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Impact of Implementing a Dedicated Outdoor Air System in Parallel with a Multi-Zone Variable-Air Volume System on Energy Consumption, Thermal Comfort, and Life Cycle Cost

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Impact of Implementing a Dedicated Outdoor Air System in Parallel with a Multi-Zone Variable-Air Volume System on Energy Consumption, Thermal Comfort, and Life Cycle Cost

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Thesis submitted to the
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in partial fulfillment of the requirements for the degree of
Master of Science
in
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Morgantown, West Virginia
2019

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ABSTRACT

Impact of Implementing a Dedicated Outdoor Air System in Parallel with a Multi-Zone Variable-Air Volume System on Energy Consumption, Thermal Comfort, and Life Cycle Cost

Khaled Alghamdi

Heating, Ventilating, and Air-Conditioning systems (HVAC) consume more than 40% of energy in commercial buildings, according to the Commercial Building Energy Consumption Survey in 2012. Therefore, efforts to reduce HVAC energy consumption would be significant in coping with energy-related issues. In that context and in order to enhance the indoor air quality without compromising for energy consumption, the concept of Dedicated Outdoor Air systems (DOAS) emerged.

The literature shows that the integration of DOAS with other HVAC systems has been studied widely, yet the impact of integrating DOAS in parallel with multi-zone Variable-Air Volume systems (multi-zone VAV) for an application requiring high ventilation air has not been researched. Therefore, the objective of this study was to assess the impact of the integration from various aspects.

For assessing the impact of implementing DOAS in parallel with multi-zone VAV, a primary school model was simulated in 17 climate zones and in 6 HVAC configurations. The simulations were conducted for conditions of 8,760 hours/year, and their results were compared to the results of a baseline model utilizing multi-zone VAV for handling the ventilation load besides handling the thermal local loads. The assessment considered the impact on energy consumption, thermal comfort, and life cycle cost.

The results showed a saving in HVAC energy in all considered climate zones when the DOAS supplied ventilation air at 12.8-15.6°C Dry Bulb Temperature (DBT) and 12.8°C Dew Point Temperature (DPT). The saving in energy ranged from 4% to 40%. In addition, the climate zones with low outdoor latent loads experienced high changes in energy consumption compared to the climate zones with high outdoor latent loads.

In terms of the change in thermal comfort, the Fanger Comfort Model was utilized to observe the change from the occupant perspectives. The change among the various configurations did not show a significant difference; the maximum percentage of occupants who would have experienced a difference in the thermal comfort was less than 0.5% in all climate zones.

Economically, the energy cost would decrease in a configuration supplying ventilation air through DOAS with conditions of 12.8-15.6°C DBT and 12.8°C DPT in all considered climate zones. In this study, the saving in energy cost ranged from \$ 500/year to \$ 6,000/year. Moreover, multi-zone VAV units could be downsized significantly. However, the saving would not have been encouraging economically when it was considered for overcoming the cost of implementing DOAS; the payback period was 11 years at the best, only for owning DOAS units without other costs associated with the DOAS implementation.

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Acronyms

ASHRAE	American Society of Heating, Refrigeration, and Air Conditioning Engineers
CAV	Constant-Air Volume system
COP	Coefficient of Performance
CRB	Commercial Reference Buildings
DBT	Dry Bulb Temperature
DOAS	Dedicated Outdoor Air Systems
DOE	U.S. Department of Energy
DPT	Dew Point Temperature
FCU	Fan Coil Unit
FIPT	Fan Powered Induction Terminal stytem
GUI	Graphical User Interface
HVAC	Heating, Ventilation, and Air Conditioning system
IDF	Input Data File
MWB	Mean Wet Bulb Temperature
NSRDB	National Solar Radiation Database
<i>PMV</i>	Predicated Mean Vote
<i>PPD</i>	Predicted Percent of Dissatisfied
PSZ	Packaged Single Zone system
PV	Photovoltaic Panels
RPM	Revolutions Per Minute
VAV	Variable-Air Volume system
SAT	Supply Air Temperature
TMY	Typical Merological Year

Nomenclature

Symbol	Units	Description
$dp_{adj.}$	<i>Pascal</i>	Adjusted Pressure Drop
V	m/s	Air Velocity
A_{du}	m^3	Body Surface Area
W_{supply}	kg_{water}/kg_{dryair}	Design Humidity Ratio of Supplied Air
W_{zone}	kg_{water}/kg_{dryair}	Design Humidity Ratio of Zone
ϵ		Heat Exchanger Effectiveness
HP	<i>horsepower</i>	Horse Power
Q_L	watt	Latent Load
η_{mech}		Mechanical Efficiency
η_{motor}		Motor Efficiency
dp	<i>Pascal</i>	Pressure Drop
A	<i>Pascal</i>	Pressure Drop Adjustment
η_{total}		Total Efficiency
Q	m^3/s	Volumetric Flow Rate
V_{OZ}	m^3/s	Volumetric Flow Rate of Ventilation Air

Chapter 1

Introduction

According to the Commercial Building Energy Consumption Survey in 2012, heating, cooling, and ventilation consumed respectively 25, 9, and 10% of the total energy usage in the commercial buildings [1]. Therefore, developing approaches aiming to reduce the energy consumption of the mentioned equipment would affect positively the efforts towards coping with energy issues. However, before investigating the potential saving in such equipment, one should define the goal of integrating Heating, Ventilation, and Air-Conditioning (HVAC) systems in buildings.

HVAC systems in buildings are mainly designed for two goals: maintaining the internal thermal conditions within a comfort range and enhancing the indoor air quality [2]. As a practice to combine both goals through one single equipment, the concept of mixing chamber was adopted. In a typical mixing chamber, the recirculated air, which makes means to maintain the zone within thermal comfort range, and outdoor air, which aims to dilute indoor air for enhancing the air quality, are mixed upstream the equipment conditioning the mixed air [3].

Several centerlized HVAC systems have been developed to utilize the concept of mixing chamber without compromising for energy consumption. As an example of that development, multi-zone Variable-Air Volume systems (multi-zone VAV), where the quantity of supplied air could be varied in the response of the demand, emerged to substitute the use of multi-zone Constant-Air Volume systems (CAV), where the air quantity of supplied air is constant. With multi-zone VAV, the saving in energy would be a result of the system ability to reduce the quantity of air at part load, which occurs at most of the time [2].

