_s^k = d_s^k = 0$ for $k>0$.

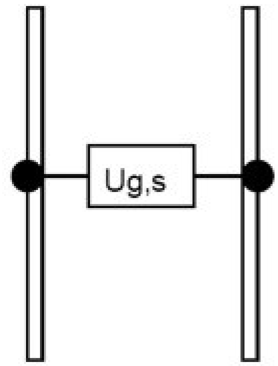


Figure 5.4.1-4: Two-node window model used in th TYPE56 energy balance equation.

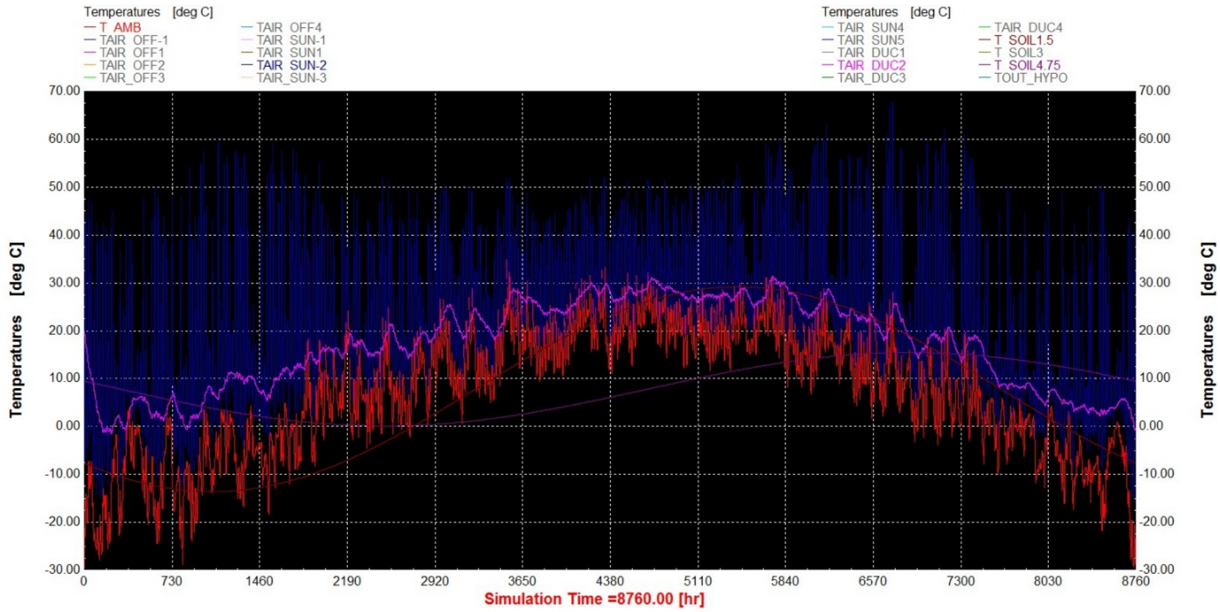
5.4.1.5. *Transfer Function Method by Mitalas*

The method of the transfer function or response factors can be described as the method to tell the "thermal history" of the wall. The wall is considered as a black box. The number of time-steps (k) related to the time-base (defined by the user) shows whether the wall is a heavy wall with a high thermal mass ($k \leq 20$) or if only a few time-steps have to be considered to describe the thermal behavior of this wall. If the time-base of the considered wall is higher than the time-constant, the calculation of the Transfer-function matrix coefficients is stopped. Therefore such a "thin" wall can be replaced by a resistance definition neglecting the thermal mass. As an example, the Figure 5.4.1-5 shows the different material layers of a wall. The wall example consists of three layers with concrete, mineral wool and gypsum from outside to inside.

Appendix H: Result Graphs for Minneapolis, DSF1

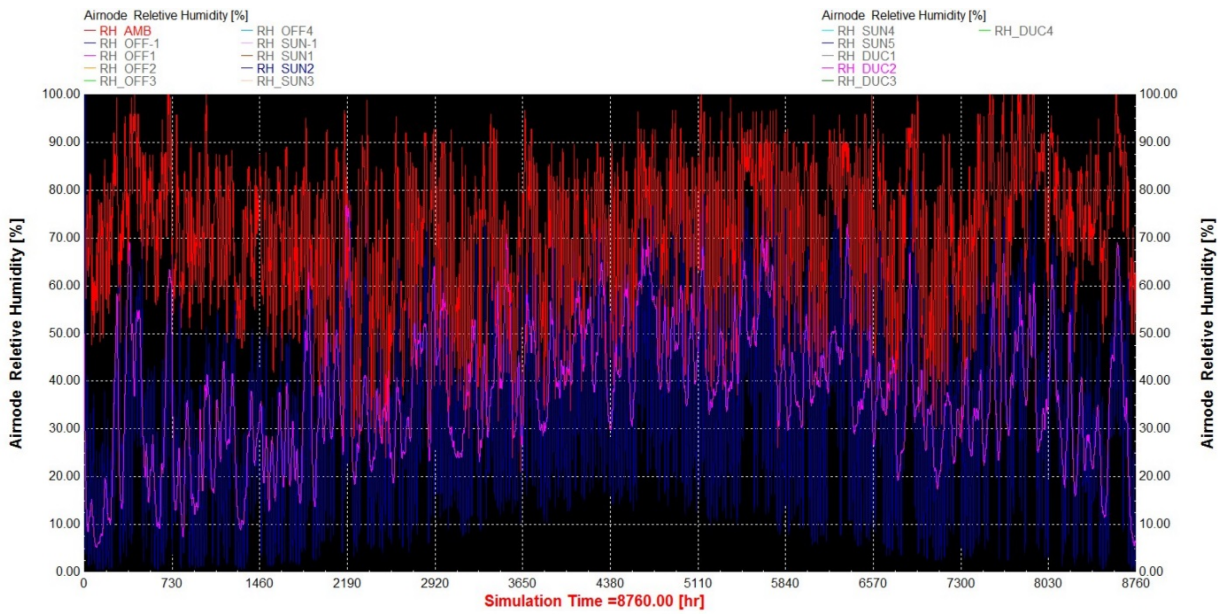
Zones Temperature *(°C)*

Run5 C (MC 4-Story DSF1 Full HVAC)



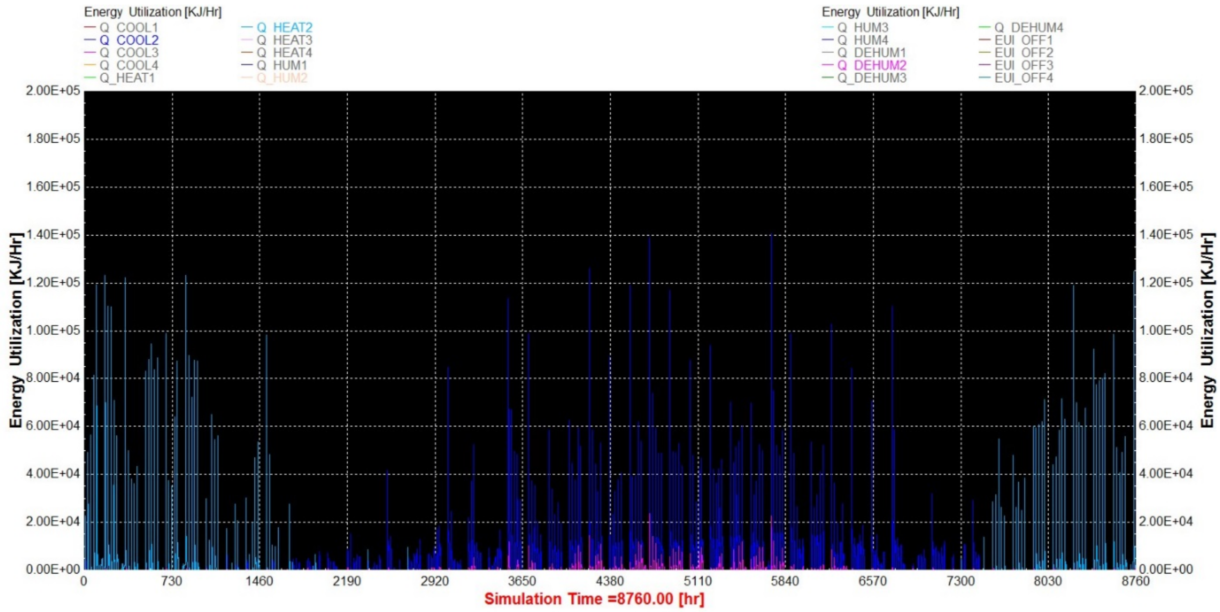
Zones Relative Humidity *(%)*

Run5 C (MC 4-Story DSF1 Full HVAC)



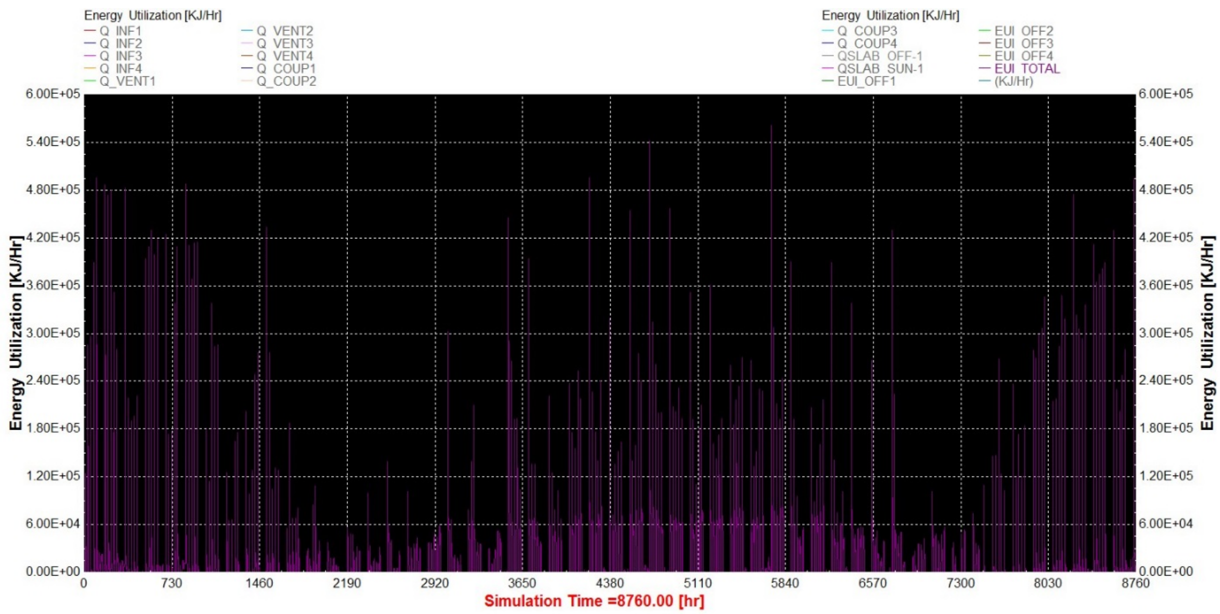
Office Load Intensity *(kJ/hr)*

Run5 C (MC 4-Story DSF1 Full HVAC)



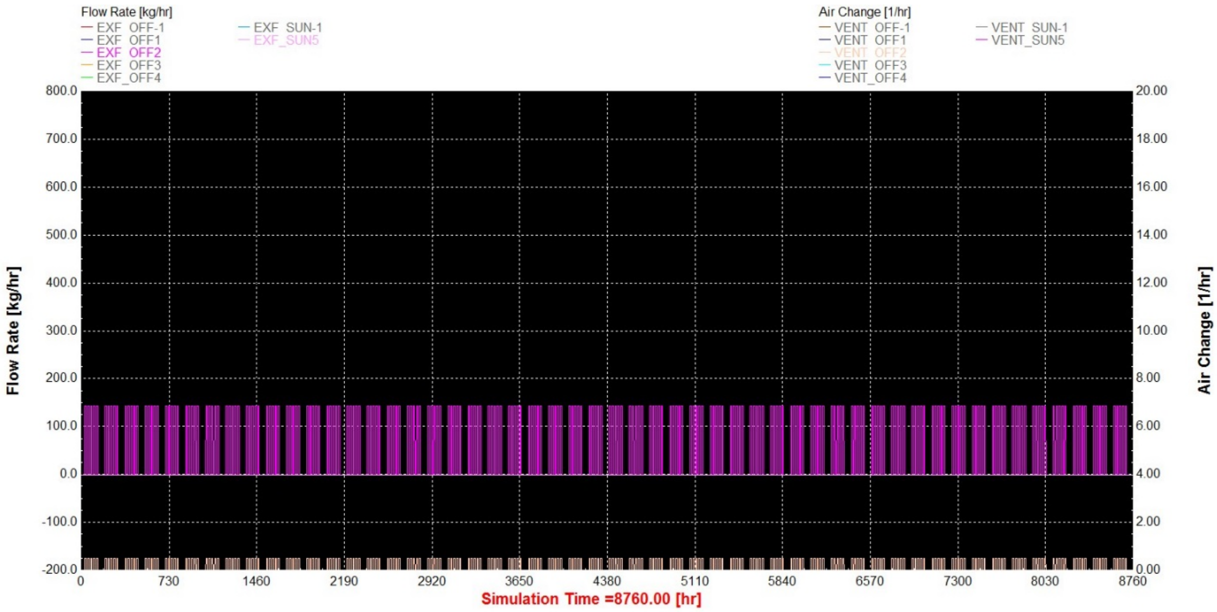
Total Offices Load Intensity *(kJ/hr)*

Run5 C (MC 4-Story DSF1 Full HVAC)



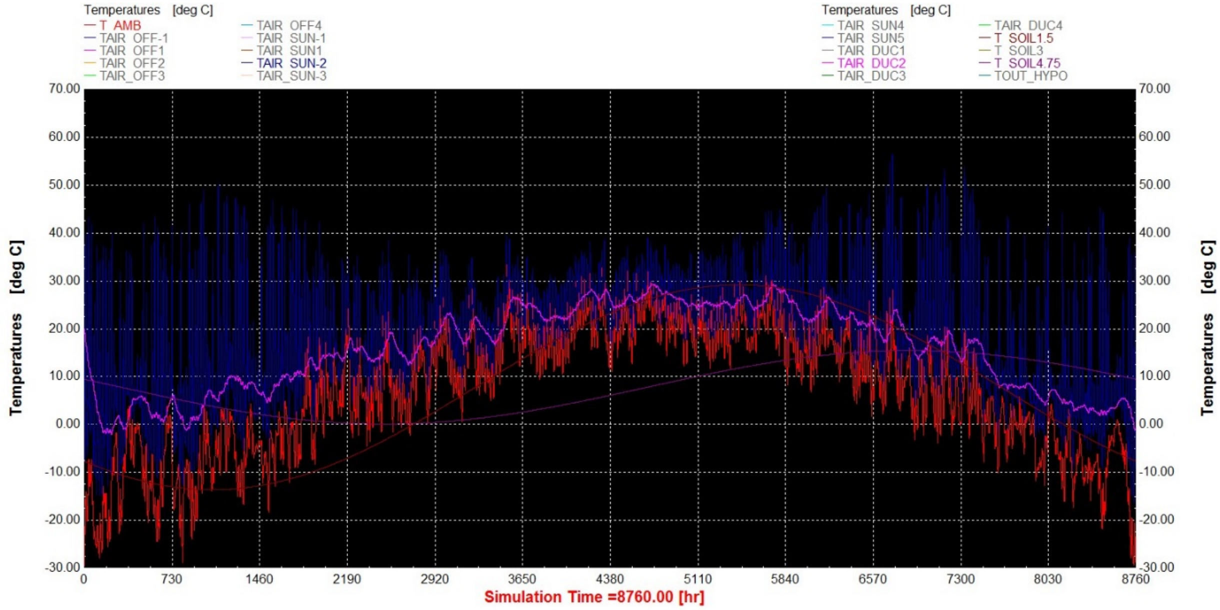
Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run5 C (MC 4-Story DSF1 Full HVAC)



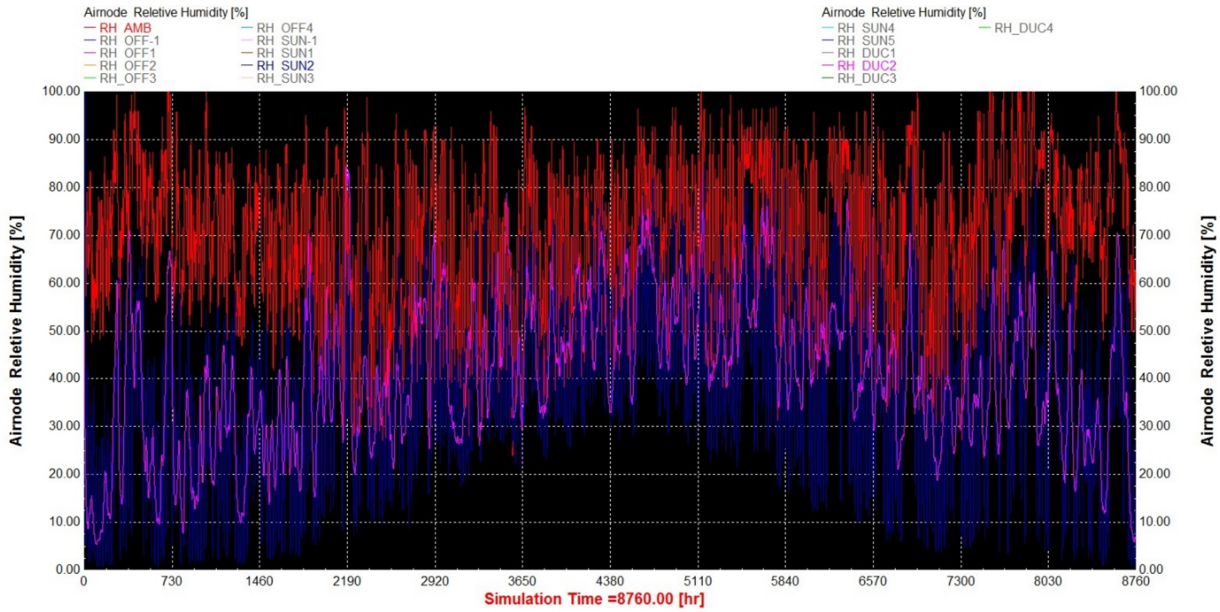
Zones Temperature *(°C)*

Run6 C (MC 4-Story DSF1 Shading Full HVAC)



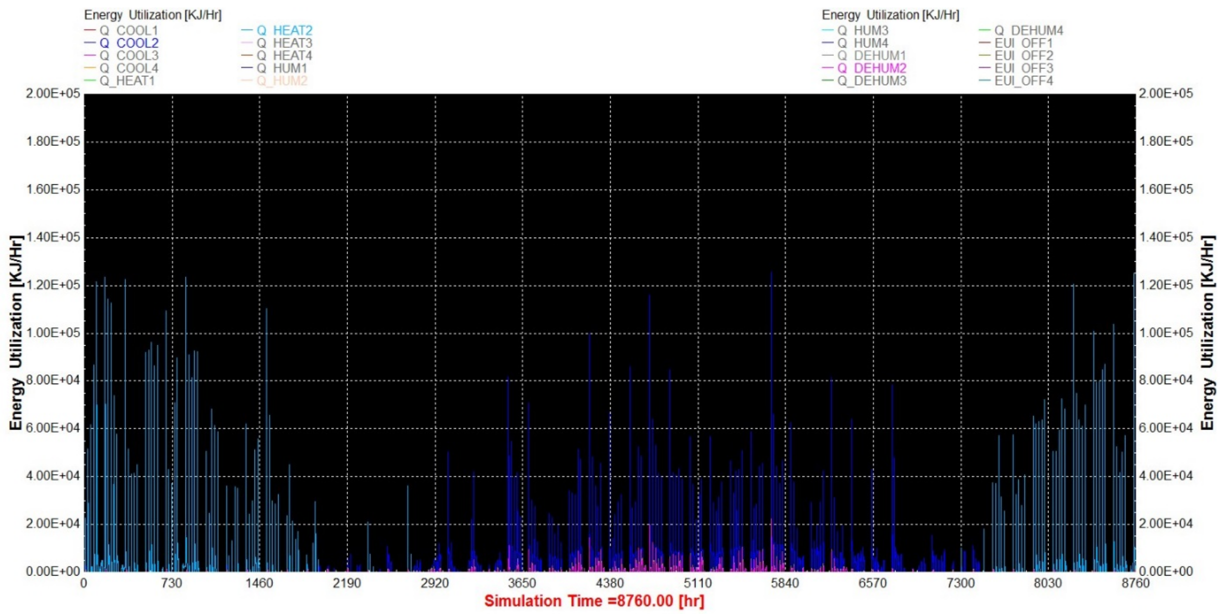
Zones Relative Humidity *(%)*

Run6 C (MC 4-Story DSF1 Shading Full HVAC)



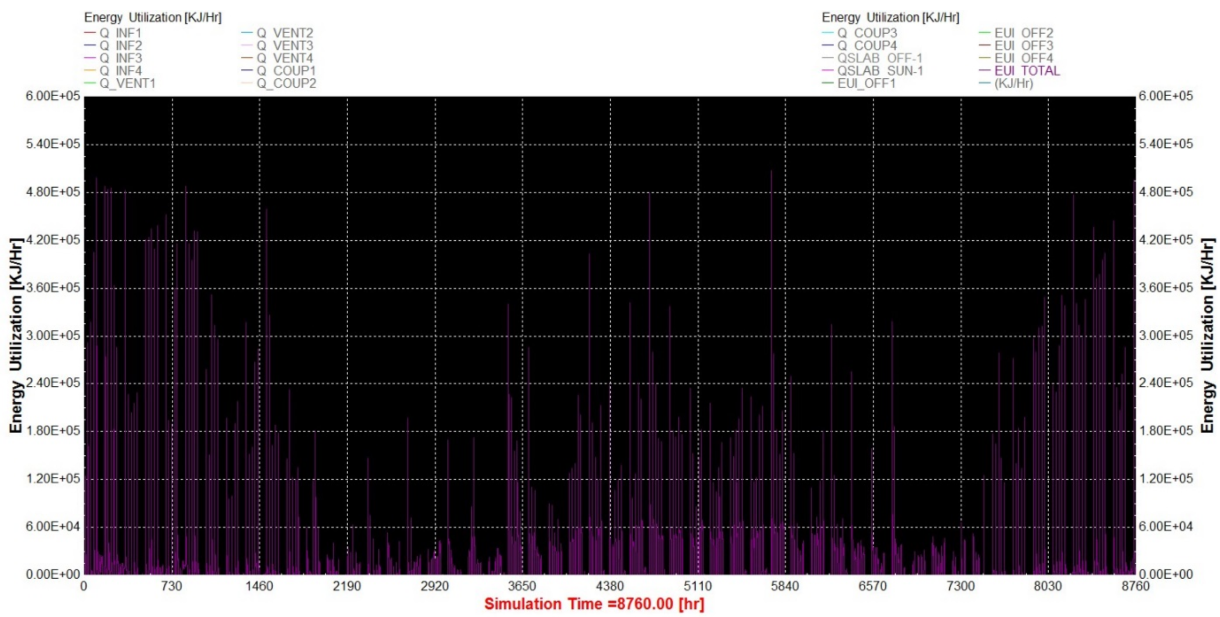
Office Load Intensity *(kJ/hr)*

Run6 C (MC 4-Story DSF1 Shading Full HVAC)



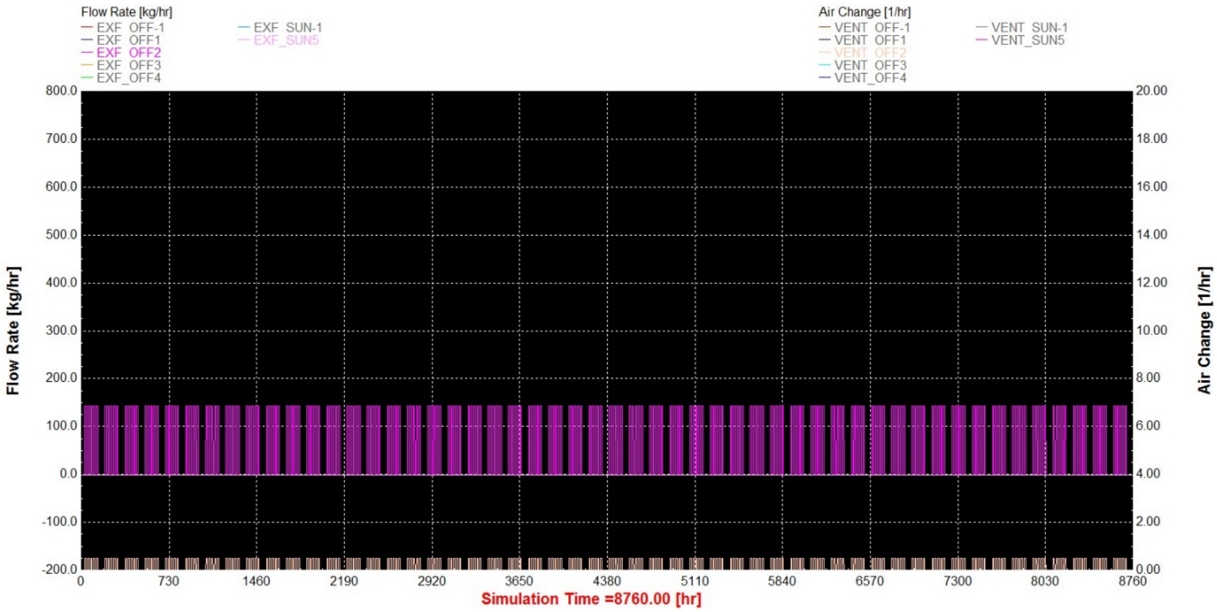
Total Offices Load Intensity *(kJ/hr)*

Run6 C (MC 4-Story DSF1 Shading Full HVAC)



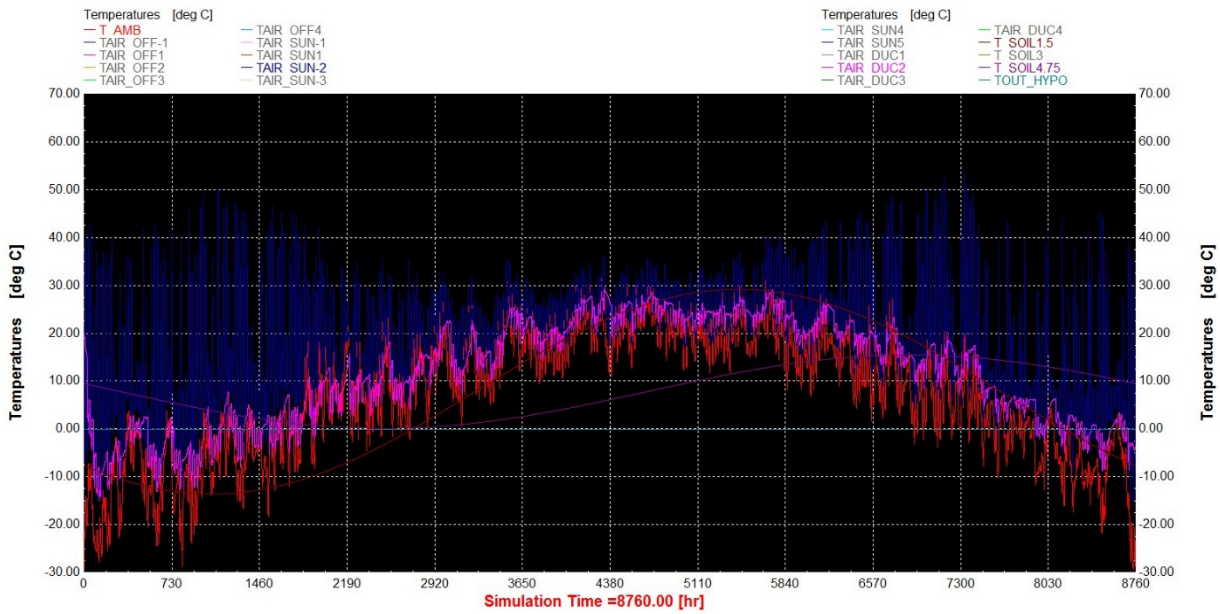
Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run6 C (MC 4-Story DSF1 Shading Full HVAC)



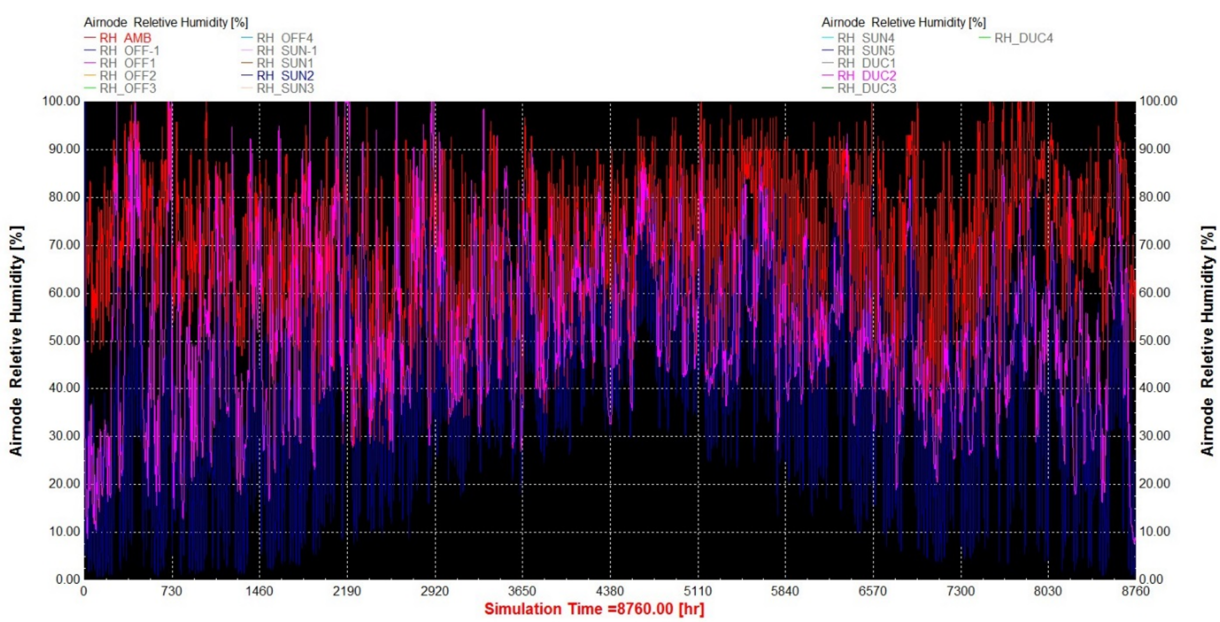
Zones Temperature *(°C)*

Run7 D (MC 4-Story MV DSF1 Full HVAC)



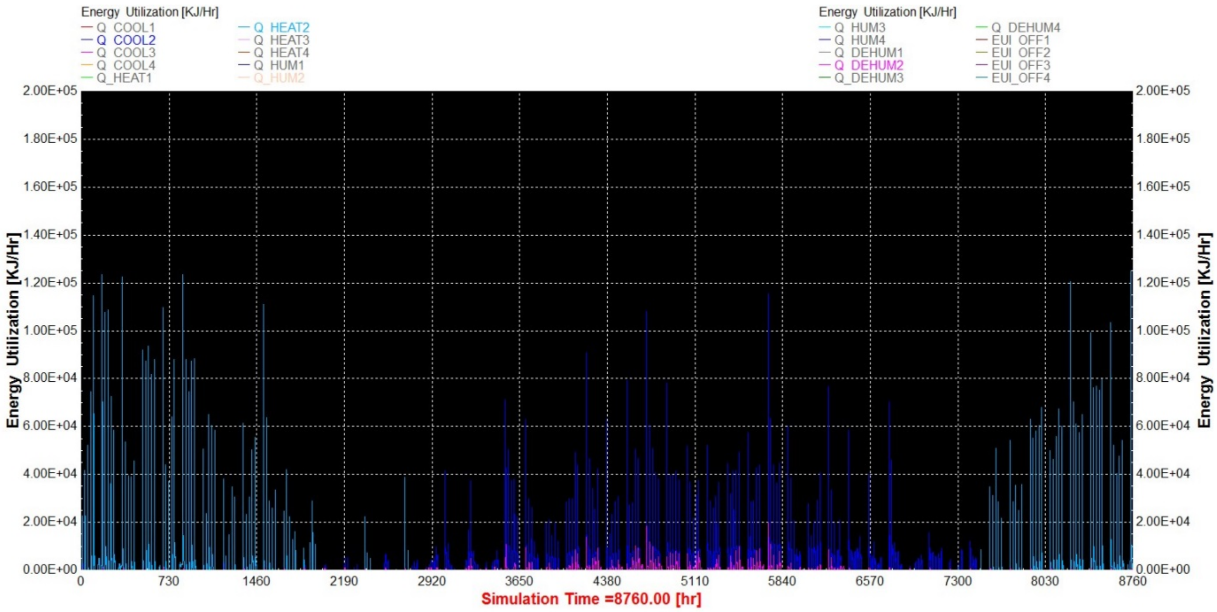
Zones Relative Humidity *(%)*

Run7 D (MC 4-Story MV DSF1 Full HVAC)



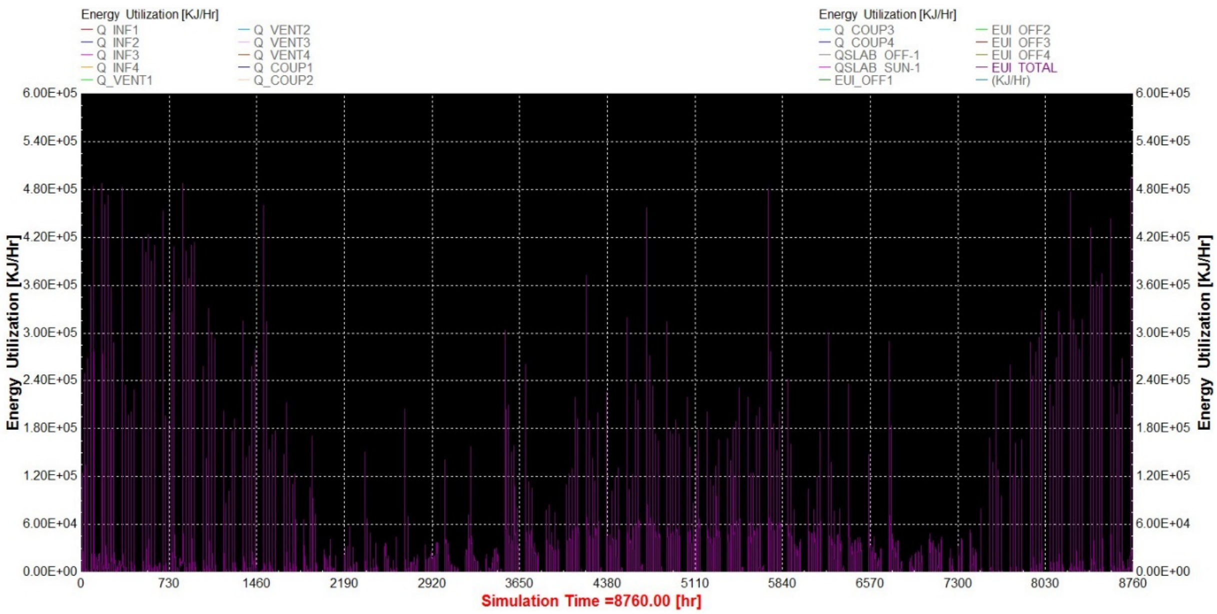
Office Load Intensity *(kJ/hr)*

Run7 D (MC 4-Story MV DSF1 Full HVAC)



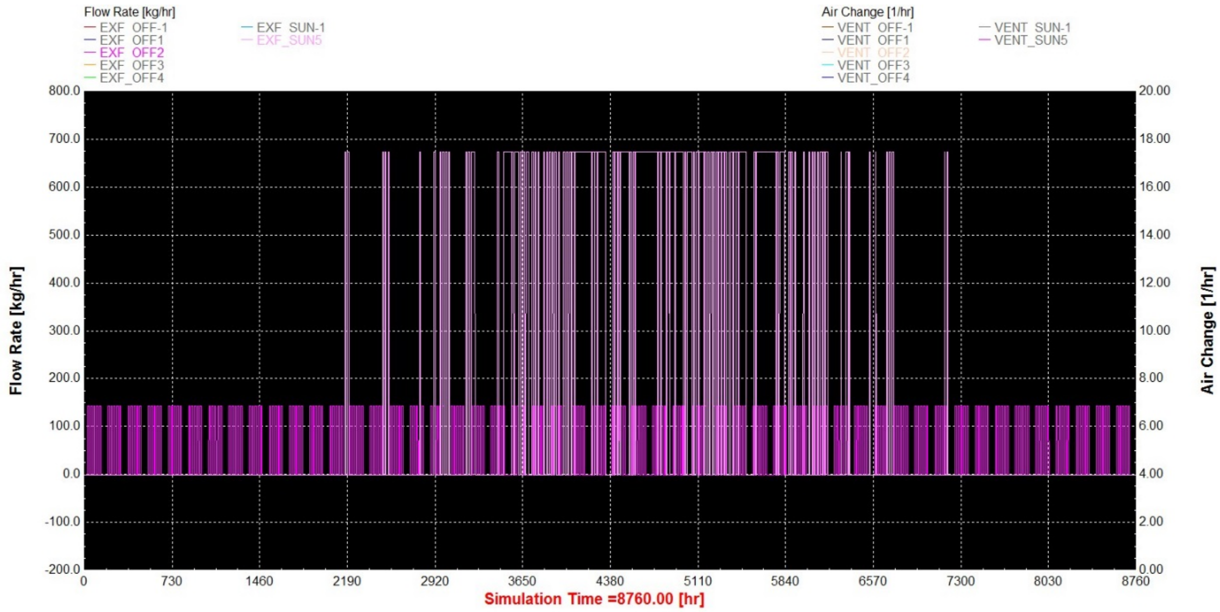
Total Offices Load Intensity *(kJ/hr)*

Run7 D (MC 4-Story MV DSF1 Full HVAC)



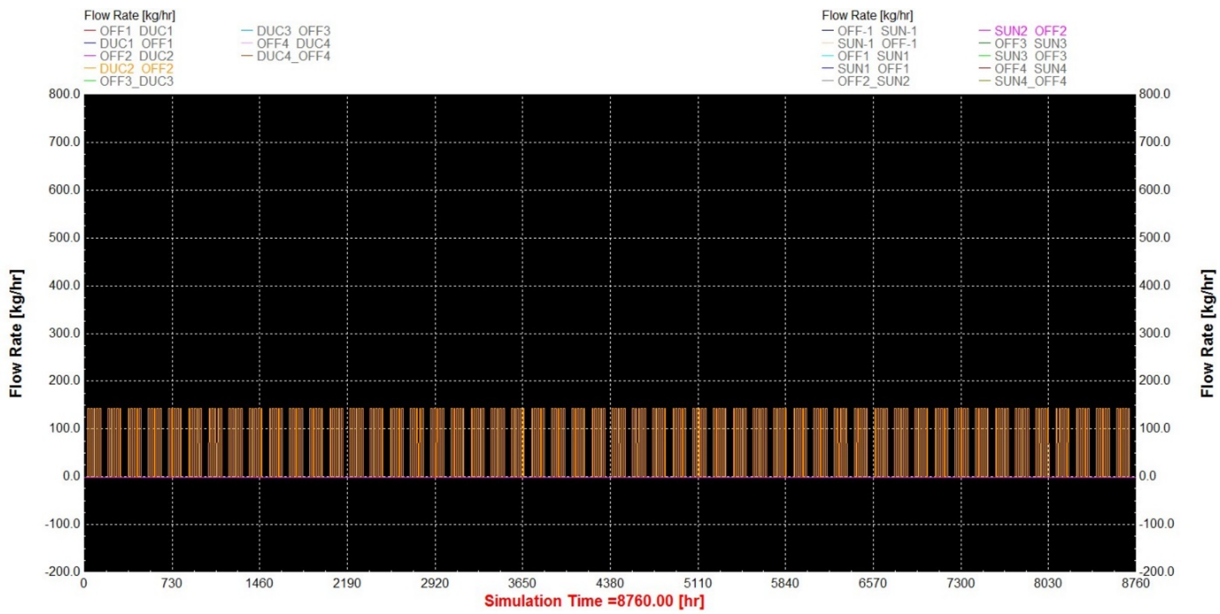
Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run7 D (MC 4-Story MV DSF1 Full HVAC)



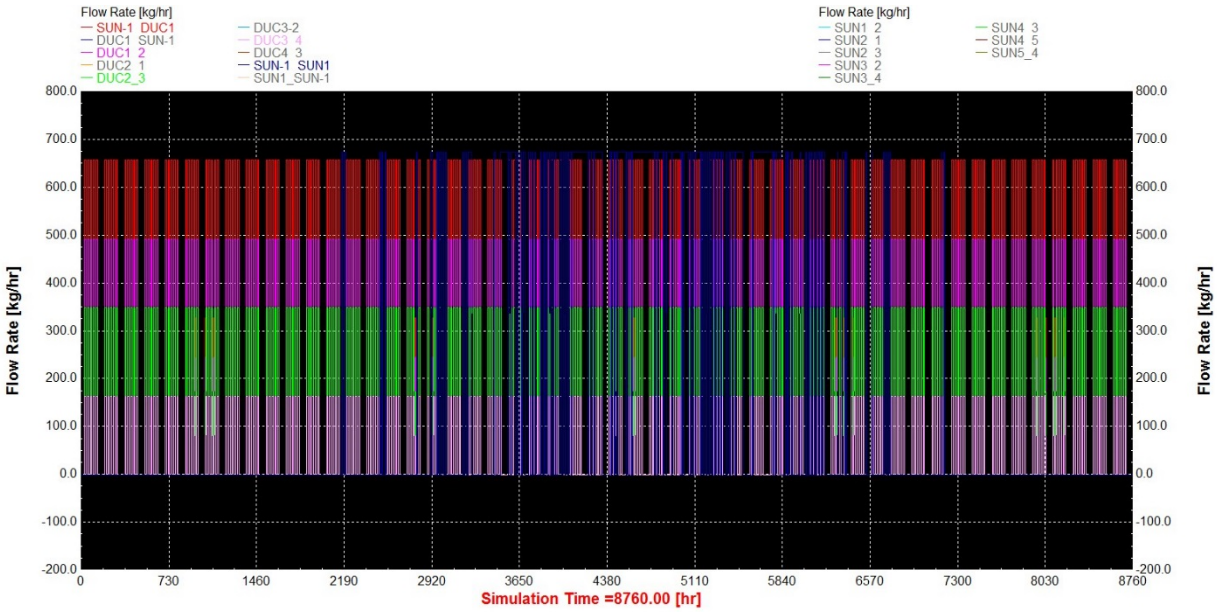
Sunspaces/Ducts-Offices Airflow *(kg/hr or 1/hr)*

Run7 D (MC 4-Story MV DSF1 Full HVAC)



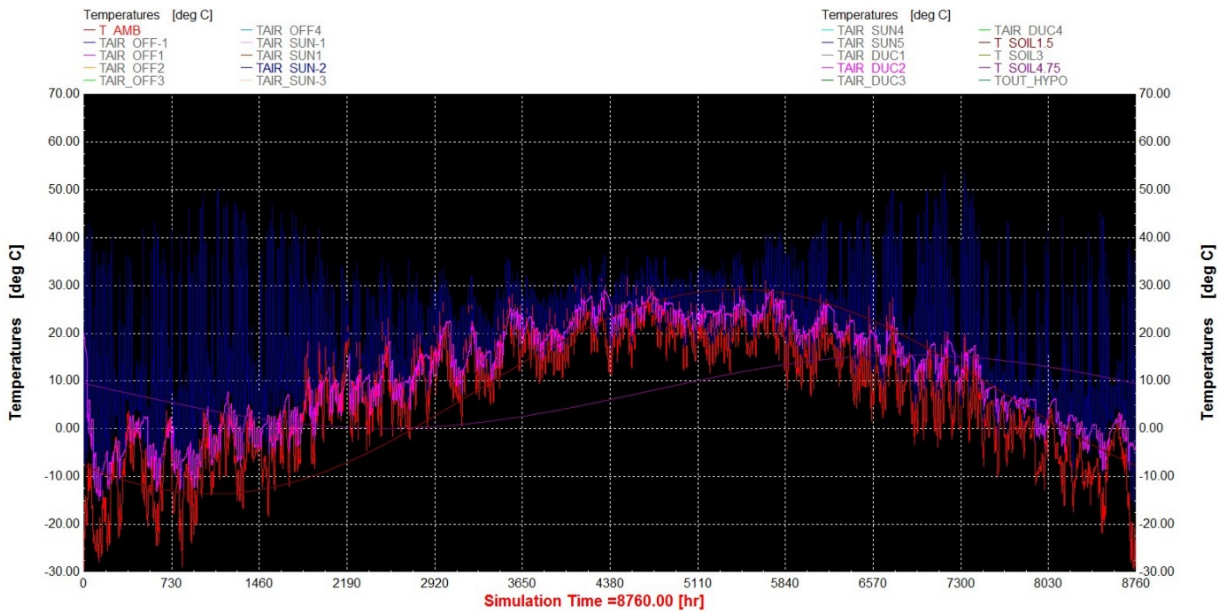
Sunspace/Duct-Sunspace/Duct Airflow *(kg/hr or 1/hr)*

Run7 D (MC 4-Story MV DSF1 Full HVAC)



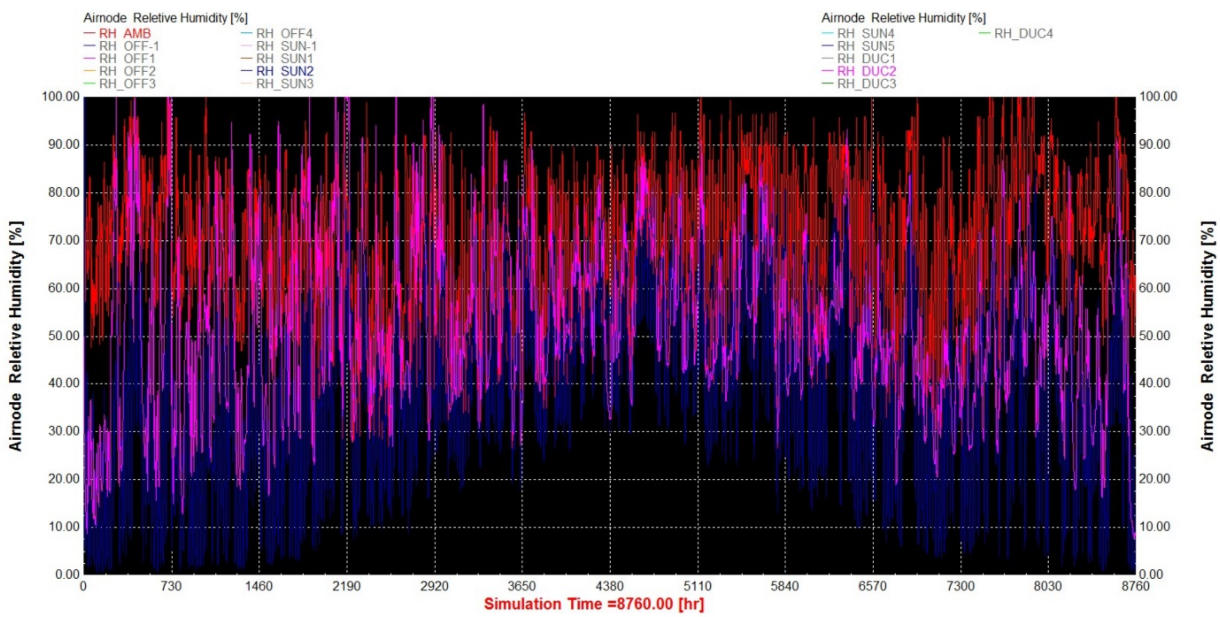
Zones Temperature *(°C)*

Run8 E (MC 4-Story NV DSF1 Full HVAC)



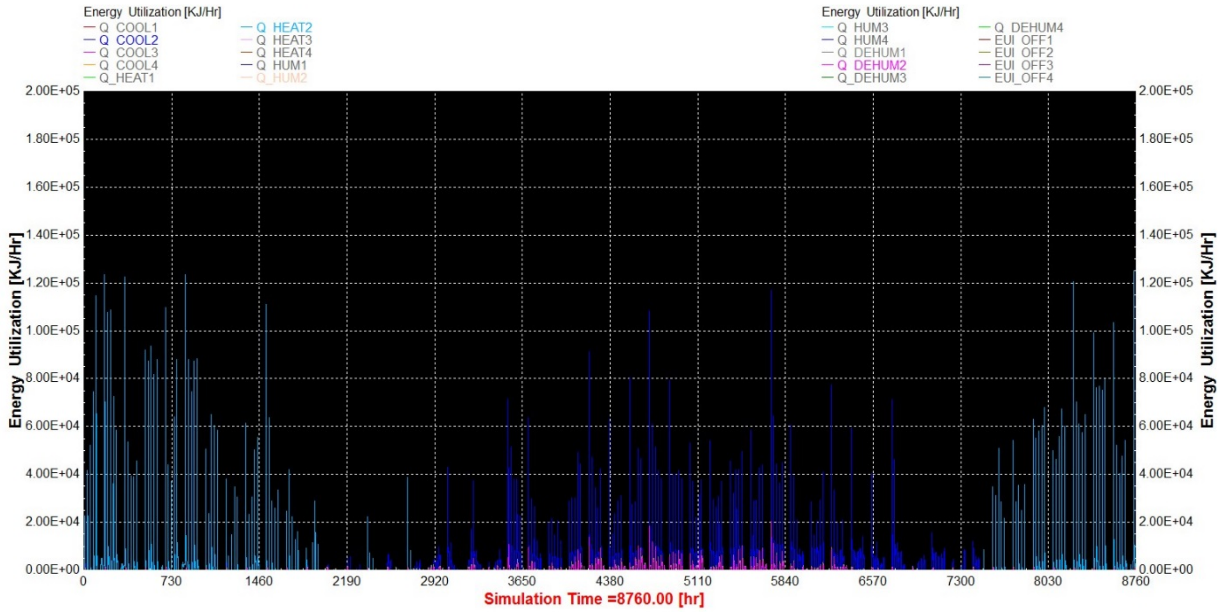
Zones Relative Humidity *(%)*

Run8 E (MC 4-Story NV DSF1 Full HVAC)



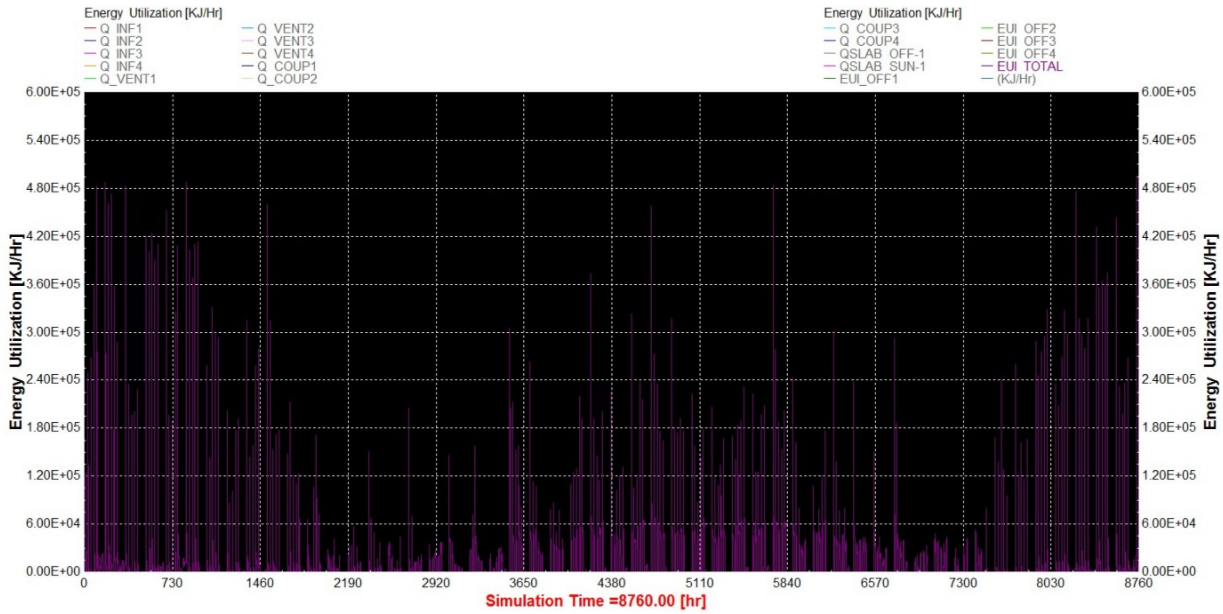
Office Load Intensity *(kJ/hr)*

Run8 E (MC 4-Story NV DSF1 Full HVAC)