Despite multi-zone VAV systems would be efficient in terms of energy saving, their utilization to maintain the goals of HVAC systems would be challenging. One challenge of utilizing multi-zone

VAV system is to maintain the minimum ventilation requirements. The ventilation load would be constant, while the zone thermal load would vary. Hence, if the thermal load decreases in a zone, the system would respond by decreasing the quantity of supply air. Since the supply air in multi-zone VAV systems consists of ventilation air and recirculation air, the response of the system would result in supplying ventilation air less than the minimum requirements. Moreover, despite ASHRAE 62.1, “Ventilation for Acceptable Indoor Air Quality,” introduces an equation to take into consideration multiple-zone systems, the quantity of outdoor air will increase by applying the equation. The increase in the outdoor quantity would meet the minimum ventilation requirements for some zones, while it would overventilate other zones [4], [5]. That would result in diminishing the benefit of utilizing VAV systems because of supplying air more than it is required for some zones.

Humidity control is another challenge in utilizing VAV. The challenge of humidity control would be observed at part-load operating conditions, which occur most of the time. At part-load operating conditions, the thermal load might decrease, while the ventilation load would not act similarly, which would result in increasing the ratio of ventilation air to the total supply air more than the design ratio. Hence, the cooling equipment, which dehumidifies the incoming outdoor air by cooling it to a low dew point, would not have sufficient capacity to remove the moisture because the load would exceed the design condition [2].

Therefore, aiming to overcome the mentioned challenges, the concept of employing separate subsystems, each of which handles a goal of the HVAC systems goals, emerged. The concept takes into account controlling both subsystems to work harmonically in order to constitute a system more efficient than the subsystems individually [2]. As an application of the subsystems approach, Dedicated Outdoor Air Systems (DOAS) have been integrated to be paired with other HVAC systems handling local thermal loads.

DOAS are systems designed particularly to supply conditioned outdoor air into buildings for ventilation requirements. The supply of the ventilation air would be in direct or in conjunction with other HVAC equipment serving the same zones as the DOAS [5], [6]. Utilizing DOAS would result in enhancing humidity control and energy saving significantly [6].

Enhancing the humidity control process is significant in utilizing DOAS because its design conditions consider the nature of outdoor air. Despite the ratio of the latent load to the sensible load in outdoor air ranges between 3:1-5:1 in most climates, except in “high-altitude and desert climates”, according to Harriman et al. in [6], the design conditions of conventional HVAC systems take into consideration the peak sensible load only, [7] in [6]. That would result in negatively impact the equipment performance to handle the high latent load when it occurs. Therefore, utilizing DOAS

would result in controlling the humidity efficiently because DOAS design considers the variation among the load peaks [6].

Additionally, energy saving is another advantage of DOAS. According to ASHRAE handbook—HVAC applications in [6], 80% of the latent load in a building comes from outdoor air. Hence, handling the ventilation load and the local load through one single system would result in increasing energy consumption due to dehumidifying the entire air, outdoor and recirculated, despite the recirculation air would not require such process. For that, through DOAS, an HVAC system in a building would handle each load more efficiently instead of treating the loads, local and ventilation, in an equal manner.

In addition, the quantity of outdoor air to meet the ventilation requirements is less in DOAS than in multi-zone systems handling ventilation and recirculation loads [6]. The reduction in the quantity of air in DOAS would be a result of applying the “100% Outdoor Air Systems” equation in ASHRAE 62.1, under the “Ventilation Rate Procedure,” while multi-zone systems are required to apply the “Multiple-Zone Recirculating Systems” equation, under the same procedure. The “100% Outdoor Air Systems” equation defines the minimum ventilation air at the system intake as the sum of the requirements of the zones that are served by the system. On the other hand, the “Multiple-Zone Recirculating Systems” equation requires to take into account several variables in order to define the minimum ventilation air at the system intake; that is likely to be more than the sum of the zones’ requirements to ensure meeting the ventilation requirements for all zones at any time [8].

In the literature, integration of DOAS in HVAC systems has been examined in order to determine the DOAS’ impacts practically. However, the impact of DOAS on energy consumption, thermal comfort, and life cycle cost, if the coupled system is multi-zone VAV, has not been conducted in an application requiring relatively high ventilation. Therefore, the aim of this study is to examine that impact for enhancing the futuristic decision-making process in designing HVAC systems under similar conditions.

In this study, Chapter 2 recalls previous studies investigating DOAS configurations, Chapter 3 states the objectives of this study, Chapter 4 describes the method utilized, Chapter 5 discusses the results obtained, and Chapter 6 concludes this study and provides suggestions for future work.

Chapter 2

Literature Review

The configuration of DOAS with other HVAC systems has been studied from various aspects.

Mumma in [9] evaluated the economic benefits of DOAS with a radiant system compared to a conventional all air VAV system for a 6-story office building in Philadelphia, PA. The study shows an encouraging economic saving toward the DOAS with the radiant system option due to saving in the initial and operating costs. In particular, the DOAS with the radiant system would reduce the plant size, unit size, ductwork, piping, plenum depth, electrical services, and mechanical shaft compared to the conventional all air VAV. However, the study was limited to one climate zone.

In addition, Mumma and Shank in [10] simulated five DOAS configurations paired in parallel with sensible equipment. Then they compared the simulation results to the results of simulating all-air VAV under identical conditions. The considered DOAS configurations: 1- A cooling coil, a heating coil, and a humidifier; 2- A run-around heat recovery was added to the configuration in (1); 3- A total-energy wheel, a cooling coil, and a heating coil; 4- A run-around heat recovery was added to the configuration in (3) to enhance the dehumidification process; 5- A reheat coil, an enthalpy wheel, a cooling coil, a sensible wheel; 6- A conventional all-air VAV without a heat recovery nor an economizer. The simulations showed the configuration in (5) had the lowest peak and annual operating energy among other configurations. In terms of energy consumption, the configuration in (5) consumed less energy by 44%, 30%, 29%, 1%, and 15% compared to the configurations in (1), (2), (3), (4), and (6), respectively. The study, though, did not consider the local load and the cost of implementing such configurations.

Moreover, Jeong et al. in [11] studied the benefit of utilizing DOAS in parallel with radiant panels compared to a VAV system. The DOAS was a constant-volume, variable-temperature system

and operated on two stages; at the low stage, the DOAS handled the load through varying the supply temperature down to 11.1°C , and as the load increased, the ceiling radiant panels handled the remaining load that could not be handled by the DOAS. The study showed that, compared to the case utilized the conventional VAV, the system utilized the DOAS reduced the chiller capacity by 25%, the cooling load by 7.6%, the fan energy by 29%, and the total energy consumption by 42%, while the pumping energy was in the DOAS case twice the case of VAV. Nevertheless, the study focused on the cooling load only.