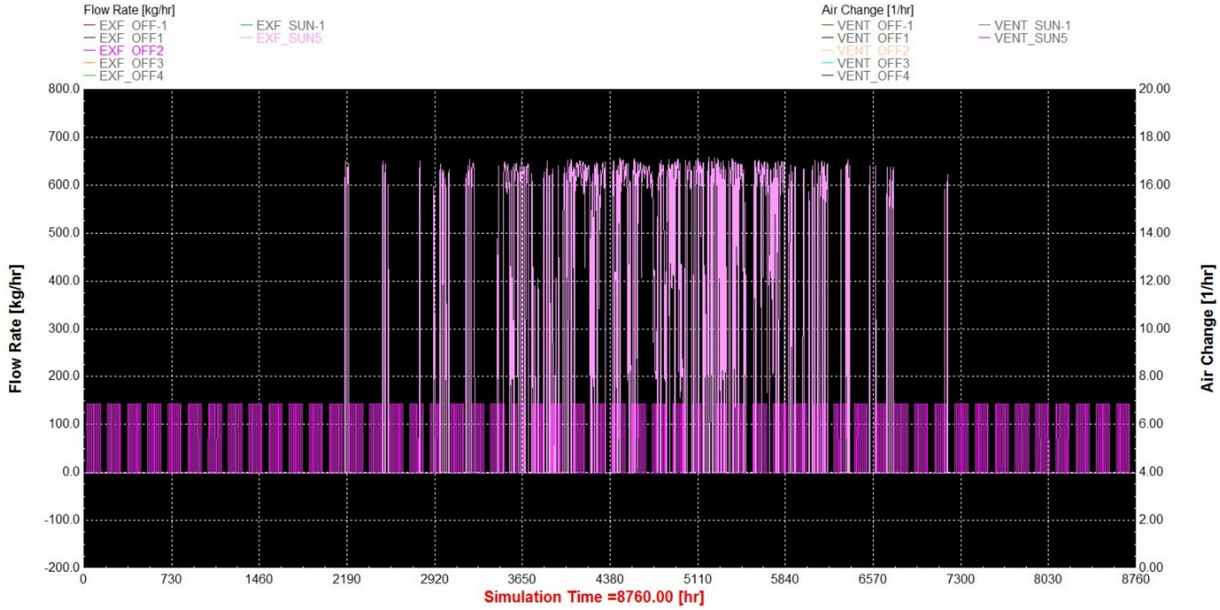
Total Offices Load Intensity *(kJ/hr)*

Run8 E (MC 4-Story NV DSF1 Full HVAC)



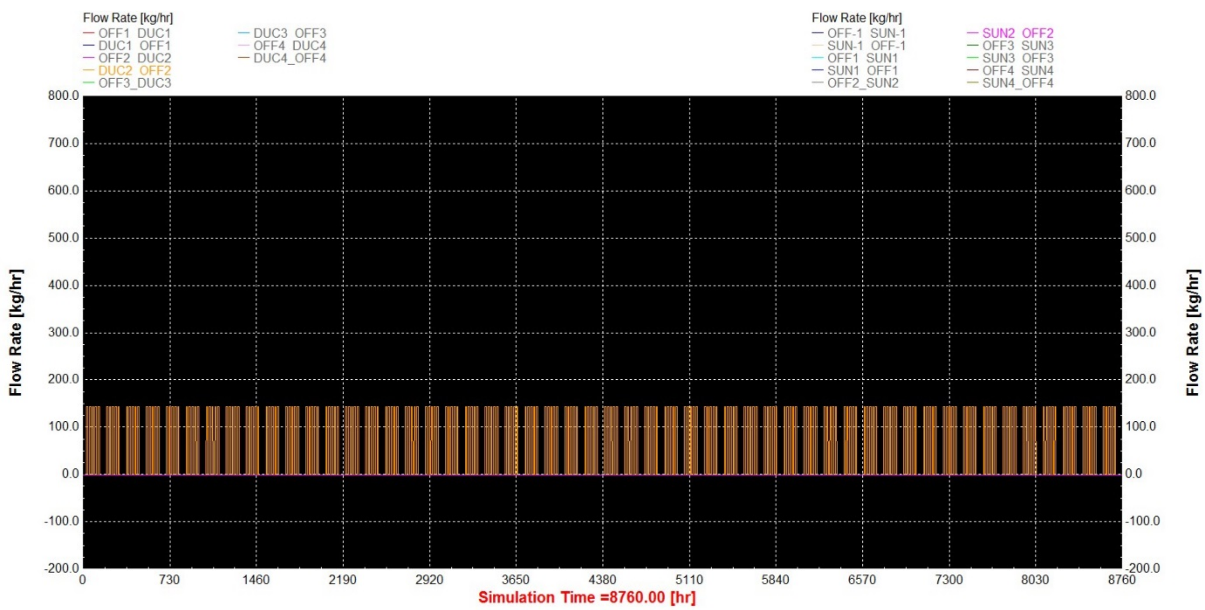
Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run8 E (MC 4-Story NV DSF1 Full HVAC)



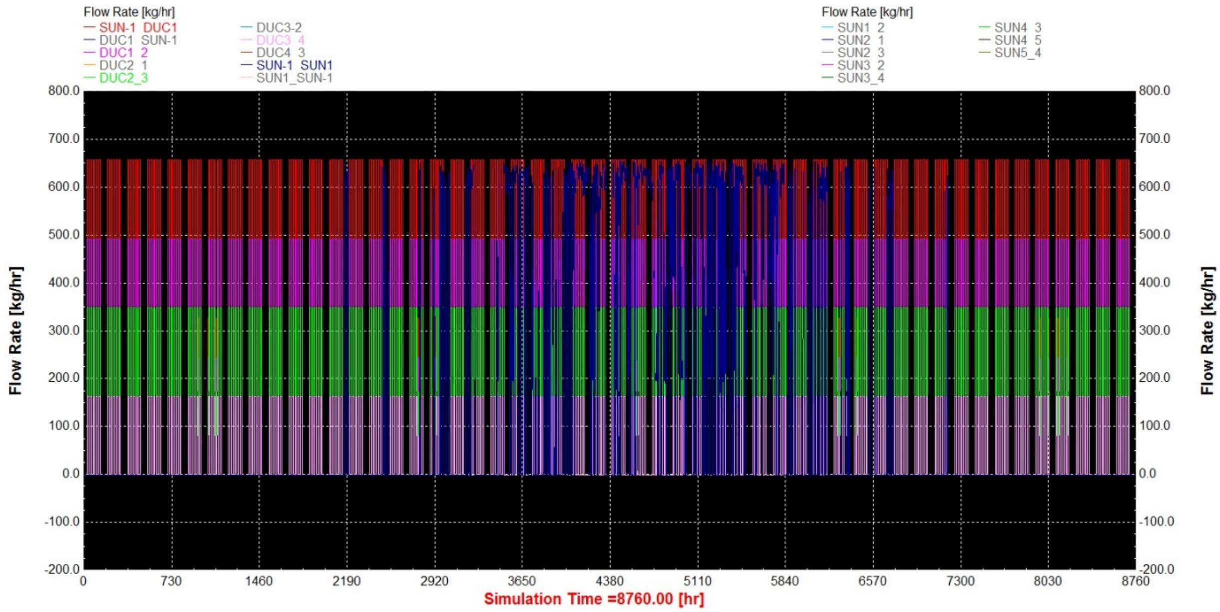
Sunspaces/Ducts-Offices Airflow *(kg/hr or 1/hr)*

Run8 E (MC 4-Story NV DSF1 Full HVAC)



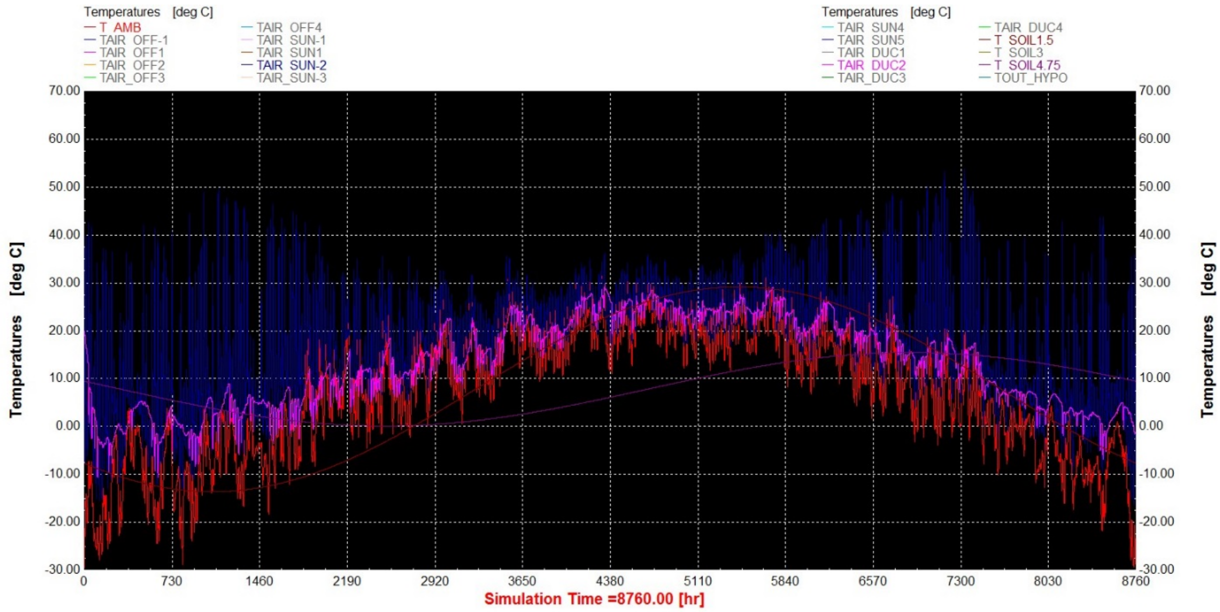
Sunspace/Duct-Sunspace/Duct Airflow *(kg/hr or 1/hr)*

Run8 E (MC 4-Story NV DSF1 Full HVAC)



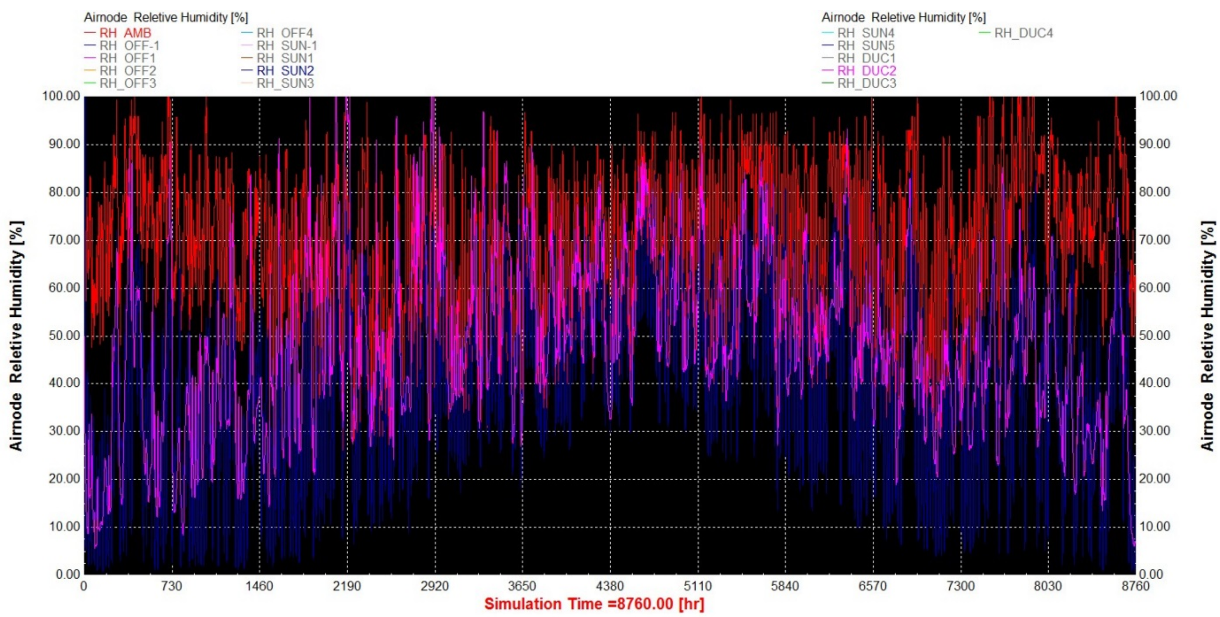
Zones Temperature *(°C)*

Run9 F (MV 4-Story MV DSF1 Semi HVAC)



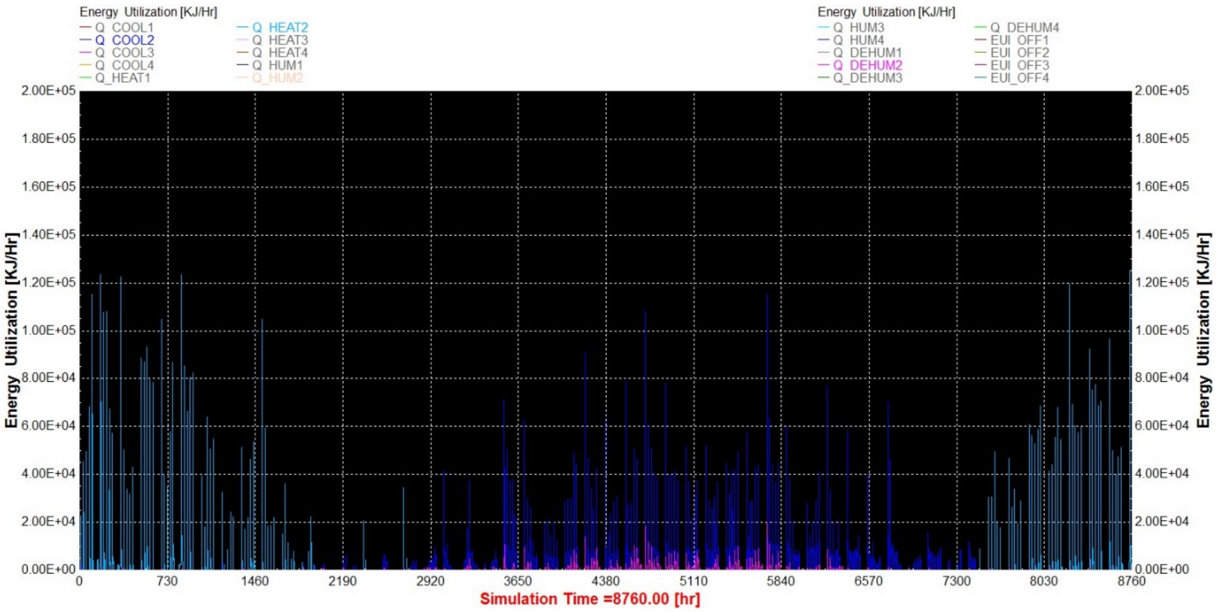
Zones Relative Humidity *(%)*

Run9 E (MV 4-Story MV DSF1 Semi HVAC)



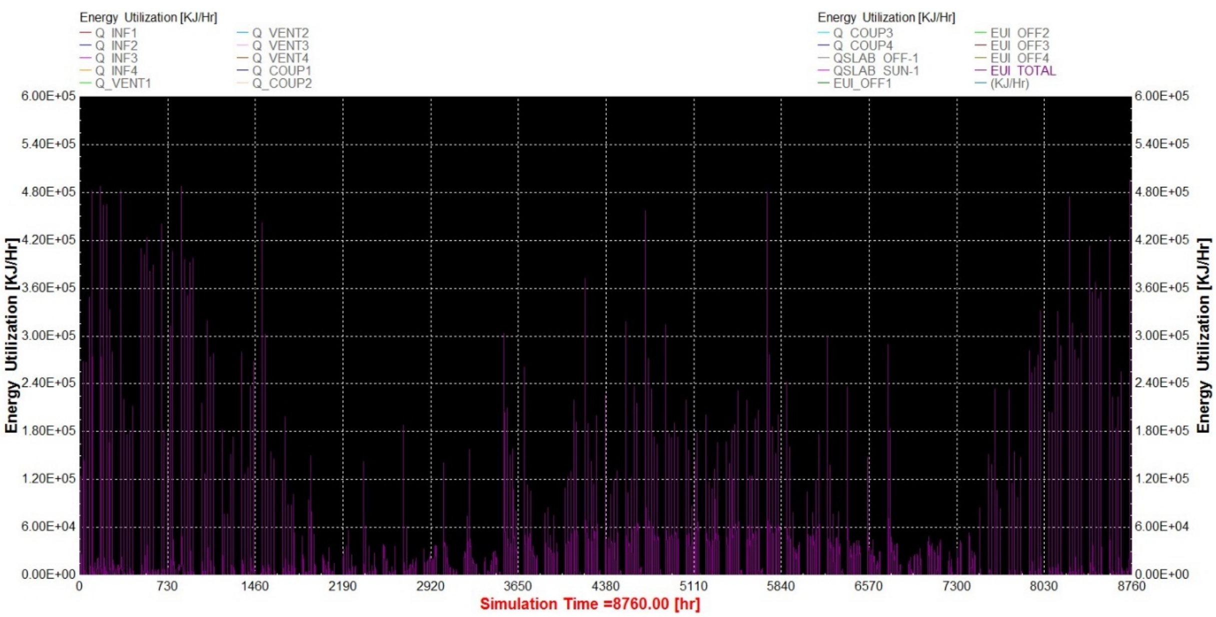
Office Load Intensity *(kJ/hr)*

Run9 F (MV 4-Story MV DSF1 Semi HVAC)



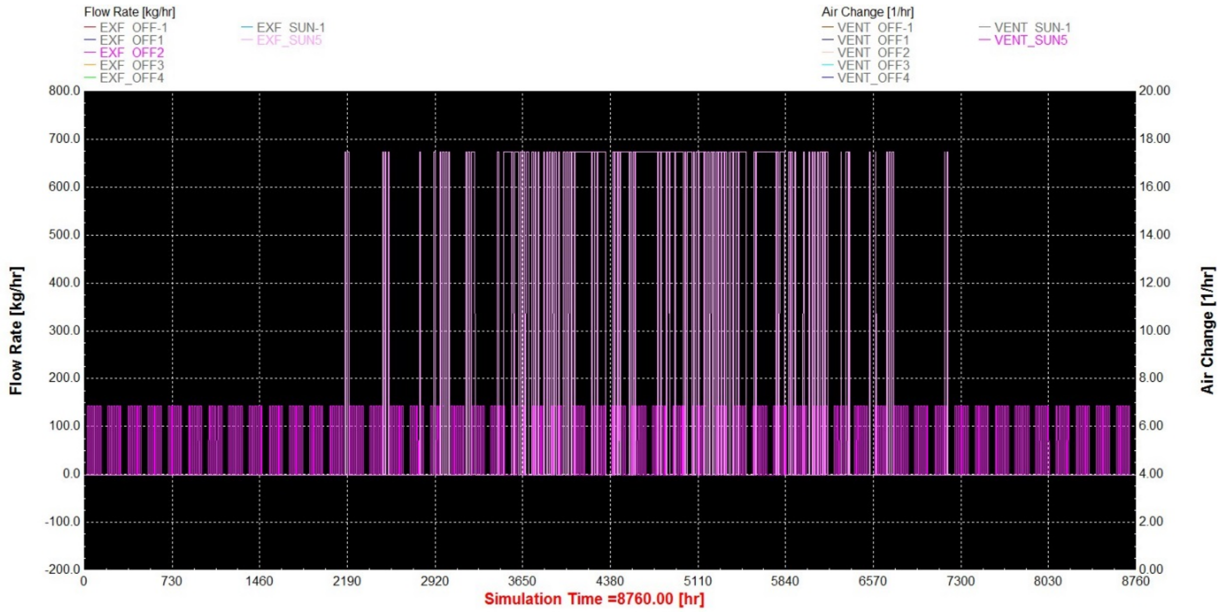
Total Offices Load Intensity *(kJ/hr)*

Run9 F (MV 4-Story MV DSF1 Semi HVAC)



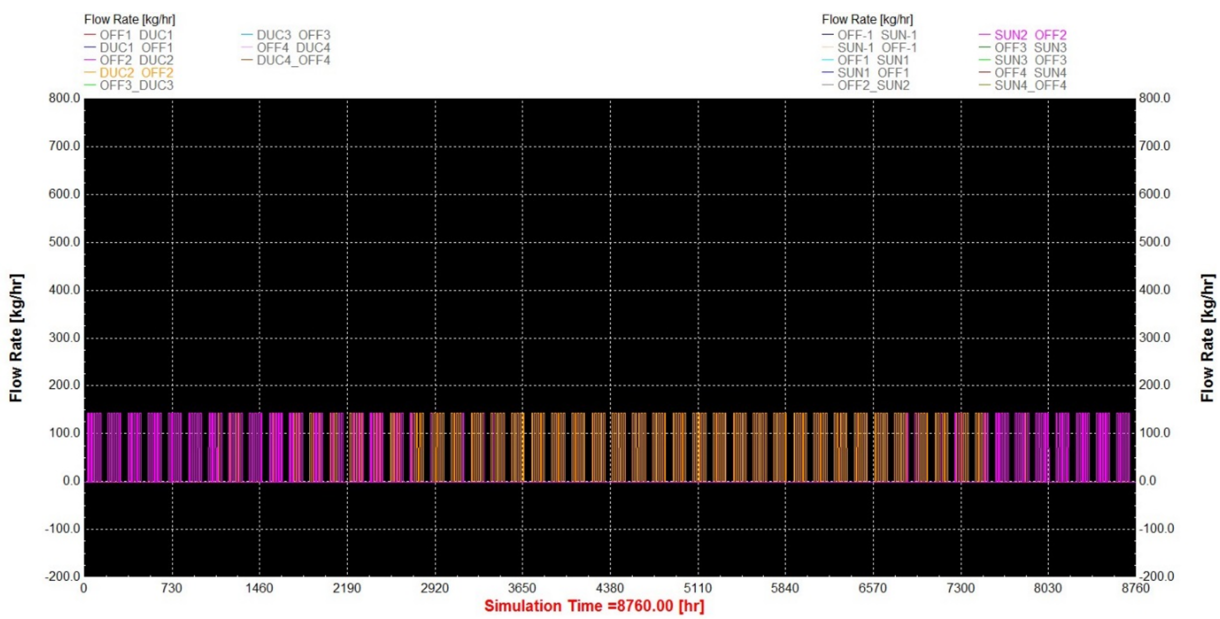
Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run9 F (MV 4-Story MV DSF1 Semi HVAC)



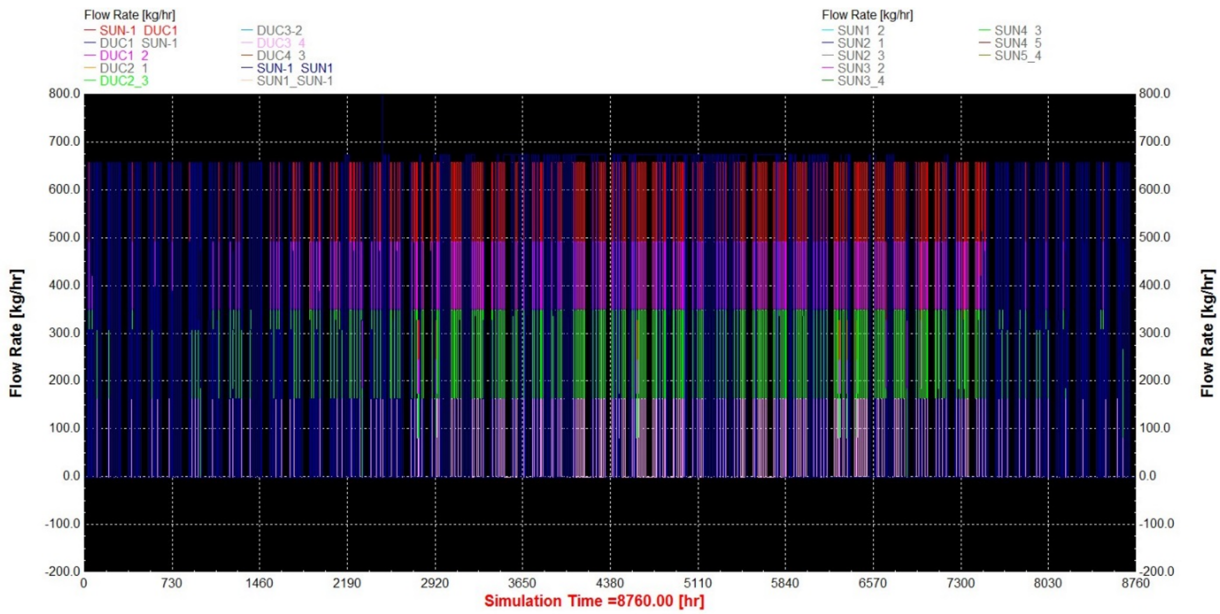
Sunspaces/Ducts-Offices Airflow *(kg/hr or 1/hr)*

Run9 F (MV 4-Story MV DSF1 Semi HVAC)



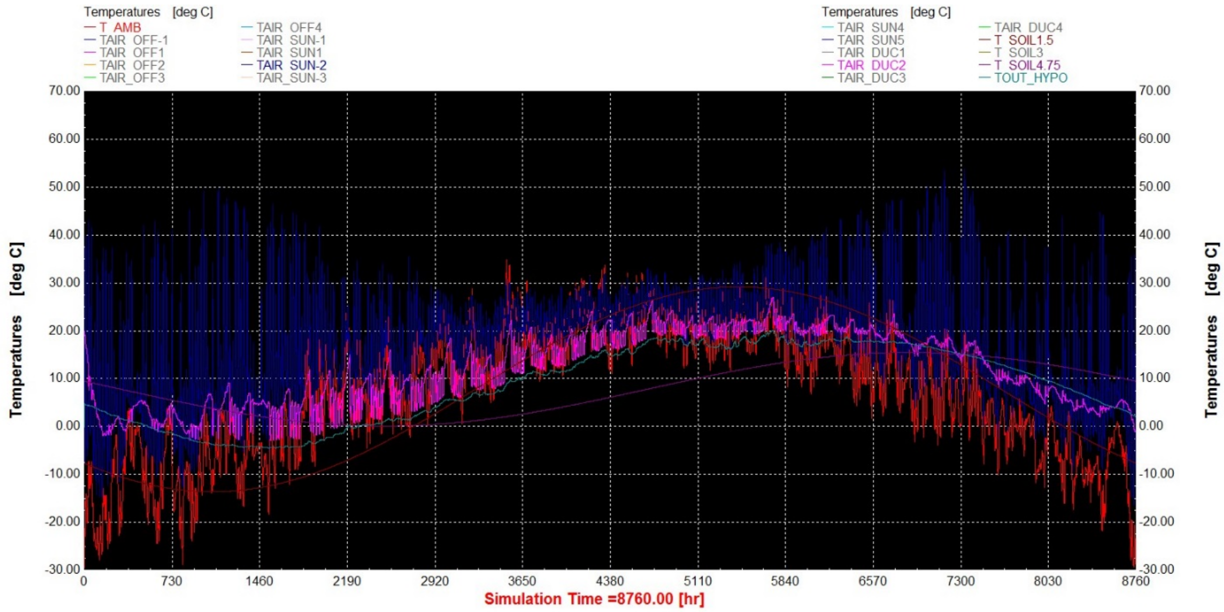
Sunspace/Duct-Sunspace/Duct Airflow *(kg/hr or 1/hr)*

Run9 F (MV 4-Story MV DSF1 Semi HVAC)



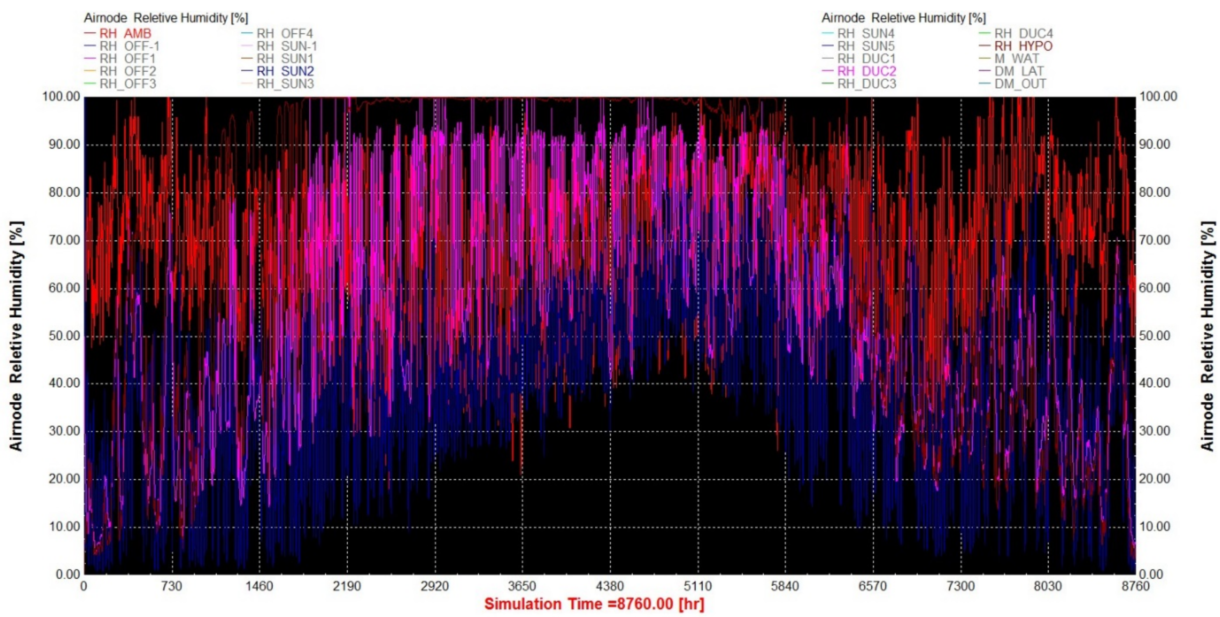
Zones Temperature *(°C)*

Run10 F (MV 4-Story MV DSF1 Semi HVAC Hypo)



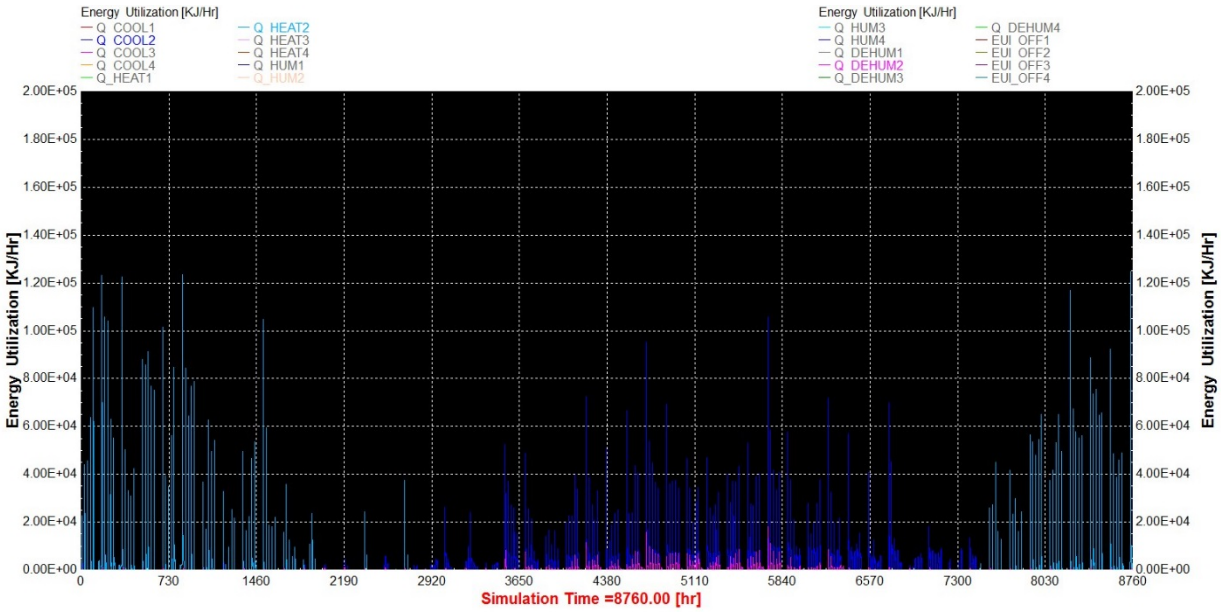
Zones Relative Humidity *(%)*

Run10 F (MV 4-Story MV DSF1 Semi HVAC Hypo)



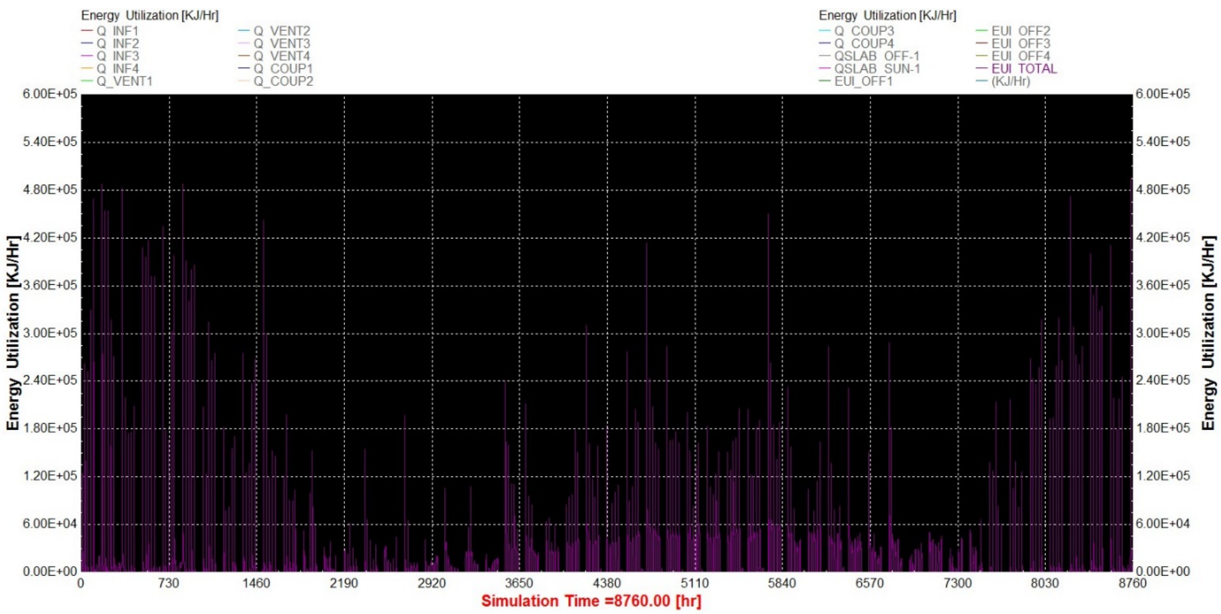
Office Load Intensity *(kJ/hr)*

Run10 F (MV 4-Story MV DSF1 Semi HVAC Hypo)



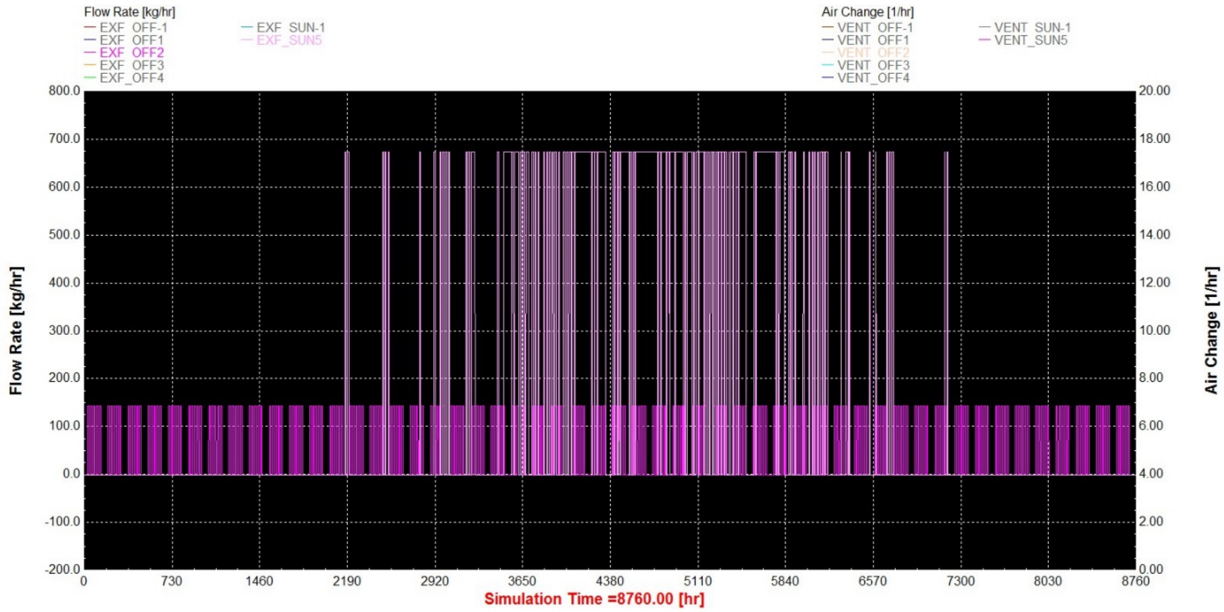
Total Offices Load Intensity *(kJ/hr)*

Run10 F (MV 4-Story MV DSF1 Semi HVAC Hypo)



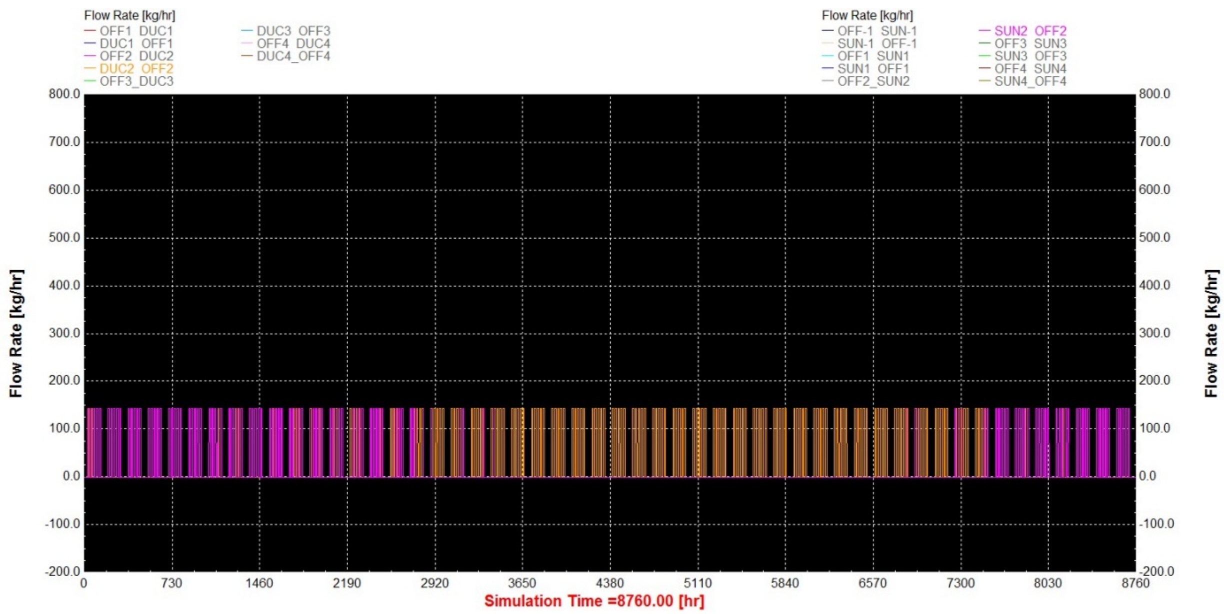
Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run10 F (MV 4-Story MV DSF1 Semi HVAC Hypo)



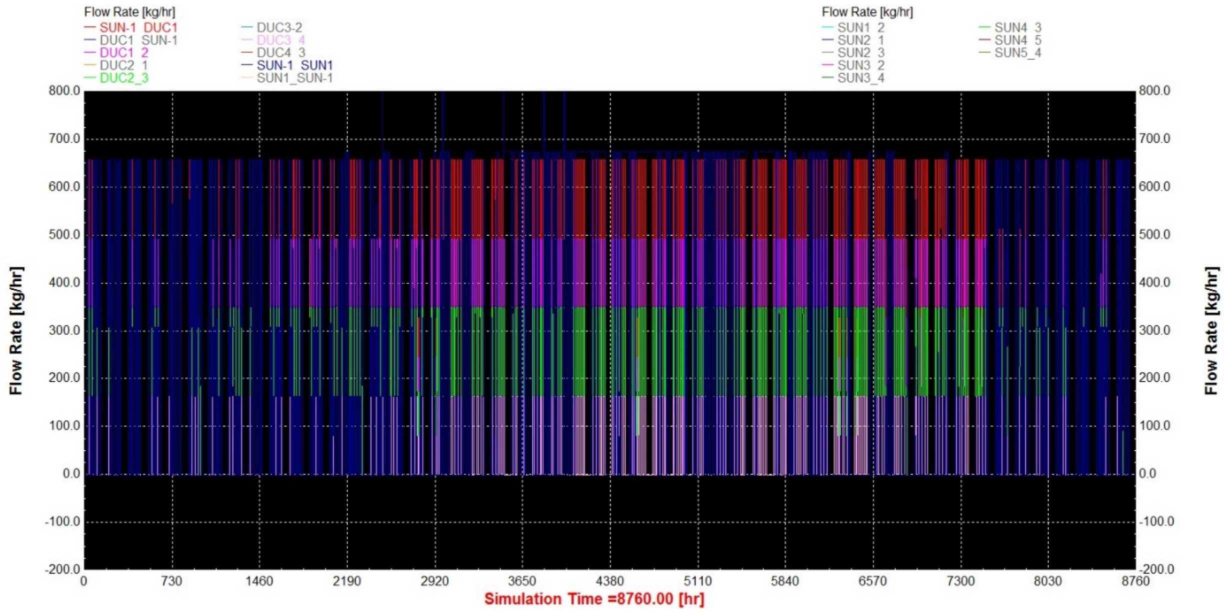
Sunspaces/Ducts-Offices Airflow *(kg/hr or 1/hr)*

Run10 F (MV 4-Story MV DSF1 Semi HVAC Hypo)



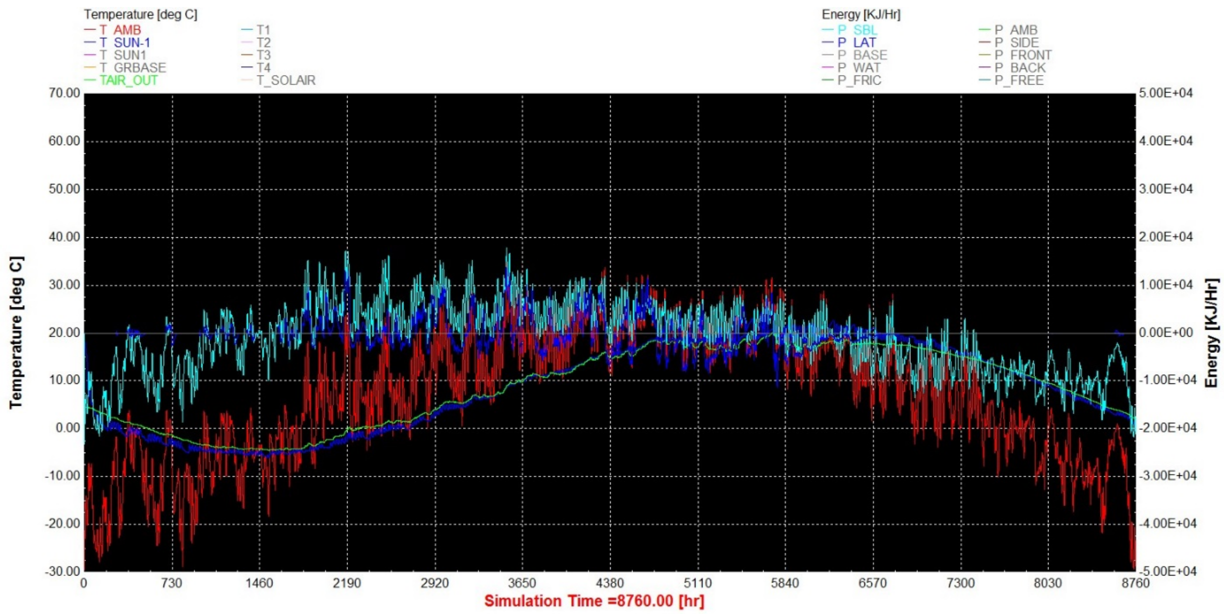
Sunspace/Duct-Sunspace/Duct Airflow *(kg/hr or 1/hr)*

Run10 F (MV 4-Story MV DSF1 Semi HVAC Hypo)



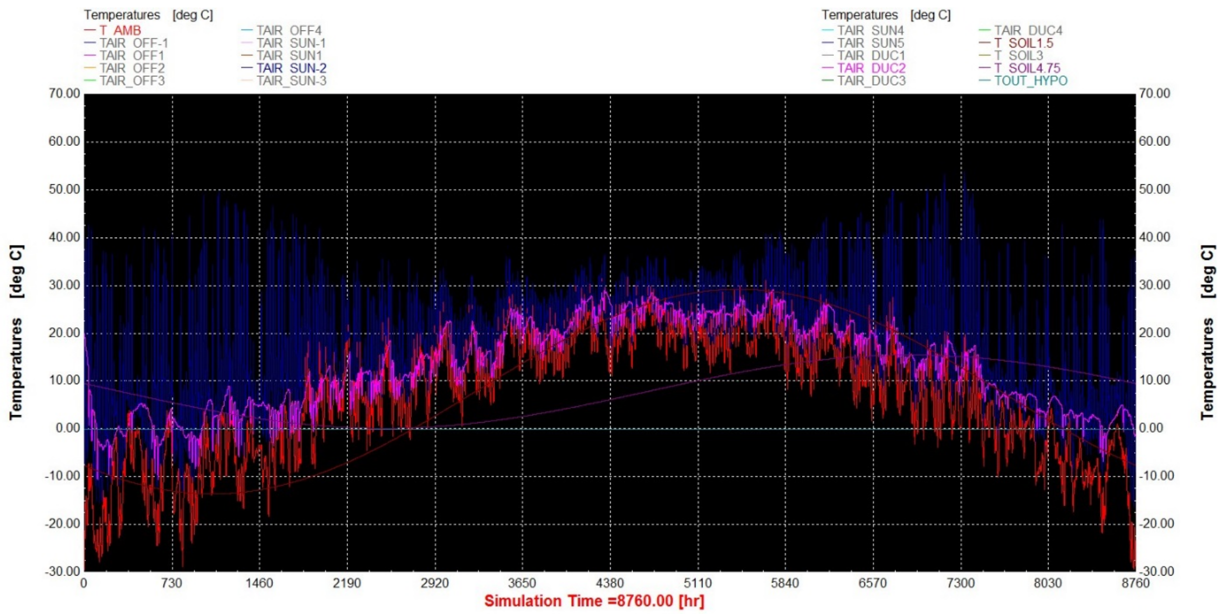
Air-Tubes Temperature and Energy *(°C and kJ/hr)*

Run10 F (MV 4-Story MV DSF1 Semi HVAC Hypo)



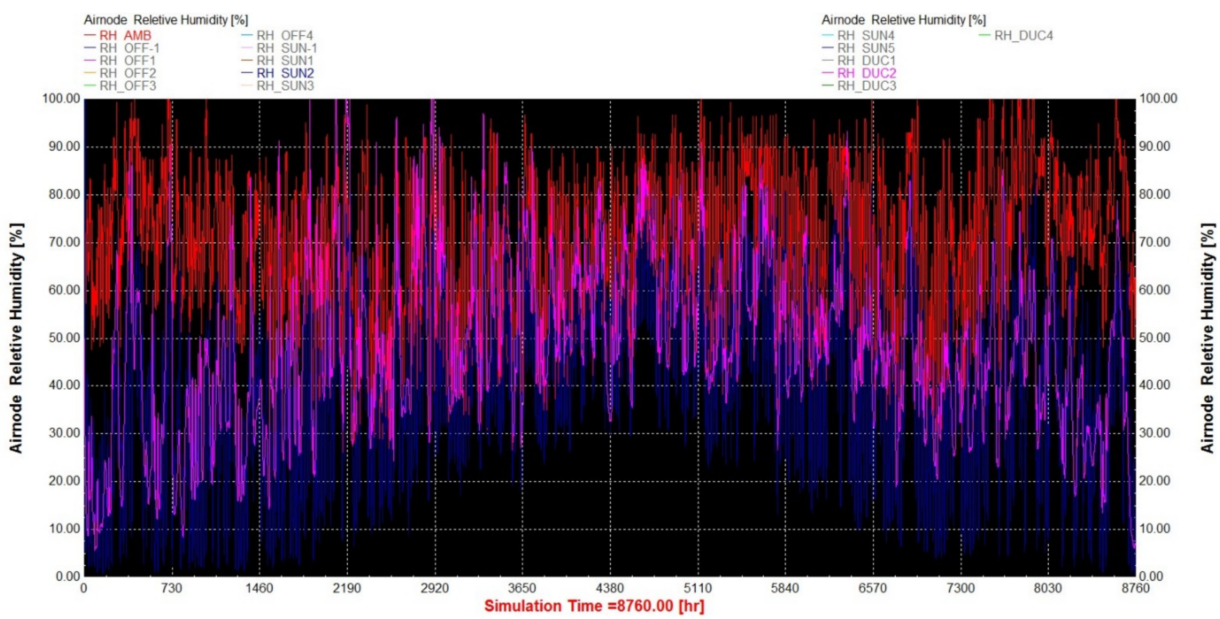
Zones Temperature *(°C)*

Run11 G (MV 4-Story NV DSF1 Semi HVAC)



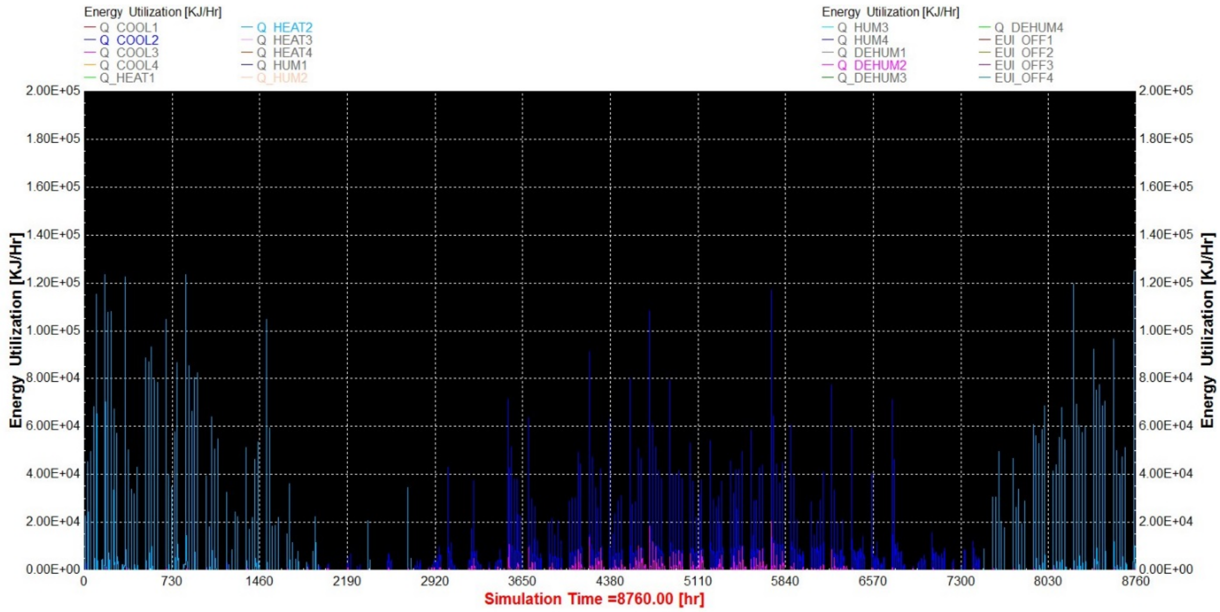
Zones Relative Humidity *(%)*

Run11 G (MV 4-Story NV DSF1 Semi HVAC)



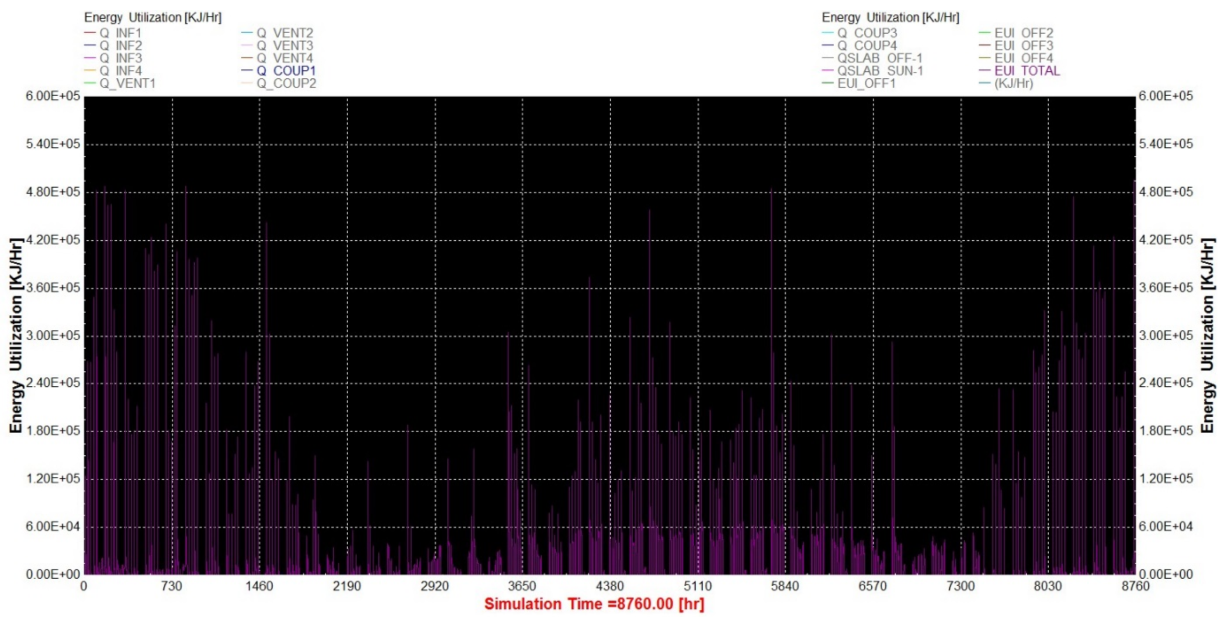
Office Load Intensity *(kJ/hr)*

Run11 G (MV 4-Story NV DSF1 Semi HVAC)