Additionally, McDowell and Emmerich in [12] investigated the benefits and limitations of DOAS in four climate zones for an office building by simulating four HVAC configurations; they employed TRANSYS & CONTAM for simulations. The HVAC configurations: 1- A water source heat pump that was supplied by ventilation air to deliver it through for each zone; 2- An economizer was added to the configuration in (1); 3- Simple DOAS that consisted of a preheat coil and an enthalpy wheel. The DOAS was paired in parallel with water source heat pumps. The whole building had one DOAS unit, while each zone had its own water source heat pump; 4- Full DOAS that consisted of a preheat coil, an enthalpy wheel, a cooling coil, and a sensible wheel. The DOAS was paired in parallel with water source heat pumps. The whole building had one DOAS unit handling the entire latent load in the building, while each zone had its own water source heat pump. The results showed that the simple DOAS configuration saved energy ranged from 14% to 37%, while the full DOAS configuration saved energy ranged from 21% to 38%; both compared to the first HVAC configuration. However, the paired system was a local system, and the considered climate zones were limited, 1A, 2B, 4A, and 6A. In addition, the study did not consider the cost of implementing such configurations.

Morover, Hallenbeck in [13] compared a design of Fan Powered Induction Terminal systems (FIPT) in series with DOAS to a design utilizing VAV systems for a governmental tower in Alexandria, VA. A DOAS unit consisted of energy recovery, a filter bank, 3 centrifugal plenum fans, a preheat coil, a cooling coil, and a reheat coil, while a FIPT unit consisted of a filter, a variable speed fan, a heating coil-where it is required, and a sensible cooling coil. For the VAV system, a water-cooled centrifugal chilled water plant, for cooling, and a standard efficiency gas-fired hydronic hot boiler system, for heating, served the VAV units. The results showed that the system utilized DOAS with FIPT, compared to the VAV system, would decrease the energy cost by 24.7% and energy consumption by 32.3%. However, the study did not take into account the initial cost to implement either designs.

In addition, in order to examine the claim that an active chilled beam with DOAS is more efficient, less expensive, and enhance air quality than a VAV with reheat, Stein and Taylor in [14] simulated

an office building in Davis, CA, with considering three HVAC configurations; active chilled beams with DOAS, VAV with reheat, and a hybrid system. The hybrid system utilized a VAV handler with a chilled water coil and an airside economizer for 70% of the zones, while the remaining zones, which with low occupancy density, were handled by active chilled beams. The simulation results by EnergyPlus showed that the VAV with reheat would consume less energy by 40%, and the hybrid system would consume energy by 33% less, both compared to the active chilled beams with DOAS. In terms of cost, compared to the VAV with reheat, the active chilled beams with DOAS and the hybrid systems would increase the initial cost by 143% and 44%, respectively. Despite the study was holistic for such building type, it focused on a specific climate zone, so the study would not be sufficient to generalize the findings upon other climates.

Additionally, Deng in [15] compared three configurations of DOAS with various HVAC systems to a multi-zone VAV system for an office building in seven climate zones. The HVAC configurations were DOAS in series with Fan Coil Units (FCU), DOAS in parallel with FCU, and DOAS with active chilled beams in series and heating radiators in parallel. The DOAS consisted of a preheat coil, an energy wheel, and a cooling coil, and the FCU consisted of a cooling coil and a heating coil; this configuration had a waterside economizer. The VAV consisted of a preheat coil, a cooling coil, and a reheat terminal, and it had an airside economizer. The results showed a potential energy saving ranged by 7.1% to 26% in systems utilizing DOAS compared to the VAV system. In addition, DOAS in parallel with FCU consumed less energy compared to the in-series configuration, except in hot climates. However, the paired systems with DOAS were local systems, not centralized, the climate zones, which were 1A, 2B, 4A, 5A, 5B, and 8, were limited.

Moreover, Inklab et al. in [16] assessed the performance of various DOAS configurations in an office building located in the hot-humid climate of Thailand through simulations by TRANSYS. The considered HVAC systems: 1- A Constant-Air Volume system (CAV) supplying ventilation requirement besides handling the local load; 2- A DOAS with a cooling coil paired in parallel with the CAV in the first configuration; 3- A run-around coil was added to the DOAS in (2) to precool the air upstream the cooling coil and reheat the air downstream the cooling coil; 4- An enthalpy wheel was added to the DOAS in (2); 5- A sensible wheel was added to the DOAS in (4); 6- A run-round coil was added to the DOAS in (5). The results from the simulations were compared to the first configurations if the ventilation were eliminated, as a practice to reduce the energy consumption. The results showed a reduction of 19-24% by DOAS compared to the first configuration if it runs without ventilation. However, the study was limited to a certain climate, did not state the results clearly, and did not consider the cost as a parameter for the comparison.

In addition, for a medium office building in 7 climate zones, Frink in [17] compared the life cycle cost of three alternative configurations utilizing DOAS with multi-zone VAV to a baseline configuration, Alternative 1, utilizing multi-zone VAV. The considered alternative configurations: Alternative 2: a DOAS supplying outdoor air at an optimized temperature in parallel with multi-zone VAV; Alternative 3: a DOAS supplying dehumidified outdoor air at a neutral temperature in parallel with multi-zone VAV; Alternative 4: a DOAS supplying outdoor air at a minimum temperature and a maximum dew point to multi-zone VAV. The results obtained by “whole building energy simulations” showed an increase in energy consumption in all alternatives and climates compared to Alternative 1, except Alternative 2 in Houston, TX; the consumption decreased by 0.4%. Moreover, in terms of life cycle cost, the payback period in the best case, which occurred in Houston, TX, would be 72 years, at least. However, the considered building type, which was an office building, has low ventilation requirements. Such building might not show the benefit of DOAS since the benefit correlates with the ratio of ventilation air to the recirculated air; as the ratio increases, the benefit increases [7] in [6]. Hence, considering a building with higher ventilation requirements would show the benefit of DOAS clearly. For instance, according to ASHRAE 62.1-2016, a 100-m² space as a classroom (age 5-8) requires minimum ventilation air of 0.185 m³/s during occupancy hours, while the same space area as an office space requires minimum ventilation air of 0.0485 m³/s [18].