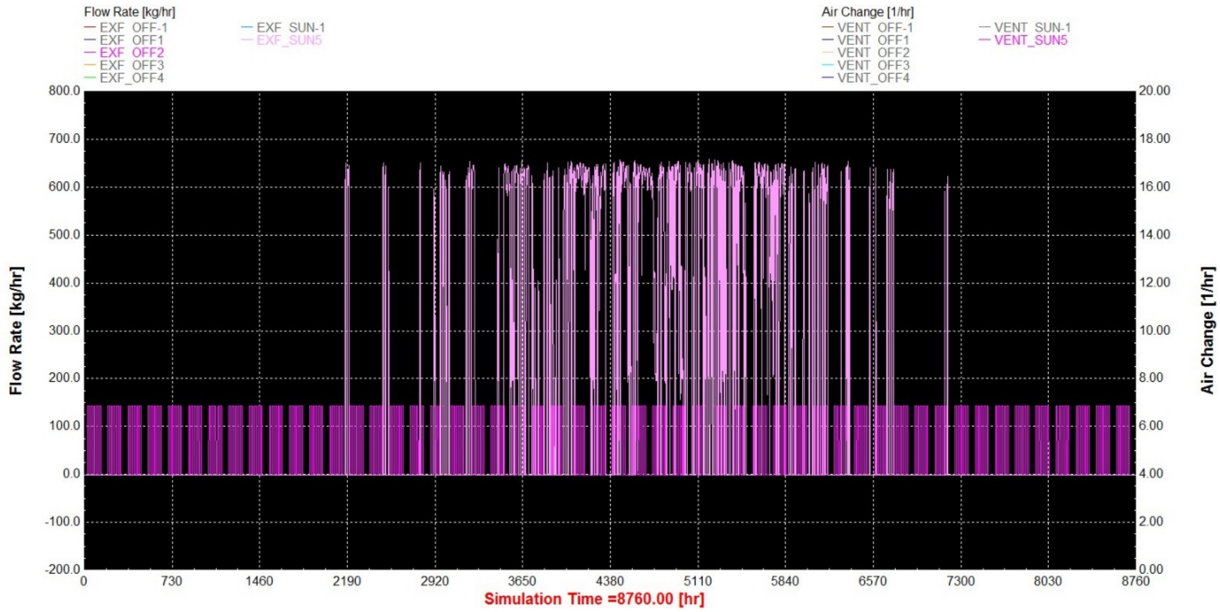
Total Offices Load Intensity *(kJ/hr)*

Run11 G (MV 4-Story NV DSF1 Semi HVAC)



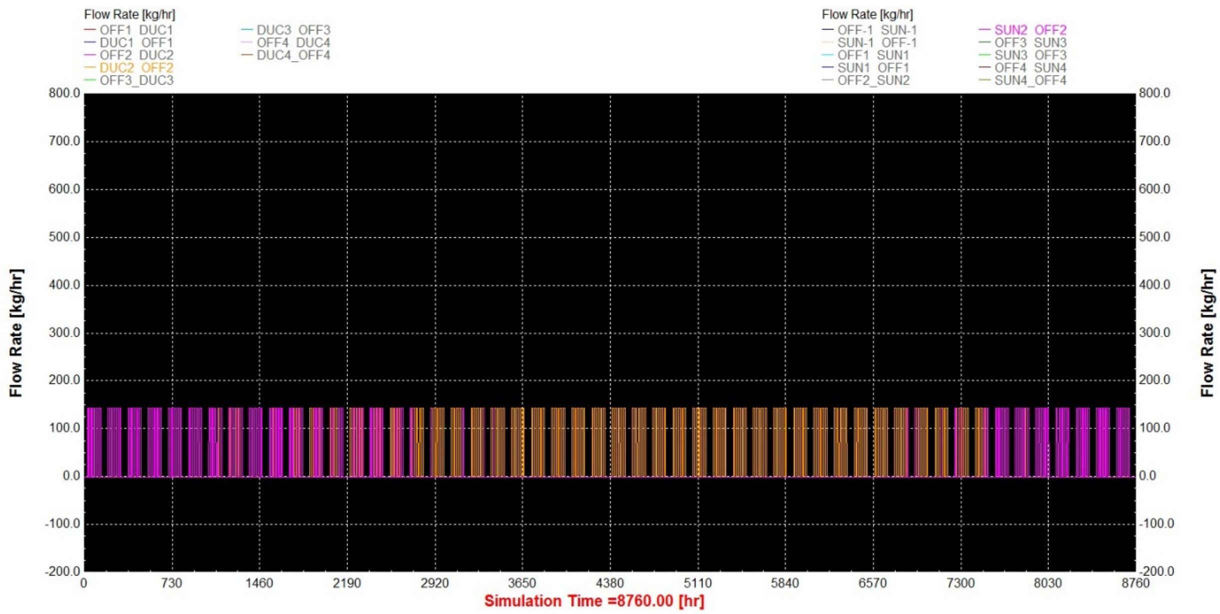
Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run11 G (MV 4-Story NV DSF1 Semi HVAC)



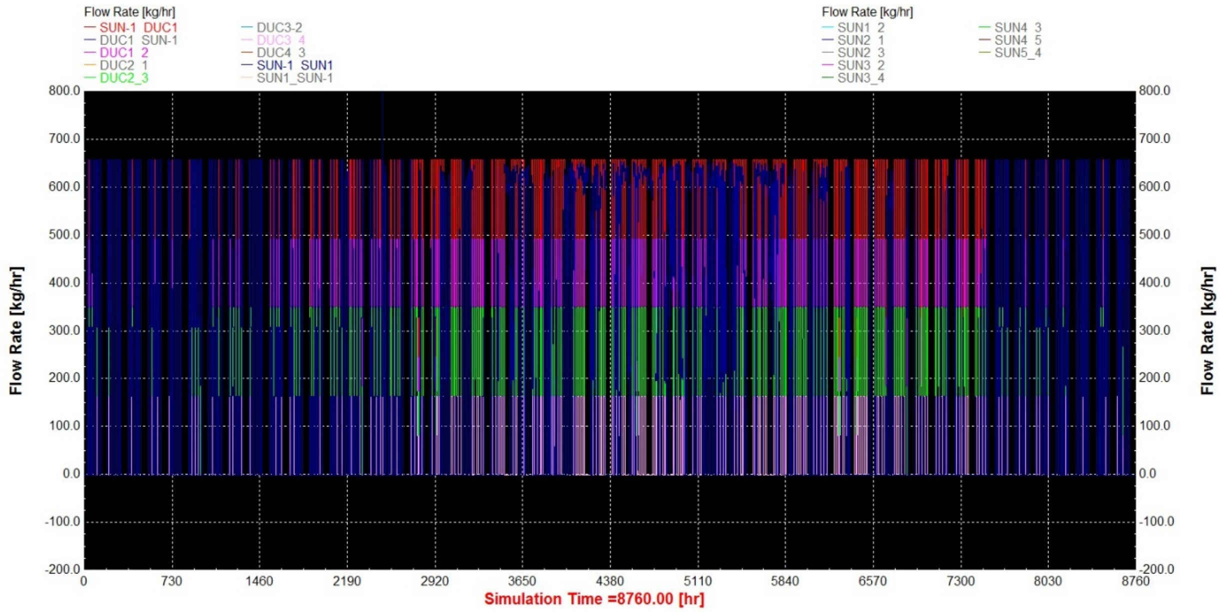
Sunspaces/Ducts-Offices Airflow *(kg/hr or 1/hr)*

Run11 G (MV 4-Story NV DSF1 Semi HVAC)



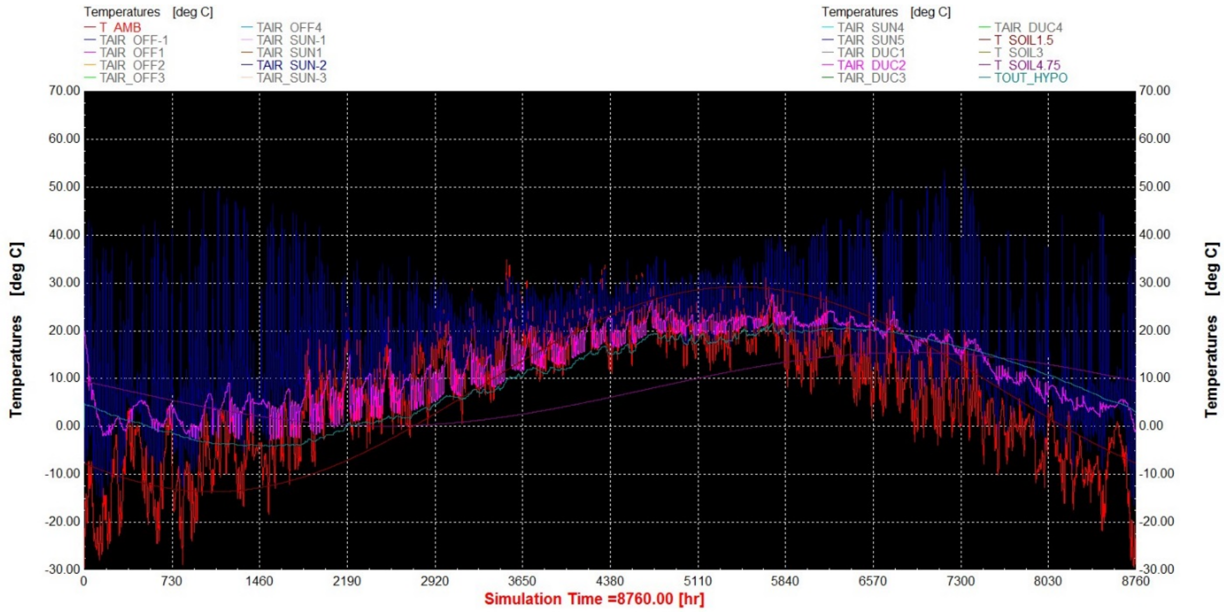
Sunspace/Duct-Sunspace/Duct Airflow *(kg/hr or 1/hr)*

Run11 G (MV 4-Story NV DSF1 Semi HVAC)



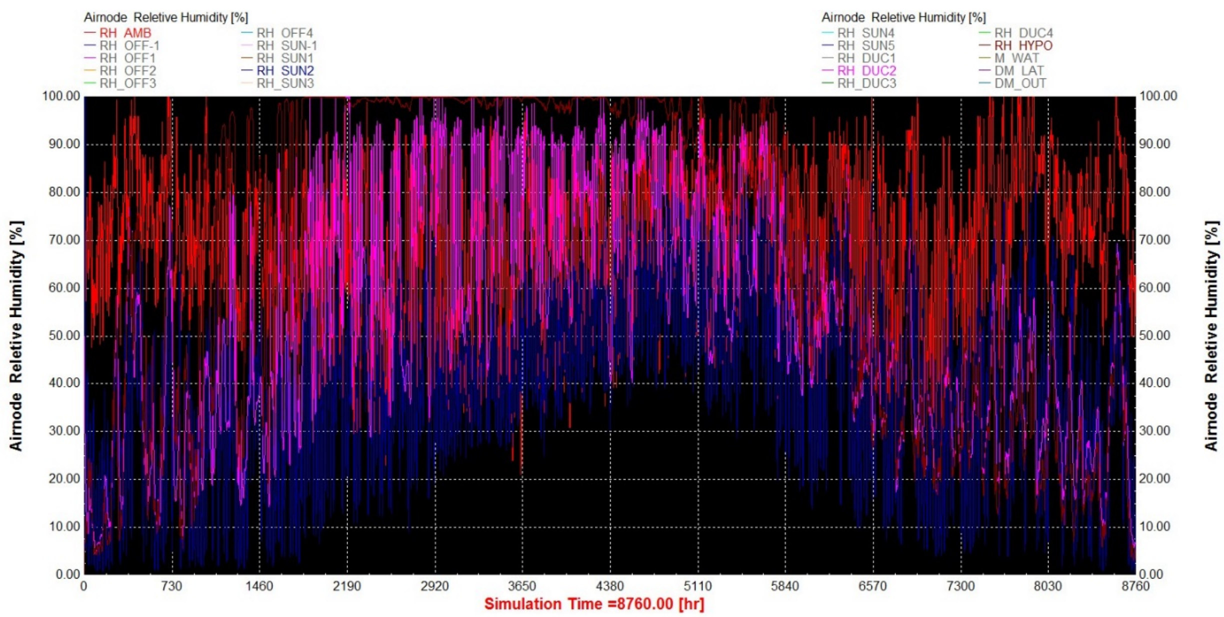
Zones Temperature *(°C)*

Run12 G (MV 4-Story NV DSF1 Semi HVAC Hypo)



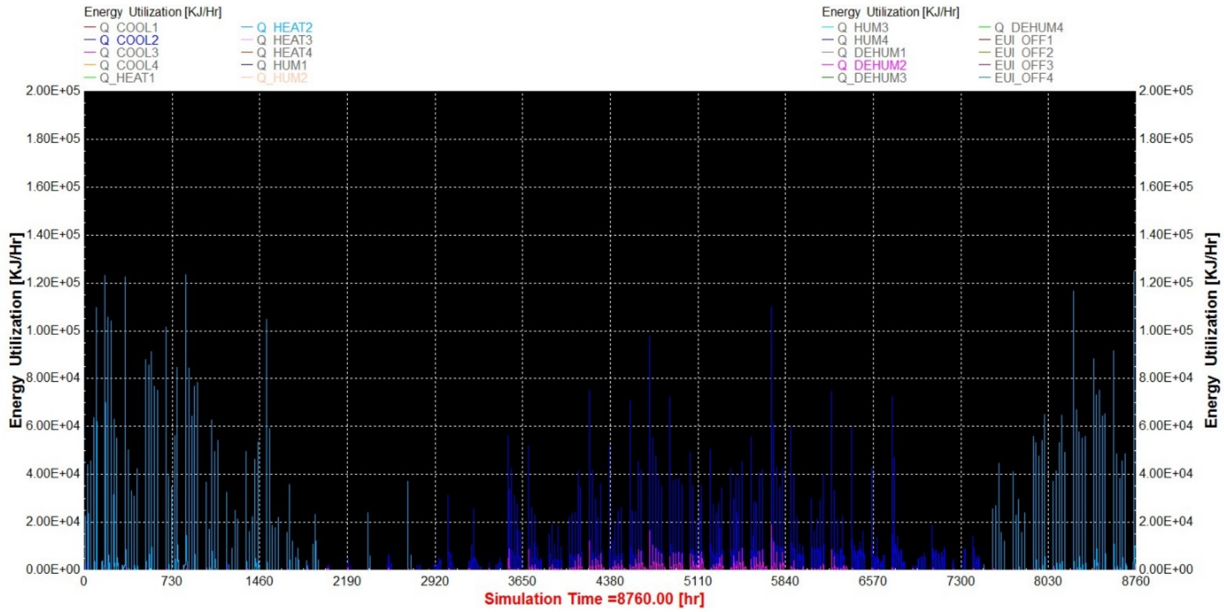
Zones Relative Humidity *(%)*

Run12 G (MV 4-Story NV DSF1 Semi HVAC Hypo)



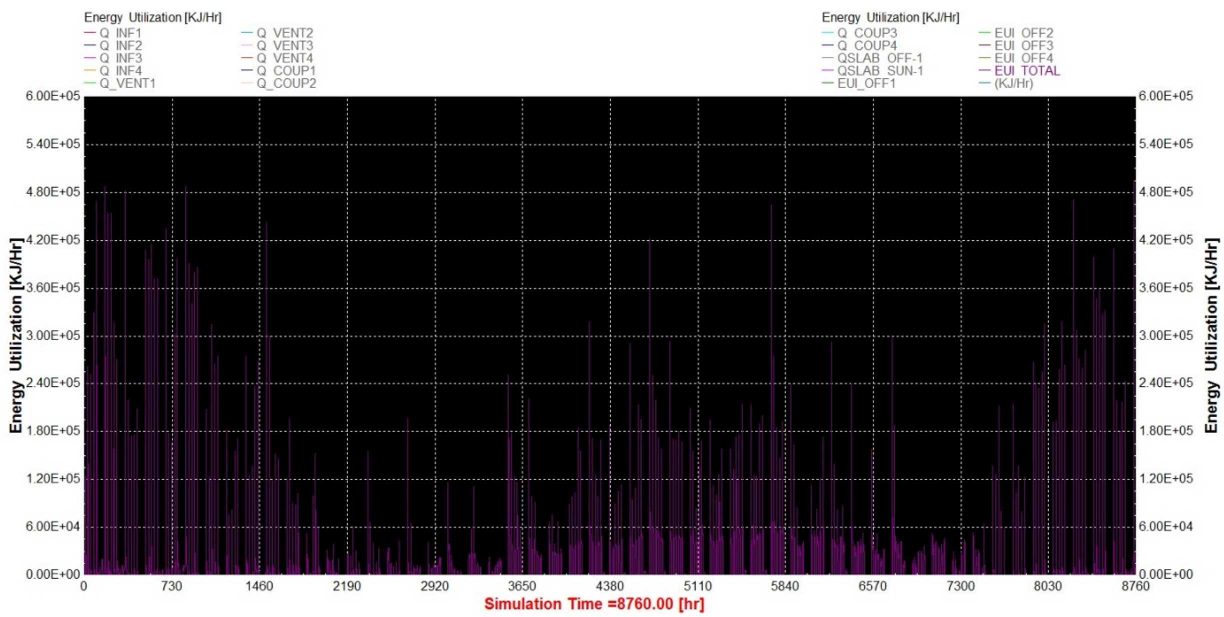
Office Load Intensity *(kJ/hr)*

Run12 G (MV 4-Story NV DSF1 Semi HVAC Hypo)



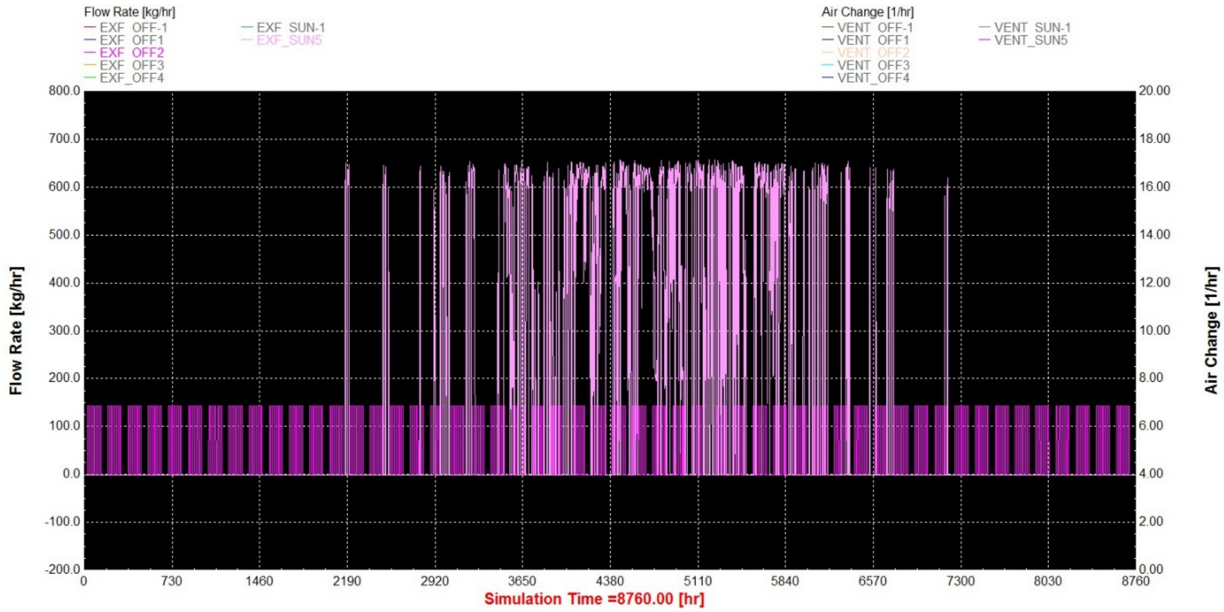
Total Offices Load Intensity *(kJ/hr)*

Run12 G (MV 4-Story NV DSF1 Semi HVAC Hypo)



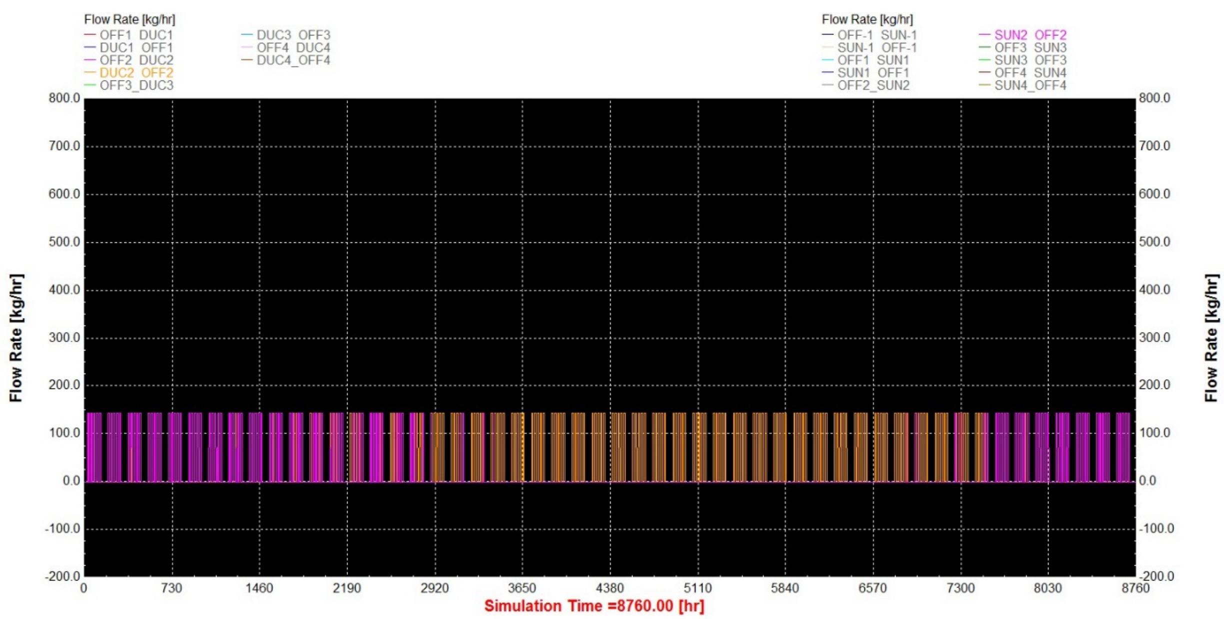
Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run12 G (MV 4-Story NV DSF1 Semi HVAC Hypo)



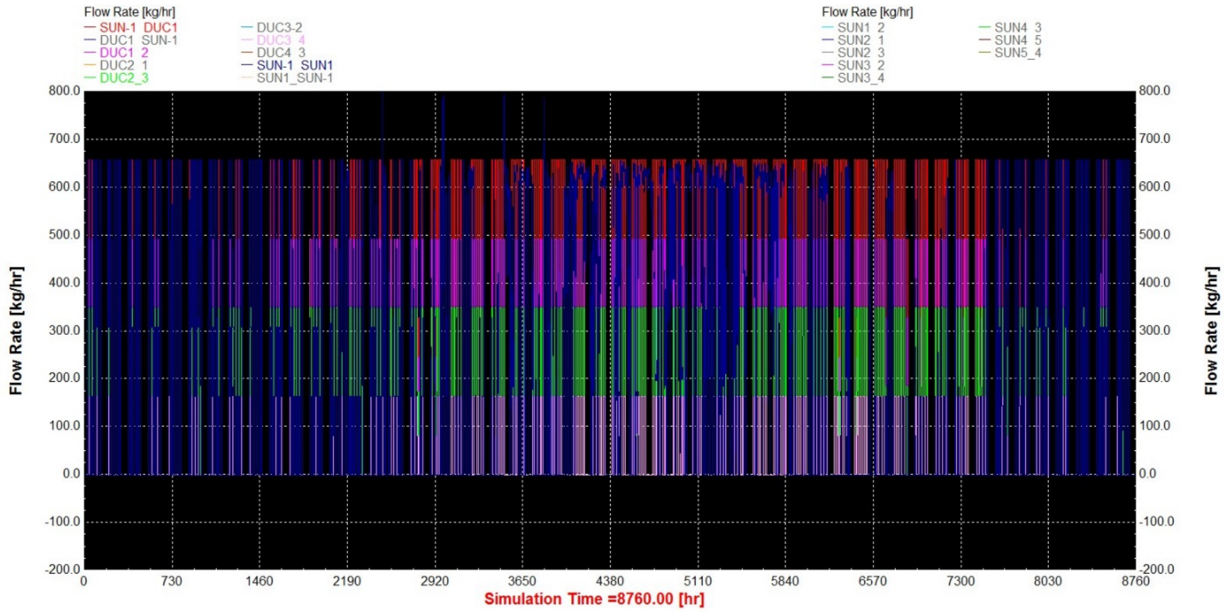
Sunspaces/Ducts-Offices Airflow *(kg/hr or 1/hr)*

Run12 G (MV 4-Story NV DSF1 Semi HVAC Hypo)



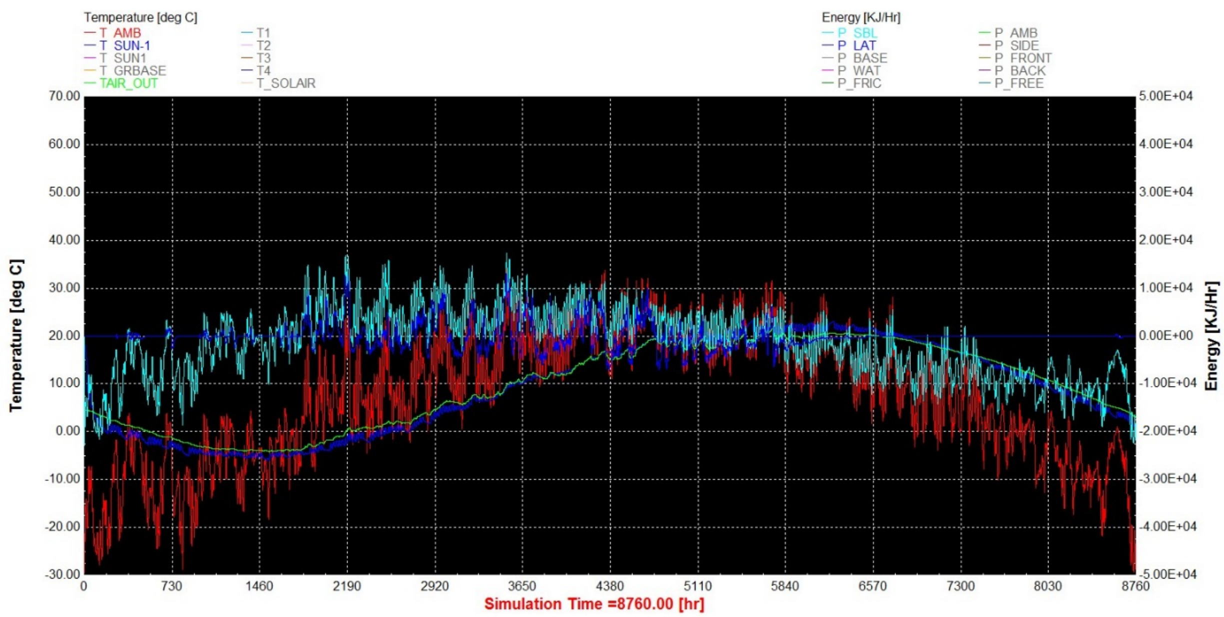
Sunspace/Duct-Sunspace/Duct Airflow *(kg/hr or 1/hr)*

Run12 G (MV 4-Story NV DSF1 Semi HVAC Hypo)



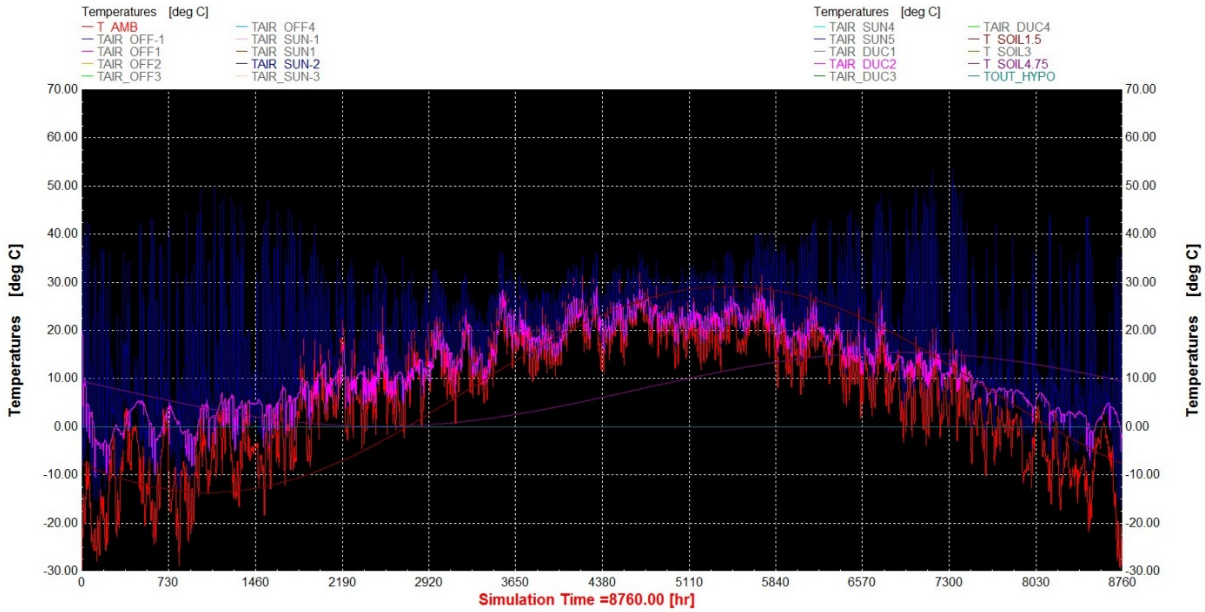
Air-Tubes Temperature and Energy *(°C and kJ/hr)*

Run12 G (MV 4-Story NV DSF1 Semi HVAC Hypo)



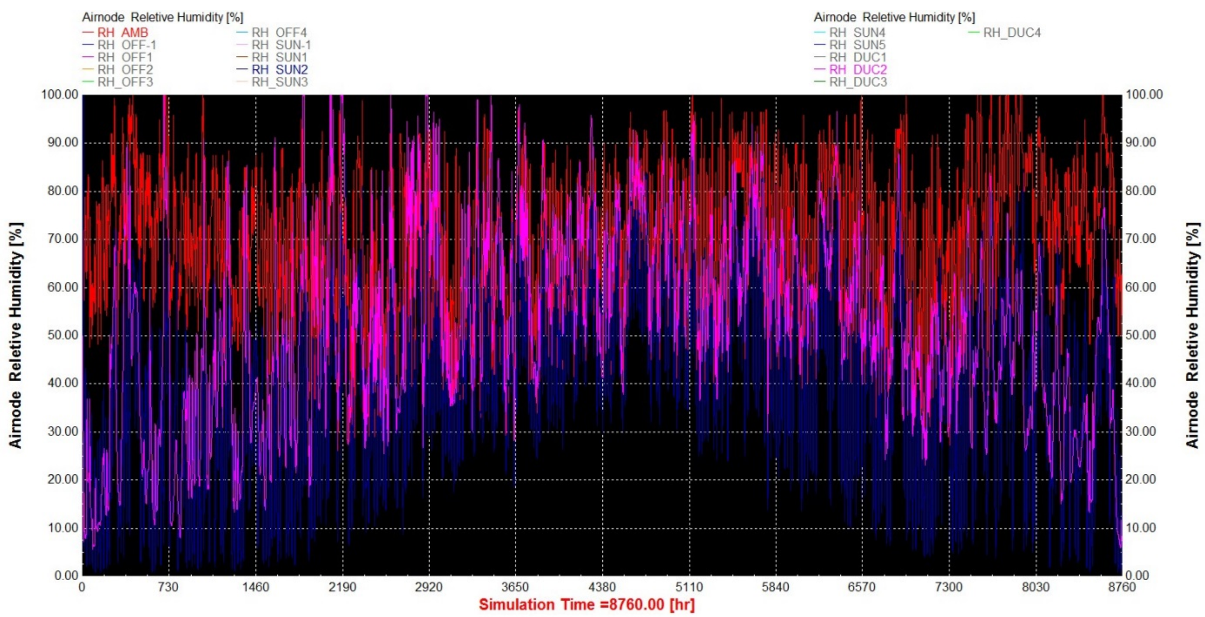
Zones Temperature *(°C)*

Run13 H (NC 4-Story MV DSF1 No HVAC)



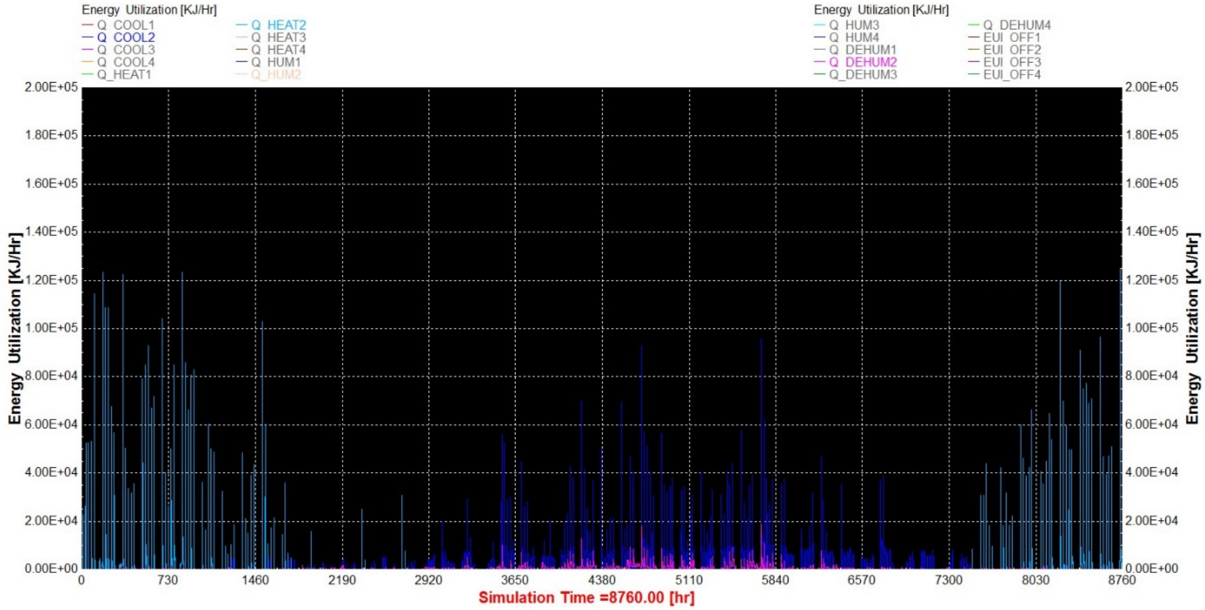
Zones Relative Humidity *(%)*

Run13 H (NC 4-Story MV DSF1 No HVAC)



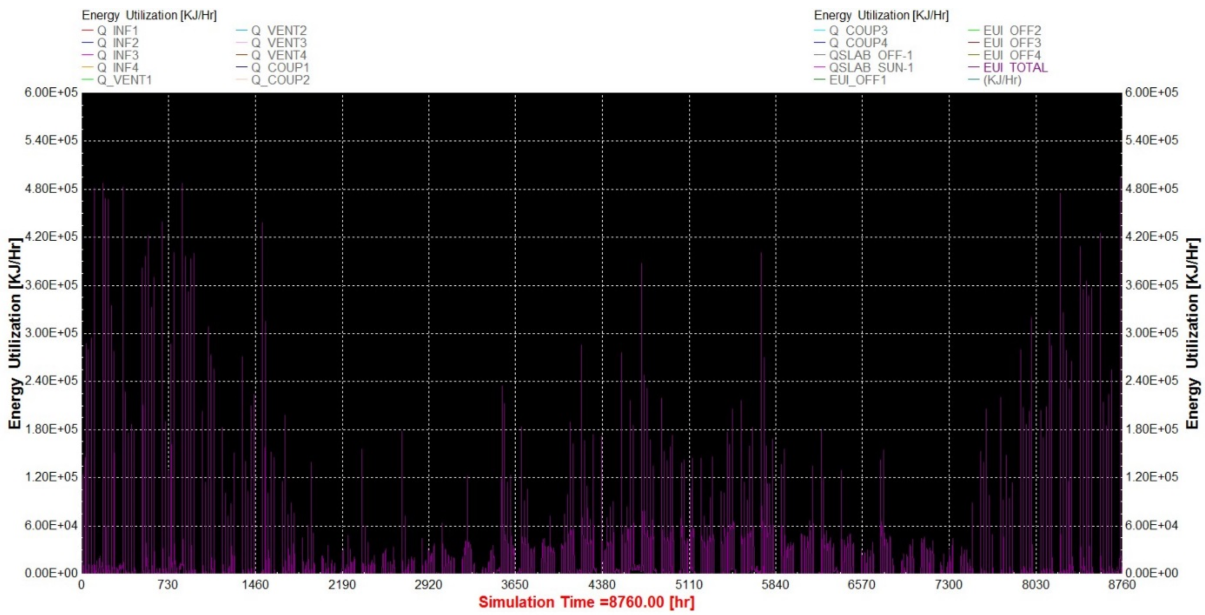
Office Load Intensity *(kJ/hr)*

Run13 H (NC 4-Story MV DSF1 No HVAC)



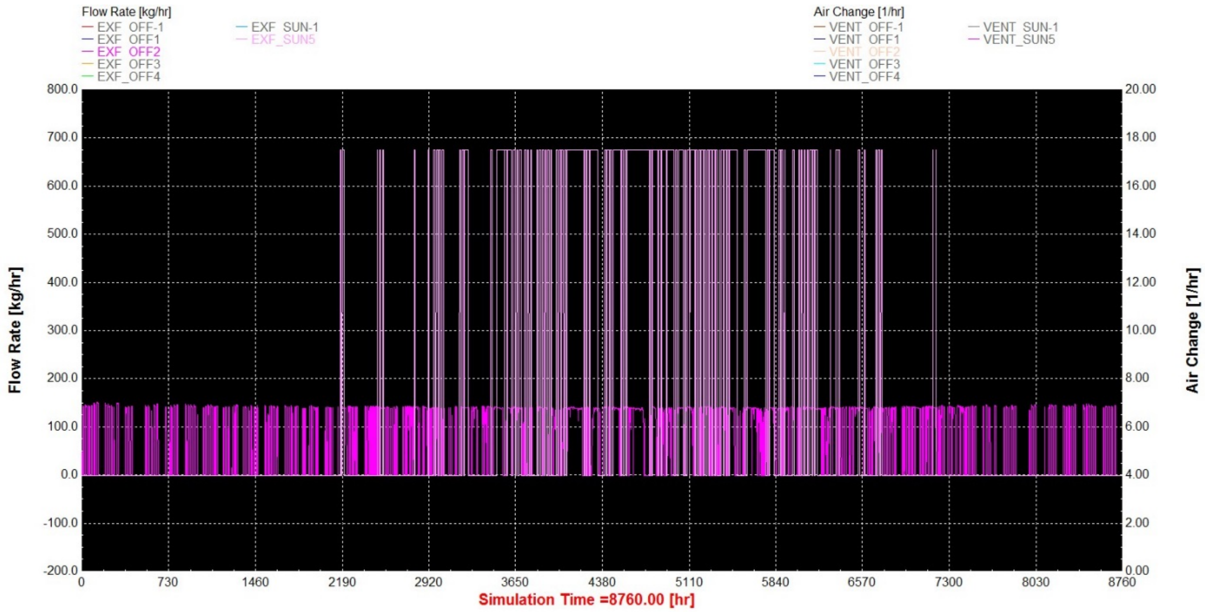
Total Offices Load Intensity *(kJ/hr)*

Run13 H (NC 4-Story MV DSF1 No HVAC)



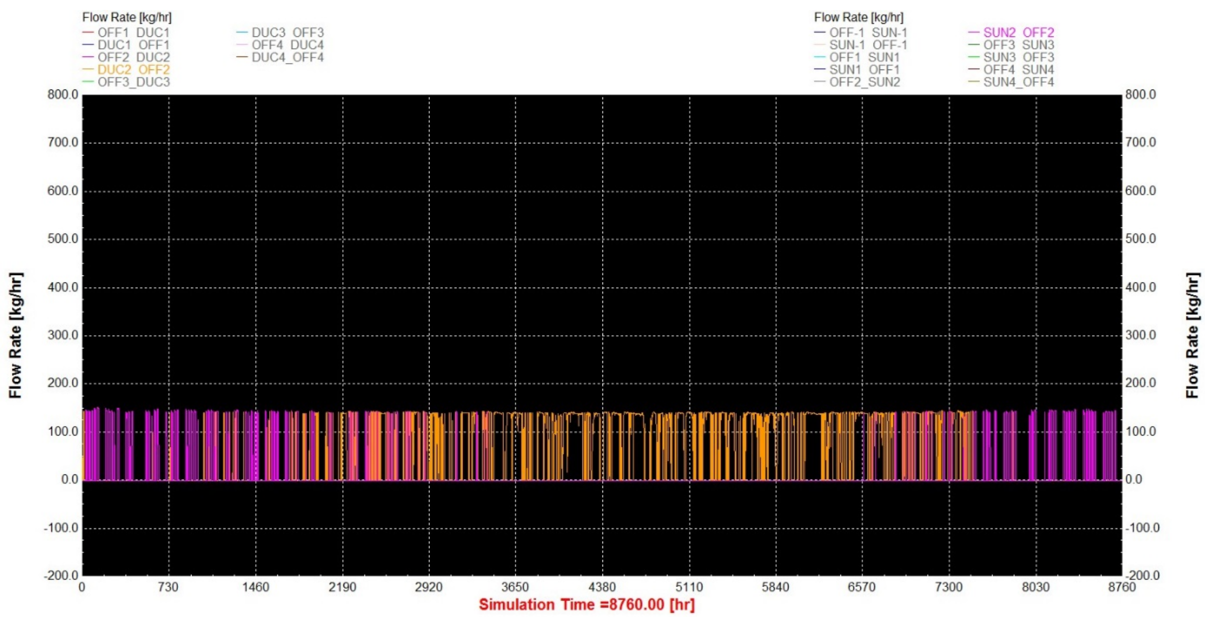
Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run13 H (NC 4-Story MV DSF1 No HVAC)



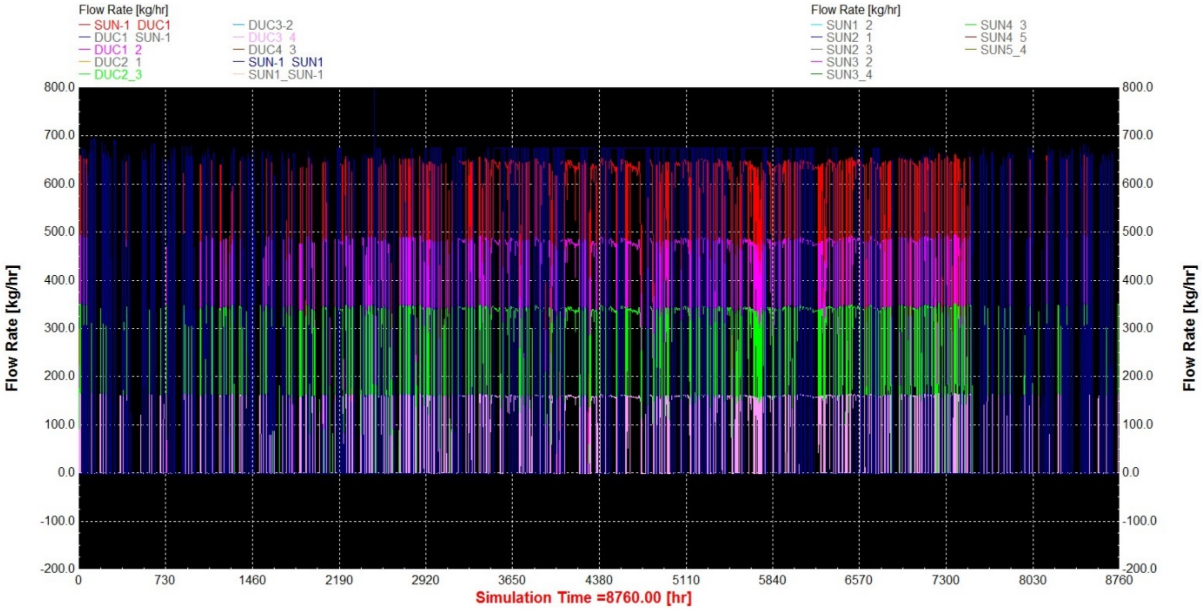
Sunspaces/Ducts-Offices Airflow *(kg/hr or 1/hr)*

Run13 H (NC 4-Story MV DSF1 No HVAC)



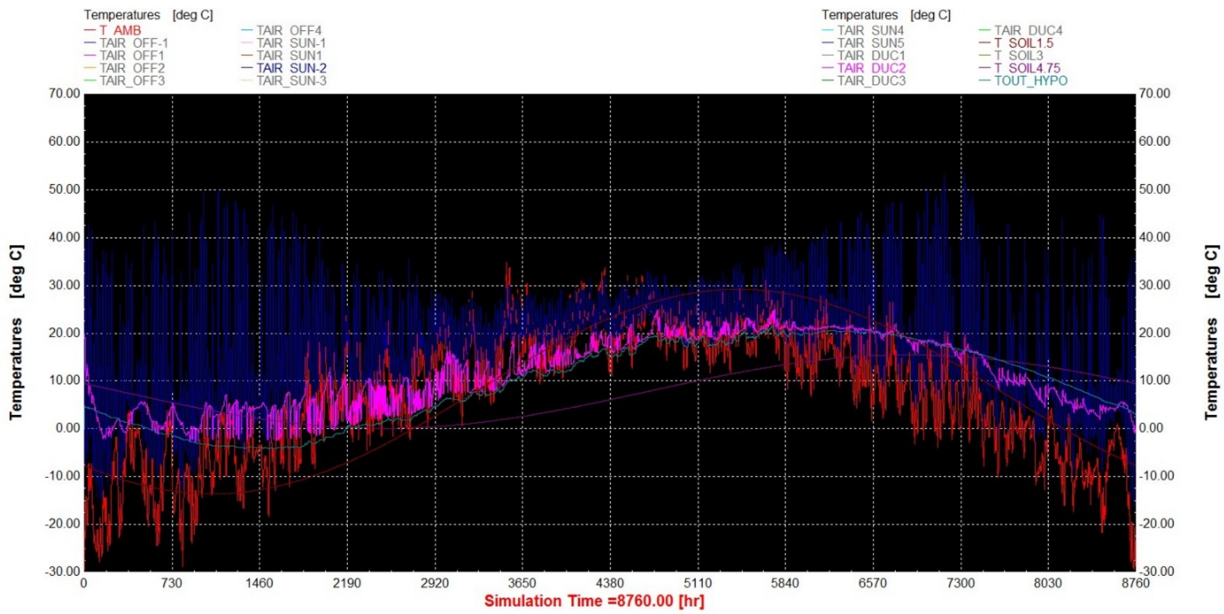
Sunspace/Duct-Sunspace/Duct Airflow *(kg/hr or 1/hr)*

Run13 H (NC 4-Story MV DSF1 No HVAC)



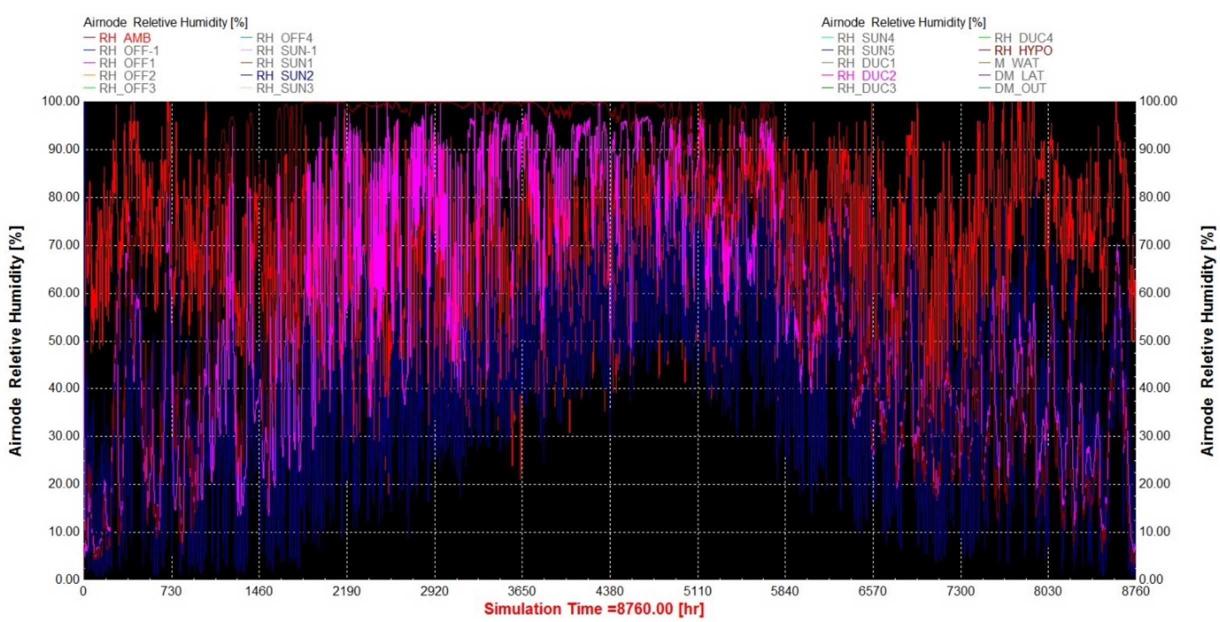
Zones Temperature *(°C)*

Run14 H (NC 4-Story MV DSF1 No HVAC Hypo)



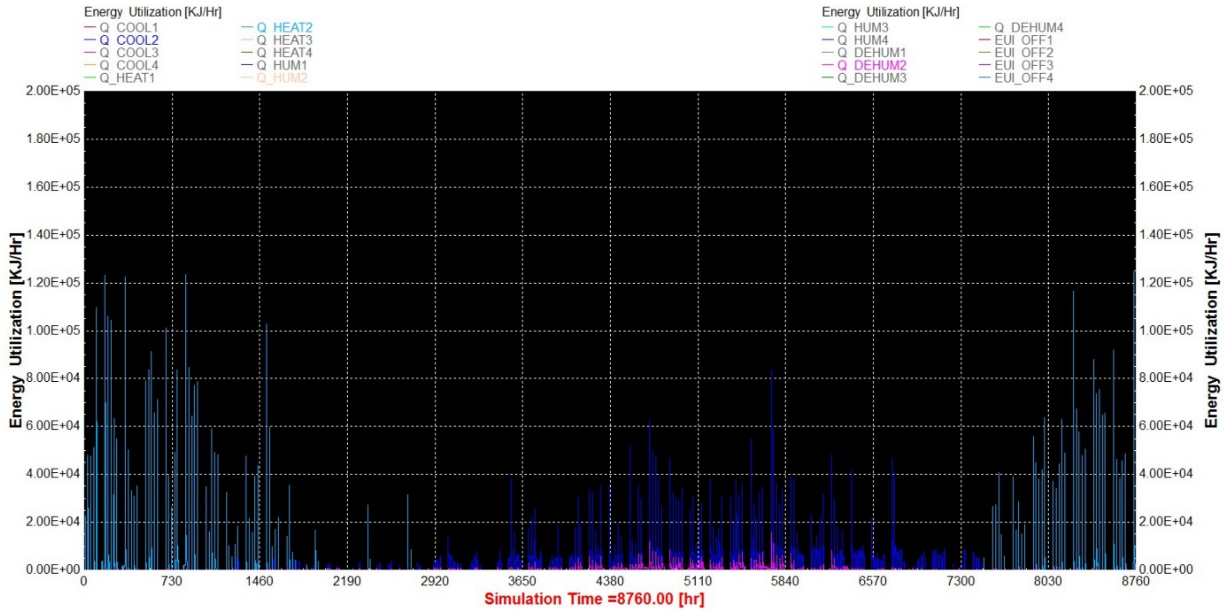
Zones Relative Humidity *(%)*

Run14 H (NC 4-Story MV DSF1 No HVAC Hypo)