For home applications, Kim et al. in [19] evaluated four DOAS configurations in parallel with secondary systems for energy-plus houses in the humid subtropical climate of Daejeon, South Korea, through simulations by TRANSYS 17. The considered configurations: 1- An air-source heat pump in parallel with an enthalpy wheel, for the ventilation, and a vapor compression dehumidifier placed in the house for dehumidification; 2- DOAS in parallel with a sensible cooling system. The DOAS consisted of an enthalpy heat exchanger and cooling coil, which is served by the same chiller in series with the cooling system; 3- DOAS in parallel with a cooling system. The DOAS consisted of an enthalpy heat exchanger and a heat pump with two condensers and an evaporator. The heat exchanger pre-cooled the outdoor air, while the evaporator dehumidified it. One of the condensers reheated the leaving air, while the second condenser, which was placed in the exhaust outlet, regulated the temperature of the first condenser. 4- Similar to the configuration in (3), but a direct evaporative cooler was introduced upstream the second condenser to reduce the exhaust air temperature through mixing it with freshly supplied outdoor air to enhance the heat extraction process in the refrigerant. In terms of energy surplus, which is the difference between energy produced through Photovoltaic panels (PV) and energy consumed by HVAC systems, configurations in (2) and (4) produced surplus energy higher than the configuration in (1) by 60% and 61.8%, and higher

than the configuration in (3) by 21.7% and 23.1%, respectively.

For supply conditions, Shank and Mumma in [20] studied the impact of various DOAS supply conditions in order to develop a methodology for selecting effective conditions in terms of energy and cost. The considered parallel systems to the DOAS were FCU and ceiling radiant cooling panels. The study found that the recommended supply conditions of DOAS coupled in parallel with a sensible terminal are either 13° C dry bulb temperature and 7° C dew point or the conditions that would maintain the space relative humidity in the space around 40%. Such supply conditions, though, would only overcool the served space if the space has an occupancy density exceeding 90 people per 93 m² and the equipment load ranged 32-54 W/m². Additionally, supplying air at a neutral temperature would increase the initial and operating costs. However, the study considered only the outdoor conditions of Atlanta, GA.

Finally, Mumma in [21] investigated the effective arrangement, parallel or series, of an FCU with DOAS through examining the suggested arrangements under identical conditions, such as supply conditions, latent and sensible loads, and thermostat setpoint. The results showed an increase of 330% in airflow, 823% in pressure drop, and 2,700% in power for the series configuration compared to the parallel configuration. In addition, despite there would be an increase in the initial cost in the parallel configuration, the energy cost in the series configuration would overcome that initial cost.

Chapter 3

Thesis Statement

Throughout the literature, the impact of coupling DOAS with a centralized HVAC system on energy consumption, thermal comfort, and life cycle cost with considering various climate zones and a building with high ventilation requirements has not to be conducted comprehensively. Therefore, the objectives of this study are:

1. Assess the impact of utilizing DOAS in parallel with multi-zone VAV on energy consumption, thermal comfort, and life cycle cost in various climate zones for a building requiring high ventilation.
2. Investigate the impact of the DOAS supply conditions on energy consumption, thermal comfort, and life cycle cost.
3. Evaluate the impact of introducing heat recovery measures on energy consumption.

Chapter 4

Methodology

In order to assess the impact of implementing DOAS in parallel with multi-zone VAV systems, the Commercial Reference Buildings (CRB) were adopted in 17 climate zones. Then, five configurations of DOAS were developed for the comparison with a baseline model utilizing for the entire load, ventilation and thermal, multi-zone VAV . Finally, 102 simulations were run using the whole energy simulation tool, EnergyPlus, and the obtained results were used to investigate the thesis of this study.

4.1 Energy Model

The Department of Energy (DOE) with three national laboratories developed CRB to be utilized in energy analysis by using the whole energy simulation tool, EnergyPlus [22]. Among the reference buildings, the primary school energy model was chosen for this study because schools have high ventilation load with less complexity than other buildings, such as hospitals, have; so the impact of DOAS would be clearly assessed. In addition, since CRB are available in various releases, each of which complies with a different version of an energy standard, the model complying with ASHRAE 90.1-2013 was selected. AHSRAE 90.1 provides the “energy standard for buildings except low-rise residential buildings” [23].

4.1.1 Geometry

The primary school model consisted of one floor with a gross area of 6,871 m² . The wall gross area is 2,512 m² with a window-to-wall ratio of 35%. Figure 4.1 shows the zones in the model, and Table 4.1 shows the breakdown of the zones.

Figure 4.1: The layout of the primary school model.

Table 4.1: The breakdown of the zones in the primary school model.

Zone	Qty.	Floor Area [m ²]		Volume [m ³]		External Wall Area [m ²]		Window Area [m ²]	
		Zone	Total	Zone	Total	Zone	Total	Zone	Total
Corner Class	6	99	594	396	2376	80	480	28	168
Multi Class (Except 2-Pod 3)	5	477	2385	1908	9540	212	1060	74.2	371
Multi Class 2-Pod 3	1	315	315	1260	1260	140	140	49	49
Corridor	3	192	576	768	2304	12	36	4.2	12.6
Computer Class	1	162	162	648	648	72	72	25.2	25.2
Main Corridor	1	546	546	2184	2184	36	36	12.6	12.6
Lobby	1	171	171	684	684	76	76	26.6	26.6
Mech.	1	252	252	1008	1008	0	0	0	0
Bath	1	190	190	760	760	40	40	14	14
Offices	1	441	441	1764	1764	168	168	58.8	58.8
Gym	1	357	357	1428	1428	68	68	23.8	23.8

Table 4.2: U-Factor [$\text{W}/\text{m}^2\text{K}$] of the opaque elements in each climate zone.

Climate Zone	Exterior Wall	Roof	Fenestration	
			U-Factor	SHGC
1A	0.704	0.273	3.5	0.23
1B	0.704	0.273	3.5	0.23
2A	0.477	0.211	3.5	0.23
2B	0.477	0.211	3.5	0.23
3A	0.437	0.221	3.2	0.22
3B	0.437	0.221	3.2	0.22
3C	0.437	0.221	3.2	0.22
4A	0.363	0.182	2.4	0.4
4B	0.363	0.182	2.4	0.4
4C	0.363	0.182	2.4	0.4
5A	0.312	0.182	2.4	0.4
5B	0.312	0.182	2.4	0.4
5C	0.312	0.182	2.4	0.4
6A	0.278	0.182	2.4	0.4
6B	0.278	0.182	2.4	0.4
7	0.278	0.159	2.3	0.47
8	0.21	0.159	2.3	0.47

4.1.2 Envelope

The construction in the primary school model was “steel-framed” for the walls and “insulation entirely above deck” for the roof. The exterior walls consisted of 25-mm stucco, 16-mm gypsum board, insulation, and 16-mm gypsum board, and the roof consisted of built-up roofing, insulation, and metal surface. To comply with ASHRAE Standard 90.1-2013, the envelop U-Factor [$\text{W}/\text{m}^2\text{K}$] was varied depending on the climate zones. Table 4.2 maps the climate zones to U-Factor of the opaque elements, which are the exterior walls, roof, and vertical fenestrations, and Figure 4.33 represents the climate zones on the United States climate zone map (the map source: [24]).