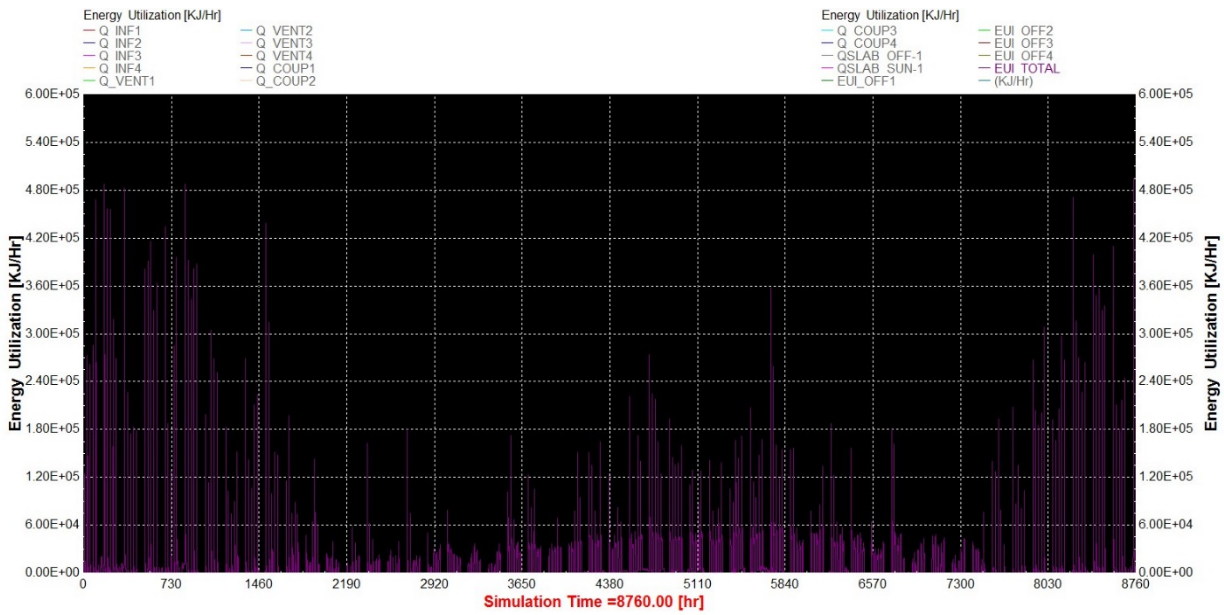
Office Load Intensity *(kJ/hr)*

Run14 H (NC 4-Story MV DSF1 No HVAC Hypo)



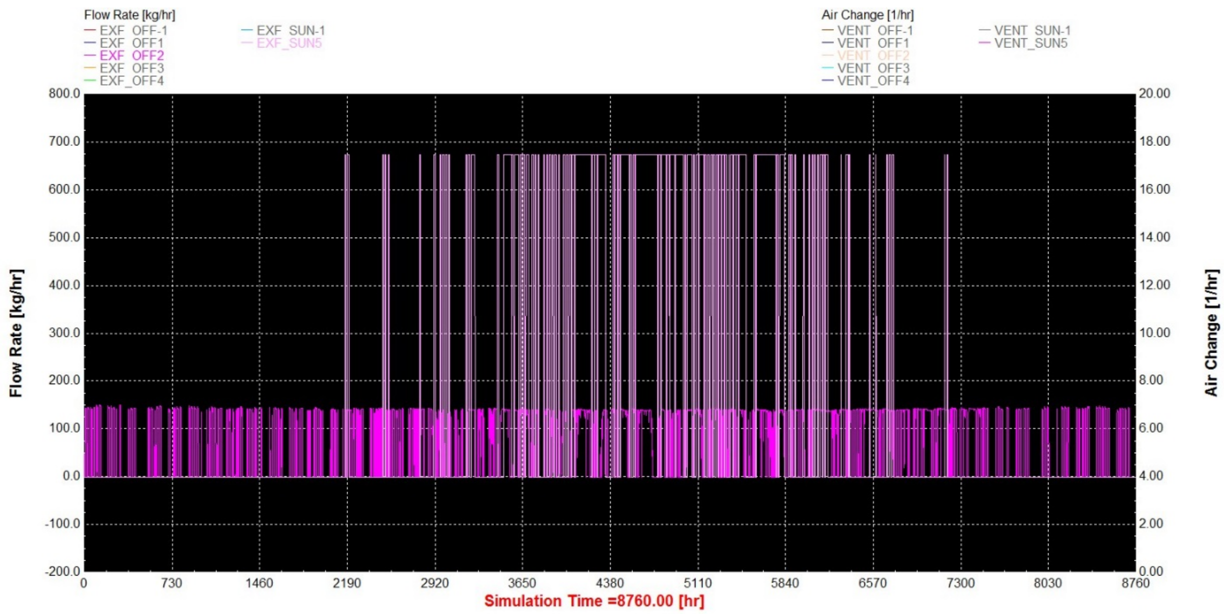
Total Offices Load Intensity *(kJ/hr)*

Run14 H (NC 4-Story MV DSF1 No HVAC Hypo)



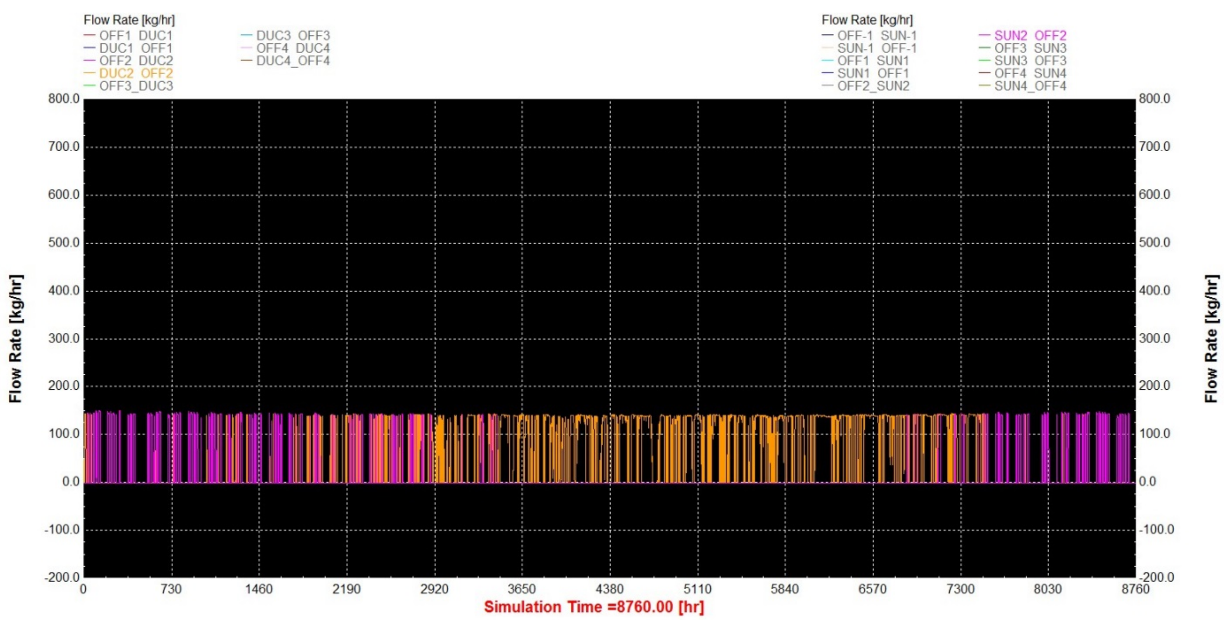
Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run14 H (NC 4-Story MV DSF1 No HVAC Hypo)



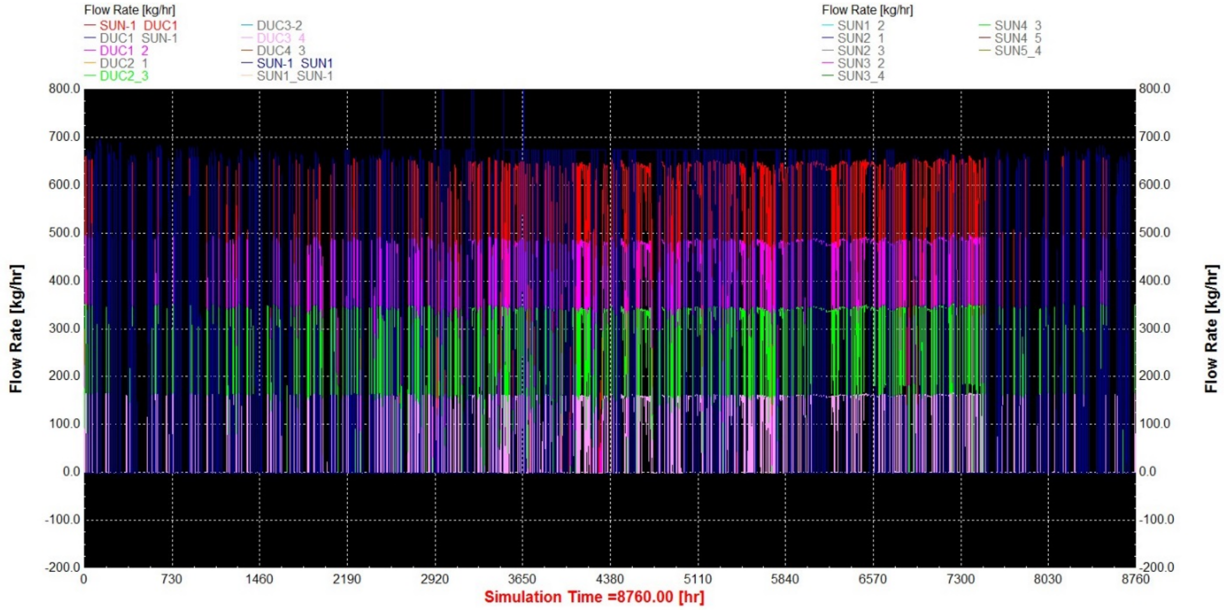
Sunspaces/Ducts-Offices Airflow *(kg/hr or 1/hr)*

Run14 H (NC 4-Story MV DSF1 No HVAC Hypo)



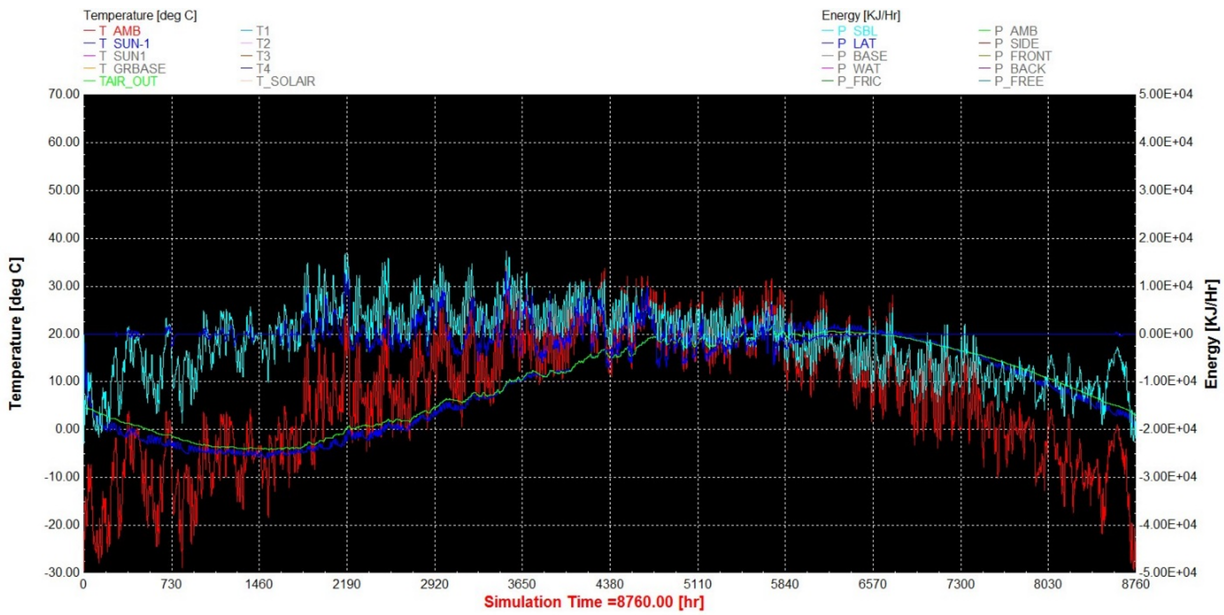
Sunspace/Duct-Sunspace/Duct Airflow *(kg/hr or 1/hr)*

Run14 H (NC 4-Story MV DSF1 No HVAC Hypo)



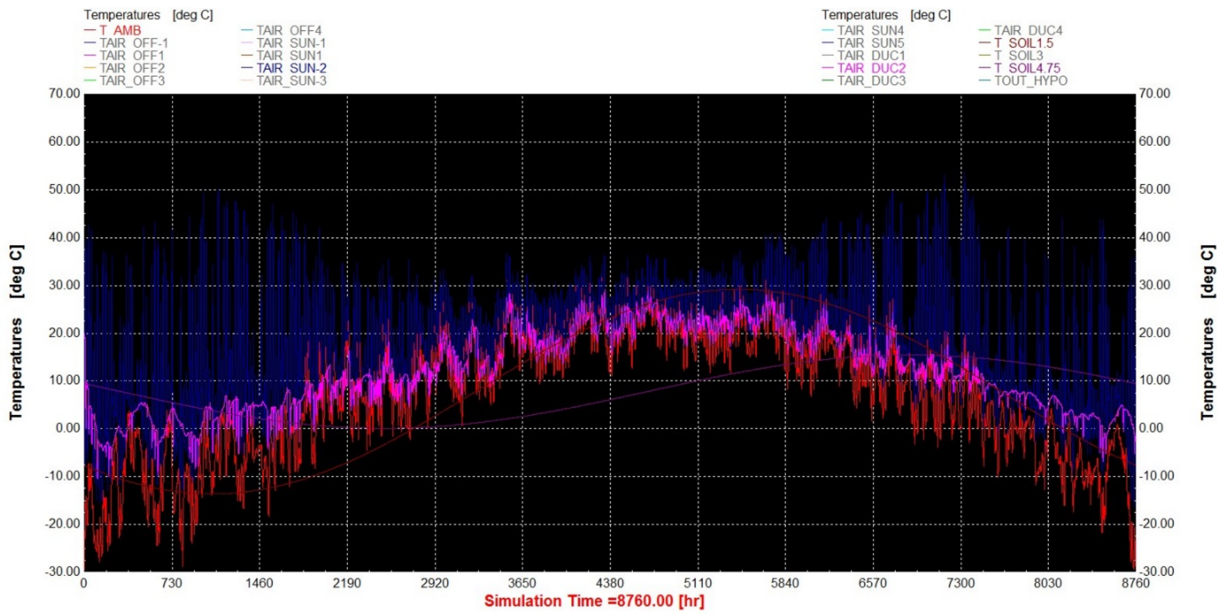
Air-Tubes Temperature and Energy *(°C and kJ/hr)*

Run14 H (NC 4-Story MV DSF1 No HVAC Hypo)



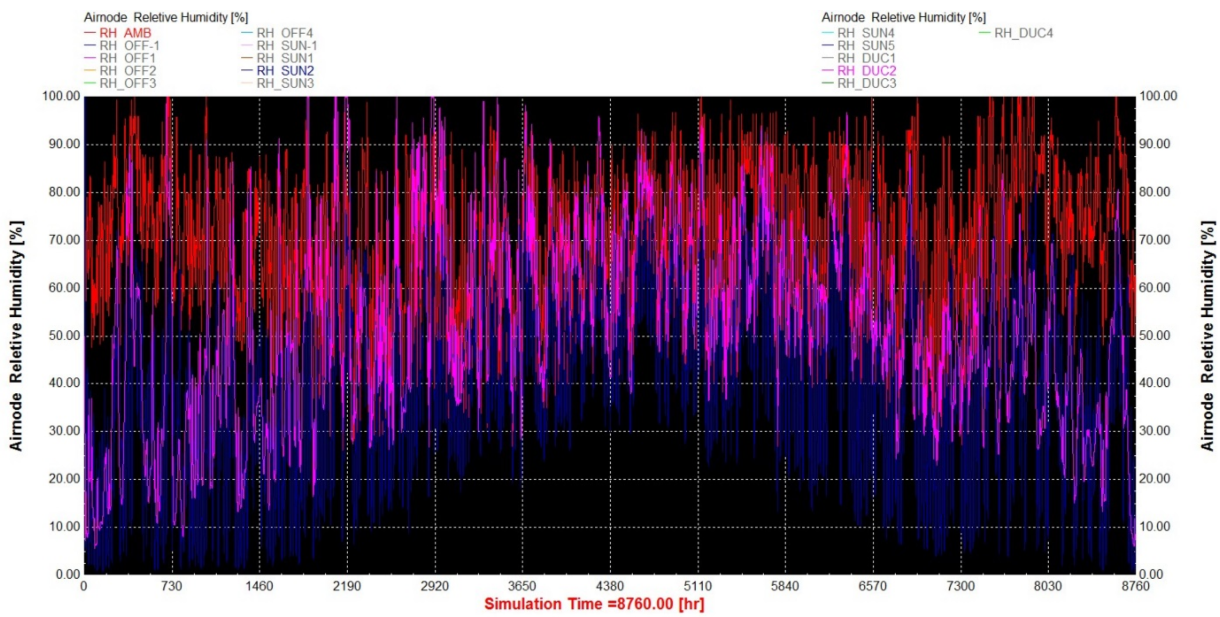
Zones Temperature *(°C)*

Run15 I (NC 4-Story NV DSF1 No HVAC)



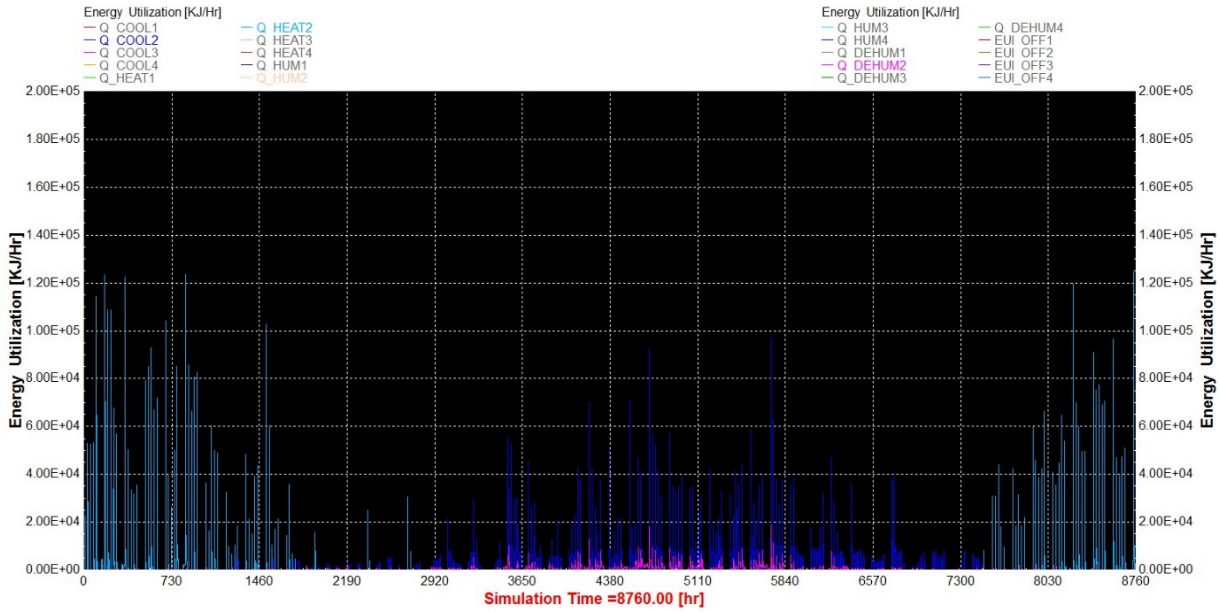
Zones Relative Humidity *(%)*

Run15 I (NC 4-Story NV DSF1 No HVAC)



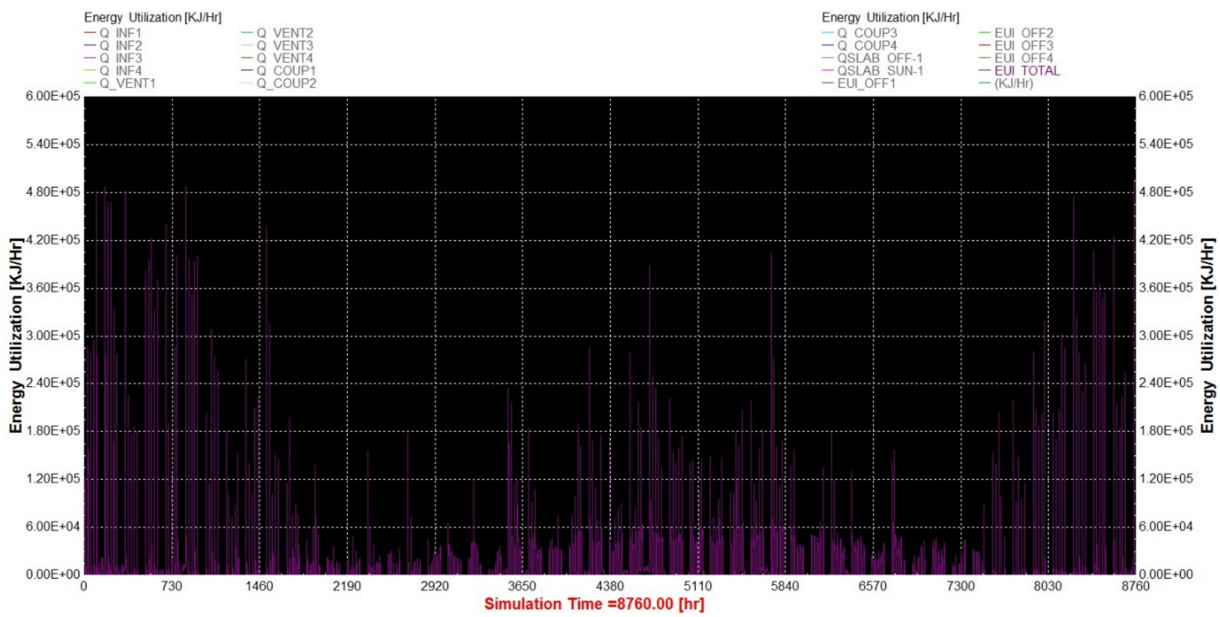
Office Load Intensity *(kJ/hr)*

Run15 I (NC 4-Story NV DSF1 No HVAC)



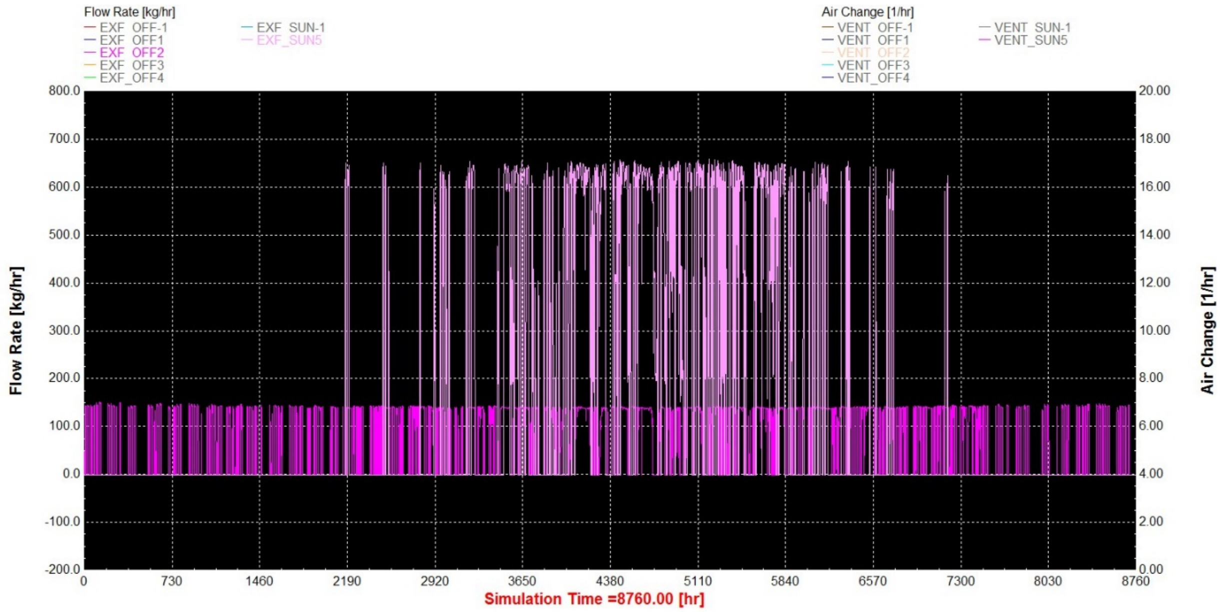
Total Offices Load Intensity *(kJ/hr)*

Run15 I (NC 4-Story NV DSF1 No HVAC)



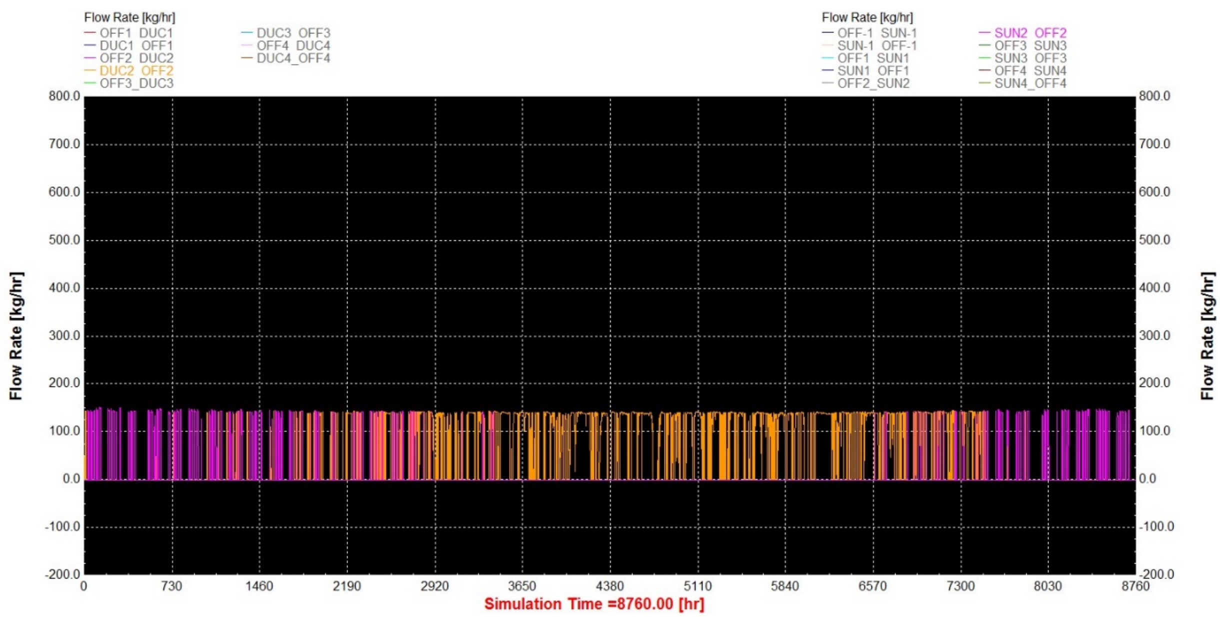
Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run15 I (NC 4-Story NV DSF1 No HVAC)



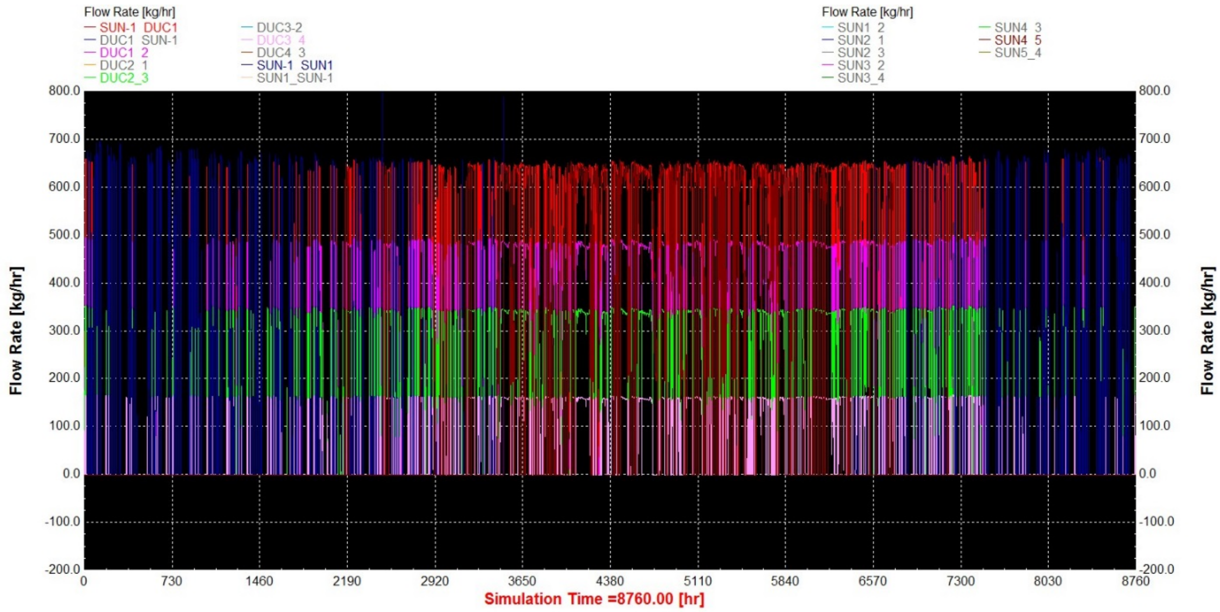
Sunspaces/Ducts-Offices Airflow *(kg/hr or 1/hr)*

Run15 I (NC 4-Story NV DSF1 No HVAC)



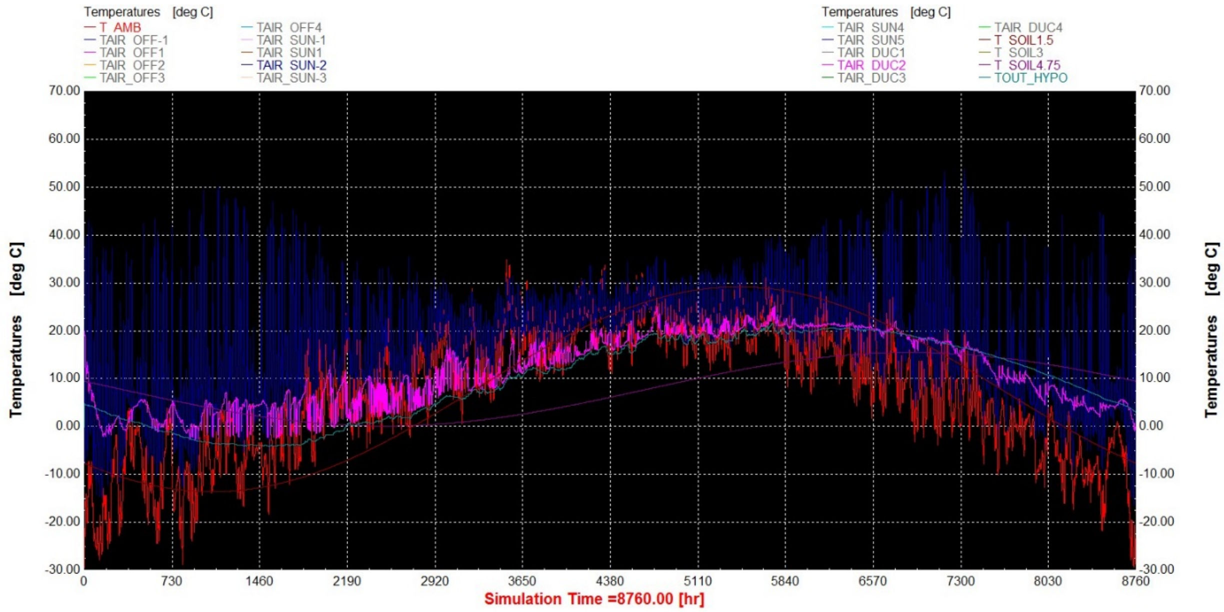
Sunspace/Duct-Sunspace/Duct Airflow *(kg/hr or 1/hr)*

Run15 I (NC 4-Story NV DSF1 No HVAC)



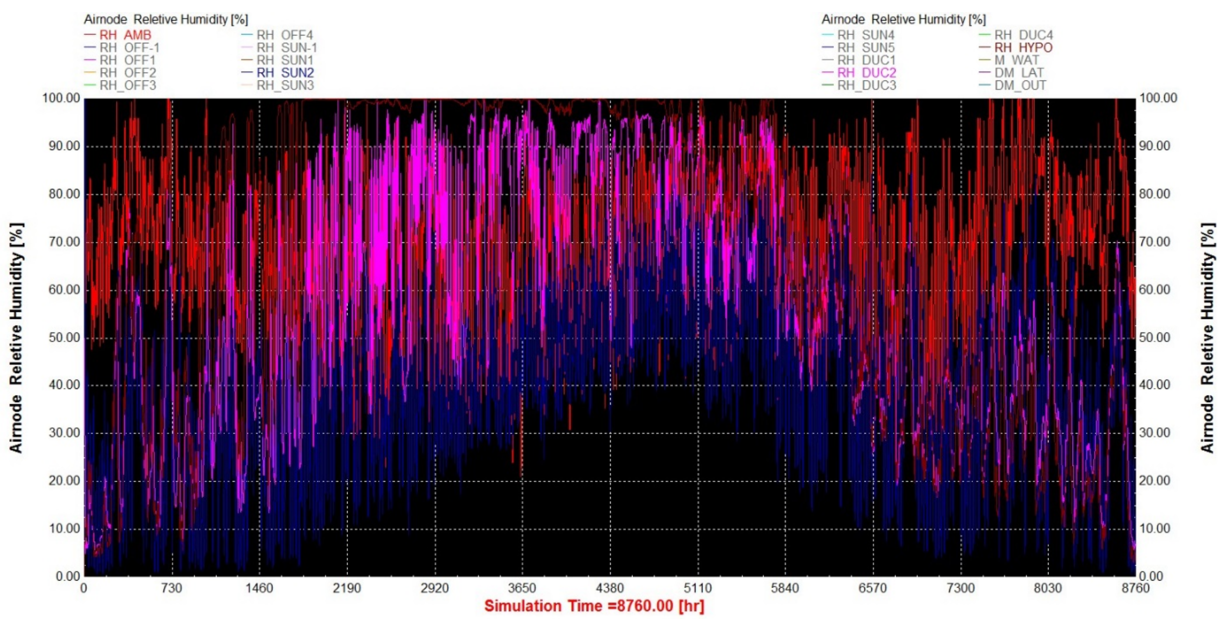
Zones Temperature *(°C)*

Run16 I (NC 4-Story NV DSF1 No HVAC Hypo)



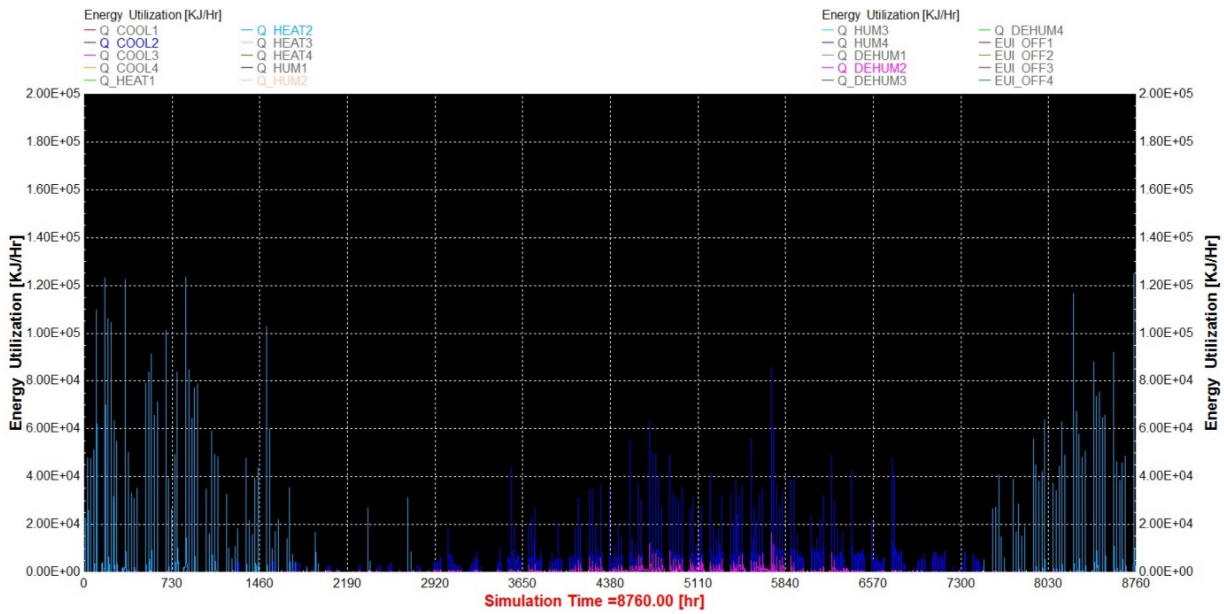
Zones Relative Humidity *(%)*

Run16 I (NC 4-Story NV DSF1 No HVAC Hypo)



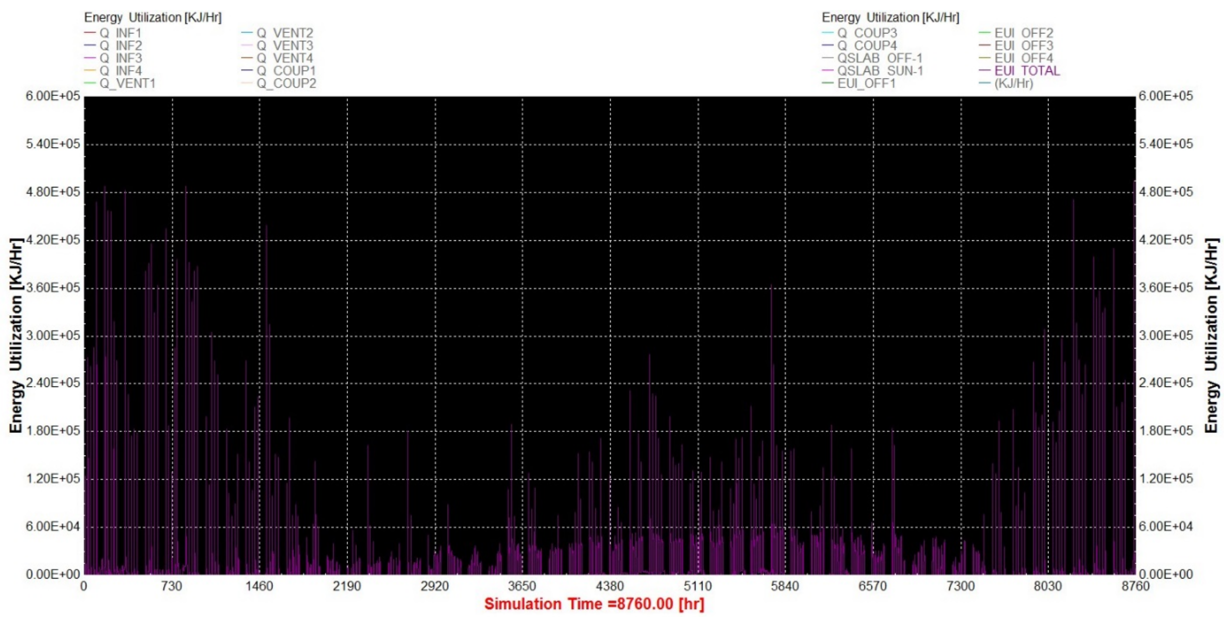
Office Load Intensity *(kJ/hr)*

Run16 I (NC 4-Story NV DSF1 No HVAC Hypo)



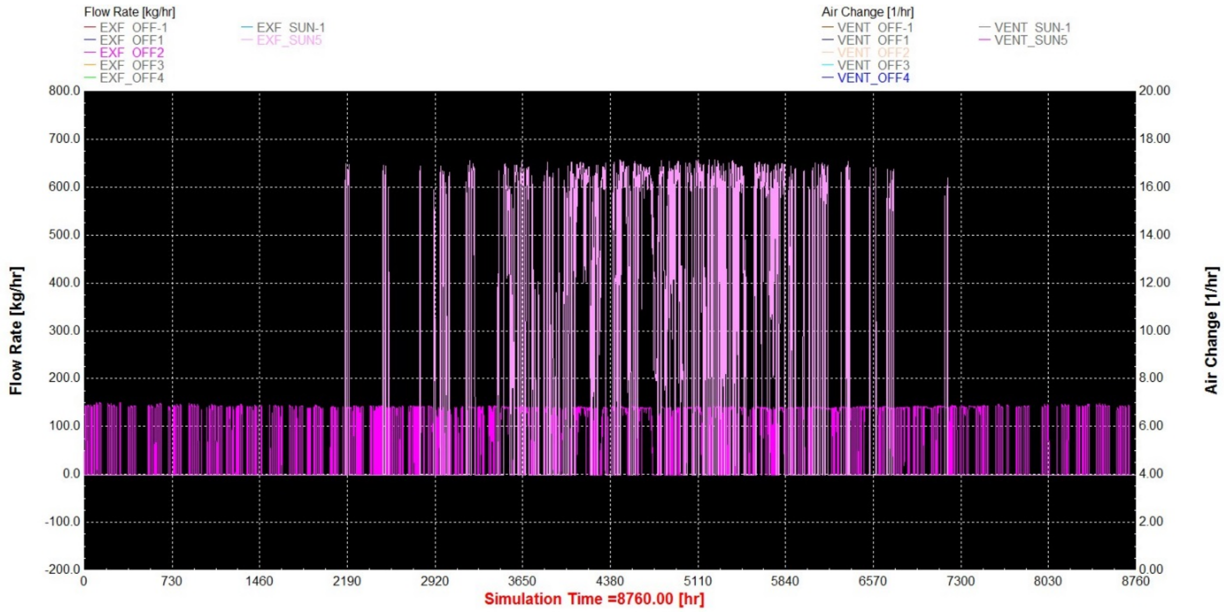
Total Offices Load Intensity *(kJ/hr)*

Run16 I (NC 4-Story NV DSF1 No HVAC Hypo)



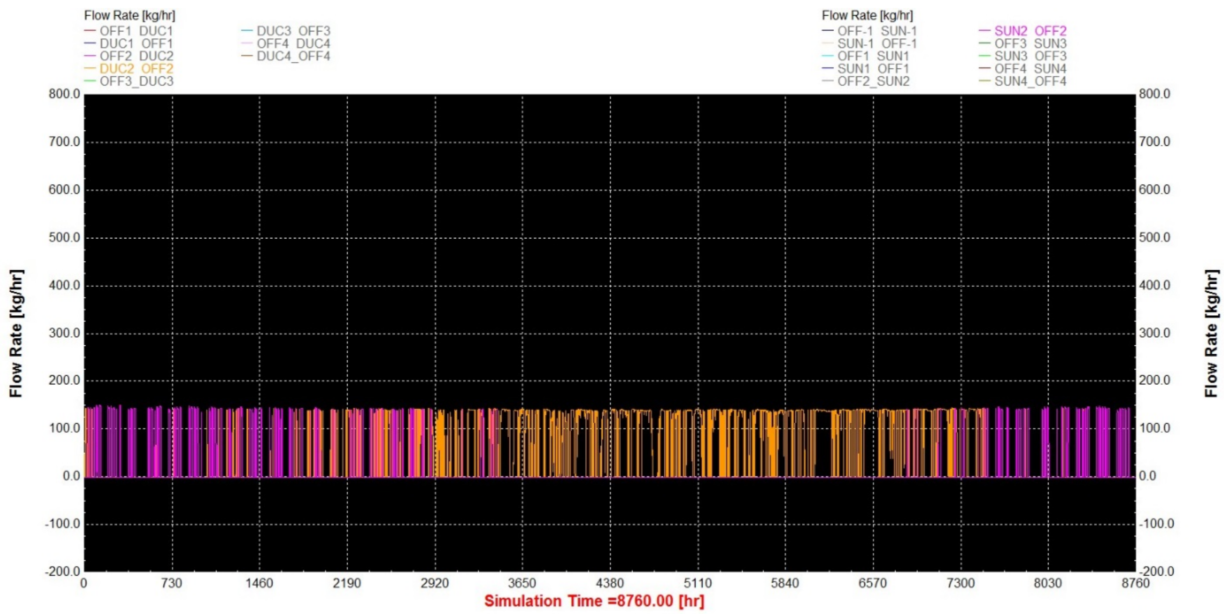
Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run16 I (NC 4-Story NV DSF1 Self No HVAC Hypo)



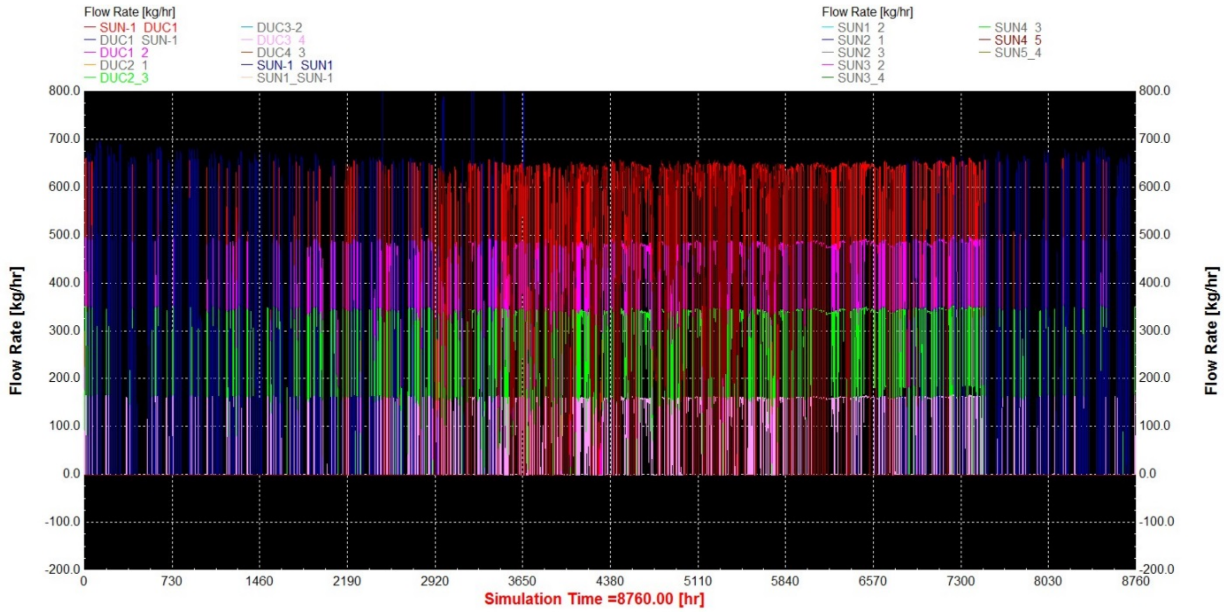
Sunspaces/Ducts-Offices Airflow *(kg/hr or 1/hr)*

Run16 I (NC 4-Story NV DSF1 No HVAC Hypo)



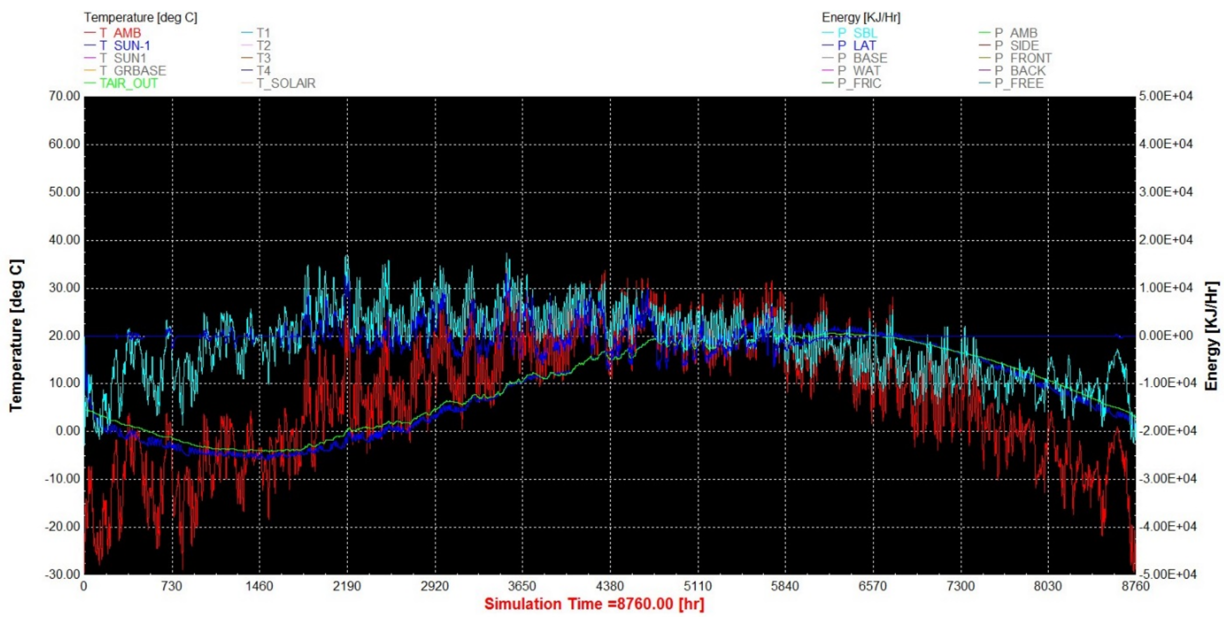
Sunspace/Duct-Sunspace/Duct Airflow *(kg/hr or 1/hr)*

Run16 I (NC 4-Story NV DSF1 No HVAC Hypo)



Air-Tubes Temperature and Energy *(°C and kJ/hr)*

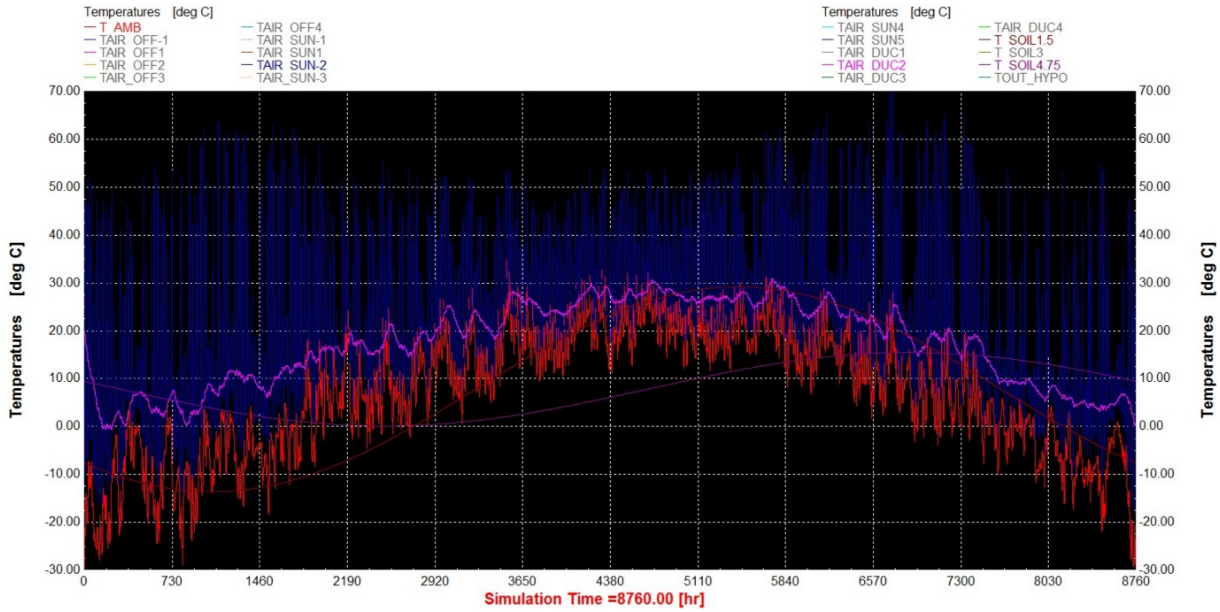
Run16 I (NC 4-Story NV DSF1 No HVAC Hypo)



Appendix I: Result Graphs for Minneapolis, DSF0.5

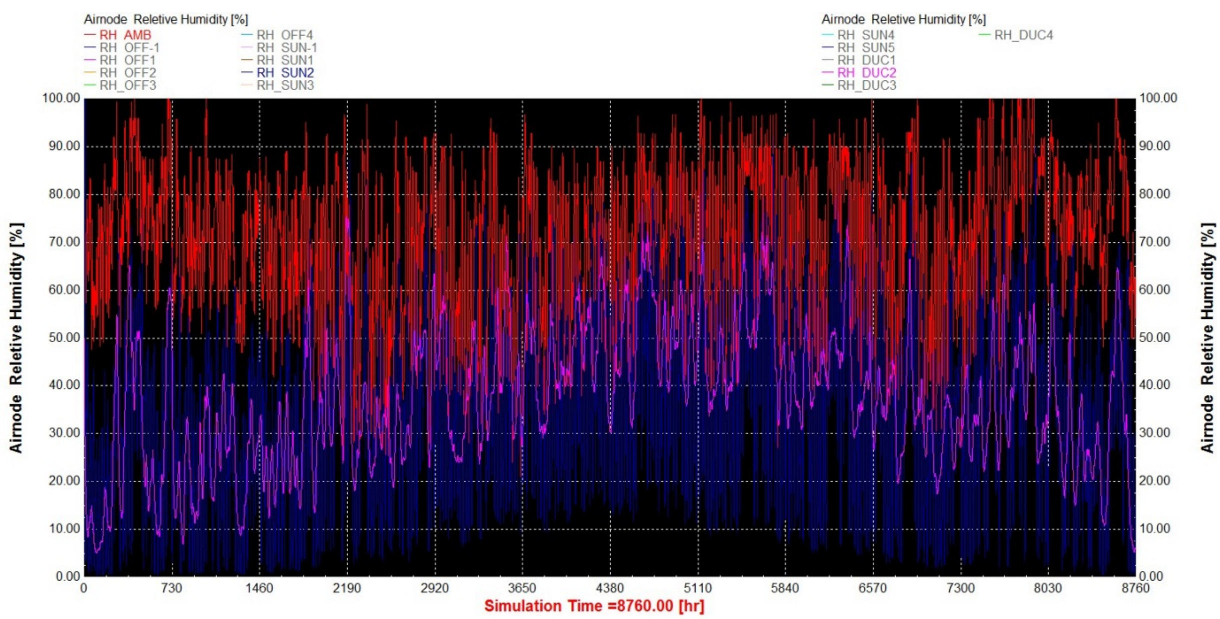
Zones Temperature *(°C)*

Run5 C (MC 4-Story DSF0.5 Full HVAC)



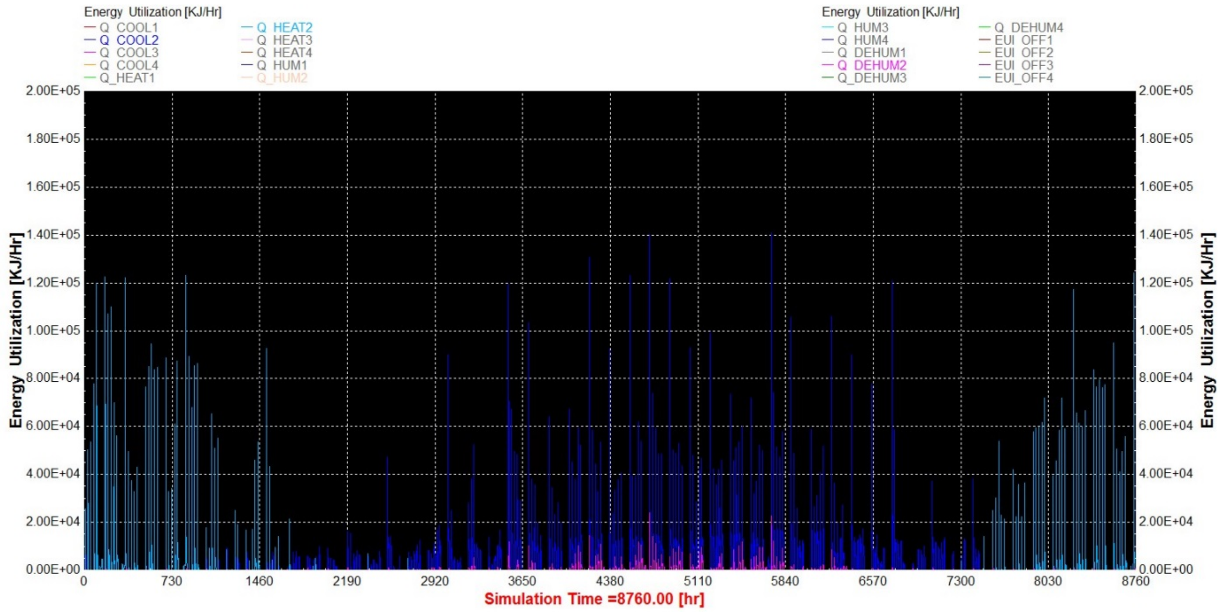
Zones Relative Humidity *(%)*

Run5 C (MC 4-Story DSF0.5 Full HVAC)



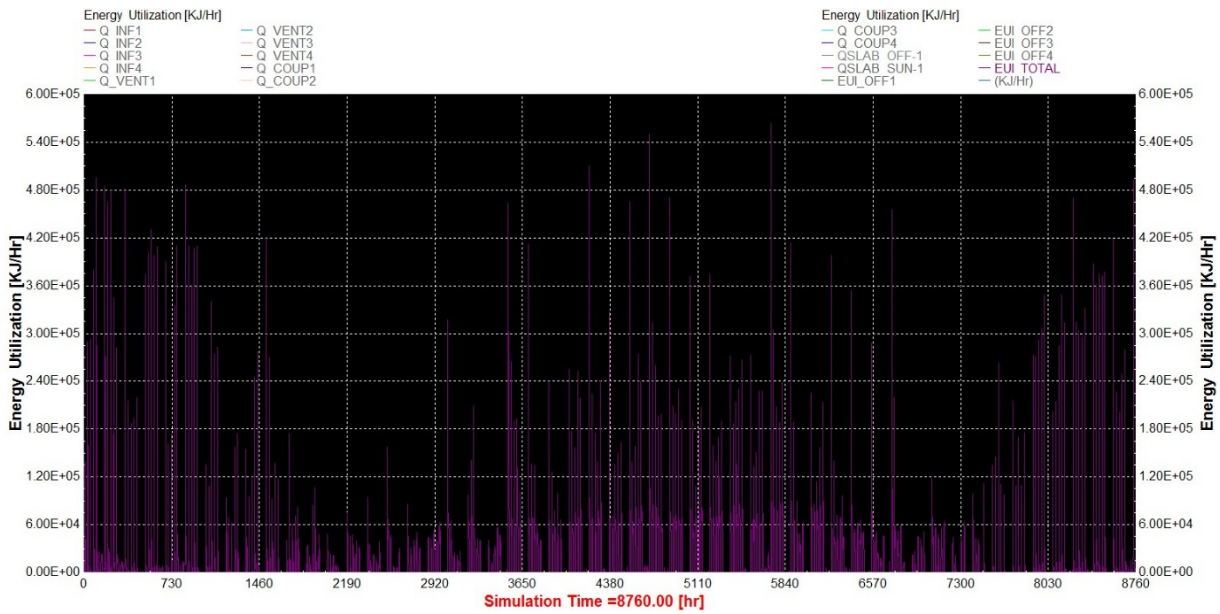
Office Load Intensity *(kJ/hr)*

Run5 C (MC 4-Story DSF0.5 Full HVAC)



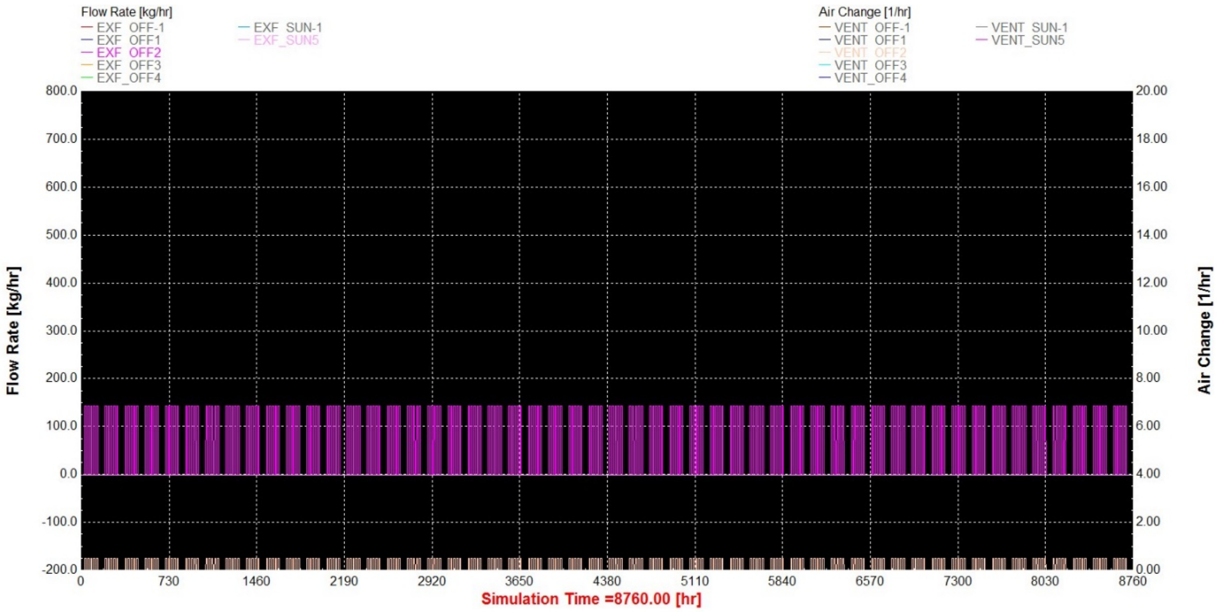
Total Offices Load Intensity *(kJ/hr)*

Run5 C (MC 4-Story DSF0.5 Full HVAC)



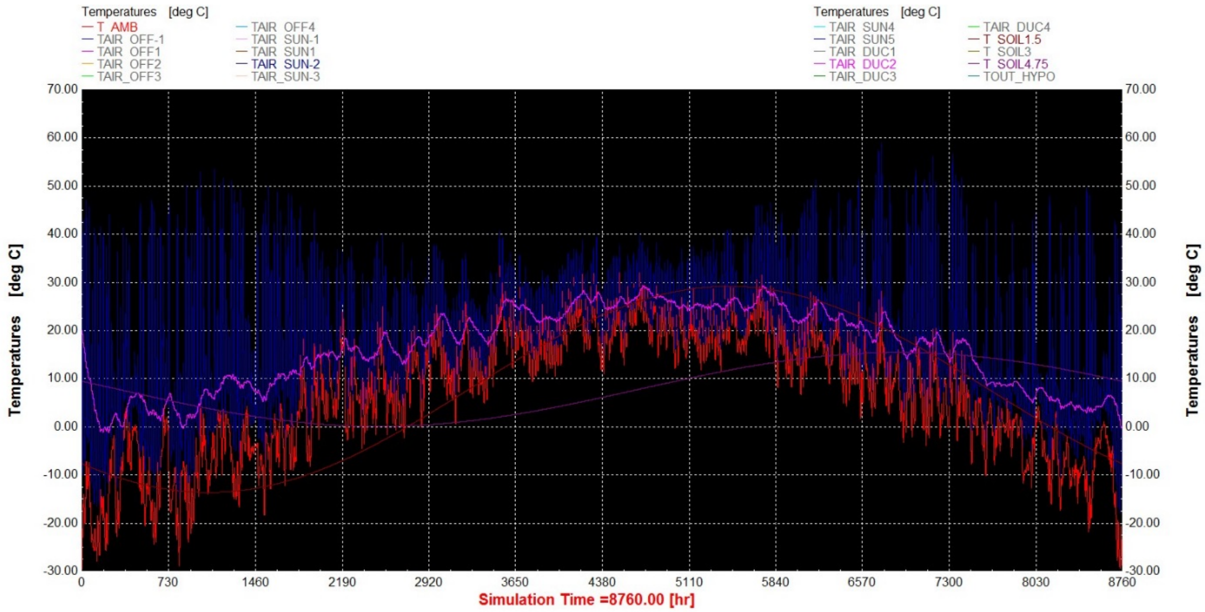
Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run5 C (MC 4-Story DSF0.5 Full HVAC)



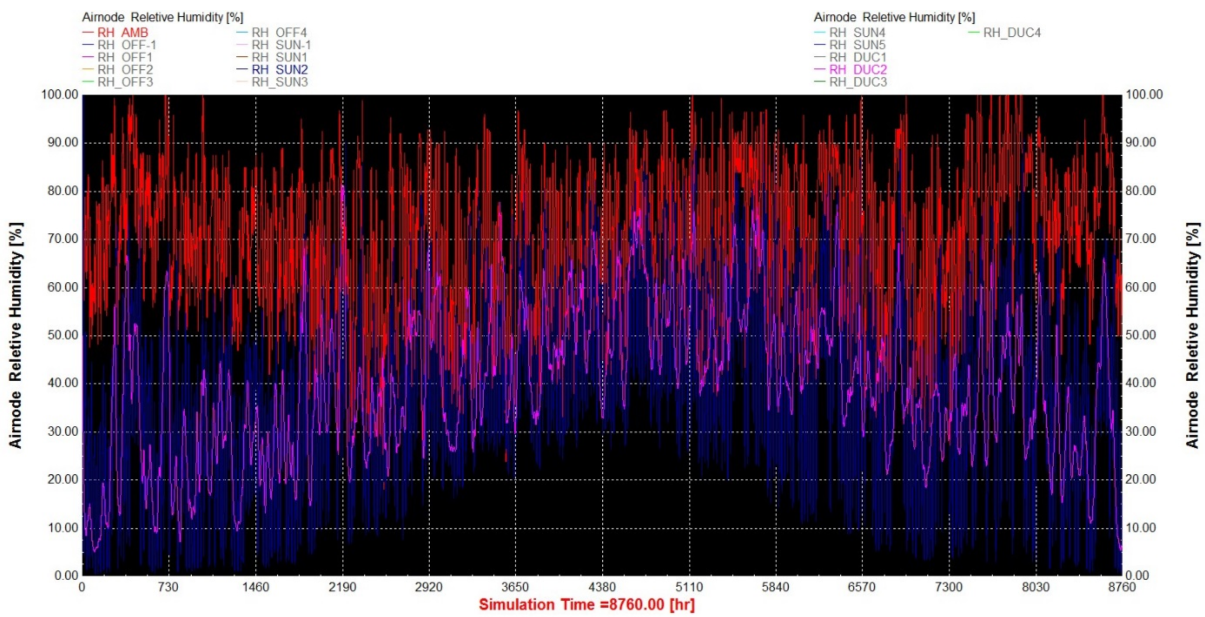
Zones Temperature *(°C)*

Run6 C (MC 4-Story DSF0.5 Shading Full HVAC)



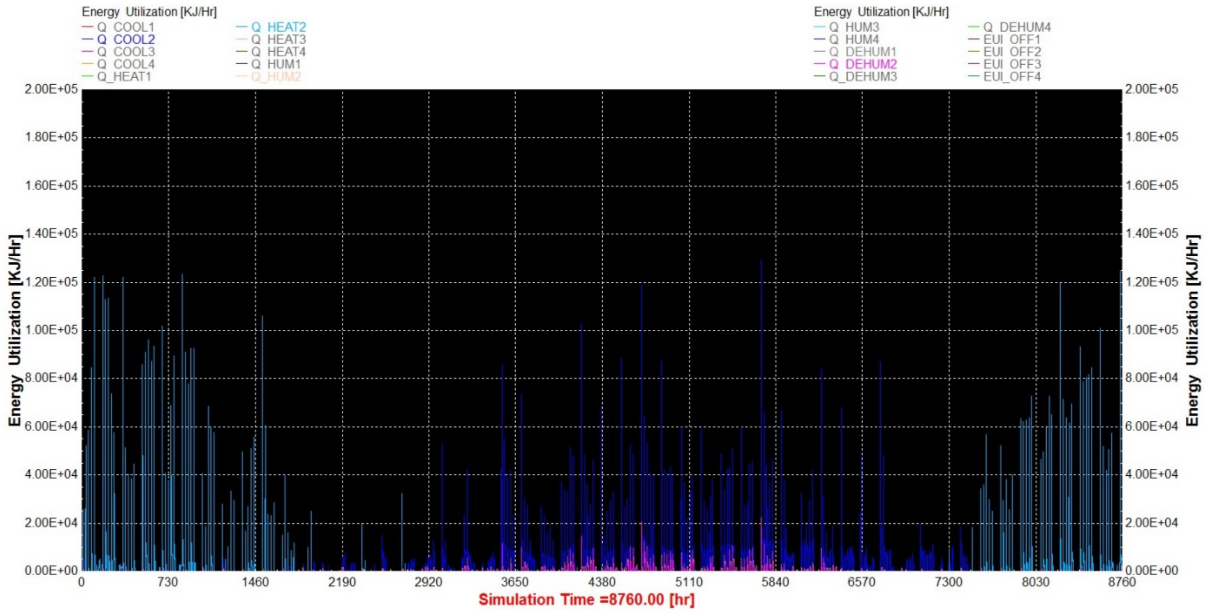
Zones Relative Humidity *(%)*

Run6 C (MC 4-Story DSF0.5 Shading Full HVAC)



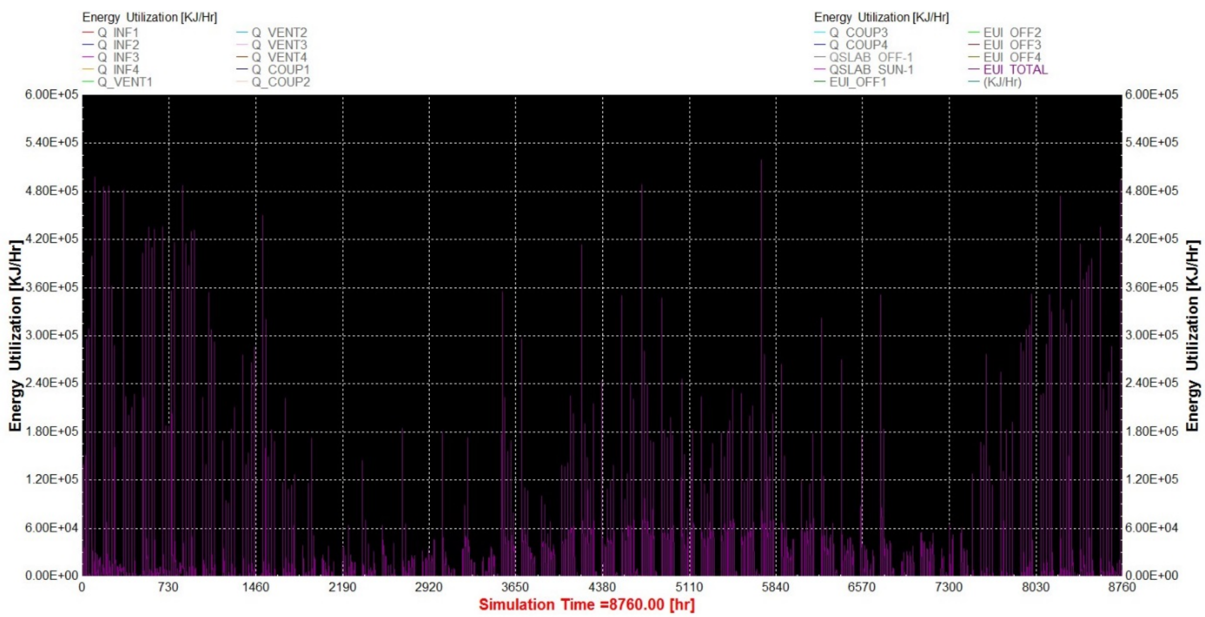
Office Load Intensity *(kJ/hr)*

Run6 C (MC 4-Story DSF0.5 Shading Full HVAC)



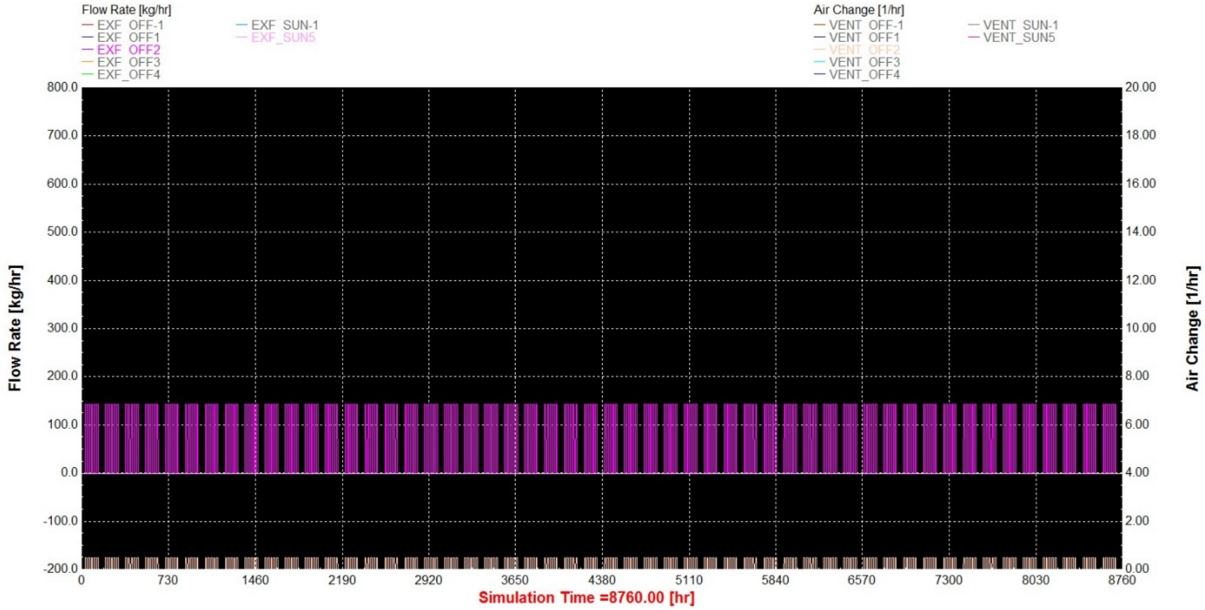
Total Offices Load Intensity *(kJ/hr)*

Run6 C (MC 4-Story DSF0.5 Shading Full HVAC)



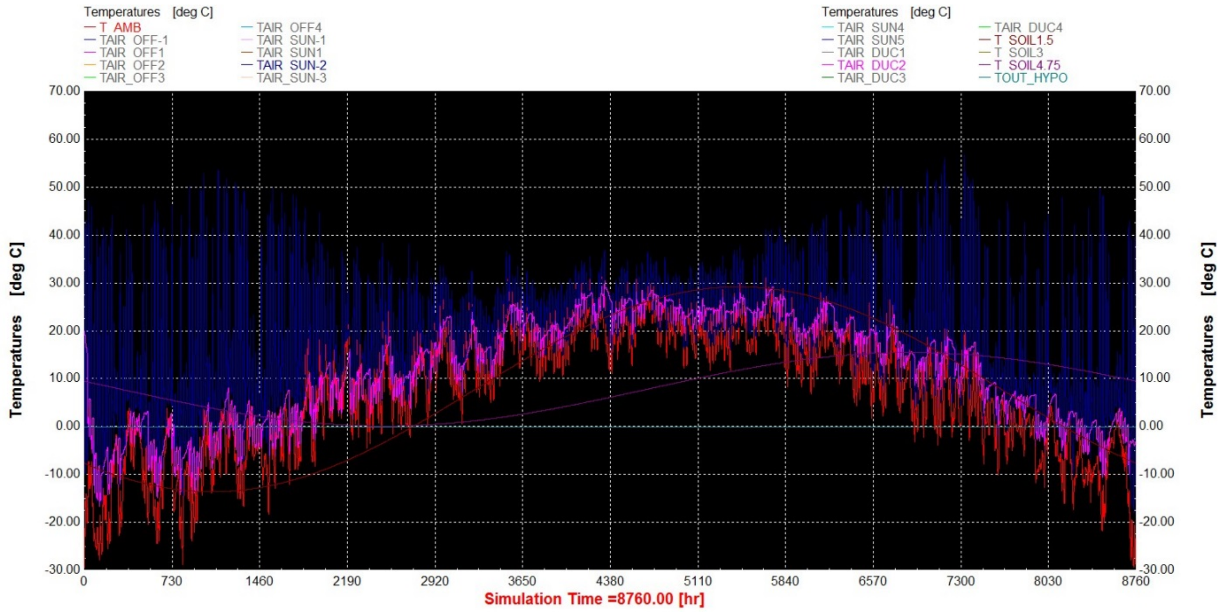
Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run6 C (MC 4-Story DSF0.5 Shading Full HVAC)



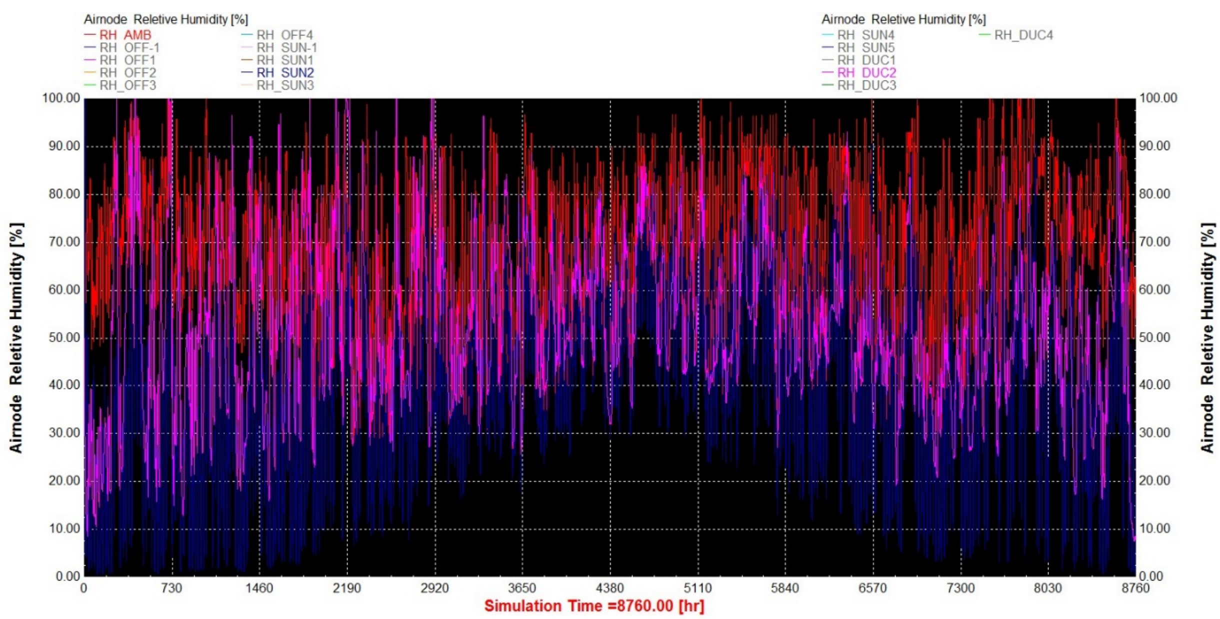
Zones Temperature *(°C)*

Run7 D (MC 4-Story MV DSF0.5 Full HVAC)



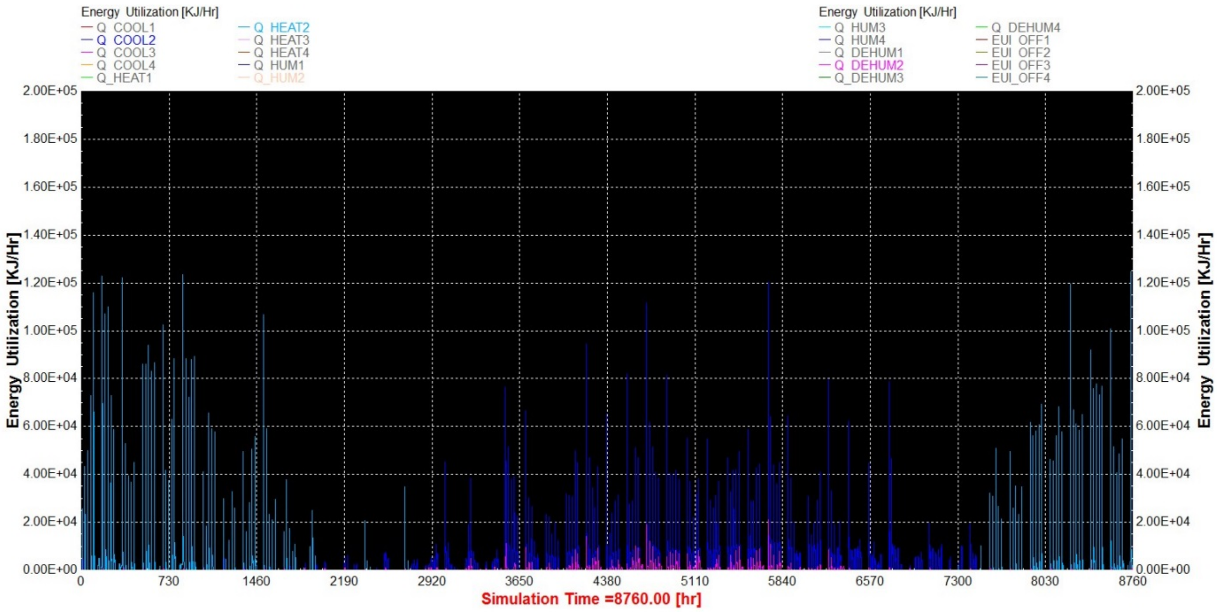
Zones Relative Humidity *(%)*

Run7 D (MC 4-Story MV DSF0.5 Full HVAC)



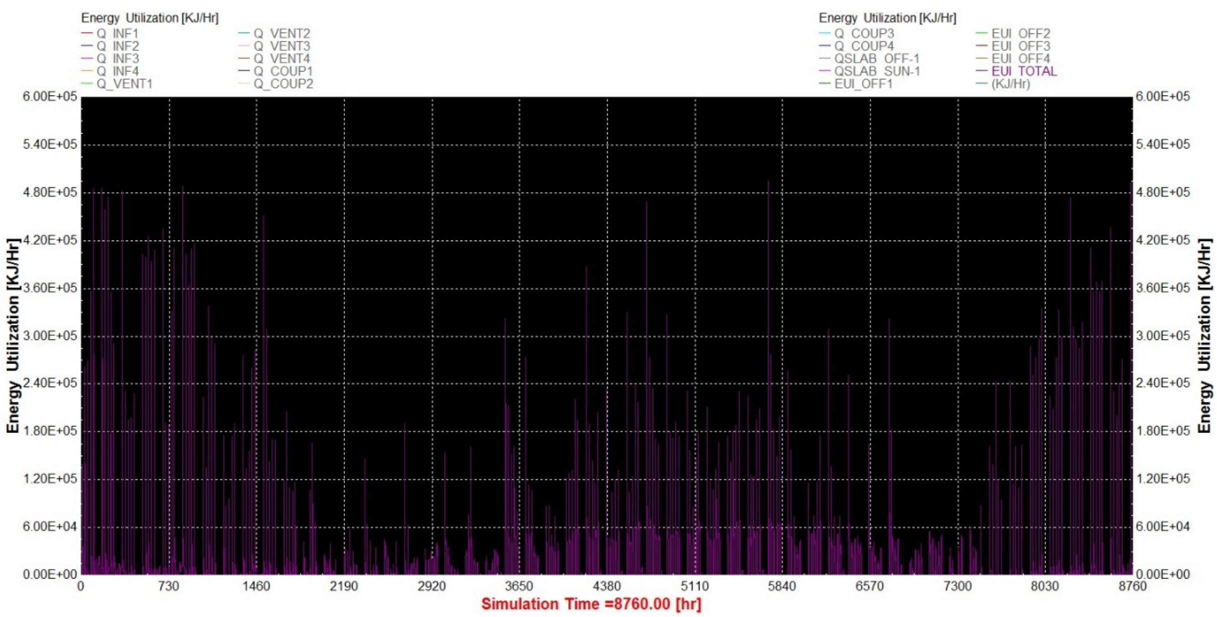
Office Load Intensity *(kJ/hr)*

Run7 D (MC 4-Story MV DSF0.5 Full HVAC)



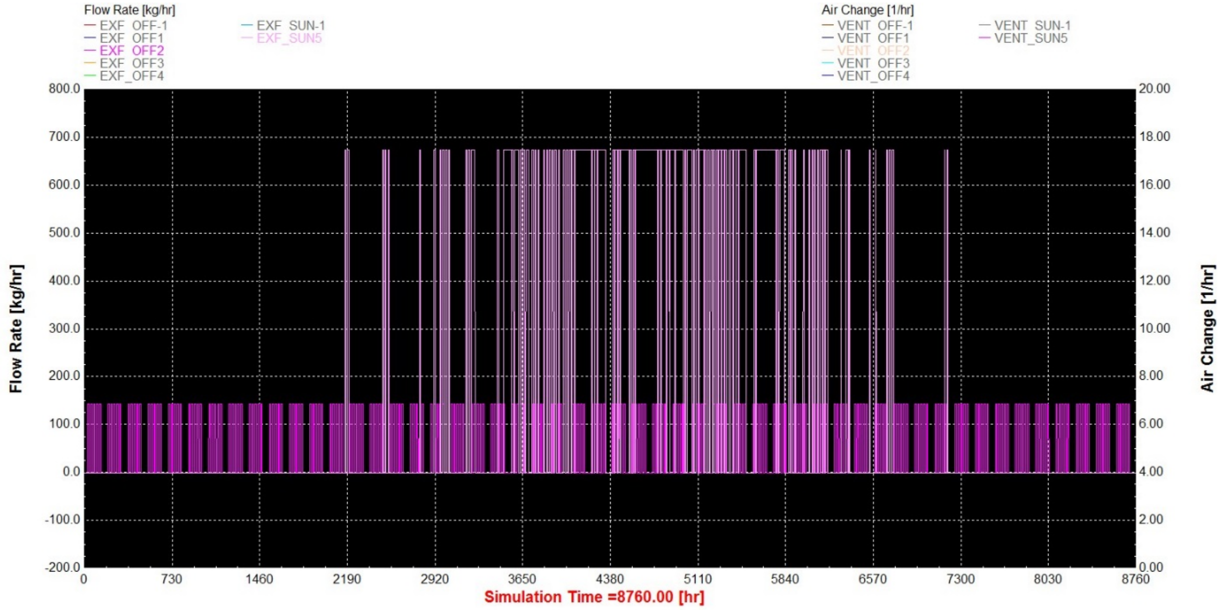
Total Offices Load Intensity *(kJ/hr)*

Run7 D (MC 4-Story MV DSF0.5 Full HVAC)



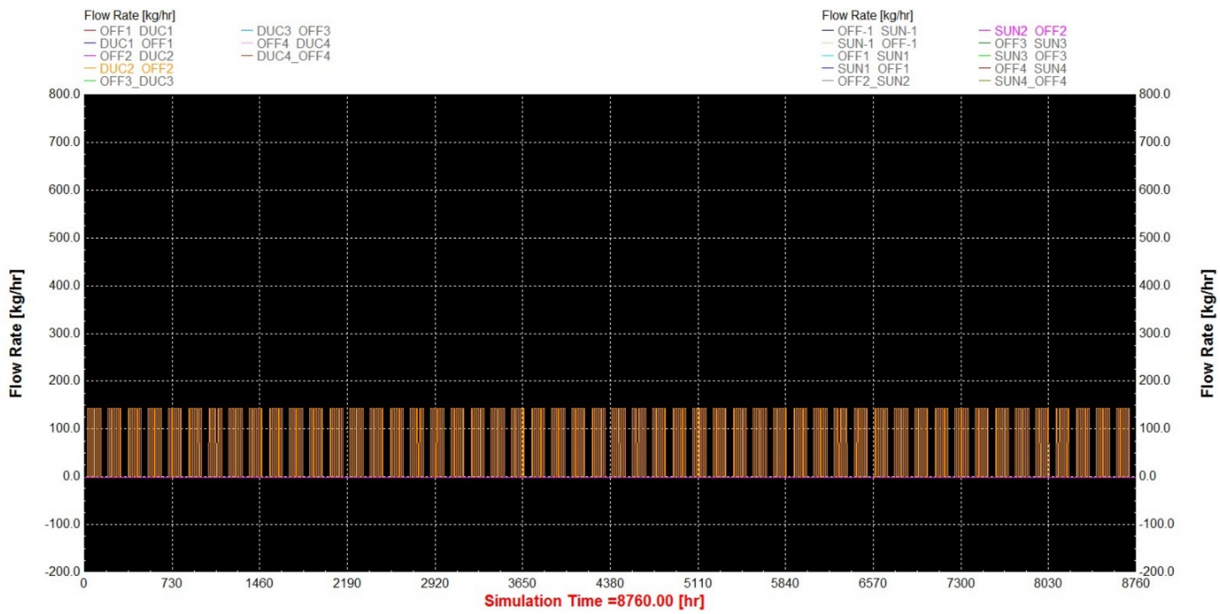
Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run7 D (MC 4-Story MV DSF0.5 Full HVAC)



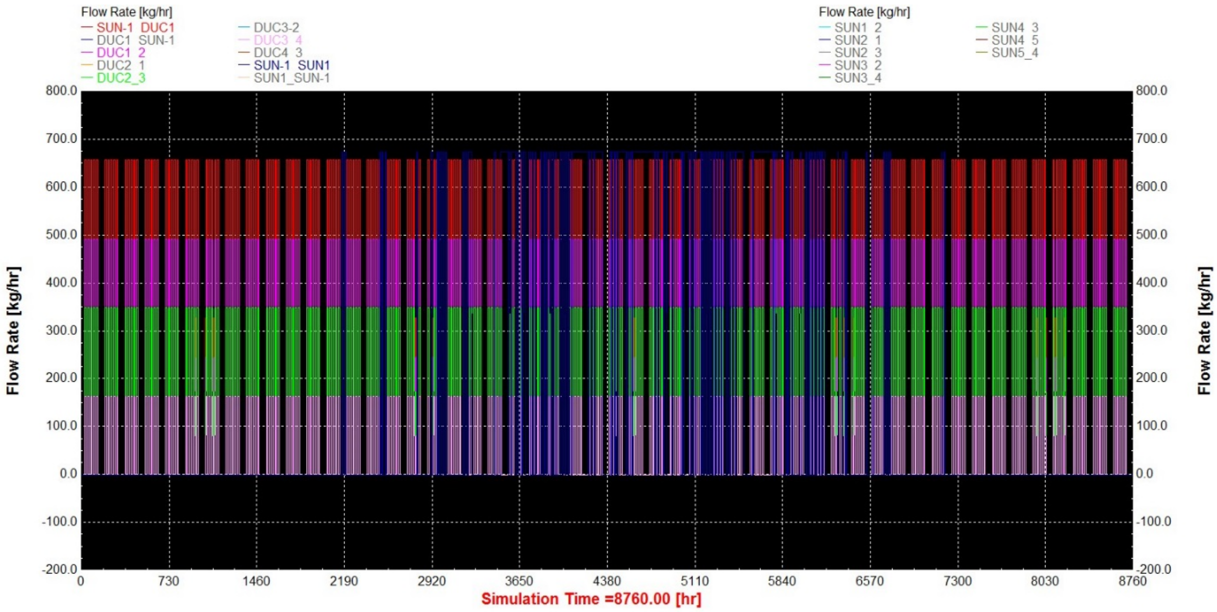
Sunspaces/Ducts-Offices Airflow *(kg/hr or 1/hr)*

Run7 D (MC 4-Story MV DSF0.5 Full HVAC)



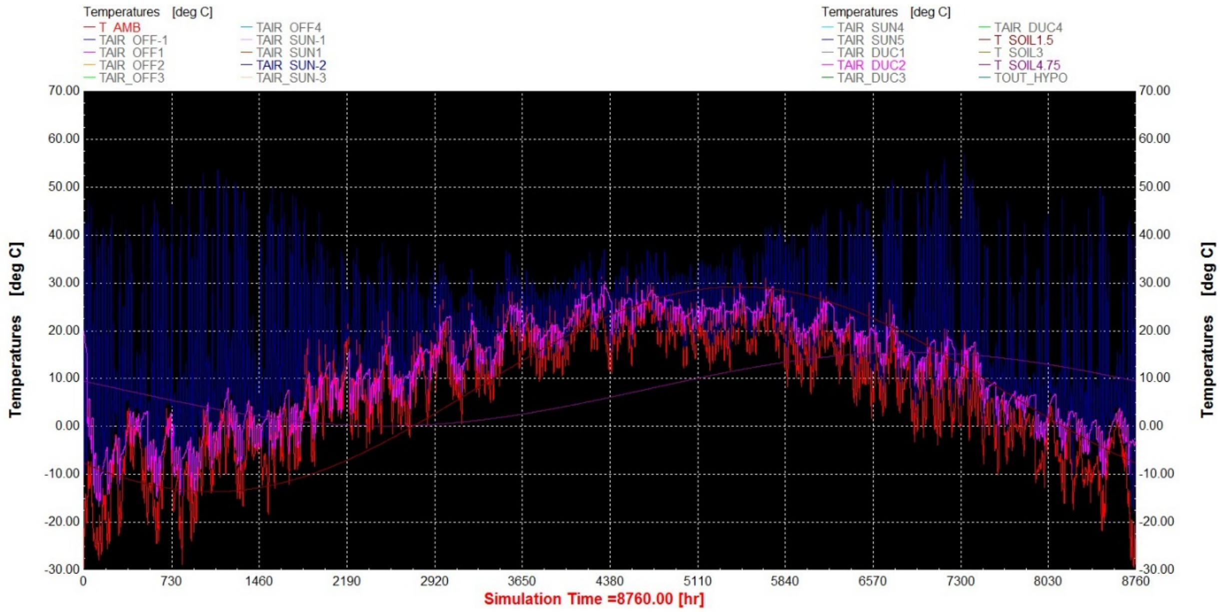
Sunspace/Duct-Sunspace/Duct Airflow *(kg/hr or 1/hr)*

Run7 D (MC 4-Story MV DSF0.5 Full HVAC)



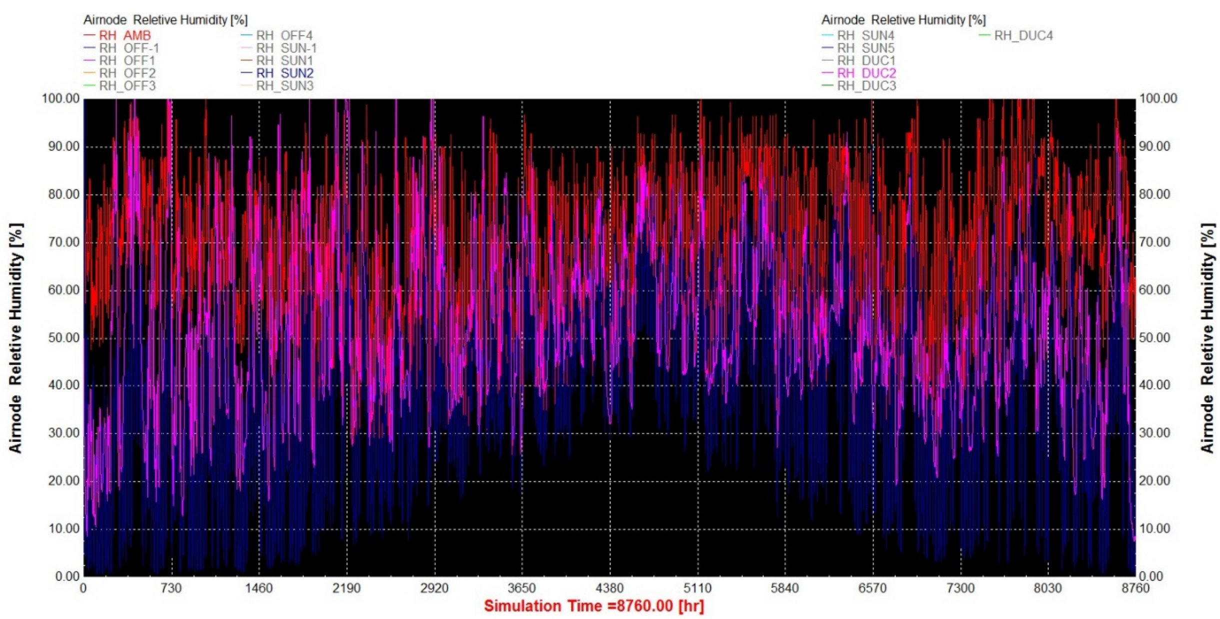
Zones Temperature *(°C)*

Run8 E (MC 4-Story NV DSF0.5 Full HVAC)



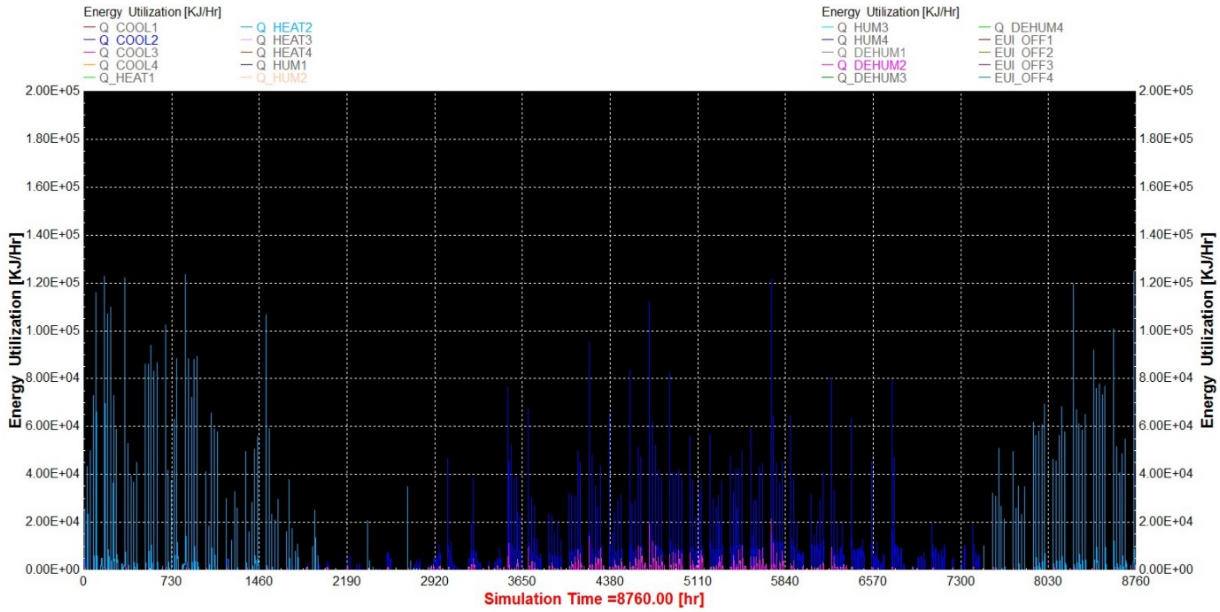
Zones Relative Humidity *(%)*

Run8 E (MC 4-Story NV DSF0.5 Full HVAC)



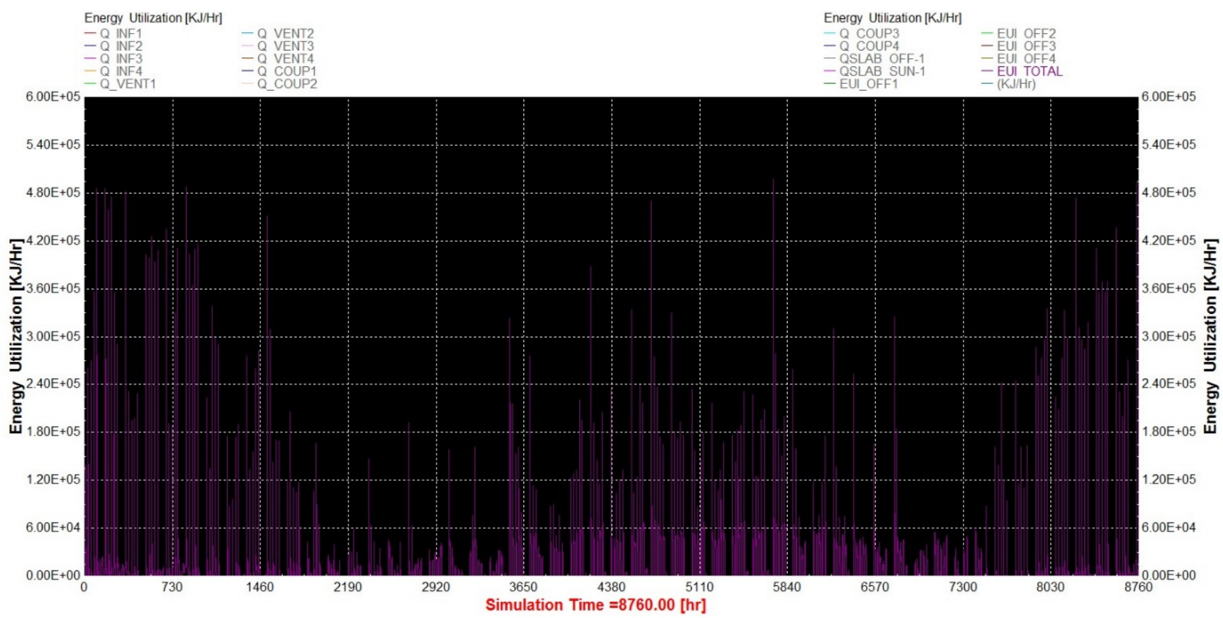
Office Load Intensity *(kJ/hr)*

Run8 E (MC 4-Story NV DSF0.5 Full HVAC)



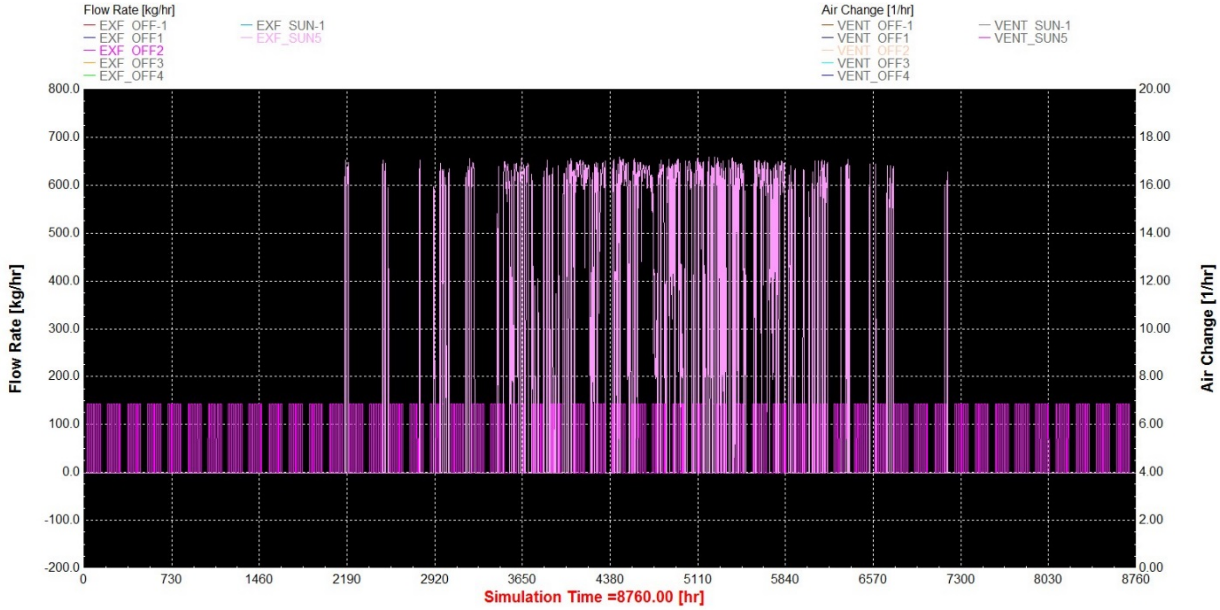
Total Offices Load Intensity *(kJ/hr)*

Run8 E (MC 4-Story NV DSF0.5 Full HVAC)



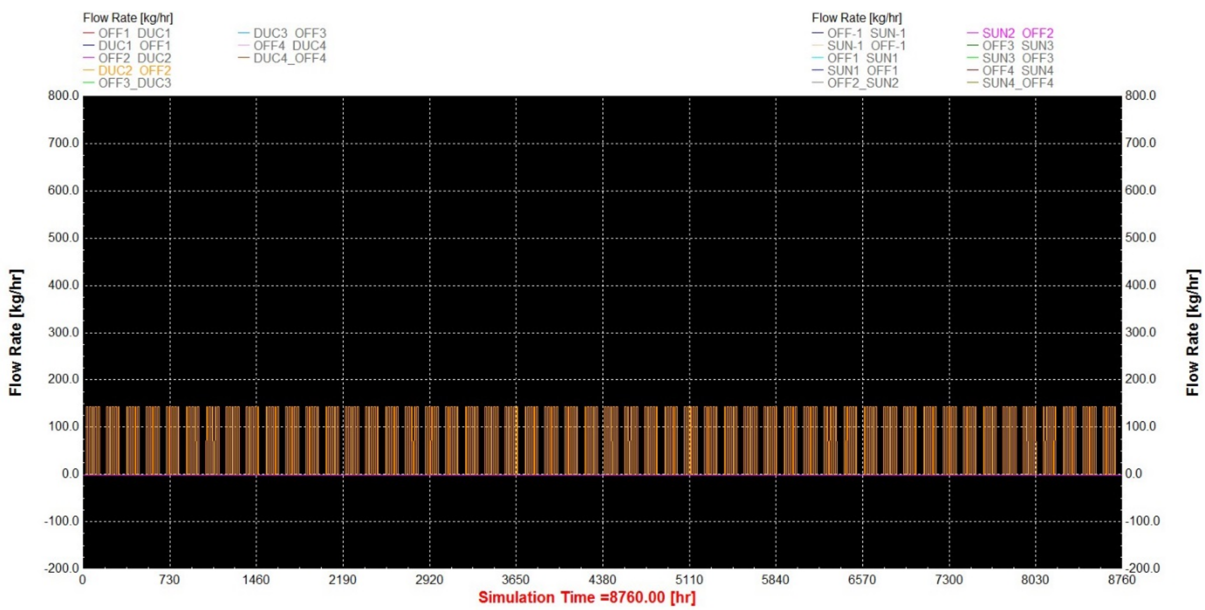
Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run8 E (MC 4-Story NV DSF0.5 Full HVAC)