4.1.3 Lighting, Plug, and Process Loads

The lighting, plug, and process loads were in terms of peak power density [W/m^2] with schedules to vary the loads over the time. For the lighting load, Lighting Power Density (LPD) was adopted from ASHRAE 90.1-2013 [23]. Table 4.3 summarizes the loads for each zone subcategory in the model, and Figure 4.3 to Figure 4.5 represent the schedules. In the schedule representations, the “Summer” period starts on 6/30 through 9/30, otherwise, it is “In Session” period. In addition, “Weekends” include special days and holidays.

Figure 4.2: The United States climate zone map.

Table 4.3: Lighting, plug, and process loads [W/m²] for each zone subcategory.

Zone	Lighting [W/m ²]	Plug and Process [W/m ²]
Classrooms	13.35	15
Corridor	7.1	4
Computer Class	13.35	20
Main Corridor	7.1	4
Lobby	9.69	4
Mech.	10.23	10
Bath	10.55	4
Offices	11.95	10.8
Gym	7.75	5
Kitchen	13.02	1630.4
Cafeteria	7	25.4
Library-Media Center	12.81	15

Figure 4.3: The schdule representation of the lighting load fraction over the day.

Figure 4.4: The schedule representation of the plug and process loads fraction over the day (except for the kitchen).

Figure 4.5: The schedule representation of the plug and process load fraction over the day in the kitchen.

4.1.4 Occupancy

The occupancy was in terms of occupancy density [m^2/Person] with schedules to vary the number of occupants over the time. The occupancy density complied with the “Occupant Density” in ASHRAE 62.1-2004. However, the “occupant density” is the same in ASHRAE 62.1-2016 except for the kitchen and gym. Table 4.4 shows the occupancy for each zone subcategory, and Figure 4.6 to Figure 4.10 represent the schedules. In the schedule representations, the “Summer” period starts on 6/30 through 9/30 (except for Computer Class it starts on 6/15 through 9/30), otherwise, it is “In Session” period. In addition, “Weekends” include special days and holidays.

4.1.5 Infiltration

The infiltration rate was derived from the DOE-2 model. The DOE-2 model is an infiltration method that takes into account the infiltration caused by the wind-driven pressure over the building [25]. Due to being exposed to the wind differently, each zone in the primary school model had a different infiltration rate, as Table 4.5 shows. The derivation of the rates were summarized by Gowri et al. in [25]. Figure 4.11 represents the schedule of the infiltration rate fraction that were varied depending on the HVAC operating conditions, on or off, and Figure 4.12 represents the schedule of the infiltration rate that was caused by the door opening.

Table 4.4: The occupancy per zone subcatogary.

Zone	Qty.	Occupancy Density [m ² /Person]	Floor Area [m ²] Zone	Total	Occupants [Person] Zone	Total
Corner Class	6	3.72	99	594	27	160
Multi Class (Except 2-Pod 3)	5	3.72	477	2385	128	641
Multi Class 2-Pod 3	1	3.72	315	315	85	85
Corridor	3	0	192	576	0	0
Computer Class	1	3.72	162	162	44	44
Main Corridor	1	0	546	546	0	0
Lobby	1	0	171	171	0	0
Mech.	1	0	252	252	0	0
Bath	1	0	190	190	0	0
Offices	1	18.58	441	441	24	24
Gym	1	3.1	357	357	115	115
Kitchen	1	6.22	168	168	27	27
Cafeteria	1	0.93	315	315	339	339
Library-Media Center	1	9.29	399	399	43	43
Total	25	4.65	4084	6871	832	1478

Figure 4.6: The schedule representation of the general occupancy fraction over the day (Note: the corresponding values of Weekends are zeros).

Figure 4.7: The schedule representation of the computer class occupancy fraction over the day (Note: the corresponding values of Weekends are zeros).

Figure 4.8: The schedule representation of the Office occupancy fraction over the day (Note: the corresponding values of Weekends are zeros).

Figure 4.9: The schedule representation of the cafeteria occupancy fraction over the day (Note: the corresponding values of Weekends are zeros).

Figure 4.10: The schedule representation of the gym occupancy fraction over the day (Note: the corresponding values of Weekends are zeros).

Table 4.5: The infiltration rate per exterior area unit for each subcategory zone.

Zone	Qty.	Infiltration Rate [$\text{m}^3/\text{s m}^2$]
Corner Class	6	0.000254
Multi Class	6	0.000175
Computer Class	1	0.000175
Lobby (due to door opening)	1	*4.34 [m^3/s] 3.03 [m^3/s]
Lobby	1	0.000175
Corridor	3	0.000034
Main Corridor	1	0.000035
Mech.	1	0
Bath	1	0.000099
Offices	1	0.000157
Gym	1	0.000091
Kitchen	1	0.000091
Cafeteria	1	0.000179
Library-Media Center	1	0.000163

*For climate zones 1A, 1B, 2A, and 2B.

Figure 4.11: The schedule representation of the infiltration rate fraction over the day.

Figure 4.12: The schedule representation of the infiltration rate fraction due to the door opening (Note: the corresponding values of Weekends are zeros).

4.1.6 HVAC

Besides maintaining the indoor thermal properties within comfort conditions, HVAC systems deliver outdoor air into buildings to enhance the indoor air quality [2]. For that, HVAC designers consider various configurations to deliver the outdoor air into the buildings in an effective way that would not compromise the indoor air quality for energy saving [26]. Among the configurations are multi-zone VAV, which was considered in the baseline model of this study, and DOAS in parallel with multi-zone VAV, which were considered for the alternative models.

Configuration

The main difference between the various models proposed for this study was the configuration of HVAC systems. While it was multi-zone VAV for the baseline model, for the alternative models were DOAS coupled in parallel with multi-zone VAV with various supplied conditions and the equipment configurations within the units.

Baseline Model

The Baseline model utilized four multi-zone VAV units serving the classrooms and common zones, except the kitchen, cafeteria, and gym; those zones were considered “specialty [zones] with unusual loads,” so they were conditioned by using Packaged Single Zone systems (PSZ) [27]. Figure 4.13

shows the distribution of the HVAC systems in the Baseline model, where each color represents a separate unit.

Figure 4.13: The distribution of HVAC systems in the Baseline model.