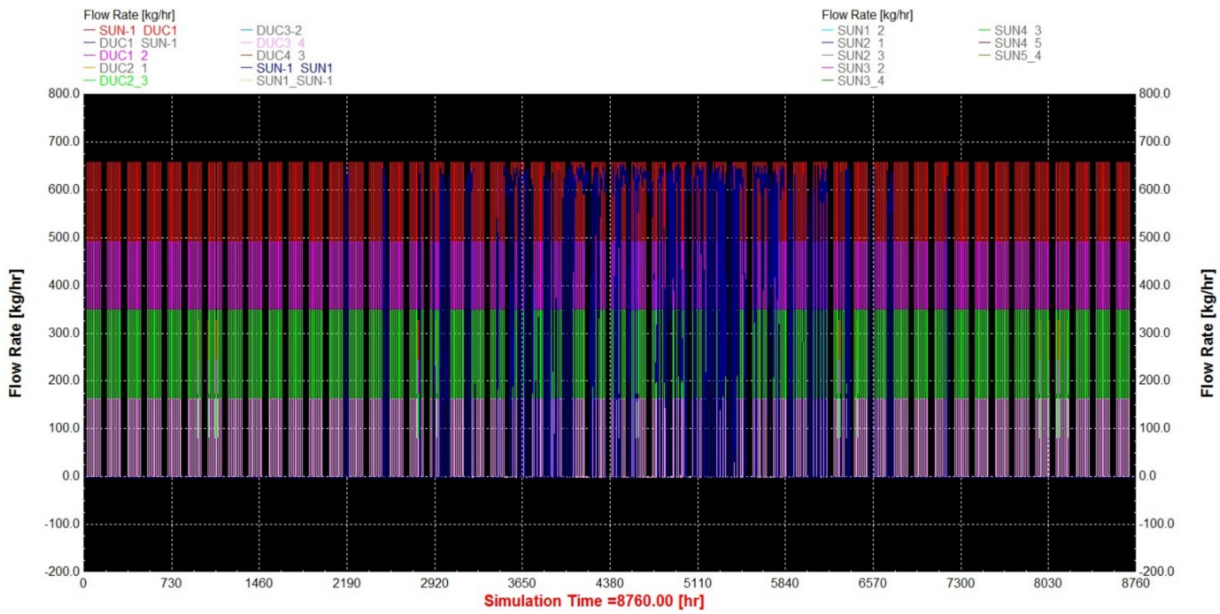
Sunspaces/Ducts-Offices Airflow *(kg/hr or 1/hr)*

Run8 E (MC 4-Story NV DSF0.5 Full HVAC)



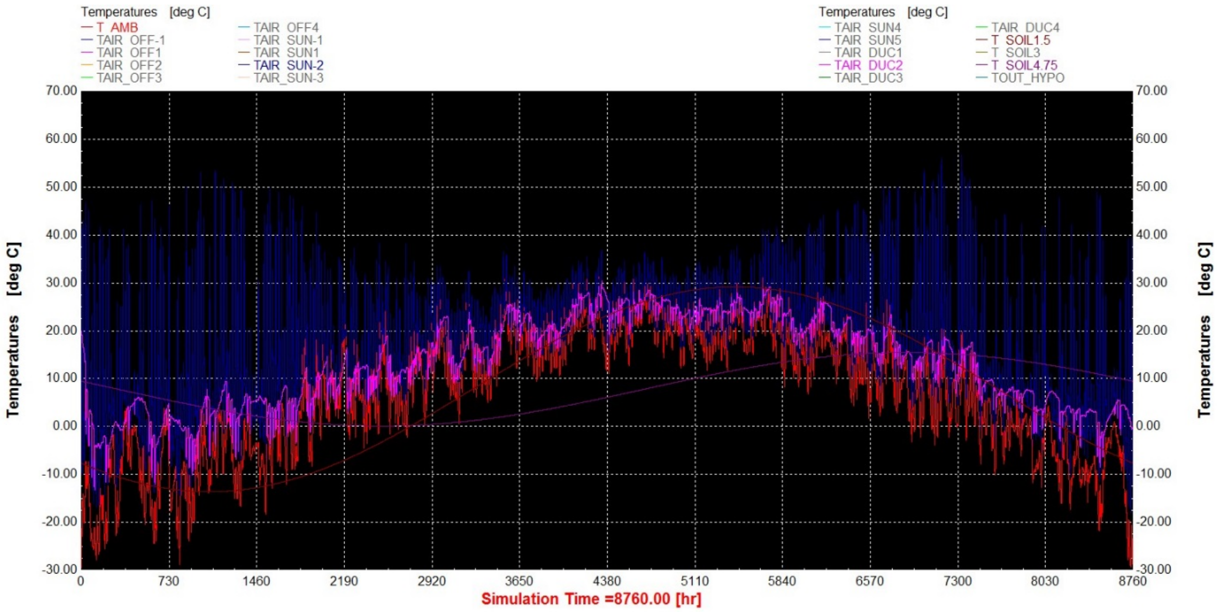
Sunspace/Duct-Sunspace/Duct Airflow *(kg/hr or 1/hr)*

Run8 E (MC 4-Story NV DSF0.5 Full HVAC)



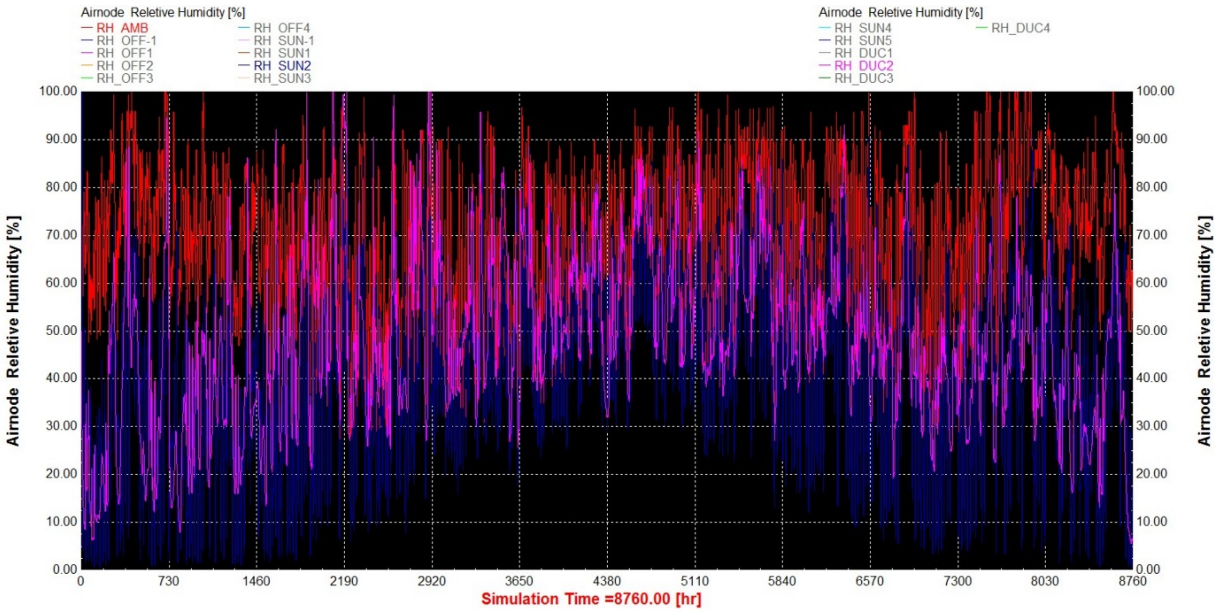
Zones Temperature *(°C)*

Run9 F (MV 4-Story MV DSF0.5 Semi HVAC)



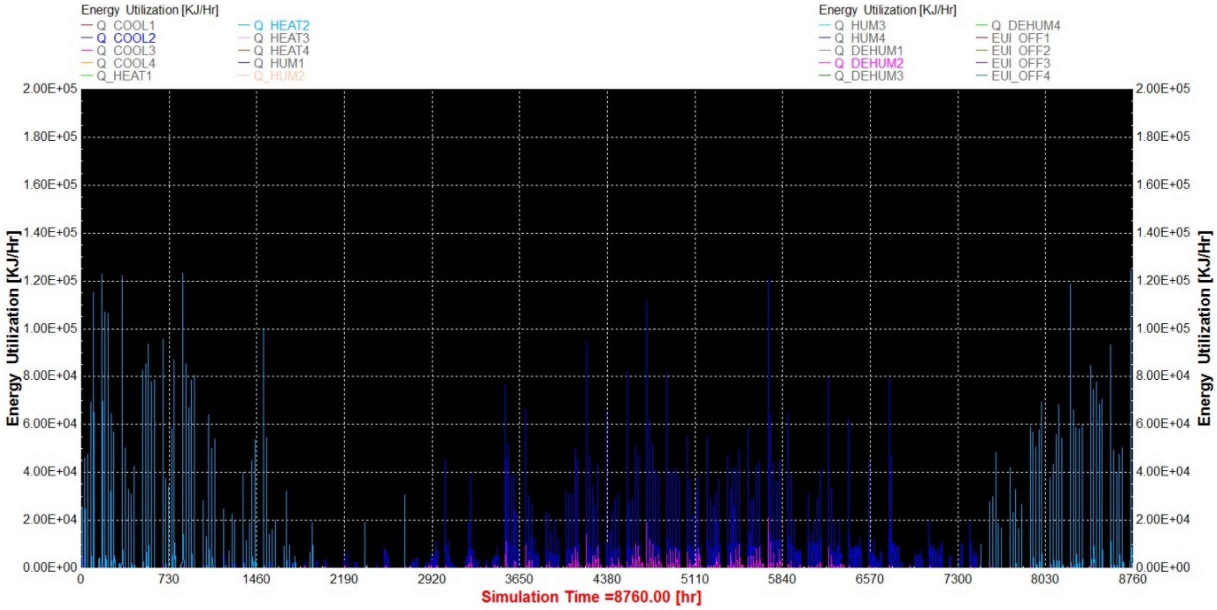
Zones Relative Humidity *(%)*

Run9 E (MV 4-Story MV DSF0.5 Semi HVAC)



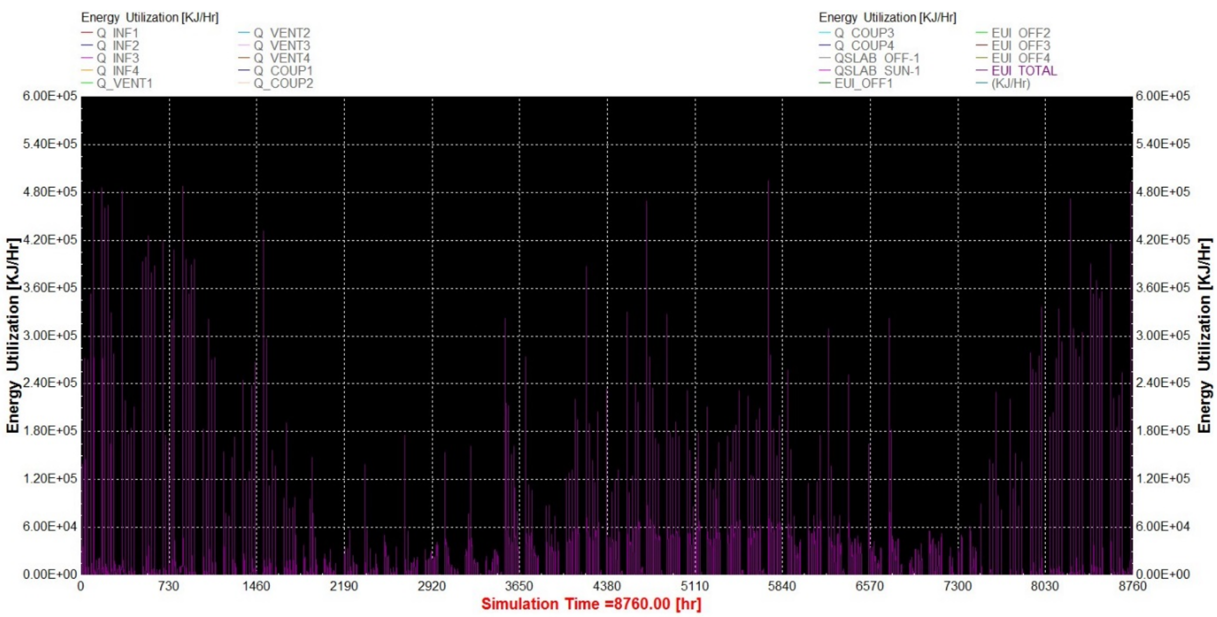
Office Load Intensity *(kJ/hr)*

Run9 F (MV 4-Story MV DSF0.5 Semi HVAC)



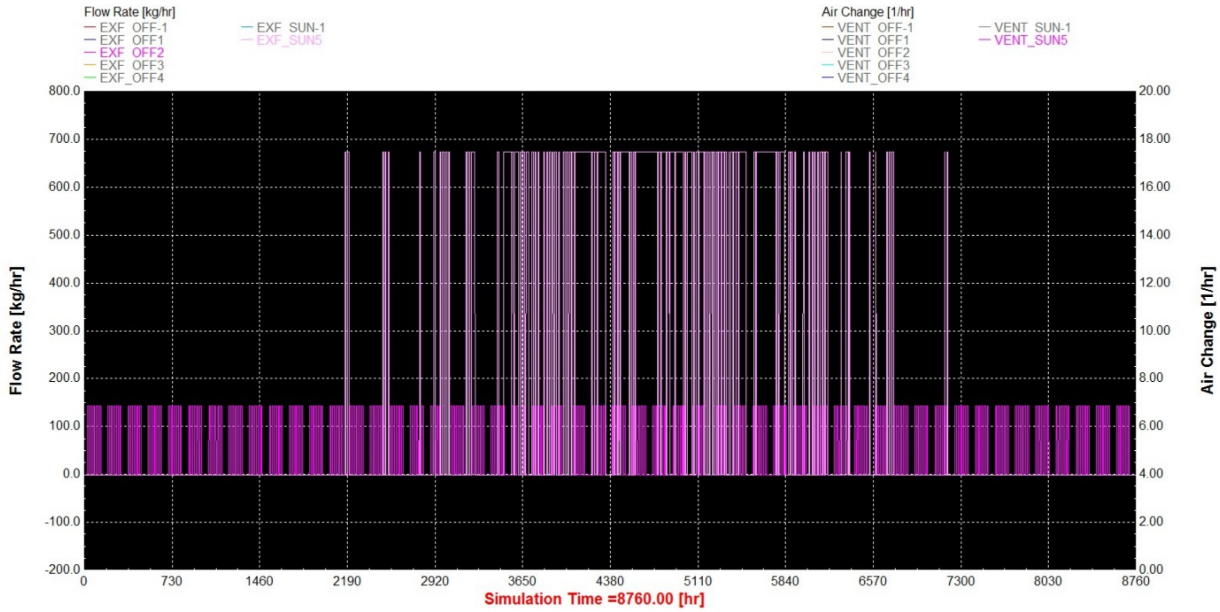
Total Offices Load Intensity *(kJ/hr)*

Run9 F (MV 4-Story MV DSF0.5 Semi HVAC)



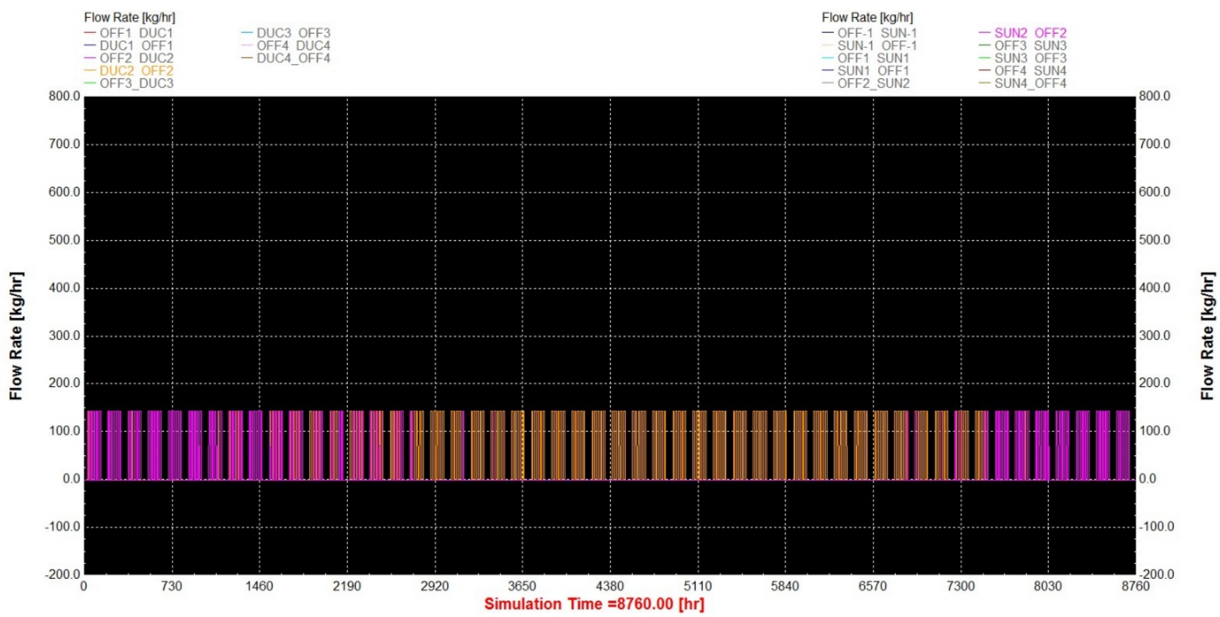
Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run9 F (MV 4-Story MV DSF0.5 Semi HVAC)



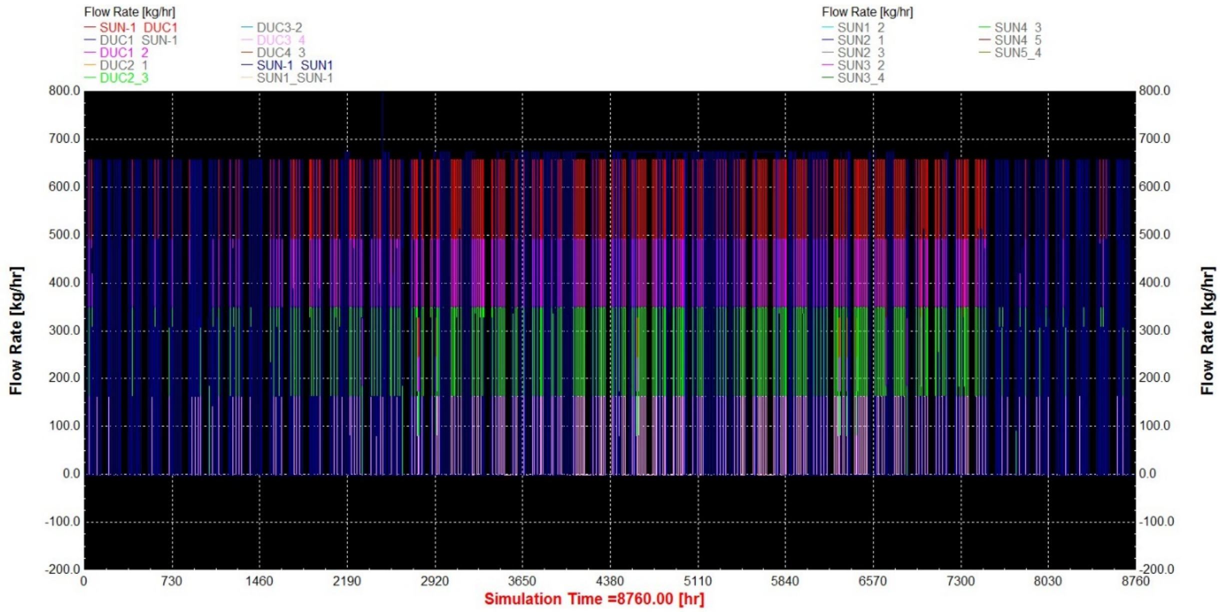
Sunspaces/Ducts-Offices Airflow *(kg/hr or 1/hr)*

Run9 F (MV 4-Story MV DSF0.5 Semi HVAC)



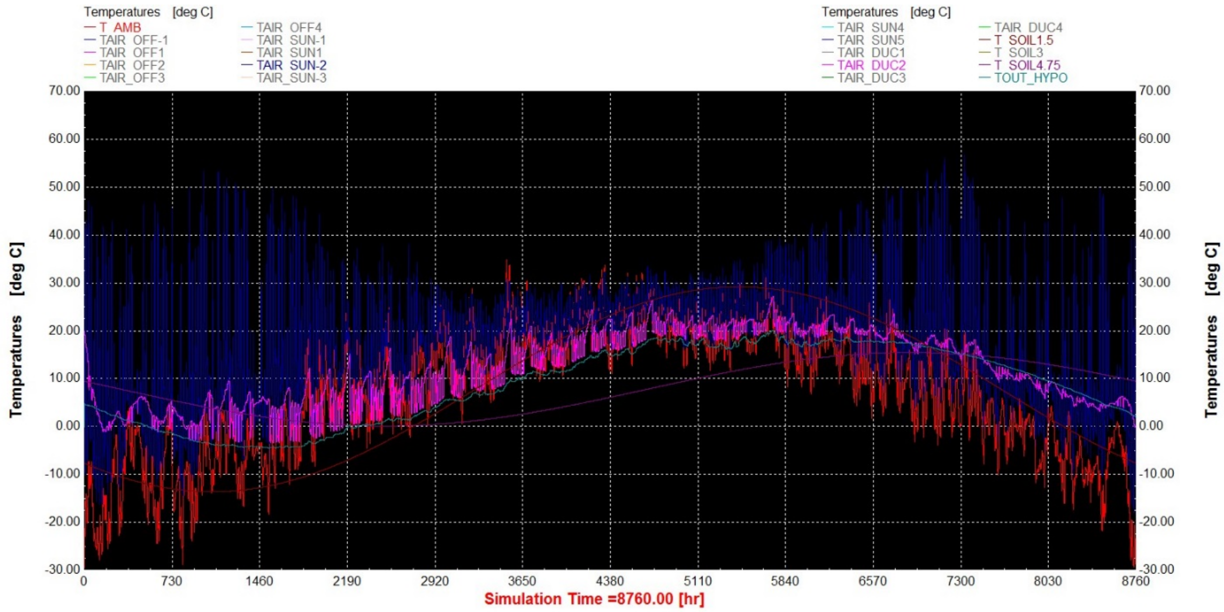
Sunspace/Duct-Sunspace/Duct Airflow *(kg/hr or 1/hr)*

Run9 F (MV 4-Story MV DSF0.5 Semi HVAC)



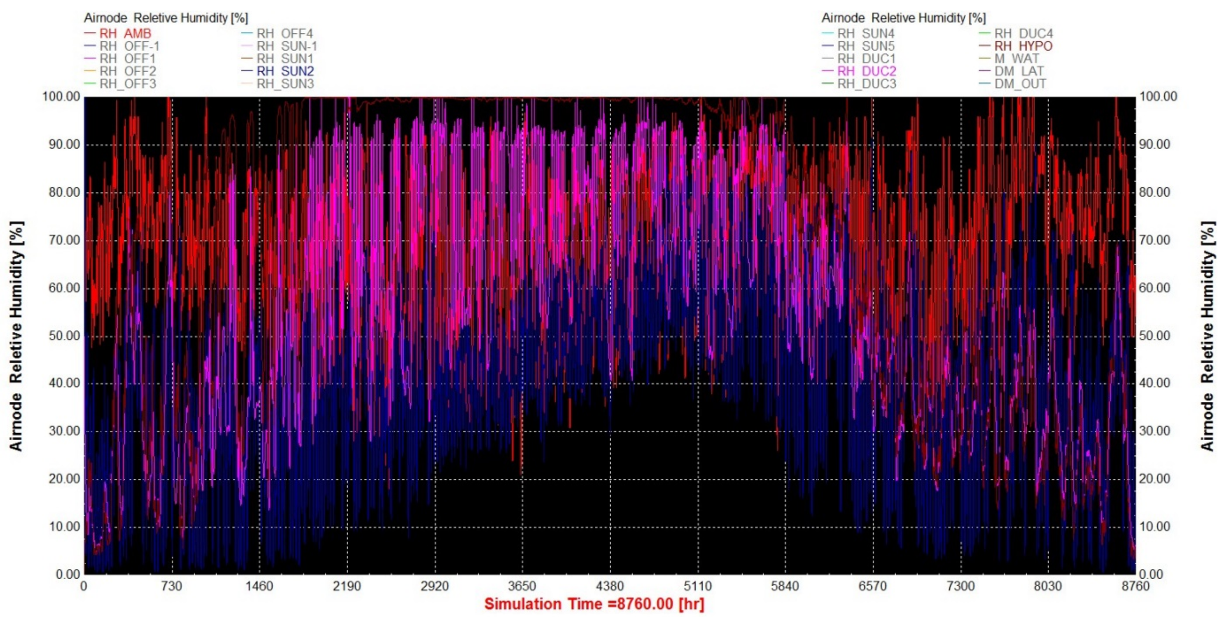
Zones Temperature *(°C)*

Run10 F (MV 4-Story MV DSF0.5 Semi HVAC Hypo)



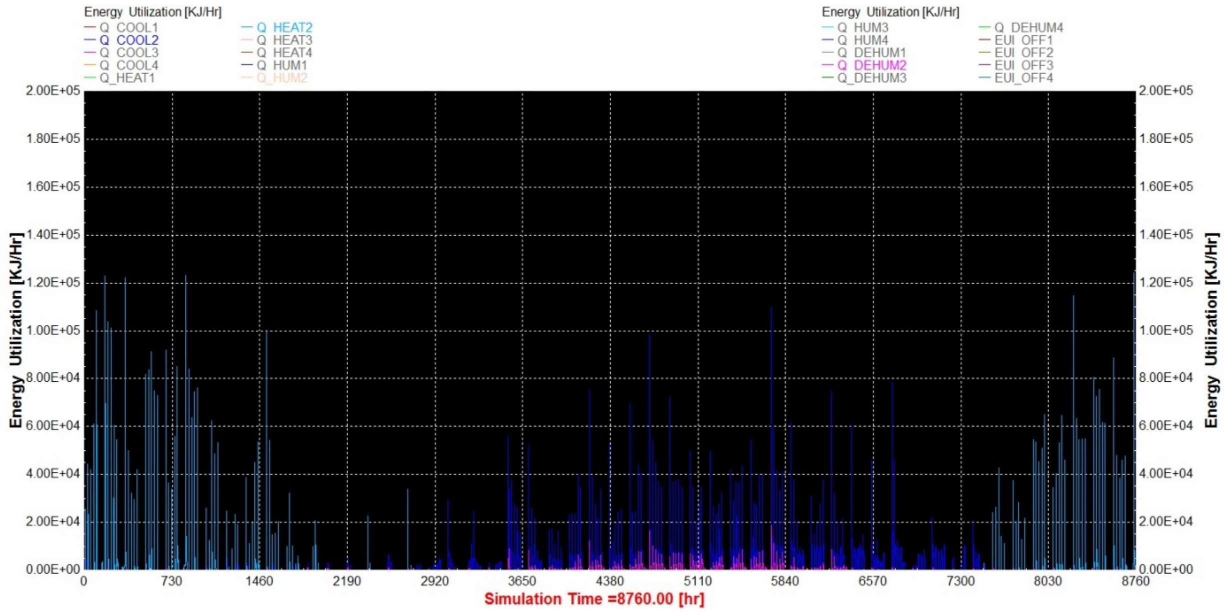
Zones Relative Humidity *(%)*

Run10 F (MV 4-Story MV DSF0.5 Semi HVAC Hypo)



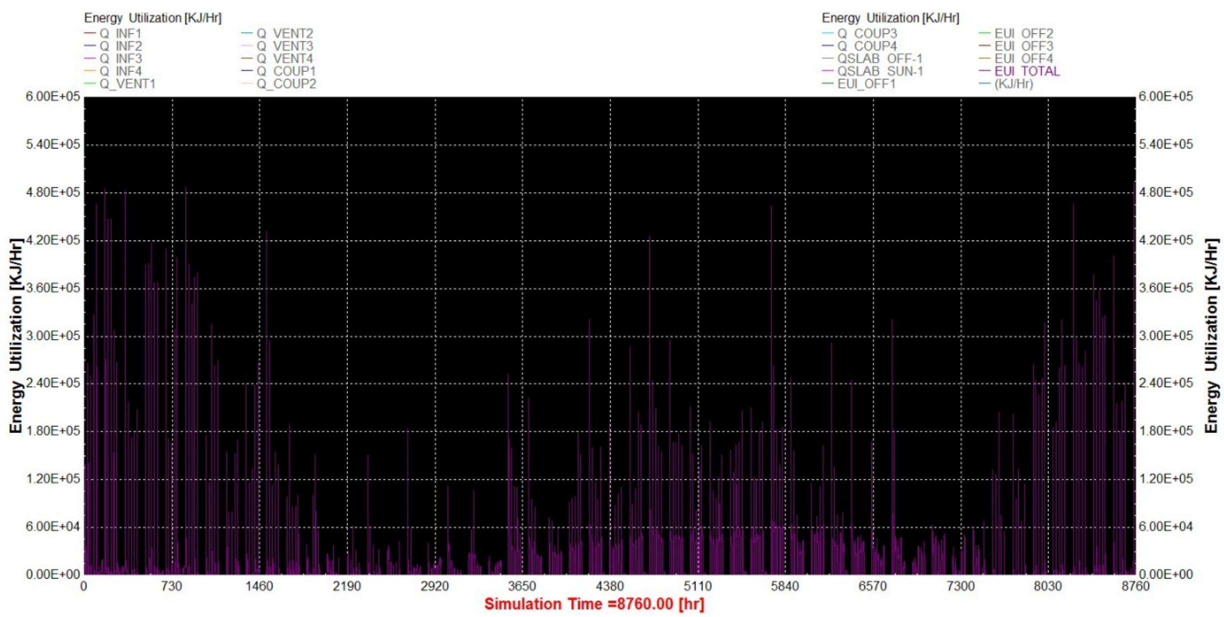
Office Load Intensity *(kJ/hr)*

Run10 F (MV 4-Story MV DSF0.5 Semi HVAC Hypo)



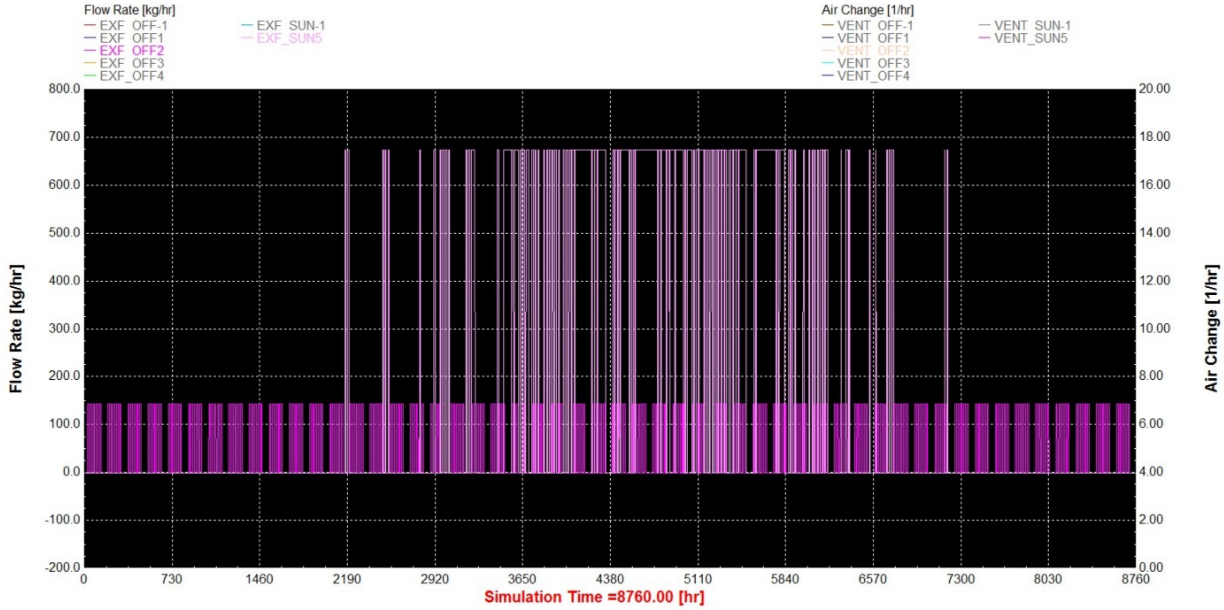
Total Offices Load Intensity *(kJ/hr)*

Run10 F (MV 4-Story MV DSF0.5 Semi HVAC Hypo)



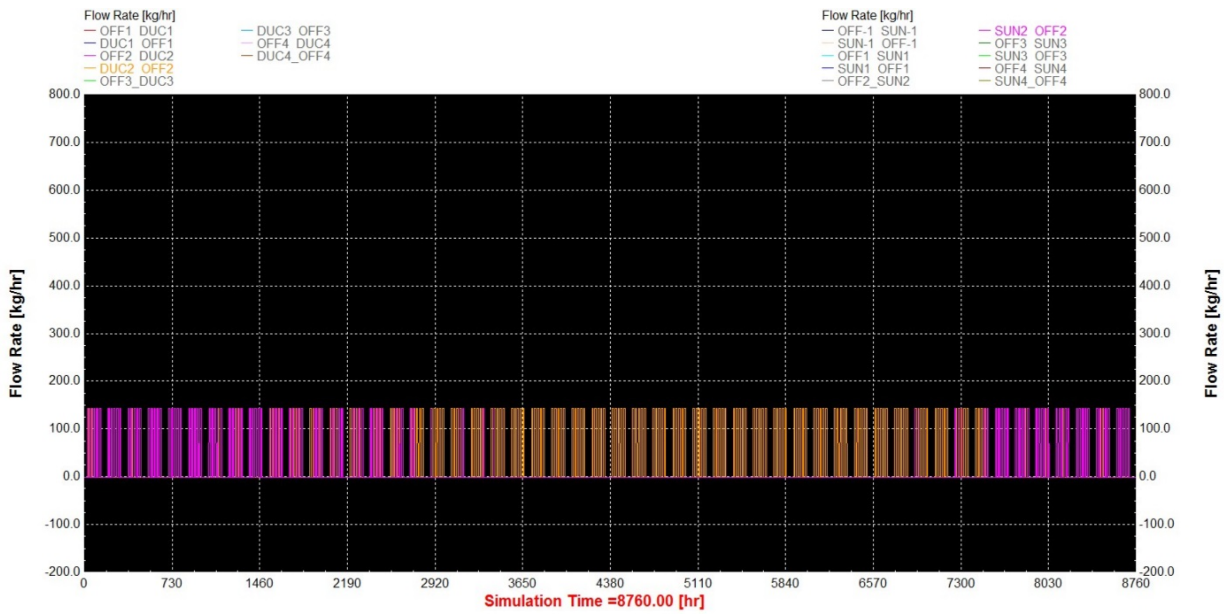
Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run10 F (MV 4-Story MV DSF0.5 Semi HVAC Hypo)



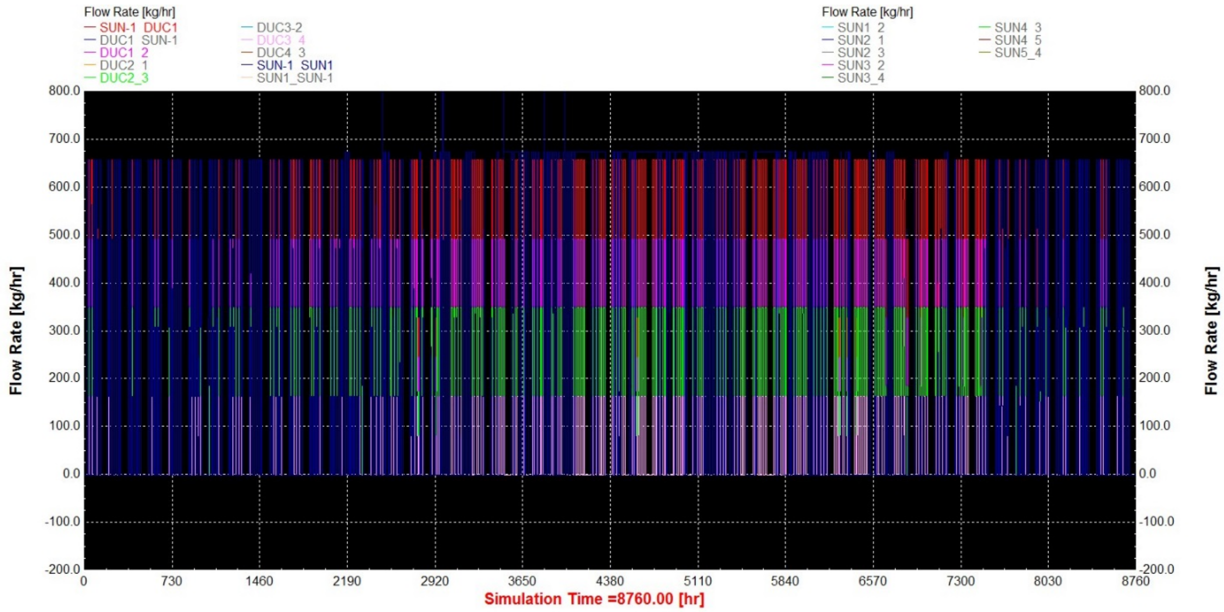
Sunspaces/Ducts-Offices Airflow *(kg/hr or 1/hr)*

Run10 F (MV 4-Story MV DSF0.5 Semi HVAC Hypo)



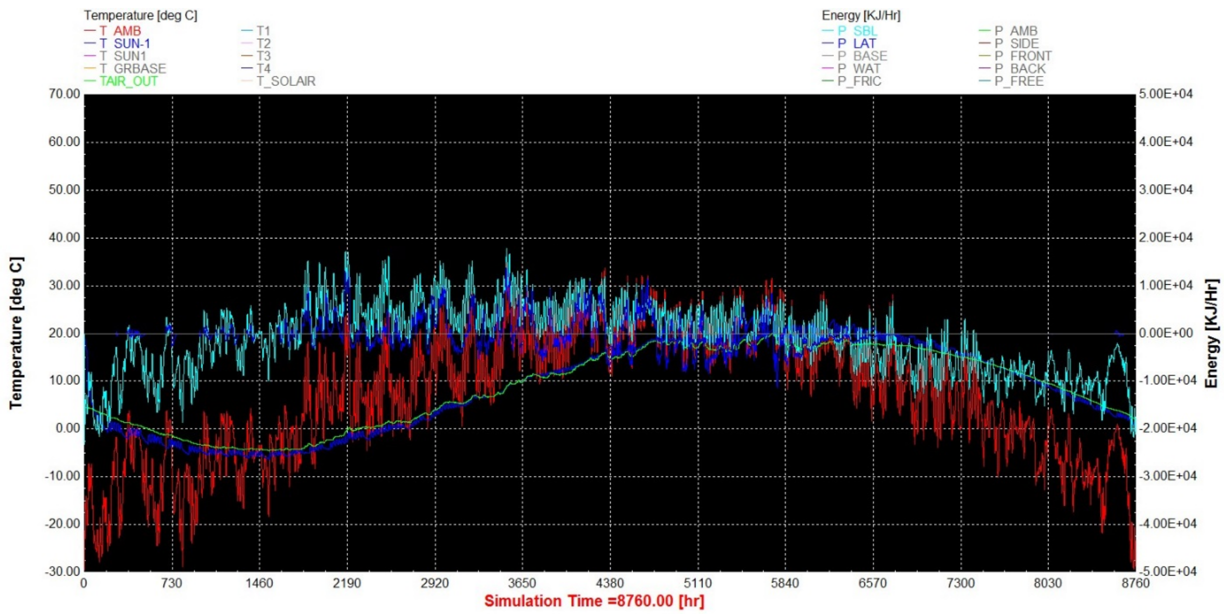
Sunspace/Duct-Sunspace/Duct Airflow *(kg/hr or 1/hr)*

Run10 F (MV 4-Story MV DSF0.5 Semi HVAC Hypo)



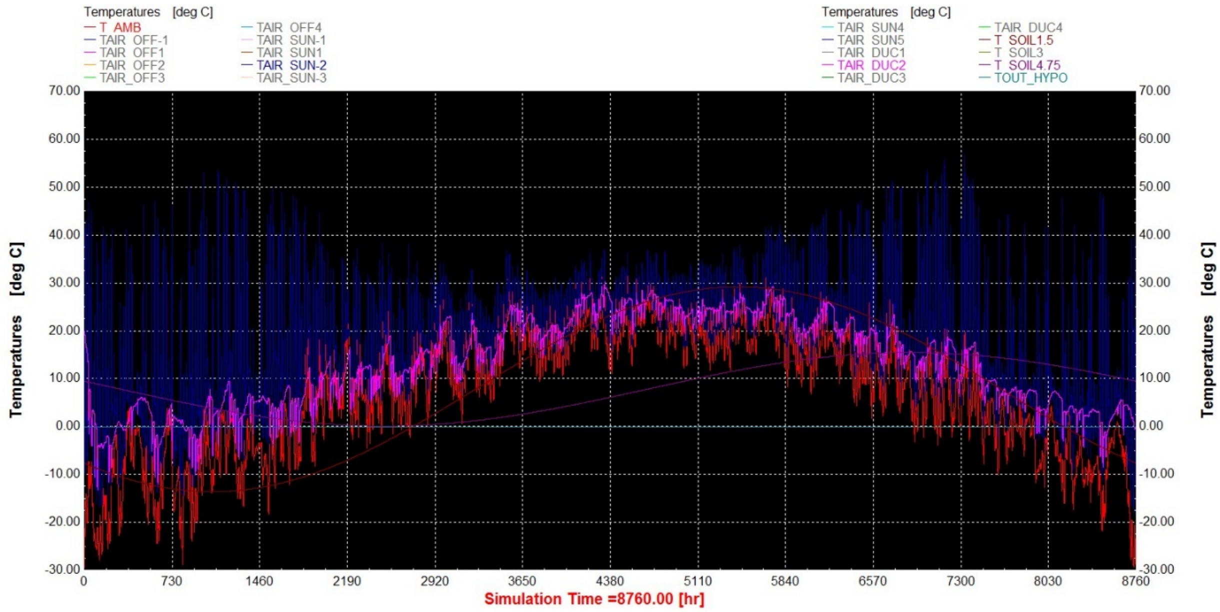
Air-Tubes Temperature and Energy *(°C and kJ/hr)*

Run10 F (MV 4-Story MV DSF0.5 Semi HVAC Hypo)



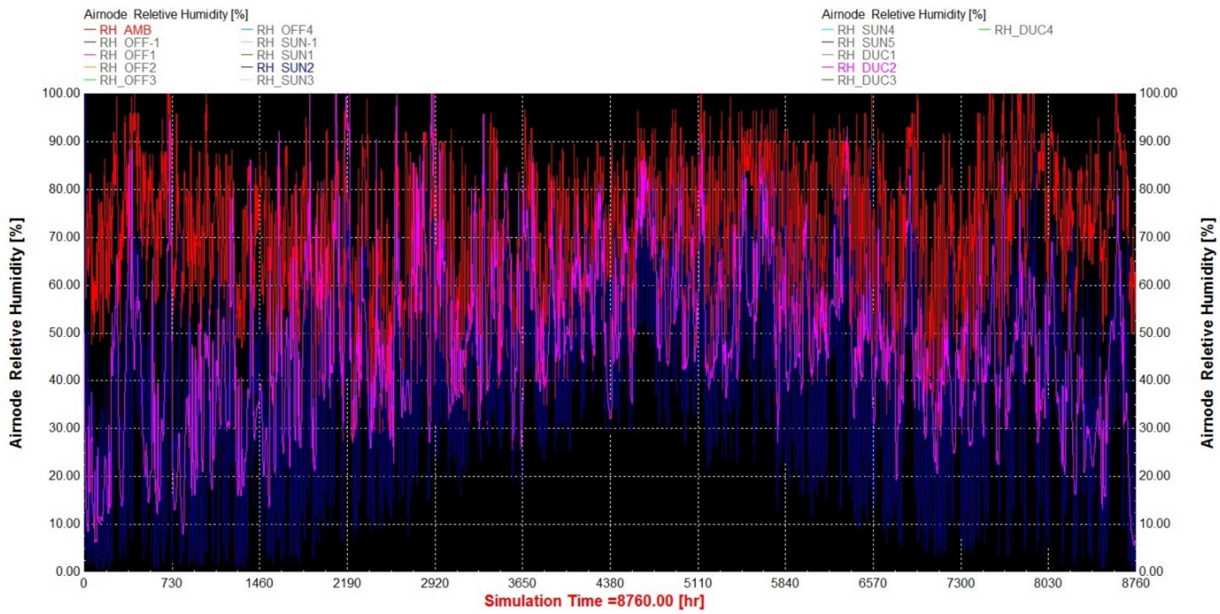
Zones Temperature *(°C)*

Run11 G (MV 4-Story NV DSF0.5 Semi HVAC)



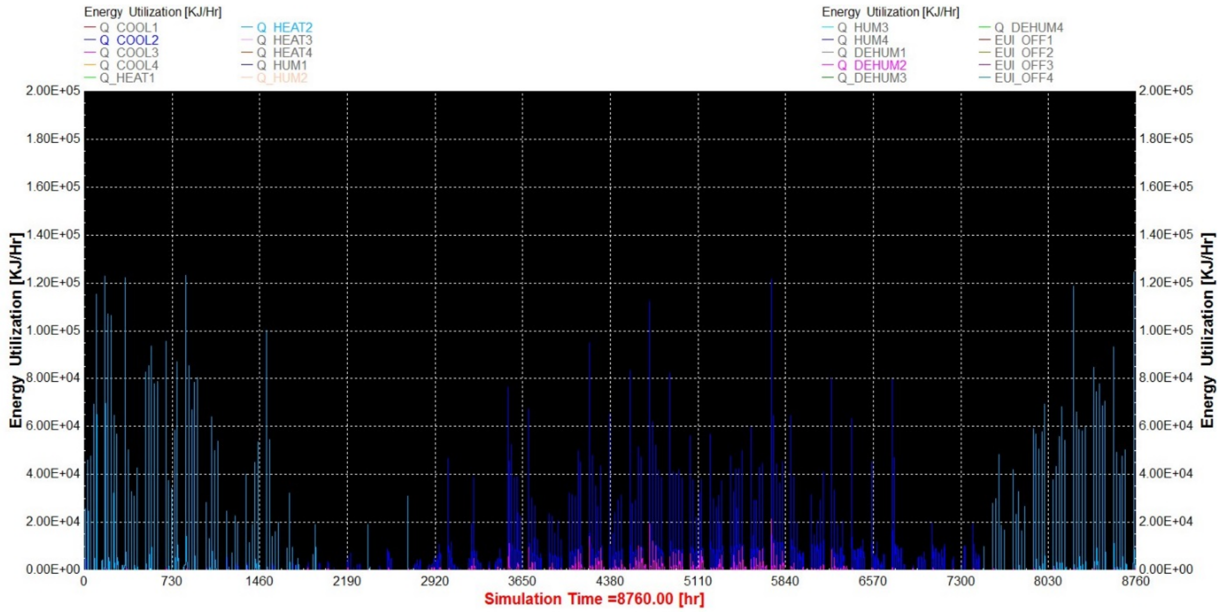
Zones Relative Humidity *(%)*

Run11 G (MV 4-Story NV DSF0.5 Semi HVAC)



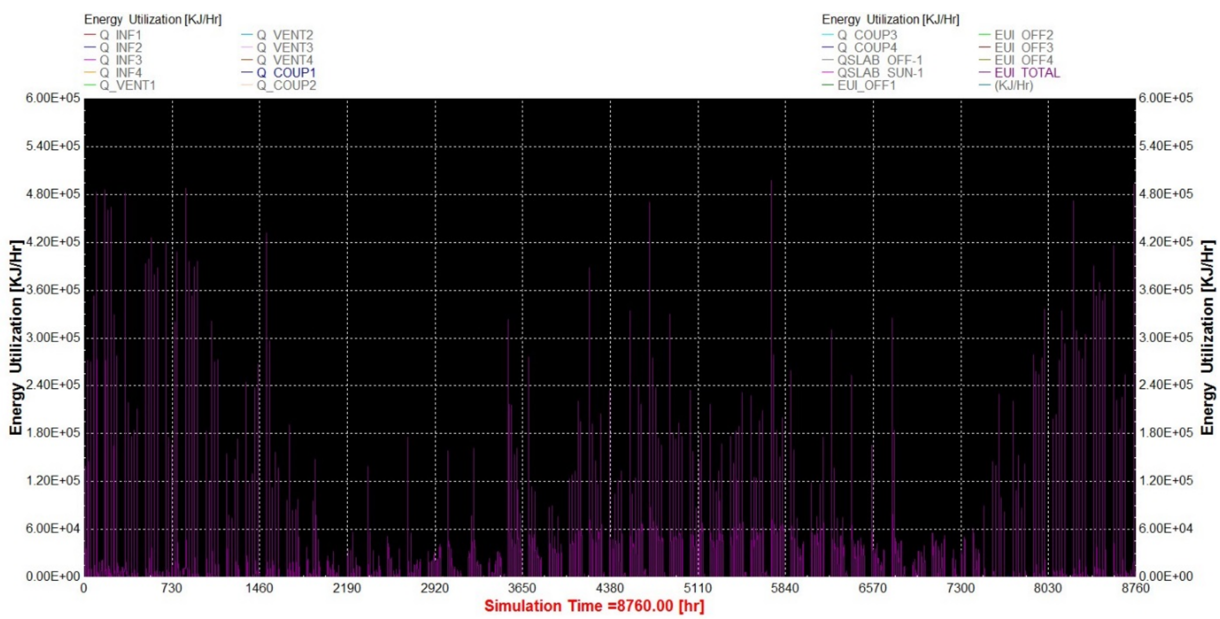
Office Load Intensity *(kJ/hr)*

Run11 G (MV 4-Story NV DSF0.5 Semi HVAC)



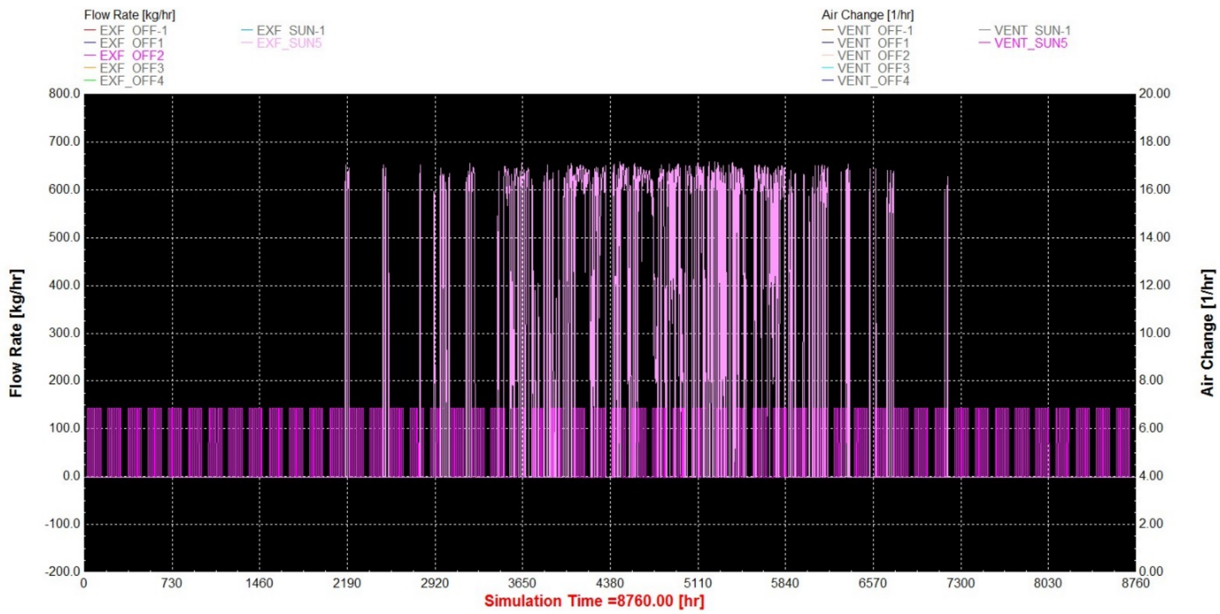
Total Offices Load Intensity *(kJ/hr)*

Run11 G (MV 4-Story NV DSF0.5 Semi HVAC)



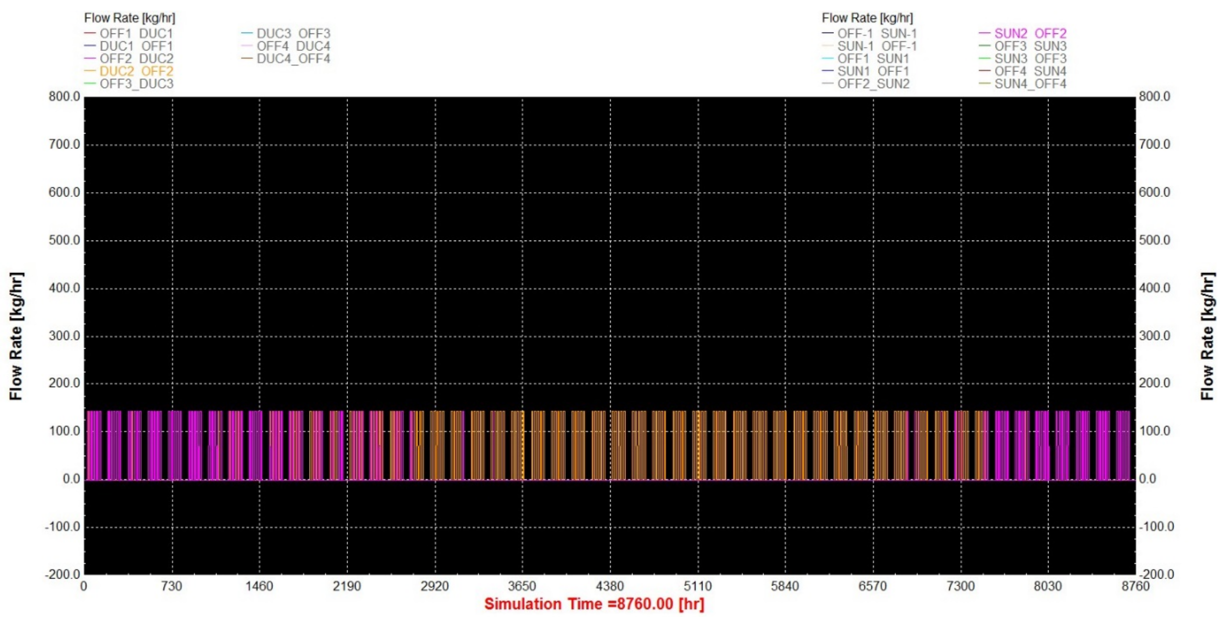
Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run11 G (MV 4-Story NV DSF0.5 Semi HVAC)