Multi-Zone VAV: A multi-zone VAV system supplies conditioned air to multiple thermal zones, which might have various loads, with considering varying the quantity of supplied air based on the zones' requirements [28]. In this study, the multi-zone VAV system consisted of a total-energy wheel, chilled-water cooling coil, hot-water heating coil, variable speed fan. The original model, the CRB model, utilized DX cooling coil, but it was replaced by the chilled-water cooling coil utilized in the Advanced Energy Design Guide for K-12 model [27]. In addition, the multi-zone VAV units had differential enthalpy-controlled economizers in all climate zones except 1A and 1B, per ASHRAE 90.1-2013 [23].

For the air terminals, VAV air terminals with reheat were used at the zone level. Using VAV with reheat air terminals would reduce the consumption of energy; such configuration would be able to reduce the quantity of air being conditioned at the central unit, and it would control reheating

the air at the zone level in accordance to the reheat needs, which might differ among zones served by the same VAV unit. However, the minimum quantity of air needs to be able to maintain the heating load, humidity control, air movement, and ventilation requirements [28].

Figure 4.14 shows the equipment configuration in a VAV unit in the Baseline model. For climate zone 3B, 3C, 4B, 4C, and 5B, the total-energy wheel was not included, as ASHRAE 90.1-2013 does not require exhaust air energy recovery in the mentioned climate zones. Additionally, some systems did not have total-energy wheel due to meeting one of the exceptions in 6.5.6.1, ASHRAE 90.1-2013 [23].

Figure 4.14: Equipment configuration in a VAV unit in the Baseline model.

The VAV units supplied the air at 12.8° C (55° F) dry bulb temperature (DBT) with maximum dew point temperature (DPT) of 12.8° C (55° F) in the cooling mode, and 15.6° C (60° F) DBT with maximum DPT of 12.8° C (55° F) in the heating mode. In addition, the air terminals could reheat the supplied air, at the zone level, up to 40° C (104° F) DBT. However, in climate zones where the cooling mode dominated, such as 1A and 1B, the VAV units supplied air at 12.8° C (55° F) DBT with maximum DPT of 12.8° C (55° F) in both modes, cooling and heating, while the air terminals could still reheat the supplied air up to 40° C (104° F) DBT.

Packaged Single Zone System (PSZ): For the cafeteria and gym, the PSZ consisted of a total-energy wheel, constant speed supply fan, DX cooling coil, and gas-fired furnace. For the kitchen, the system had the same configuration as that for the cafeteria and gym but without total-energy wheel, as ASHARE 90.1-2013 gives an exception for commercial kitchens. In addition, for all PSZ in climate zones 3B, 3C, 4B, 4C, and 5B, the total-energy wheel was not included, as ASHRAE 90.1-2013 does not require exhaust air energy recovery in the mentioned climate zones. Also, some systems did not have total-energy wheel due to meeting one of the exceptions in the articles 6.5.6.1,

ASHRAE 90.1-2013 [23]. Figure 4.15 shows the general equipment configuration in a PSZ unit.

Figure 4.15: Equipment configuration in a PSZ unit in all models.

The PSZ supplied the air at 12.8° C (55° F) DBT with maximum DPT of 12.8° C (55° F) in the cooling mode, and 15.6° C (60° F) DBT with maximum DPT of 12.8° C (55° F) in the heating mode. However, in climate zones where the cooling mode dominated, such as 1A and 1B, the PSZ units supplied air at 12.8° C (55° F) DBT with maximum DPT of 12.8° C (55° F) in both modes, cooling and heating.

Alternative Models

Generally, all alternative models utilized DOAS in parallel with multi-zone VAV. The DOAS supplied the outdoor air to the zones directly for ventilation, while the multi-zone VAV handled local heating and cooling loads. Figure 4.16 shows the configuration of the HVAC systems in the alternative models, and Figure 4.17 maps the HVAC systems to the served zones.

In addition, to assess the impact of DOAS broadly, various supply conditions of DOAS were considered in this study. The considered supply conditions were 12.8-15.6°C DBT with 12.8°C DPT, 12.8-15.6°C DBT with 6.9°C DPT, and 21-24°C DBT with 6.9°C DPT. The first set of supply conditions, 12.8-15.6°C DBT with 12.8°C DPT, were adopted from the multi-zone VAV supply conditions in the primary school model of CRB; such supply conditions, however, represent an optimal humidity ratio while the DBT complies with a common practice of supplying the air at a temperature lower than the desired room temperature by 11°C (20°F), which would remove part of the local sensible load in the served zones. Additionally, the second supply conditions, 12.8-15.6°C DBT with 6.9°C DPT, was drier than the first configuration in order to handle the local latent load through the DOAS. The third supply conditions aimed to handle the local latent load through the DOAS while being neutral in terms of the sensible load, neither add nor remove a sensible load

to/from the served zones. Handling the local latent load in zones served by DOAS through the DOAS would result in reducing the size of the cooling equipment handling the local loads since the equipment, under such conditions, would condition dry air at a warm temperature [6].

Figure 4.16: The configuration of HVAC systems in the alternative models at the zone level.

For the kitchen, cafeteria, and gym, the HVAC systems remained the same as the baseline model since the scope of this study was to assess the impact of DOAS if coupled with multi-zone VAV system.

DOAS: In this study, two equipment configurations were utilized for DOAS. The first configuration consisted of a total-energy wheel, chilled-water cooling coil, hot-water heating coil, and variable speed fan, while the second configuration consisted of a total-energy wheel, sensible wheel, chilled-water cooling coil, hot-water heating coil, and variable speed fan. The first configuration was utilized in alternatives 1-3, while the second configuration was utilized in alternative 4-5. Figure 4.18 and Figure 4.19 shows the first and second configurations, respectively.

The sensible wheel in the second configuration aimed to enhance the dehumidification process. Where the second configuration was utilized, the air would leave the cooling coil cooled to a degree

Figure 4.17: The distribution of HVAC systems in the alternative models.

Figure 4.18: The first equipment configuration in a DOAS unit in the alternative models.

Figure 4.19: The second equipment configuration in a DOAS unit in the alternative models.

that cannot deliver the air at, as a by-product of the dehumidification process to a low DPT. Hence, instead of heating the leaving air by the heating coil only, the sensible wheel would absorb the heat of incoming outdoor air upstream the cooling coil and release it downstream the cooling coil. That would reduce the load on the cooling coil, as well as on the heating coil. Figure 4.20 shows the potential energy saving by introducing the sensible wheel for the cooling design conditions in Miami, FL. The potential saving is 41 [kJ/kg dry air] that equals 58% of the total energy requiring to condition a unit [kg dry air] of outdoor air in Miami, FL, to 23° C DBT and 6.9° C DPT, at the cooling design conditions.