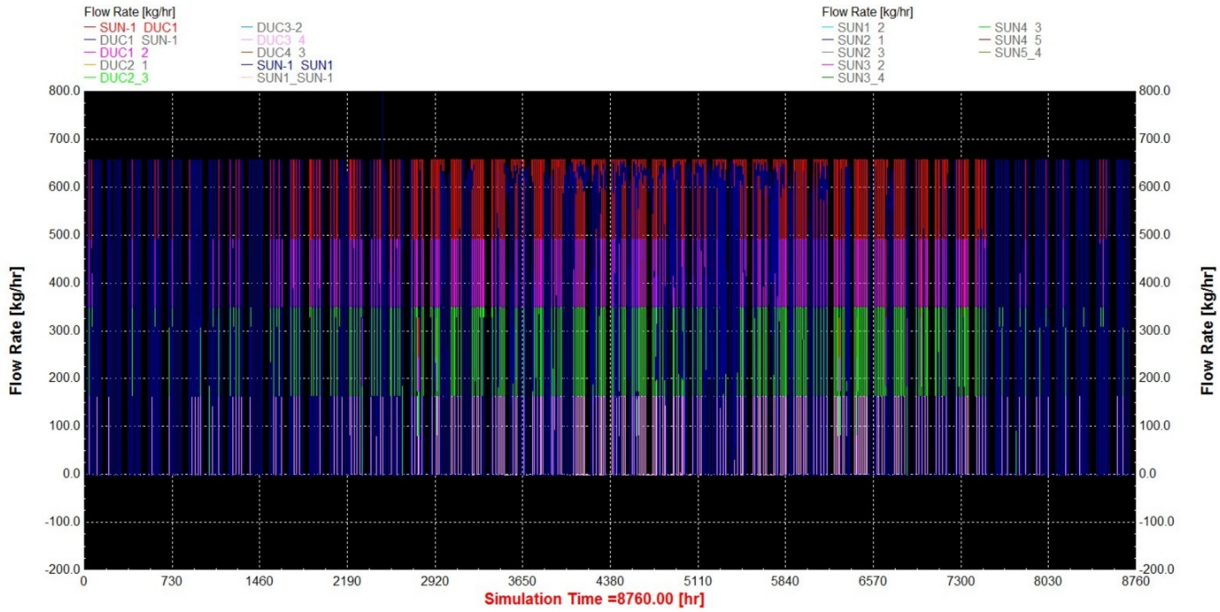
Sunspaces/Ducts-Offices Airflow *(kg/hr or 1/hr)*

Run11 G (MV 4-Story NV DSF0.5 Semi HVAC)



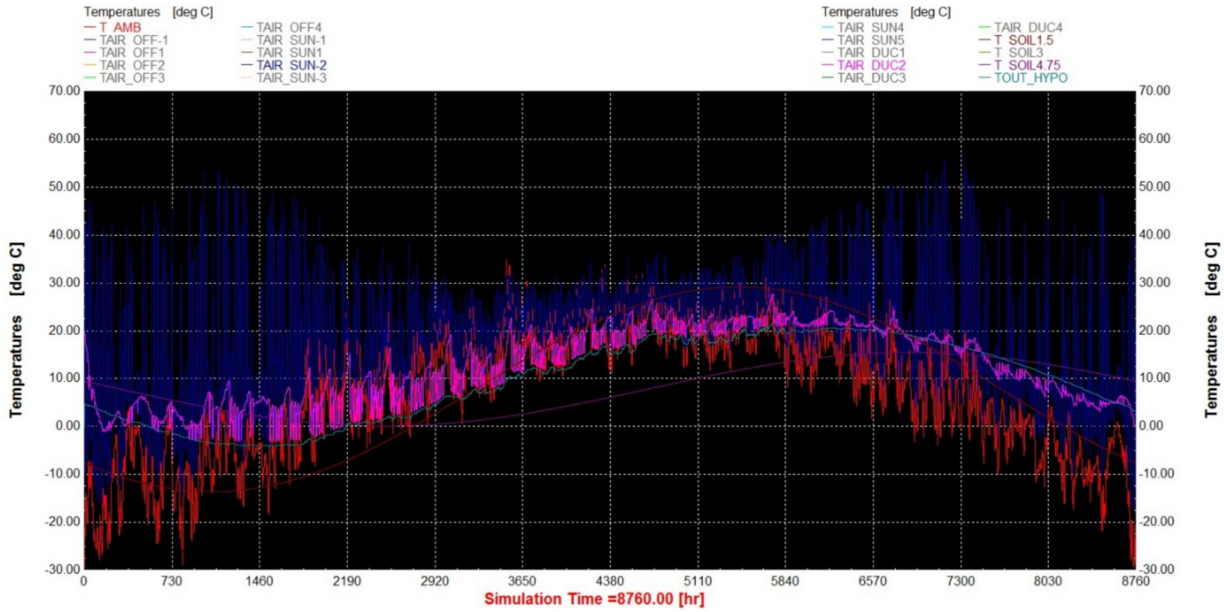
Sunspace/Duct-Sunspace/Duct Airflow *(kg/hr or 1/hr)*

Run11 G (MV 4-Story NV DSF0.5 Semi HVAC)



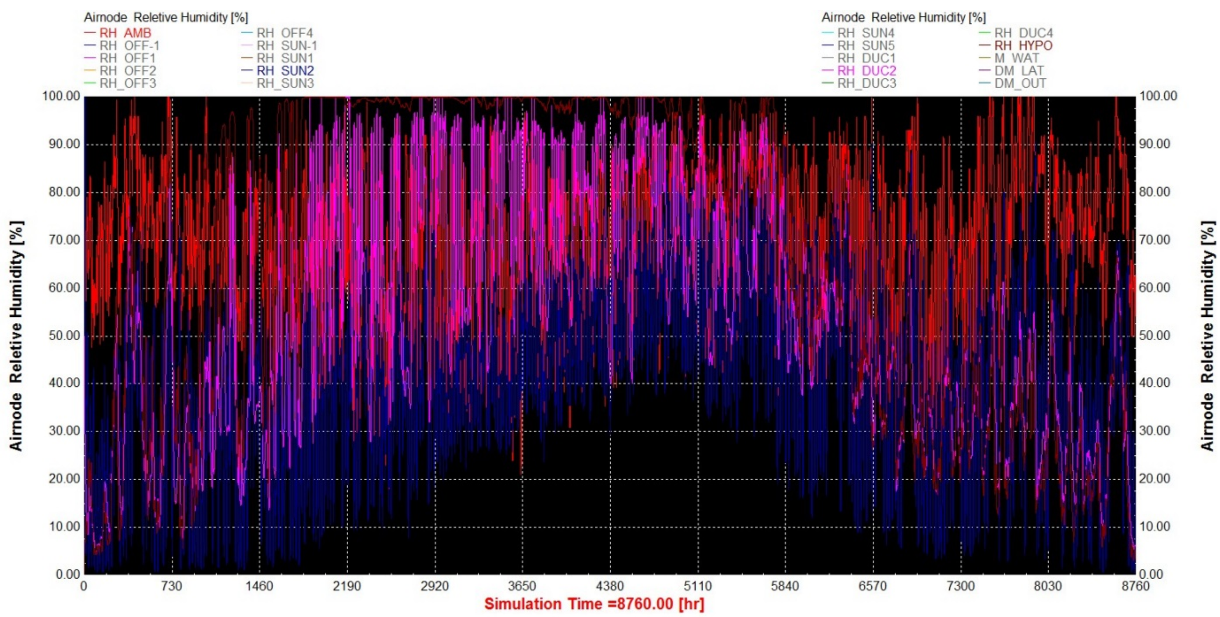
Zones Temperature *(°C)*

Run12 G (MV 4-Story NV DSF0.5 Semi HVAC Hypo)



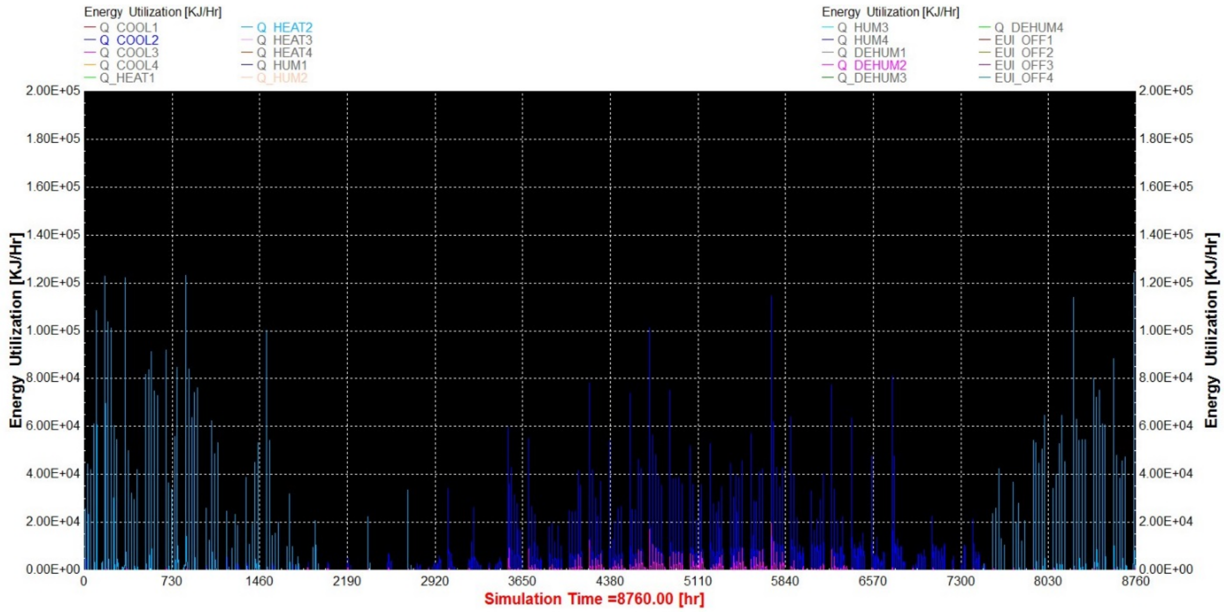
Zones Relative Humidity *(%)*

Run12 G (MV 4-Story NV DSF0.5 Semi HVAC Hypo)



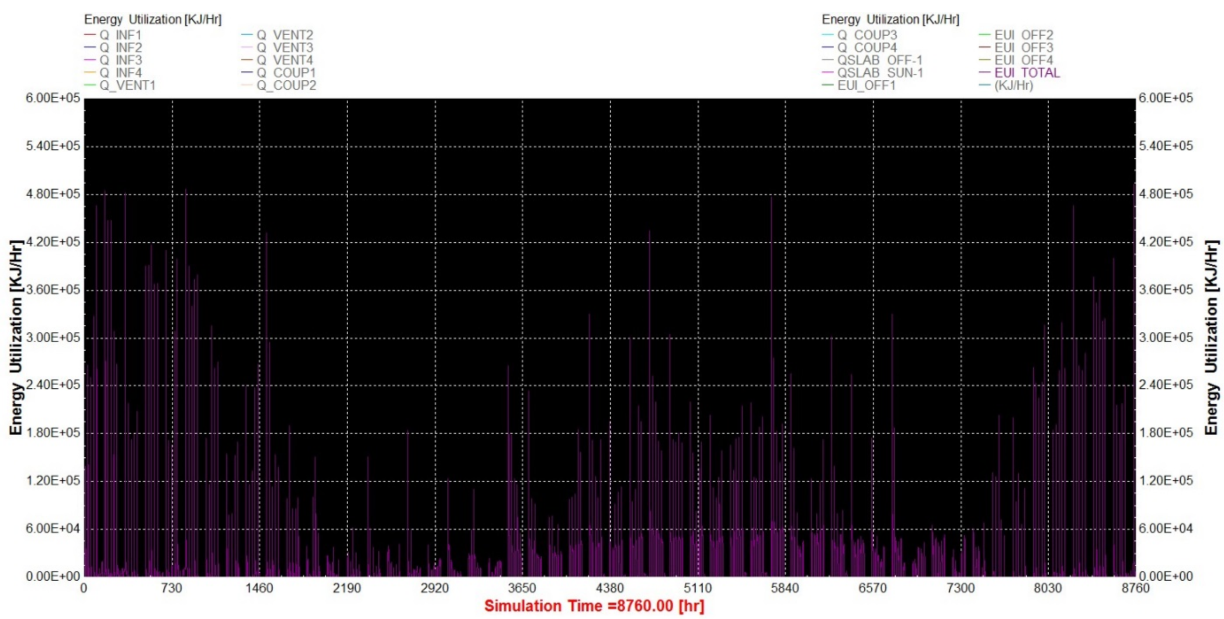
Office Load Intensity *(kJ/hr)*

Run12 G (MV 4-Story NV DSF0.5 Semi HVAC Hypo)



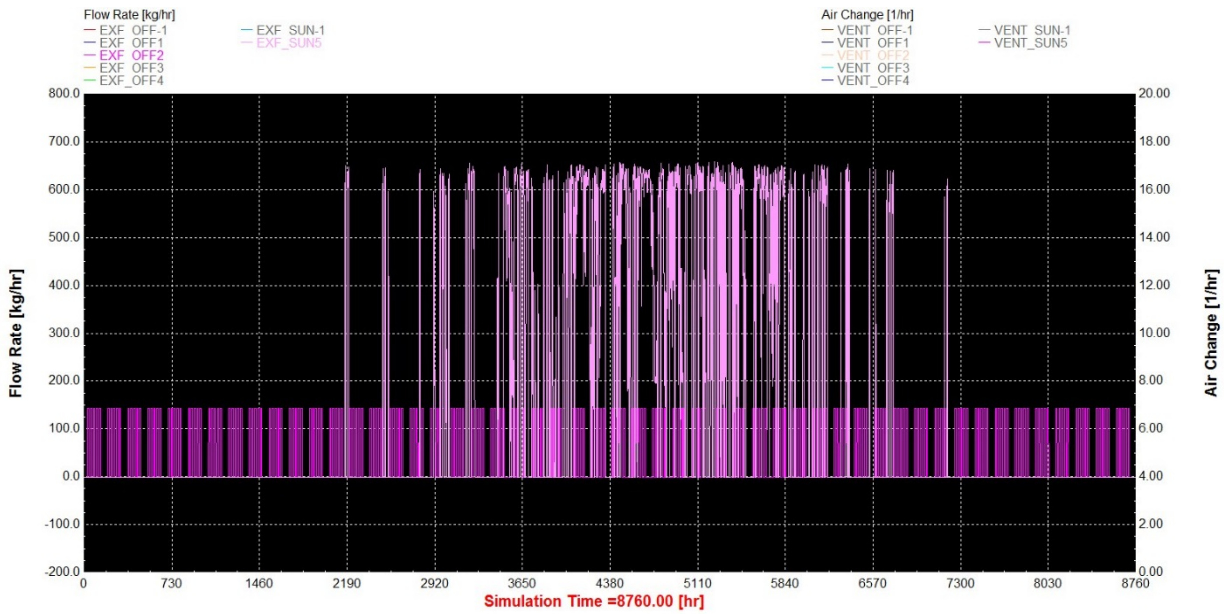
Total Offices Load Intensity *(kJ/hr)*

Run12 G (MV 4-Story NV DSF0.5 Semi HVAC Hypo)



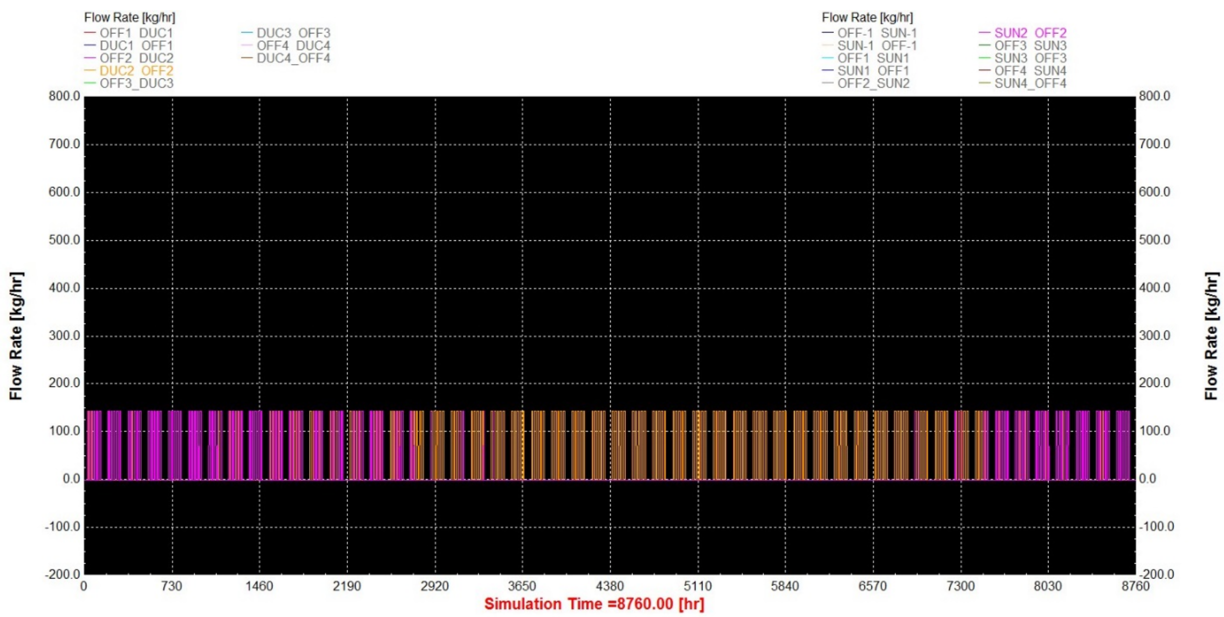
Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run12 G (MV 4-Story NV DSF0.5 Semi HVAC Hypo)



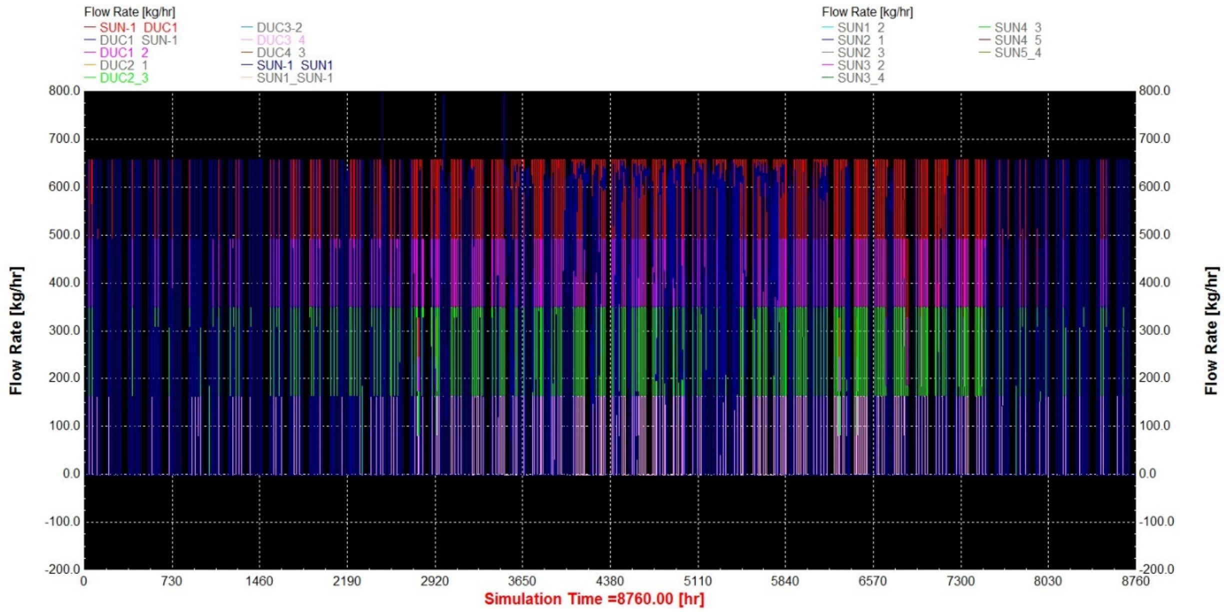
Sunspaces/Ducts-Offices Airflow *(kg/hr or 1/hr)*

Run12 G (MV 4-Story NV DSF0.5 Semi HVAC Hypo)



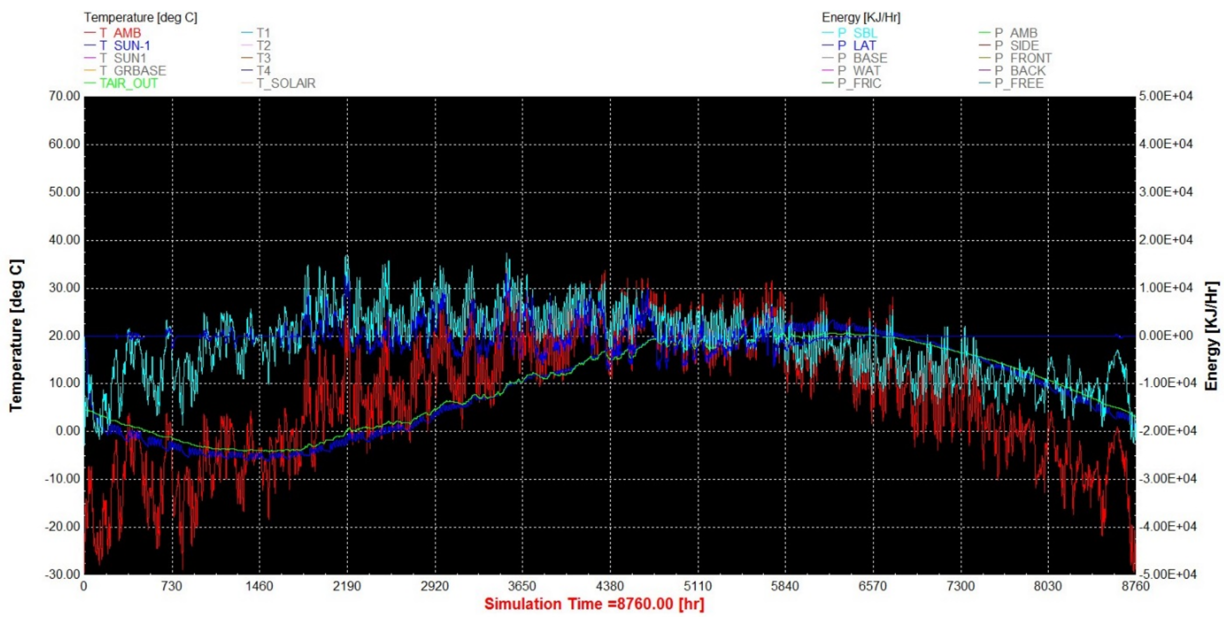
Sunspace/Duct-Sunspace/Duct Airflow *(kg/hr or 1/hr)*

Run12 G (MV 4-Story NV DSF0.5 Semi HVAC Hypo)



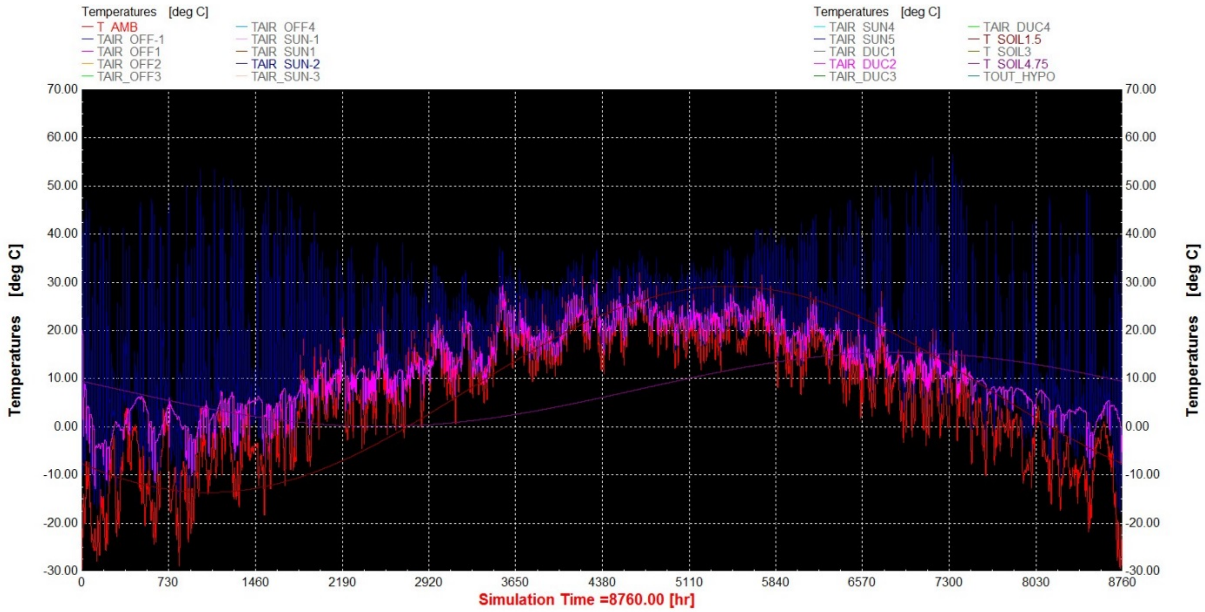
Air-Tubes Temperature and Energy *(°C and kJ/hr)*

Run12 G (MV 4-Story NV DSF0.5 Semi HVAC Hypo)



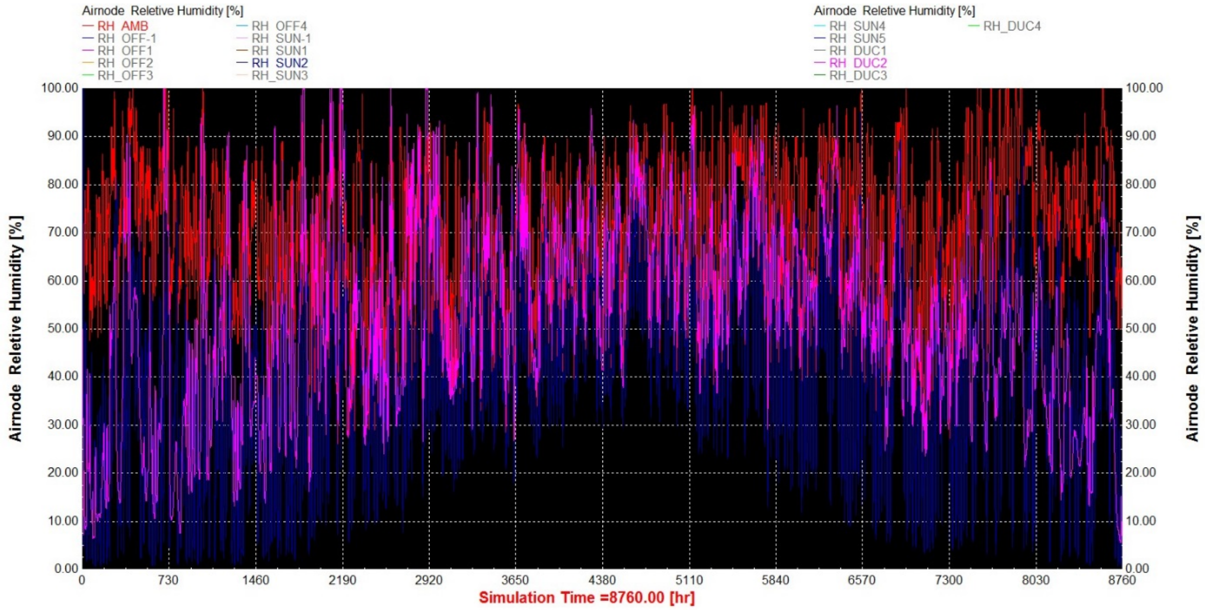
Zones Temperature *(°C)*

Run13 H (NC 4-Story MV DSF0.5 No HVAC)



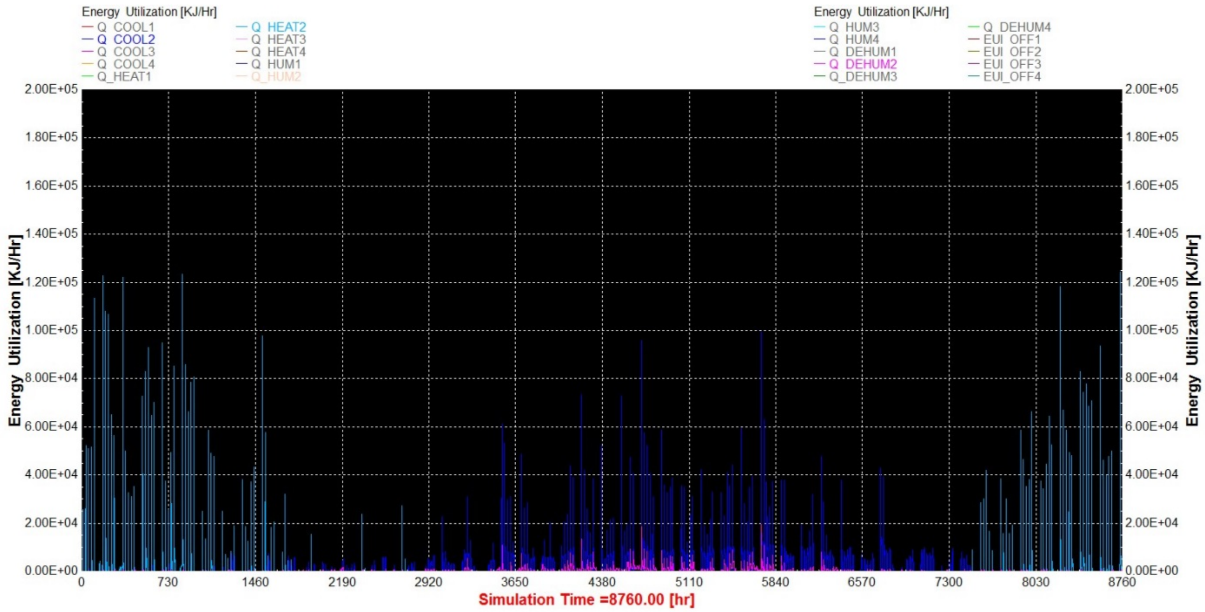
Zones Relative Humidity *(%)*

Run13 H (NC 4-Story MV DSF0.5 No HVAC)



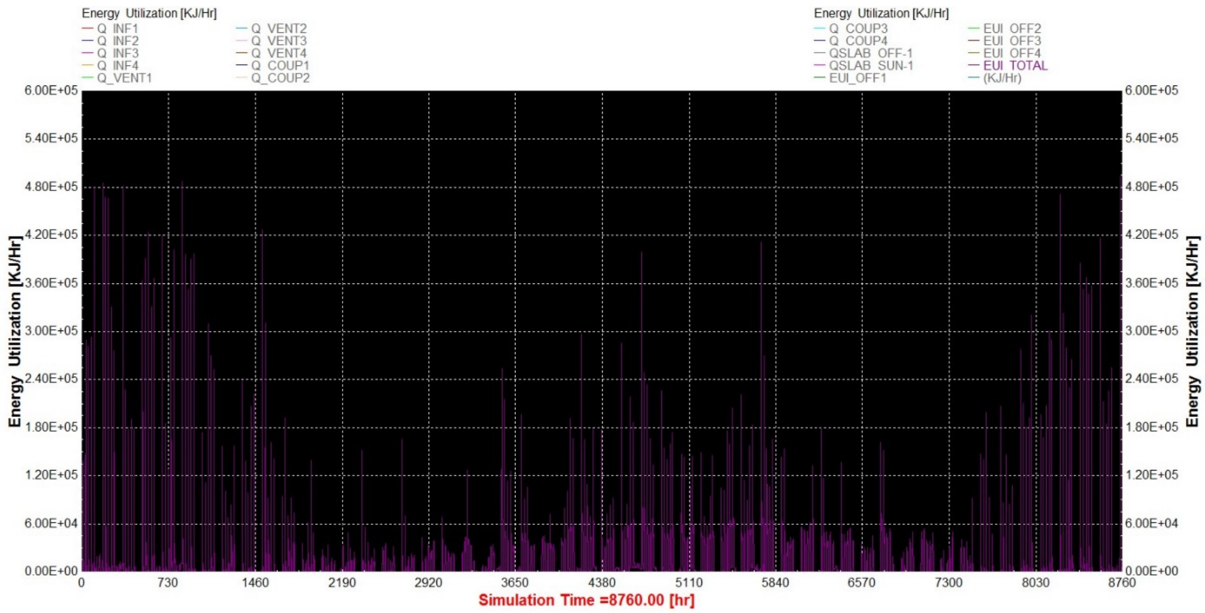
Office Load Intensity *(kJ/hr)*

Run13 H (NC 4-Story MV DSF0.5 No HVAC)



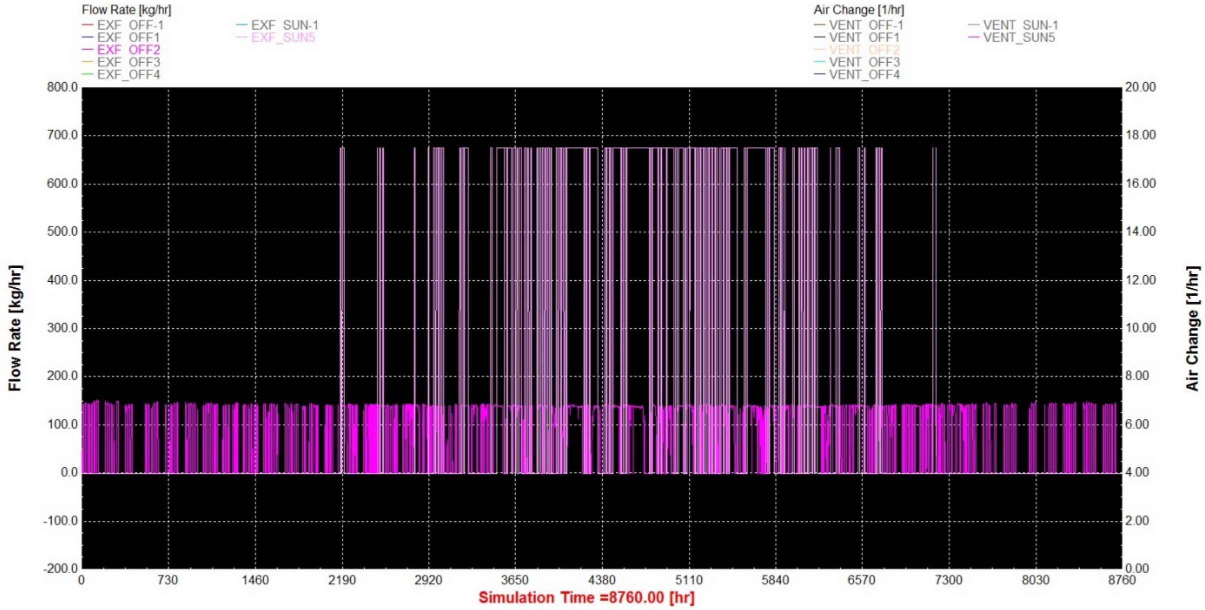
Total Offices Load Intensity *(kJ/hr)*

Run13 H (NC 4-Story MV DSF0.5 No HVAC)



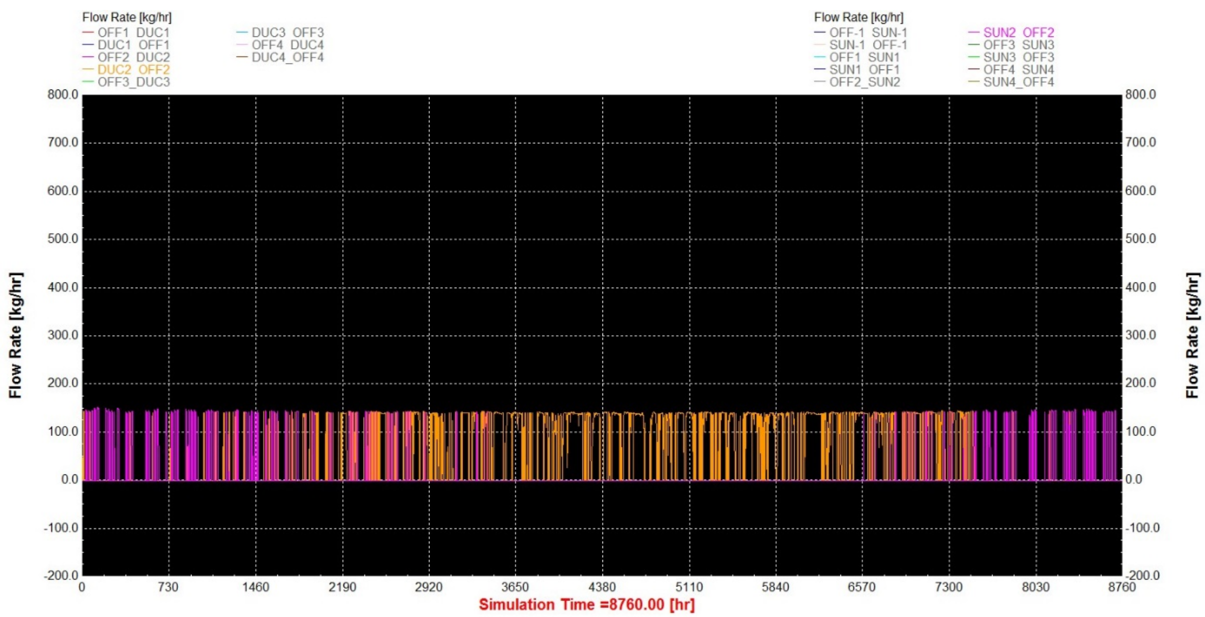
Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run13 H (NC 4-Story MV DSF0.5 No HVAC)



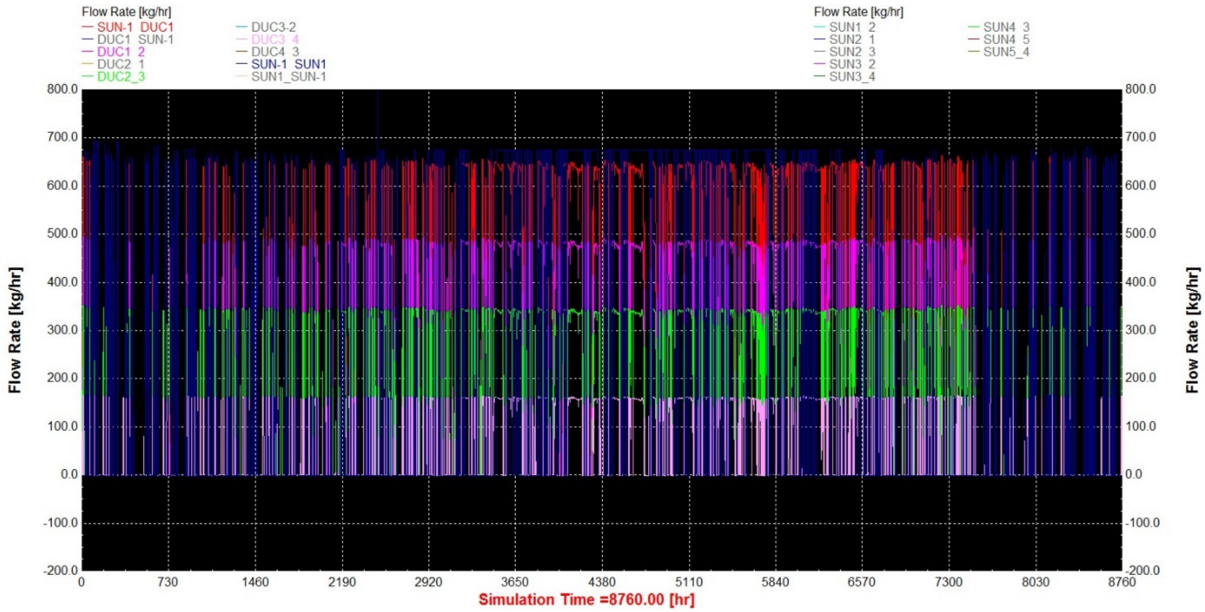
Sunspaces/Ducts-Offices Airflow *(kg/hr or 1/hr)*

Run13 H (NC 4-Story MV DSF0.5 No HVAC)



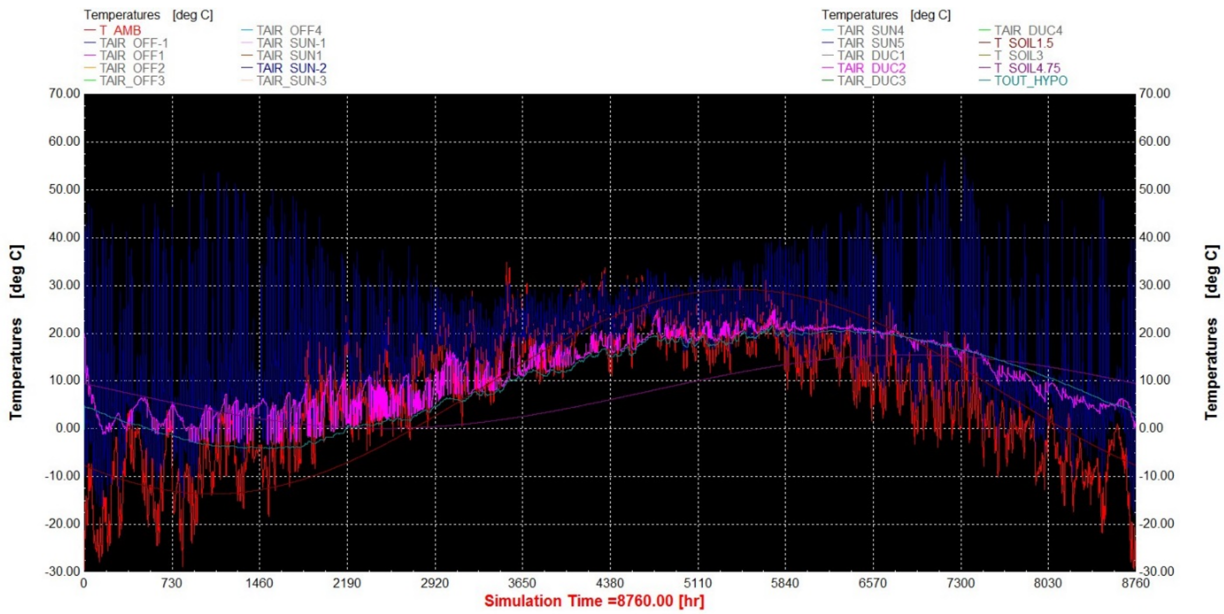
Sunspace/Duct-Sunspace/Duct Airflow *(kg/hr or 1/hr)*

Run13 H (NC 4-Story MV DSF0.5 No HVAC)



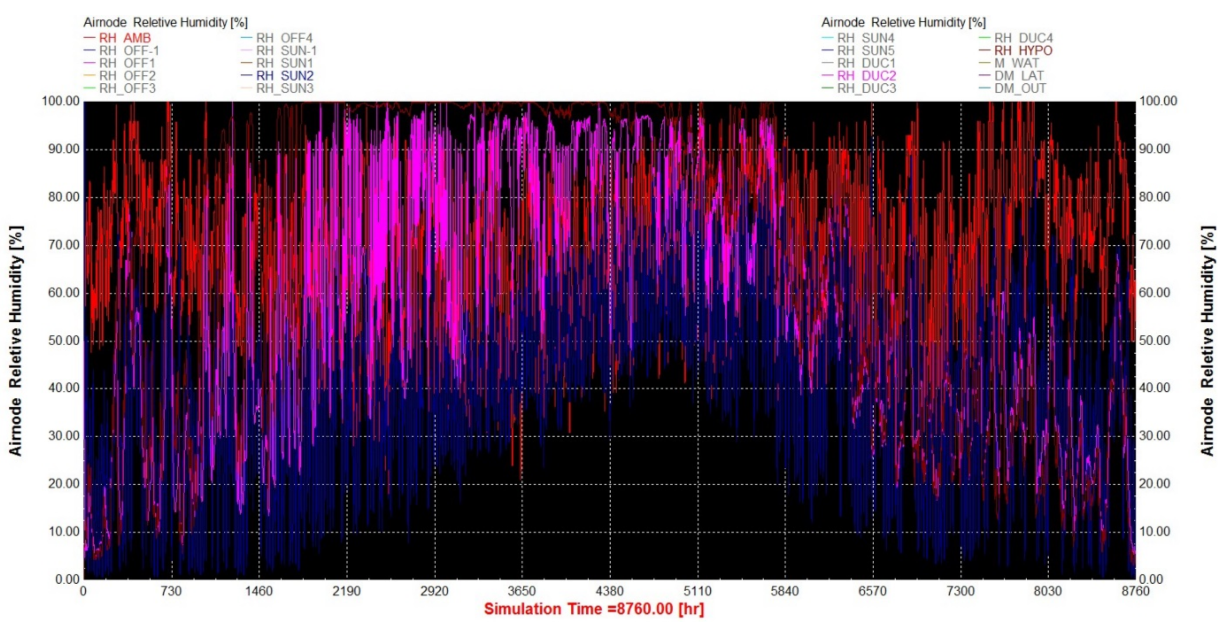
Zones Temperature *(°C)*

Run14 H (NC 4-Story MV DSF0.5 No HVAC Hypo)



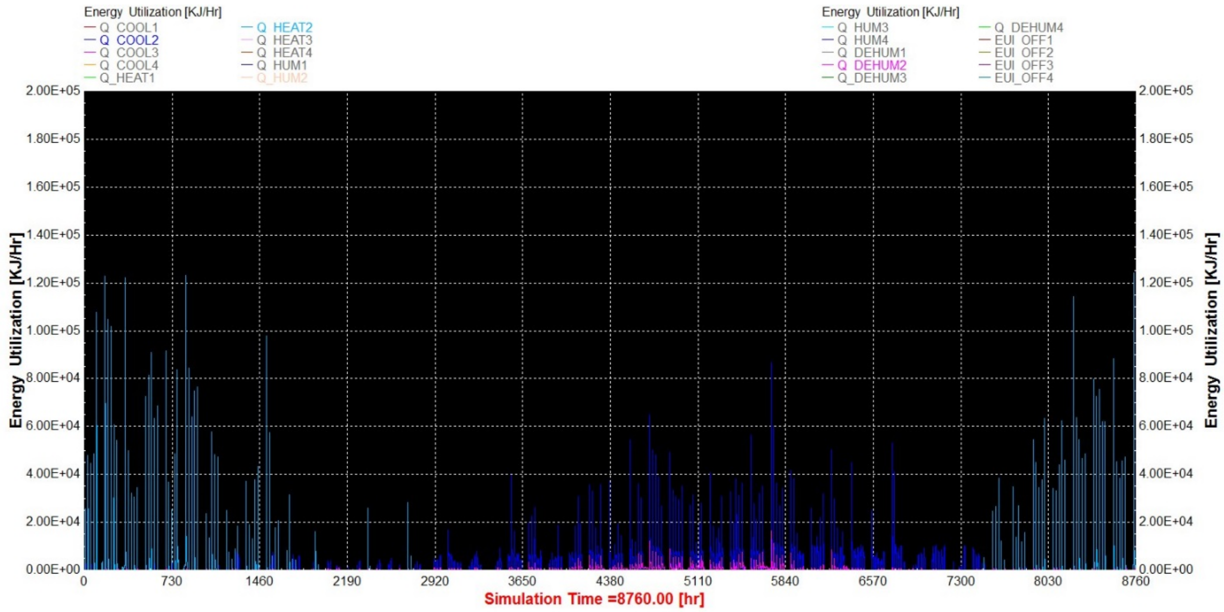
Zones Relative Humidity *(%)*

Run14 H (NC 4-Story MV DSF0.5 No HVAC Hypo)



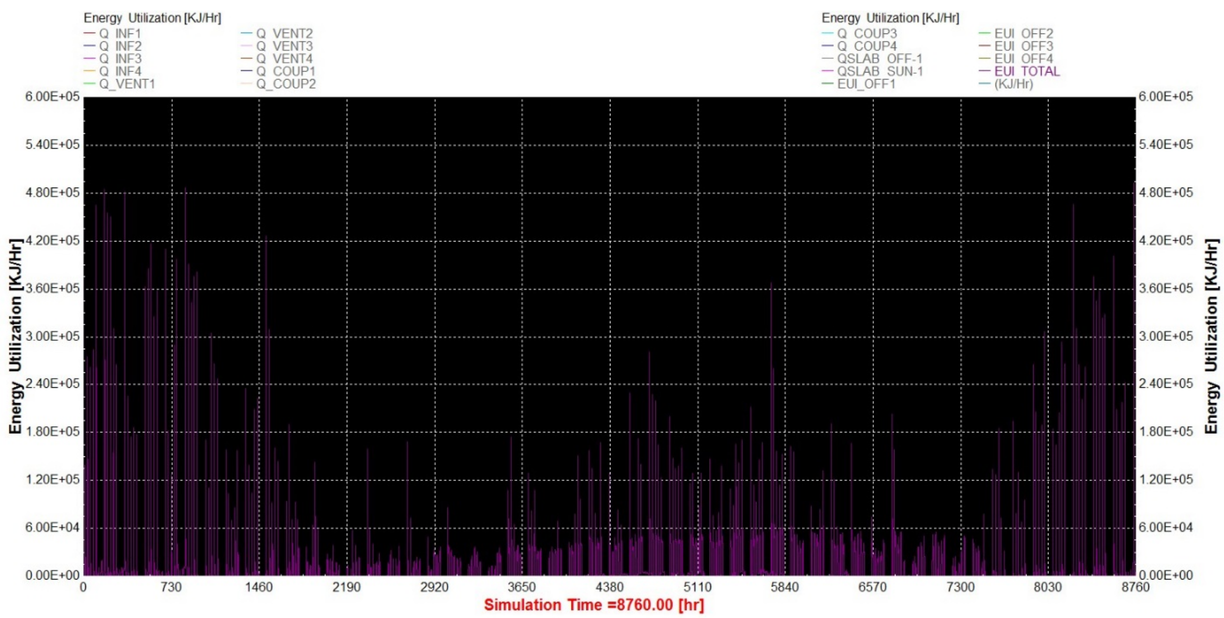
Office Load Intensity *(kJ/hr)*

Run14 H (NC 4-Story MV DSF0.5 No HVAC Hypo)



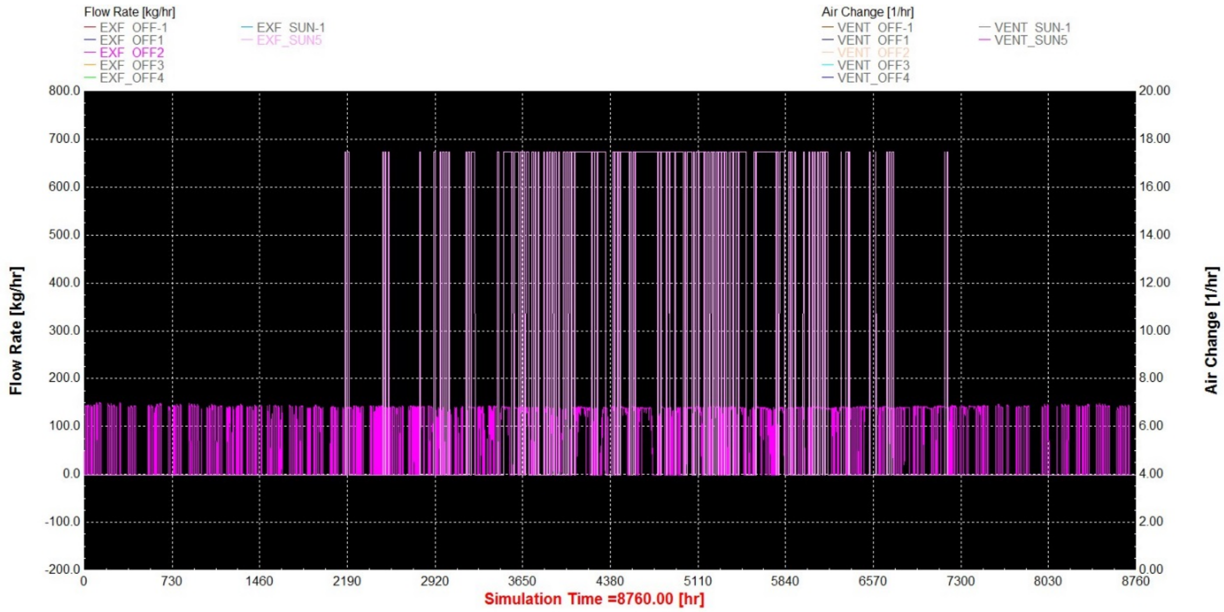
Total Offices Load Intensity *(kJ/hr)*

Run14 H (NC 4-Story MV DSF0.5 No HVAC Hypo)