Supply Conditions: Supplying the ventilation air at a cold temperature would result in removing part of the local cooling load within the zone. Consequently, the capacity of the equipment handling the local load would be reduced. However, applying such an approach could overcool the zone, which results in increasing the local heating load. Alternatively, the ventilation air might be supplied at a neutral temperature to the zone; so no thermal load would be added nor removed from/to the zone. Nevertheless, such an alternative approach would not only overlook the potential free cooling, as a by-product of ventilation process, but it would also increase the heating load on the DOAS unit in order to reheat the air to a neutral temperature.

Moreover, instead of considering the humidity ratio of the supplied ventilation air to be within the comfort condition in itself, it could be dry enough to offset part or the entire local latent load. Hence, the latent load on the unit handling the local load would be reduced, which result in downsizing

Figure 4.20: Representation of the potential saving by introducing the sensible wheel in the DOAS seconded configuration at the design cooling condition of Miami, FL.

Table 4.6: Mapping of the alternative models to the configuration and the supply air conditions.

Alternative	DOAS Configuration	Dry Bulb Temperature [$^{\circ}$ C]	Dew Point Temperature [$^{\circ}$ C]
Alternative 1	1st	12.8-15.6*	12.8
Alternative 2	1st	12.8-15.6*	6.9
Alternative 3	1st	21-24	6.9
Alternative 4	2nd	12.8-15.6*	6.9
Alternative 5	2nd	21-24	6.9

* In climate zones where the cooling mode dominated, air was supplied at 12.8 $^{\circ}$ C (55 $^{\circ}$ F) only.

the unit capacity. However, if the air were dehumidified to offset the local latent load and supplied without being reheated, it would result in overcooling the zone and cause undesired draft on the occupants.

Therefore, in order to study the effects of DOAS supply conditions, all the mentioned conditions were considered. In terms of DBT, in the Alternative 1, Alternative 2, and Alternative 4 models, the air was supplied cold, while in the Alternative 3 and Alternative 5 models was neutral. Moreover, in terms of DPT, in the Alternative 2-5 models, the air was supplied at DPT of 6.9 $^{\circ}$ C (44.4 $^{\circ}$ F), while in the Alternative 1 models was supplied at 12.8 $^{\circ}$ C (55 $^{\circ}$ F) DPT. Table 4.6 maps the DOAS configuration and the supplied air conditions to the alternative models.

To determine the design DPT in the Alternative 2-5 models, the latent load of 55 [W/Person] was assumed, based on “Standing, light work; walking” in Table 7-14 SI in [28]. Then, Equation 4.1 was applied to determine the design humidity ratio that corresponded to the lowest humidity ratio obtained [7]:

$$Q_L = 3 * V_{OZ} * (W_{zone} - W_{supply}) \quad (4.1)$$

where, Q_L = the latent load [W] = 55 * Σ occupants, V_{OA} = the quantity of outdoor air [m³/s], W_{zone} = the design humidity ratio of the zone = 0.0085 [kg_{water}/kg_{dryair}], and W_{supply} = the design humidity ratio of the supplied air in kg_{water}/kg_{dryair}. Table 4.7 represents the results obtained.

Multi-Zone VAV: The multi-zone VAV in the alternative models were designed to handle the local loads in the zones without providing the ventilation requirements. The systems consisted of a chilled- water cooling coil, hot-water heating coil, variable speed fan, and reheat VAV air terminals. Additionally, the VAV units had differential enthalpy-controlled economizers in all climate zones except 1A and 1B. Figure 4.21 shows the equipment configuration in a VAV unit in the alternative models.

The VAV units supplied the air at 12.8 $^{\circ}$ C (55 $^{\circ}$ F) DBT with maximum DPT of 12.8 $^{\circ}$ C (55 $^{\circ}$

Table 4.7: The design humidity ratio of the air supplied by DOAS to offset the local latent load.

Zone	Area [m ²]	OA Flow Rate [m ³ /s]	Max # of Occupants	Latent Load [W]	W_{supply} [gram/kg]
Corner Class 1_Pod 1	99	0.19	24	1293.2	6.18
Multiple Class 1_Pod 1	477	0.9	113	6230.8	6.18
Corner Class 2_Pod 1	99	0.19	24	1293.2	6.18
Multiple Class 2_Pod 1	477	0.9	113	6230.8	6.18
Corner Class 1_Pod 2	99	0.19	24	1293.2	6.18
Multiple Class 1_Pod 2	477	0.9	113	6230.8	6.18
Corner Class 2_Pod 2	99	0.19	24	1293.2	6.18
Multiple Class 2_Pod 2	477	0.9	113	6230.8	6.18
Corner Class 1_Pod 3	99	0.19	24	1293.2	6.18
Multiple Class 1_Pod 3	477	0.9	113	6230.8	6.18
Corner Class 2_Pod 3	99	0.19	24	1293.2	6.18
Multiple Class 2_Pod 3	315	0.59	75	4114.7	6.18
Computer Class	162	0.3	38	2116.1	6.18
Offices	441	0.19	21	1152.1	6.48
Library-Media Center	399	0.34	42	2293.3	6.28

* 6.18 [gram/kg] corresponds to 6.9° C DPT.

* if the economizer is enabled

Figure 4.21: The equipment configuration in a VAV unit in the alternative models.

Table 4.8: HVAC equipment types and specifications.

Equipment Name	Equipment Type	Specifications
Boiler	Hot-water boiler fueled by natural gas with 81° C (178° F) leaving water temperature	Efficiency = 0.8
Chiller	Air-cooled electric chiller adopted from EIR model in DOE-2 with 6.67° C (44° F) leaving water temperature	COP = 2.8
Pump	Variable speed	Motor efficiency: 0.8 - cooling system 0.9 - heating system
Total-energy wheel	Rotary	Sensible effectiveness: 0.7 - heating air flow 0.75 - cooling air flow Latent effectiveness: 0.6 - heating air flow 0.6 - cooling air flow
Sensible wheel	Flat plate & counter flow*	Effectiveness = 0.32 – Alternative 4 0.65 – Alternative 5
DX cooling coil system	Variable-speed	COP = 3.8

F) during the cooling mode, and 15.6° C (60° F) DBT with maximum DPT of 12.8° C (55° F) in the heating mode. In addition, the air terminals could reheat the supplied air, at the zone level, up to 40° C (104° F) DBT. However, in climate zones where the cooling load dominated, such as 1A and 1B, the VAV units supplied air at 12.8° C (55° F) DBT with maximum DPT of 12.8° C (55° F) in both modes, cooling and heating, while the air terminals could still reheat the supplied air up to 40° C (104° F) DBT.

Equipment Specifications

Table 4.8 summarizes the specifications of equipment utilized in this study. The efficiency and COP were specified in accordance with ASHRAE 90.1-2013.