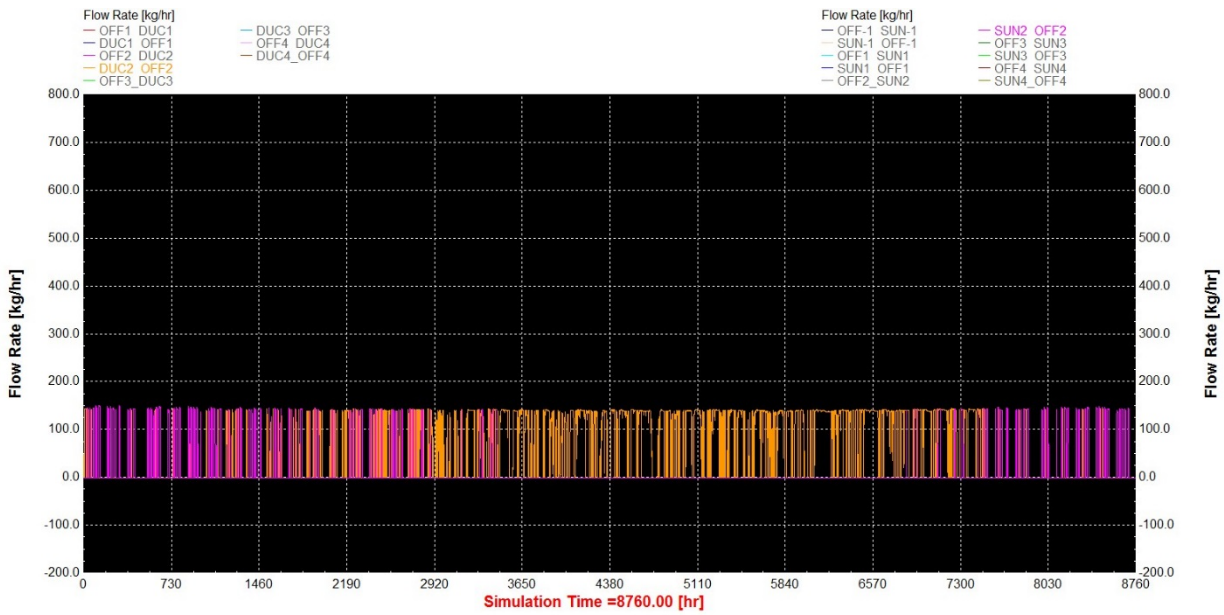
Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run14 H (NC 4-Story MV DSF0.5 No HVAC Hypo)



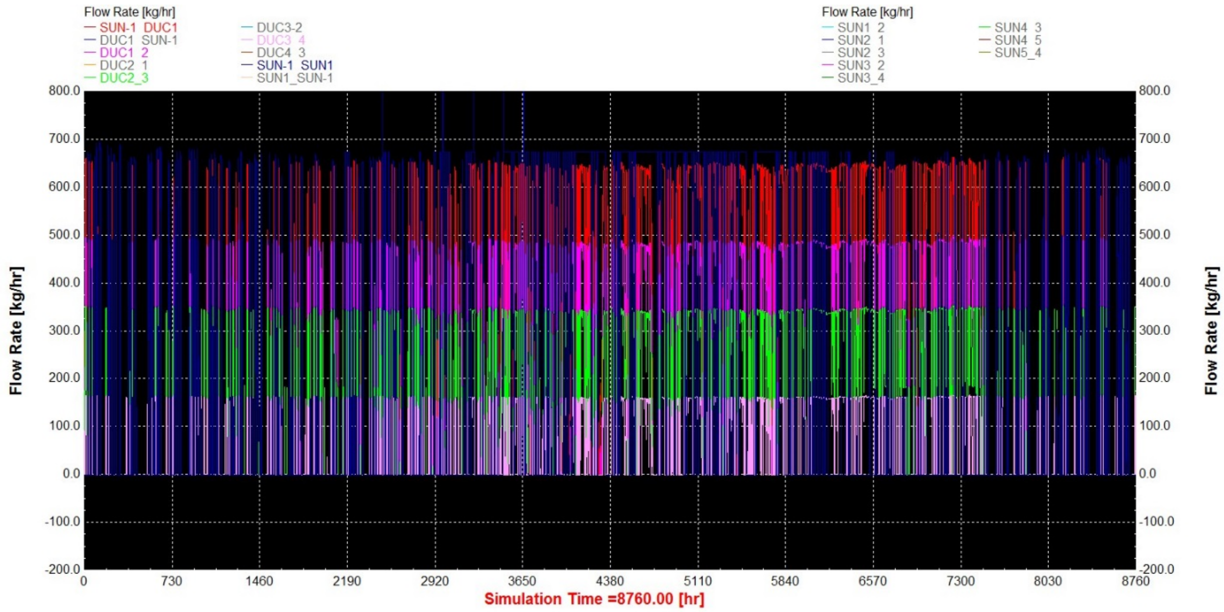
Sunspaces/Ducts-Offices Airflow *(kg/hr or 1/hr)*

Run14 H (NC 4-Story MV DSF0.5 No HVAC Hypo)



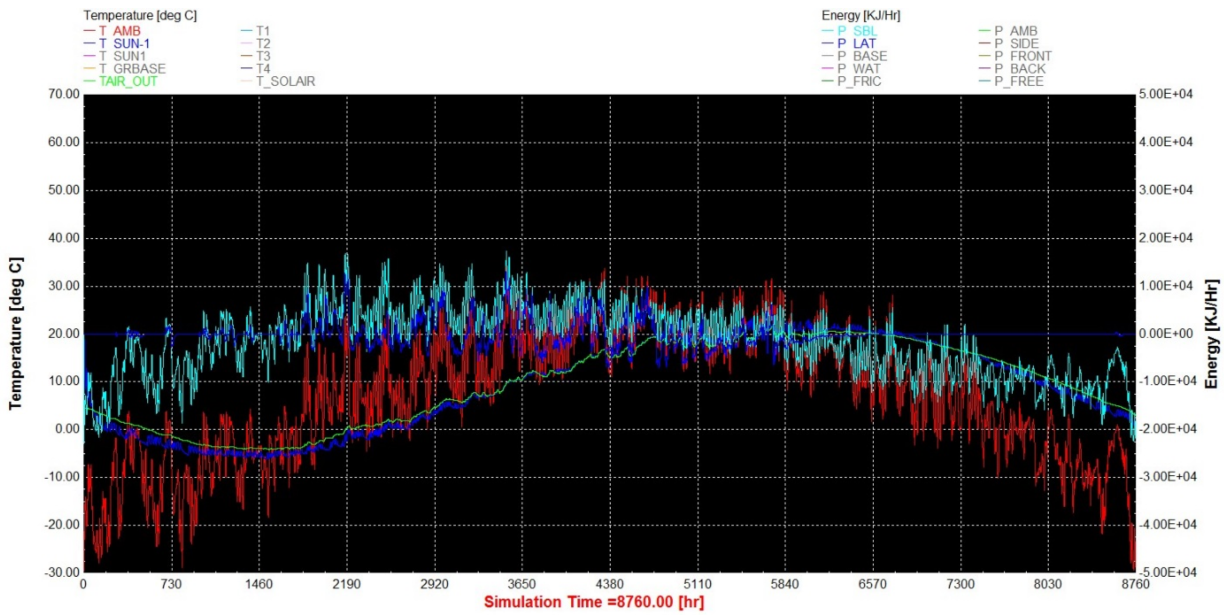
Sunspace/Duct-Sunspace/Duct Airflow *(kg/hr or 1/hr)*

Run14 H (NC 4-Story MV DSF0.5 No HVAC Hypo)



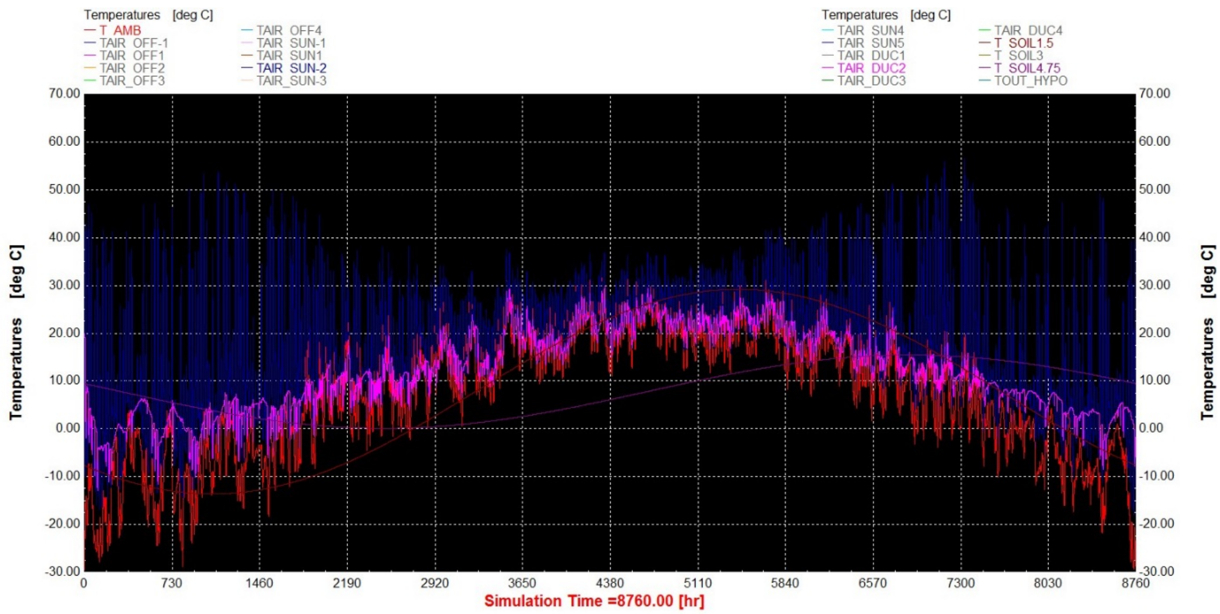
Air-Tubes Temperature and Energy *(°C and kJ/hr)*

Run14 H (NC 4-Story MV DSF0.5 No HVAC Hypo)



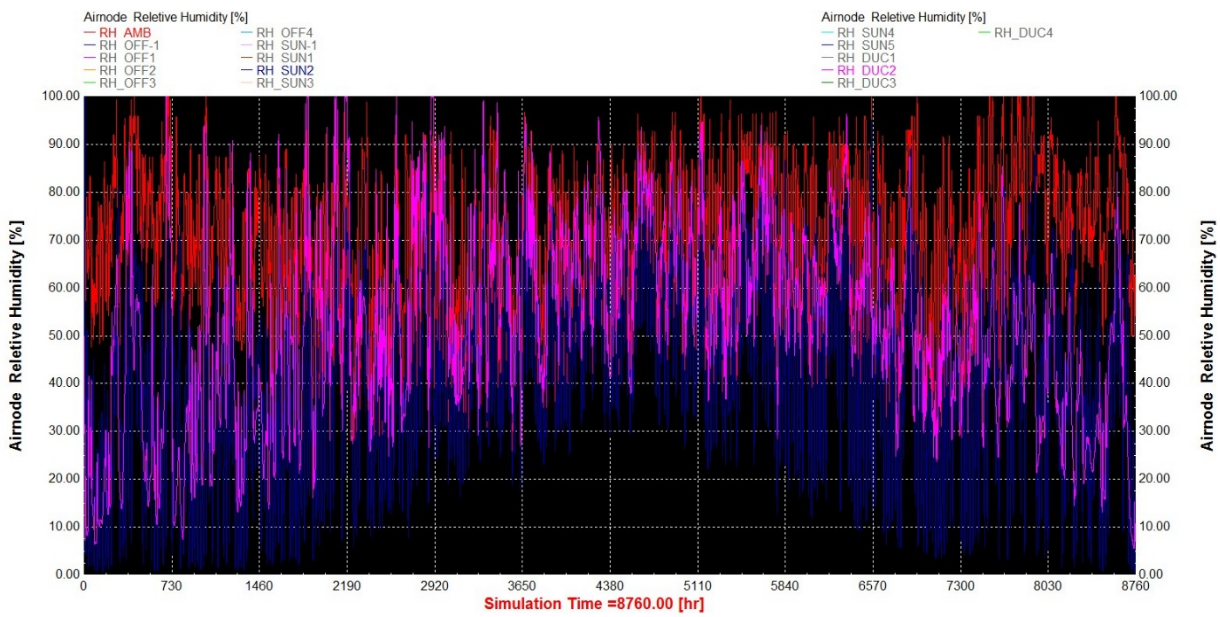
Zones Temperature *(°C)*

Run15 I (NC 4-Story NV DSF0.5 No HVAC)



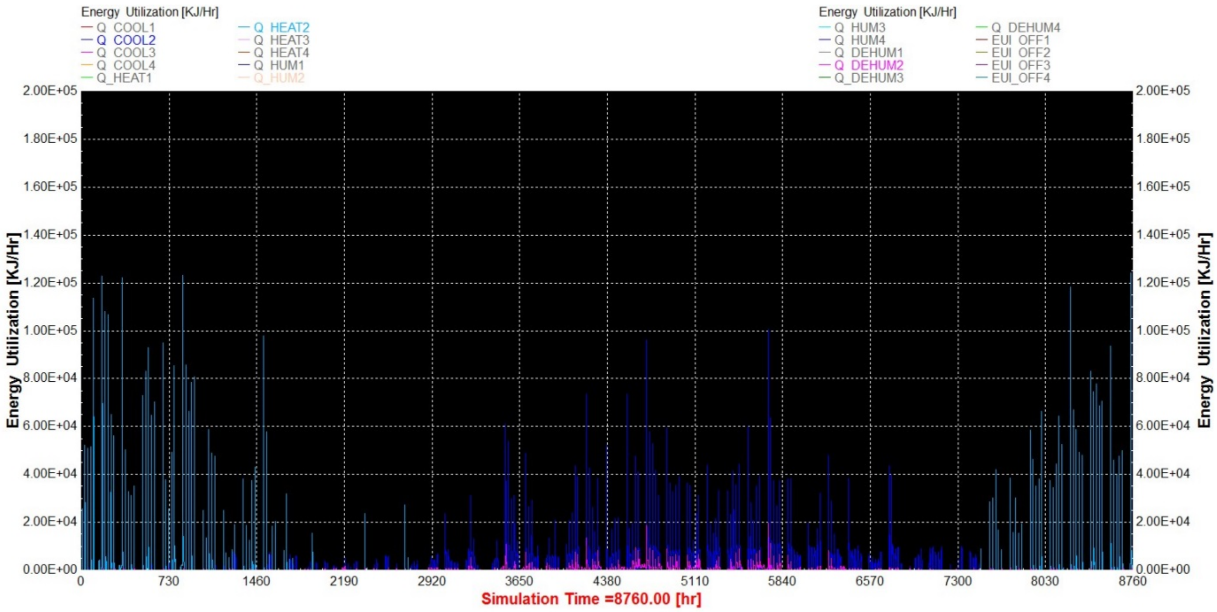
Zones Relative Humidity *(%)*

Run15 I (NC 4-Story NV DSF0.5 No HVAC)



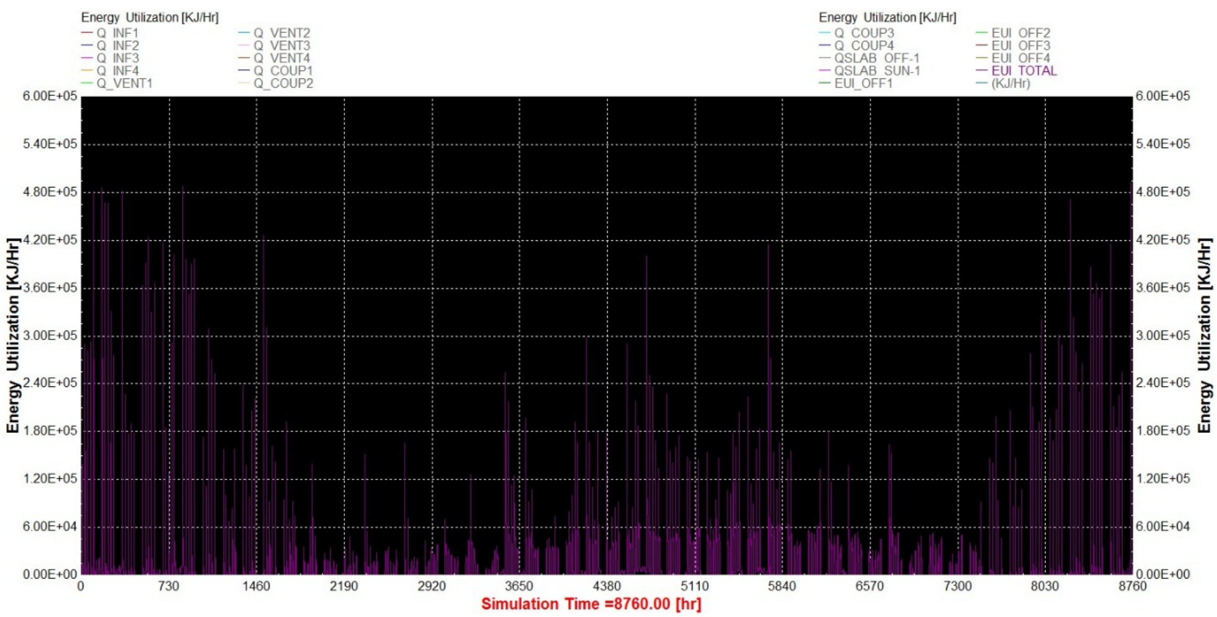
Office Load Intensity *(kJ/hr)*

Run15 I (NC 4-Story NV DSF0.5 No HVAC)



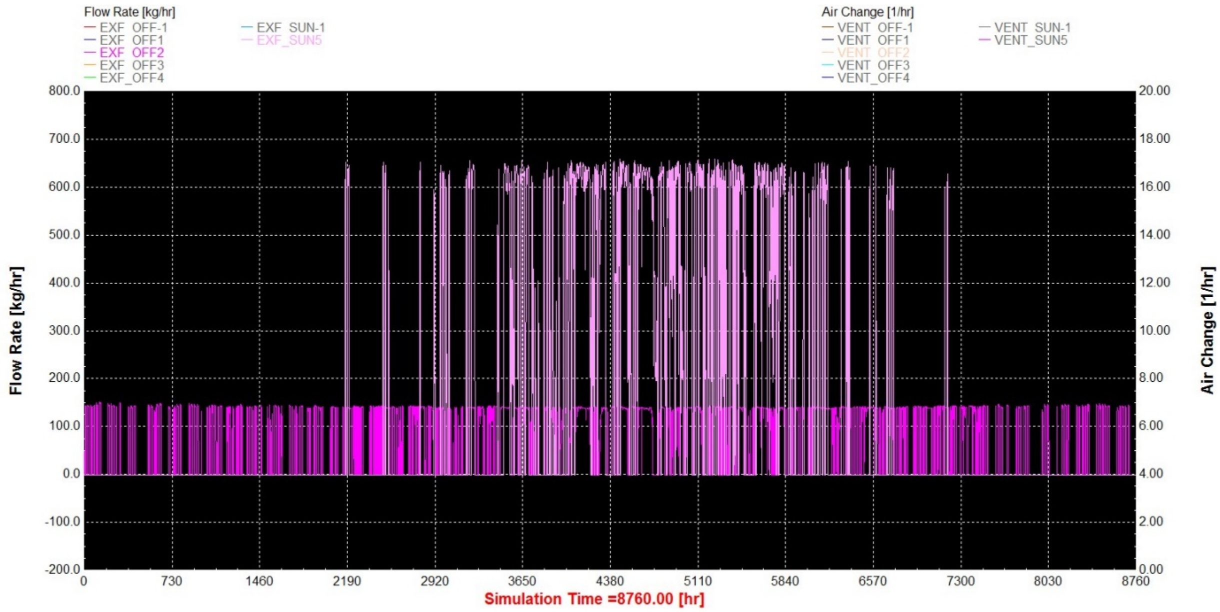
Total Offices Load Intensity *(kJ/hr)*

Run15 I (NC 4-Story NV DSF0.5 No HVAC)



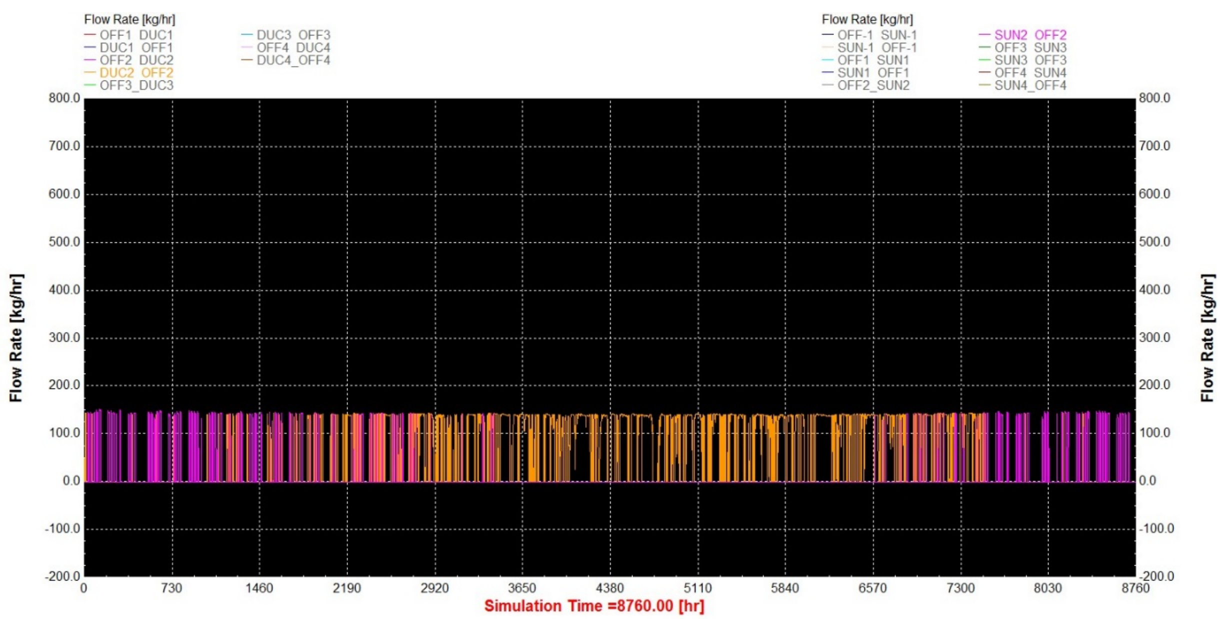
Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run15 I (NC 4-Story NV DSF0.5 No HVAC)



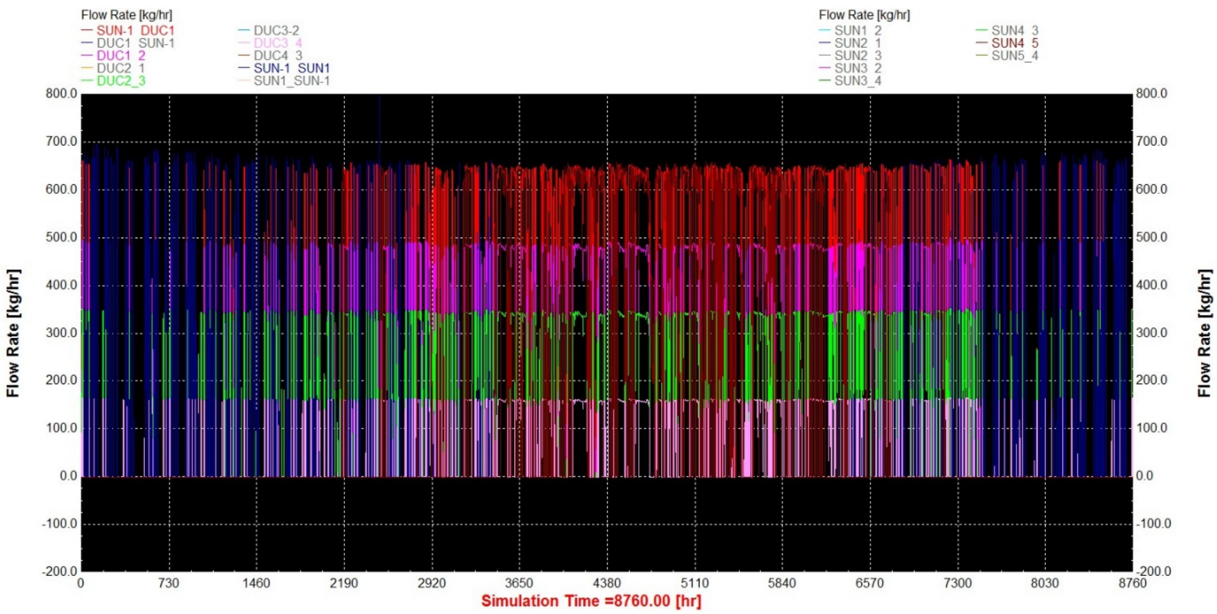
Sunspaces/Ducts-Offices Airflow *(kg/hr or 1/hr)*

Run15 I (NC 4-Story NV DSF0.5 No HVAC)



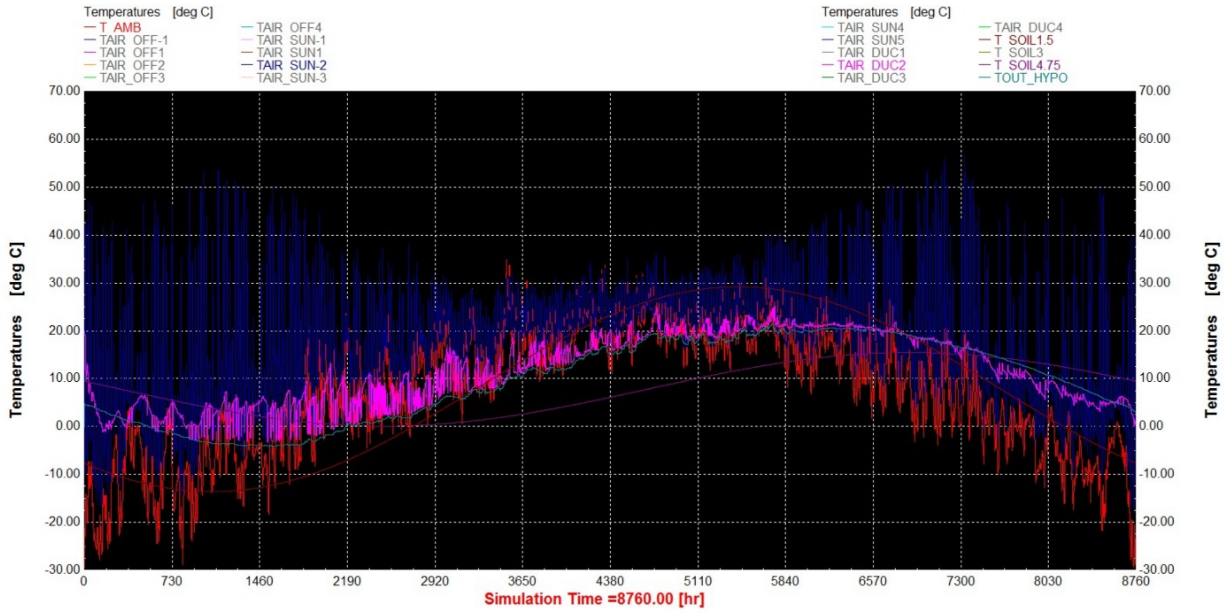
Sunspace/Duct-Sunspace/Duct Airflow *(kg/hr or 1/hr)*

Run15 I (NC 4-Story NV DSF0.5 No HVAC)



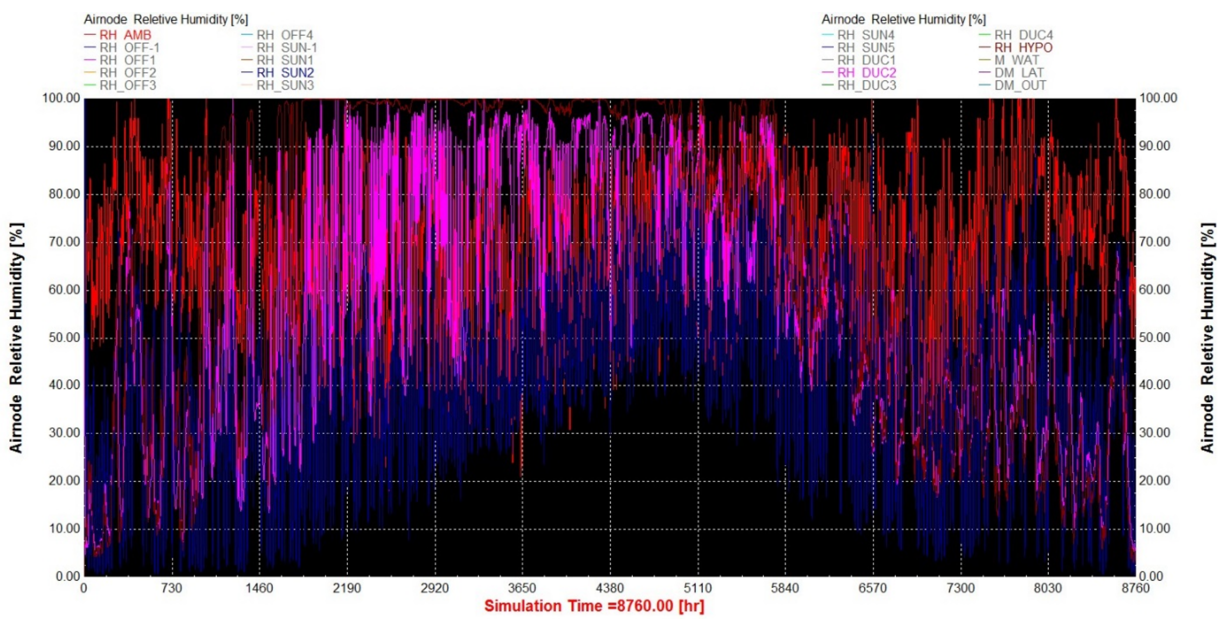
Zones Temperature *(°C)*

Run16 I (NC 4-Story NV DSF0.5 No HVAC Hypo)



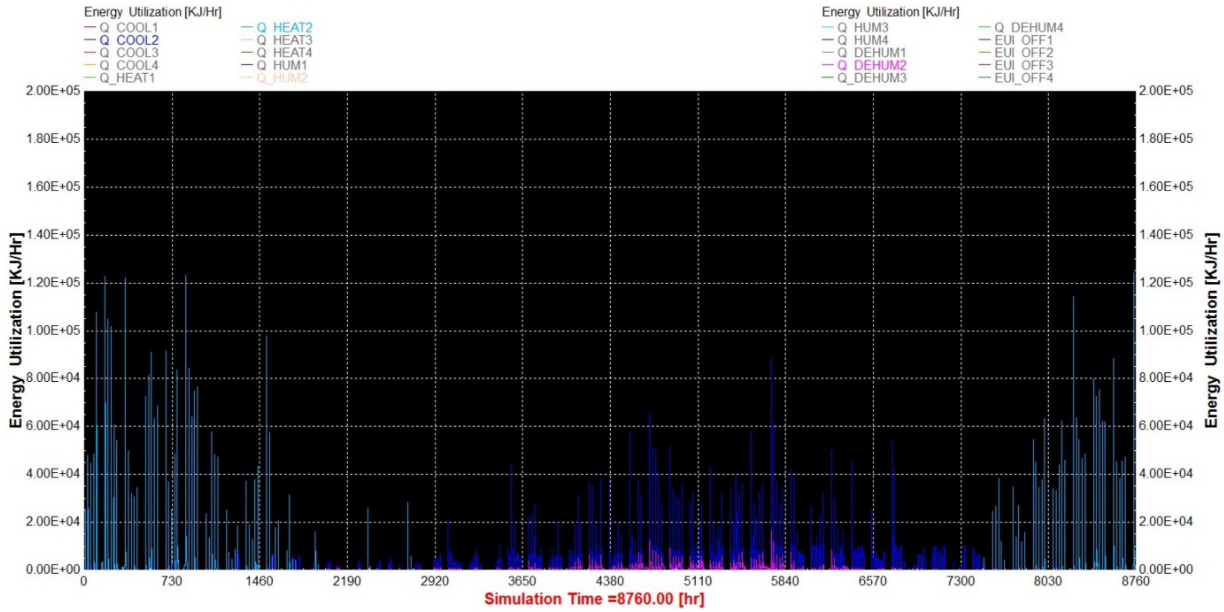
Zones Relative Humidity *(%)*

Run16 I (NC 4-Story NV DSF0.5 No HVAC Hypo)



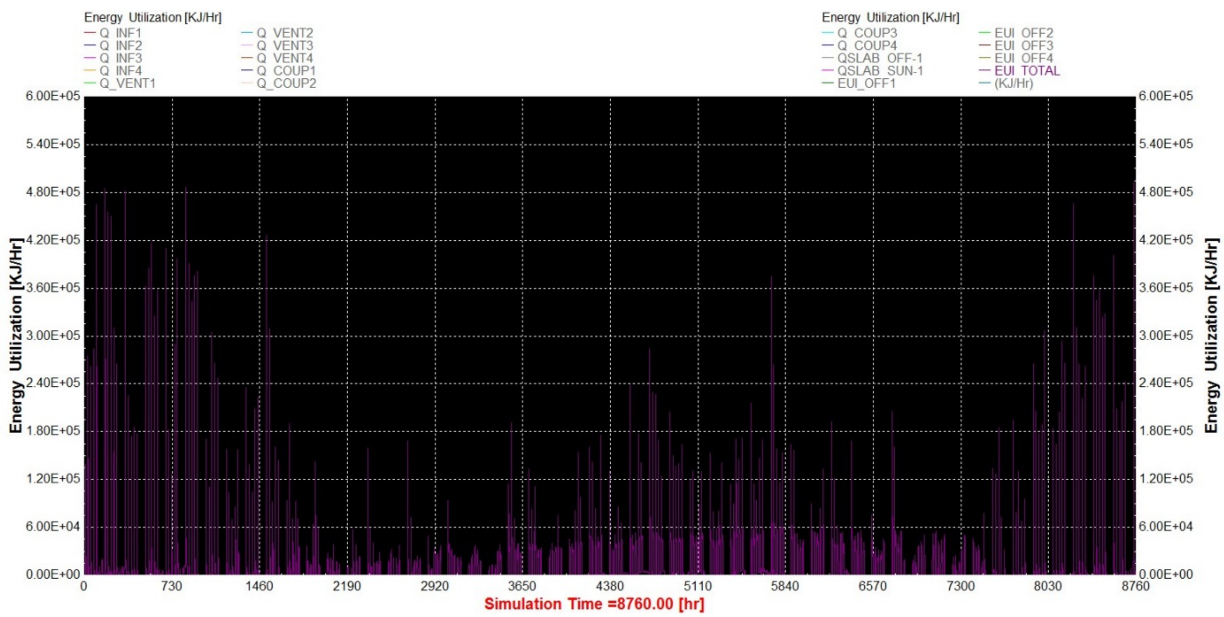
Office Load Intensity *(kJ/hr)*

Run16 I (NC 4-Story NV DSF0.5 No HVAC Hypo)



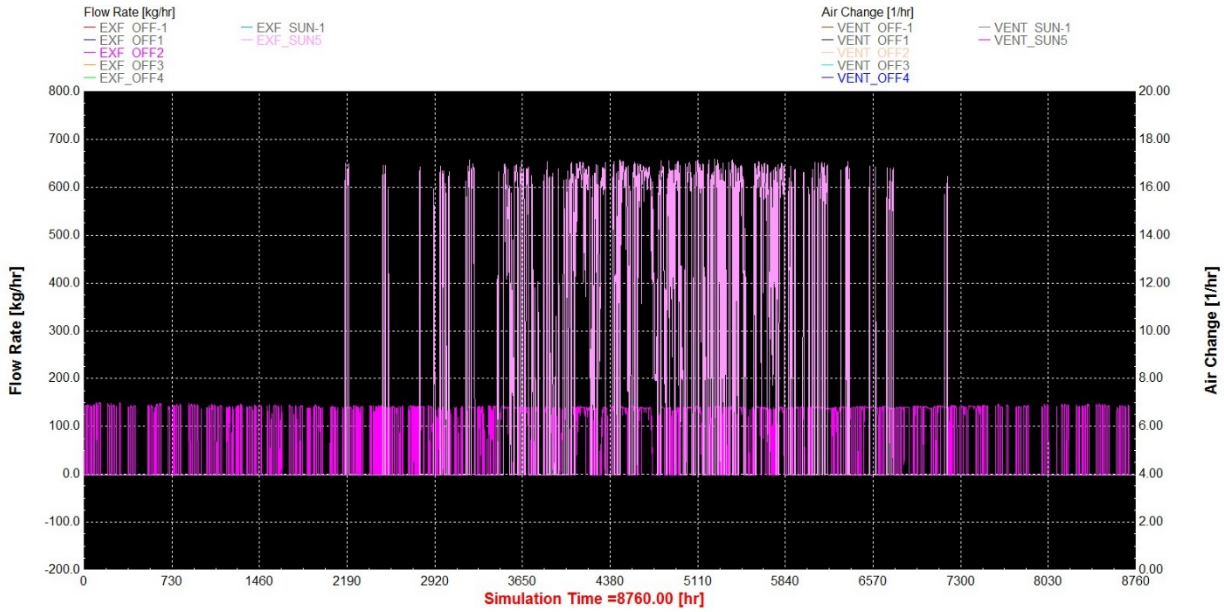
Total Offices Load Intensity *(kJ/hr)*

Run16 I (NC 4-Story NV DSF0.5 No HVAC Hypo)



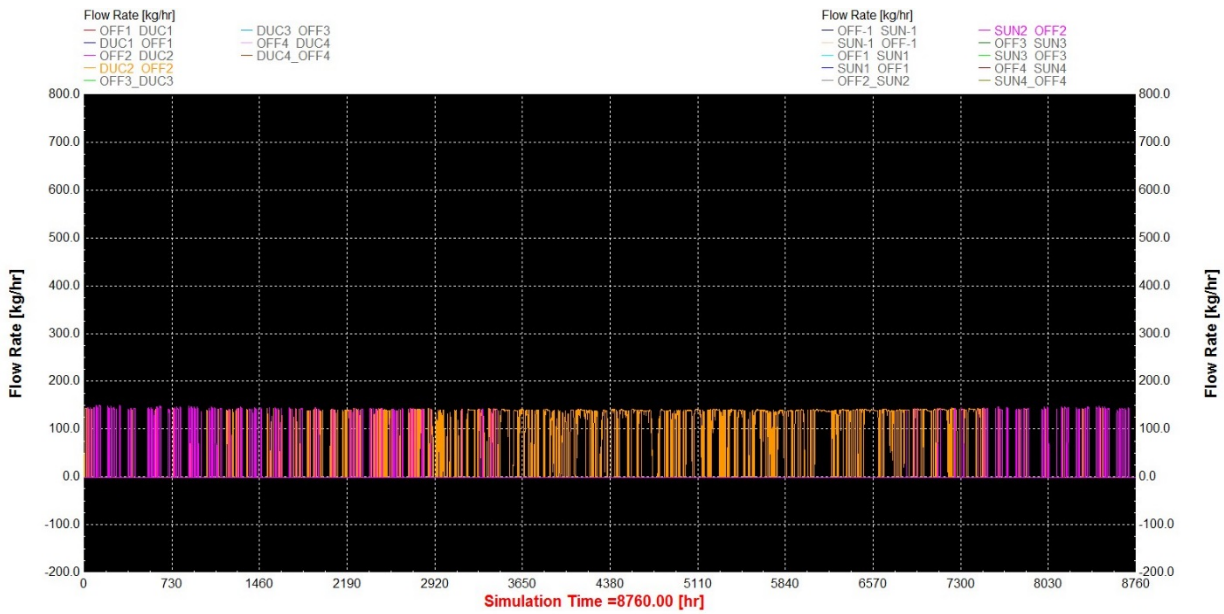
Offices-Ambient Airflow *(kg/hr or 1/hr)*

Run16 I (NC 4-Story NV DSF0.5 Self No HVAC Hypo)



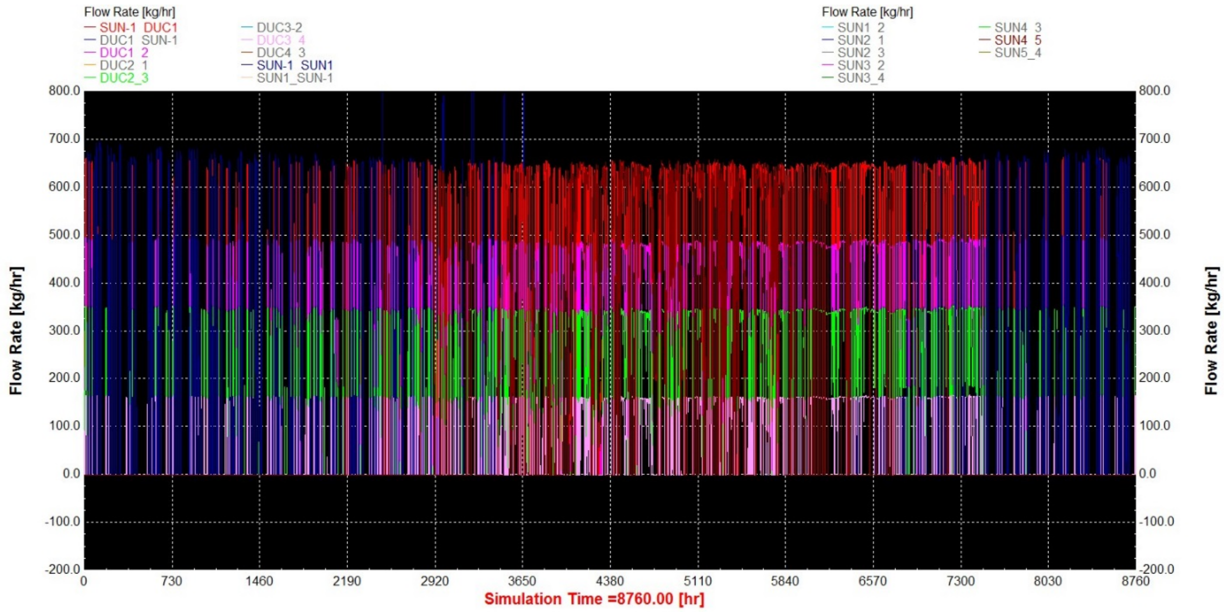
Sunspaces/Ducts-Offices Airflow *(kg/hr or 1/hr)*

Run16 I (NC 4-Story NV DSF0.5 No HVAC Hypo)



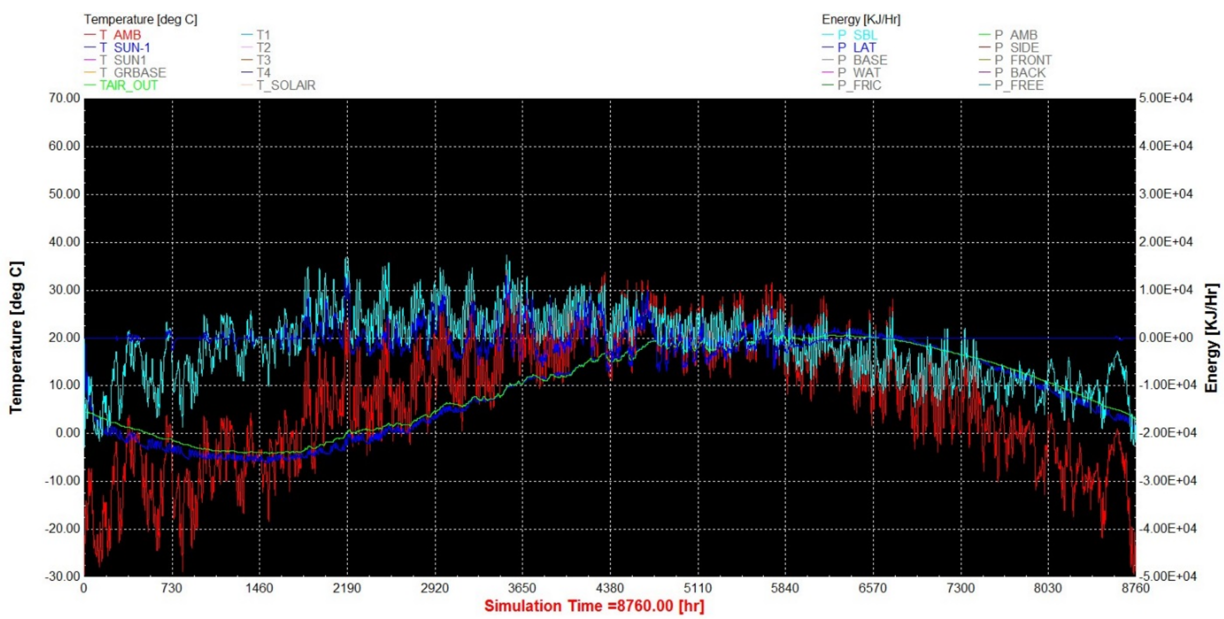
Sunspace/Duct-Sunspace/Duct Airflow *(kg/hr or 1/hr)*

Run16 I (NC 4-Story NV DSF0.5 No HVAC Hypo)



Air-Tubes Temperature and Energy *(°C and kJ/hr)*

Run16 I (NC 4-Story NV DSF0.5 No HVAC Hypo)



CURRICULUM VITAE

Payman Sadeghi

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Email: psadeghi@uwm.edu
Linkedin: http://www.linkedin.com/in/paymansadeghi
Portfolio: http://issuu.com/paymansadeghi/docs/payman_sadeghi_portfolio

1.0 Education

Ph.D. in Architecture, (Jan. 2010 - Aug. 2017)
School of Architecture and Urban Planning, University of Wisconsin-Milwaukee, Milwaukee, WI
PhD's thesis title: High-Performance Building Envelope: An Energy Evaluation of a Double Skin Façade (DSF) Linked into the Earth
Committee members: Professor Michael Utzinger, Brian Schermer, James Wasley from UWM, and David Bradley

Continuous MSc/MA in Architecture Engineering (includes BS/BA) (Sep. 1996 - Dec. 2005)
Department of Architecture, Faculty of Architecture & Civil Engineering, Qazvin Azad University, Qazvin, IRAN
Master's thesis title: Energy Efficient Residential Complexes: A Design Based on Passive System Solutions, Tehran, IRAN

2.0 Professional Development

Green Building Core Concepts Course, LEED Green Associate (Apr. 7, 2012)
E3 Group, University of Wisconsin Milwaukee (UWM), Milwaukee, WI
eQUEST Energy Modeling (Feb. 21–22, 2012)
ComeEd Training and Nicor, Naperville, Illinois
TRaNsient Systems Simulation Program (TRNSYS) Training (Jun. 2010 and Jun. 2011)
TESS, Experts in Energy Modeling & Analysis, Madison, WI
Passive Thermal Design for Energy Efficiency and Indoor Comfort Certificate (Feb. 10, 2011)
Energy Center of Wisconsin, ComeEd Training, Chicago, Illinois, USA
IACET – 0.65 Continuing Education Units

3.0 Academic Positions

Adjunct Instructor at BGSU, (Jan. 2017 – Aug.2017)
Accomplishments: Implement a BIM and performance evaluation approach towards architectural design using Revit and Green Building Studio for:

- ARCH 2710 Computer-Aided Design for Architecture (spring and summer 2017)

Adjunct Lecturer at SARUP, UWM (Jan. 2013 - Jun. 2013)
Accomplishments: Simulate and evaluate different options throughout the entire process of architectural design via application of advanced software such as Ecotect, Green Building Studio, Revit, and Climate Consultant for:

- ARCH 790 Sustainable Building Performance Simulation (spring 2013)

Teacher Assistant at SARUP, UWM (Jan. 2010 – Jun. 2014)
Accomplishments: Conduct discussion sessions, design critic, exam/assignment's evaluation, and grading through mastering building code and zoning, environmental, tectonic, and structural concepts such as lighting, acoustics, thermal comfort, and energy for:

- ARCH 301 Architectural Structures & Construction (spring 2014)
- ARCH 305 Introductions to Building Technologies, formerly 210 (fall 2013 & fall 2012)
- ARCH 522 Environmental Systems: Lighting and Acoustical Design (fall 2011 & fall 2010)
- ARCH 210 Introductions to Building Technologies (spring 2011 & spring 2010)

4.0 Professional Positions

Building Performance Research Intern at HGA Architects and Engineers (Jan. 2016 - Apr. 2016)
Accomplishments: Explore impact of design decisions on the Energy Used Intensity (EUI) Through a case-study evaluation of two similar, 260000 SF, LEED-certified buildings designed by HGA and application of performance-driven software, the type of programming and design approaches constructive to achieve high-performance, ecological built environments was studied.

Design and Sustainability Consultant at Community Design Solutions (Jun. 2009 - Aug. 2014)
Accomplishments: Examine architectural delivery as a professional committed to sustainability in the following selected projects for which I was mostly the lead designer; that includes but not limited to involvement in community design charretts, meeting with steering committee, site analysis, ecological strategies' application, programming, planning and zoning, schematic design, material selection, 3D modeling, and project presentation.

- Wausau East Riverfront Sustainable Master Plan (May 2011 – Jan. 2012)
  Published in "World Landscape Architecture"at http://worldlandscapearchitect.com/wausau-north-east-riverfront
- Jackpot Gallery Renovation (Aug. 2010 – Jan. 2011)
- Renovation Planning for Plankinton Building's 5th Floor (Jan. 2010 – Jul. 2010)
- Cardinal Stritch Library Renovation (Sep. 2009 – May 2010)
- Milwaukee Red Cross Façade Renovation (Jun. 2009 – Aug. 2009)

Research Assistance for Carbon Neutral Design Case-Studies of AIA (Jun. 2012 - Aug. 2012)
http://www.tboake.com/carbon-aia/index.html
Accomplishments: Analyze "Envelope- Controlling Aperture Solar Gains" and investigate "Lesson Learned" section for the performance and post-occupancy evaluation of selected case studies amongst AIA/COTE Top Ten Green Projects based on the interviews with their architect, mechanical engineer, and project manager. Some selected case-studies were:

- The Aldo Leopold Legacy Center (Baraboo, WI),
- Global Ecology Resource Center (Stanford, CA),
- LIHI Denny Park Apartments (Seattle, WA), and
- Wild Sage Cohousing (Boulder, CO)

Architect/Intern Architect (Feb. 2000 – Aug. 2007)
Accomplishments: Involve in various projects from schematic to detail design as a member of design team. Meeting with steering committee and clients, coordination with structural/mechanical/electrical engineers, construction documents, 3D modeling, project presentation, regular site and construction supervision, and shop drawing design were among the responsibilities for projects below:

- Khuzestan Regional Electricity Complex with Bavand Consultants (Jul. 2006 - Aug.2007)
- Tehran International Tower with Armeh No Construction Co. (Mar. 2006 – Jul. 2006)
- Aghdasiyeh Residential Complex with Azad Consulting Architects (Jul. 2005 – Mar. 2006)
- Iran National Library with Iran Borgeh Construction Co. (May 2003 – Jun. 2005)
- Ilam Province Azadi Student Camp with Parsaz Consultants (Jan. 2003 – May 2003)
- Numerous Commercial/Residential Bldgs with Sedaghati Consultants (Feb. 2000 – Jun. 2003)

Freelance Architect (Jan. 2003 - Aug. 2007)
Accomplishments: Involve in several projects from programming to schematic and detail design as the architect. Meeting with clients, coordination with structural/mechanical/electrical engineers, construction documents, 3D modeling, project presentation, regular site/construction supervision, and shop drawing design were among the responsibilities in these selected projects:

- Aligoodarz Residential Bldg (Jun. 2007 – Aug. 2007), Residential Façade Renovation (Mar. 2007 – May 2007), Karaj Office Bldg (Dec. 2006 – Aug. 2007), Maygoon Villa Landscape (Jul. 2006 – Aug. 2006), Asalouyeh Mixed-Use Bldg (Nov. 2004 – Dec. 2004), Karaj Meat Product Factory (May 2004 – Jun. 2004), and Bam Residential Building (Jan. 2003 – Feb. 2003)

5.0 Credentials

Living Building Award for passive and active solar design and dedication to living building challenge educational opportunities presented by Urban Ecology Center, March 2010
HGA Research Scholarship for a research collaboration between HGA Architects and Engineers and UWM School of Architecture and Urban Planning, October 2015

6.0 Publications

Sadeghi, P., M. Utzinger (2012), Simulation Software Application: Analyzing Energy Utilization Intensity of Architectural Design Options, published on The International Journal of Environmental, Cultural, Economic and Social Sustainability, Volume 8, Vancouver, Canada, also presented at Sustainability Conference 2012, Eighth International Conference on Environmental, Cultural, Economic and Social Sustainability, Vancouver, Canada, January 10-12, 2012 & Architectural Research Centers Consortium (ARCC) Conference 2012 in Milano, Italy, June 7-10, 2012.

7.0 Additional Skills

Modeling & Presentation Software: Revit, AutoCAD, 3D Studio, Sketch-up, Rhino, and Adobe CS6
Management & Analysis Software: MS Project, Office, and SPSS
Performance & Simulation Software: TRNSYS, ECOTECT, eQUEST, Green Building Studio, Climate Consultant, and CONTAM