For the sensible wheel, the “flat-plate, counter flow” model was used as a substitution because EnergyPlus, the simulation tool, has only a total-energy wheel model for wheel heat exchangers. For the fan, ASHRAE 90.1-2013 sets limitations on fan power, so there were assumptions needed in order to determine the efficiency before defining the limitations. Table 4.9 summarizes the assumptions, which was adopted from [29].

After determining the motor horsepower, the first motor size in ASHRAE 90.1-2013, Table 10.8-1, was selected; so the efficiency of the motor was defined. Then, Equation 4.2 was solved for the

Table 4.9: Assumptions to determine the fans efficiency.

Assumed item	Assumed value
Fan type	Variable speed
Fan mechanical efficiency (η_{mech})	0.65
Motor type	Open Drip-Proof, 4 Poles, and 1800 RPM
	If $Q < 2.2 \text{ m}^3/\text{s}$, $dp = 995 \text{ Pa}$
Pressure raise (dp)	If $2.2 \text{ m}^3/\text{s} < Q < 9.44 \text{ m}^3/\text{s}$, $dp = 1572 \text{ Pa}$
	If $Q > 9.44 \text{ m}^3/\text{s}$, $dp = 1388 \text{ Pa}$
Motor horsepower (HP)	$HP = (Q \cdot dp / \eta_{mech} 745.7) \cdot (1.1)$

pressure rise.

$$\frac{Q \cdot dp}{\eta_{total}} = Q \cdot (2118.88) \cdot (0.0013) \quad (4.2)$$

Where, Q = the volumetric flow rate [m^3/s], dp = the pressure rise [Pa], and $\eta_{total} = (\eta_{mech}) (\eta_{motor})$.

Additionally, since the total-energy wheel requires increasing the pressure rise of the fan in order to overcome the pressure drop caused by it, ASHRAE 90.1-2013 gives an adjustment to account for the pressure drop. Therefore, Equation 4.3 was applied in order to account for that pressure rise, in accordance with ASHRAE 90.1-2013, Table 6.5.3.1-2 [23].

$$A = \left(\frac{(2.2) \cdot (\epsilon) - (0.5)}{4131} \cdot Q \right) (248.84) \quad (4.3)$$

Where, A = the pressure drop adjustment [PA], ϵ = the total-energy wheel effectiveness, Q = the volumetric flow rate [cfm], and 248.84 to convert the pressure from [inwc] to [Pa]. Hence, Equation 4.2 becomes:

$$dp_{adj.} [Pa] = (\eta_{total}) (745.7) (2118.88) (0.0013) + A \quad (4.4)$$

The same process was applied for the pressure raise required to account for the sensible wheel, when applicable.

Thermostat

In in the heating season, the thermostat was set at 21° C (70° F) during the occupied hours, with a setback of 5.4° C (10° F) in the unoccupied hours. In addition, in the cooling season, the thermostat was set at 24° C (75° F) during occupied hours, with a setback of 2.7° C (5° F) in unoccupied hours, except in the climate zones 1B, 2B, and 3B; the thermostat was set without the setback. Figure

Table 4.10: The ventilation requirements per zone subcategory.

Zone	Qty.	Ventilation [m^3/s]	
		Zone	Total
Corner Class	6	0.19	1.12
Multi Class (Except 2-Pod 3)	5	0.89	4.48
Multi Class 2-Pod 3	1	0.59	0.59
Computer Class	1	0.3	0.3
Offices	1	0.19	0.19
Gym	1	0.54	0.54
Kitchen	1	2.12	2.12
Cafeteria	1	1.49	1.49
Library-Media Center	1	0.34	0.34

4.22 shows the thermostat setting in the different seasons and occupancy situations. “Weekends” included the special days and holidays.

Figure 4.22: The thermostat setting in the heating and cooling seasons in all models.

Outdoor Air Requirements

The ventilation requirements in the CRB model, which is the baseline model in this study, were based on ASHRAE 62.1-2007. However, the considered values still comply with the most recent version of ASHRAE 62.1, ASHRAE 62.1-2016, except for the kitchen [18]. Table 4.10 shows the ventilation requirements per zone as considered in the CRB model. The same values were adopted for the alternative models, as well.

The corridors, main corridor, bath, and mechanical room were considered with zero ventilation since they are not occupiable zones.

4.2 Simulation Tool

In this study, the whole building energy simulation engine, EnergyPlus, was utilized because the CRB models were developed on Input Data File (IDF) formats, which is EnergyPlus input files.

4.2.1 Overview

EnergyPlus does not have a Graphical User Interface (GUI). Developers utilize EnergyPlus as a simulation engine for their simulation software, some of which are DesignBuilder and Openstudio. However, EnergyPlus has a component called “EP-Launch,” which was used in this study, for the inputs, running simulations, and representing results. On EP-Launch, the inputs can be created through “IDF-Editor”, which is a spreadsheet-like interface [30]. Figure 4.23 and Figure 4.24 show the screens of “EP-Launch” and “IDF-Editor”, respectively.

Prior to start modeling buildings in IDF-Editor, SketchUp, a 3D modeling program, could be used to model the geometry of the buildings then save it as an EnergyPlus input file. For that, extensions, such as Euclid and OpenStudio plug-in, could be utilized in SketchUp in order to facilitate the geometry inputs. In addition, such extensions have the ability to specify the materials of the constructions [31]. Figure 4.25 shows the Euclid toolbar, the left vertical bar, on SketchUp, as well as the information of an element in the building, the box in the center.

4.2.2 Modeling HVAC Systems

EnergyPlus is flexible in modeling HVAC systems, as well as it provides templates that ready to be used with less flexibility. However, in this study, the HVAC systems was modeled manually through “IDF-Editor” in order to take advantage of that flexibility, especially with many configurations considered.

Loops, Sides, and Nodes

Mainly in EnergyPlus, an HVAC system has two loops: liquid and air. Each of the loops has two sides: supply and demand. Components in the supply side of a loop conditions the working fluid to states required by a component in the demand side. For example, a chiller, which is located on the supply side, cools the working fluid for a cooling coil, which is located on the demand side.

Figure 4.23: The EP-Launch screen.

Figure 4.24: The IDF-Editor screen.

Figure 4.25: The Euclid tool bar, the left tool bar, on SketchUP, as well as the information of a constructed element, the roof of Multi Class 1-Pod 1.

Additionally, each component within each loop has at least two nodes: inlet and outlet [32]. For instance, the cooling coil in the previous example has inlet and outlet nodes in the cooling loop and has two other nodes in the air loop. Figure 4.26 illustrates the given examples.

Figure 4.26: An illustration of the loop, side, and node concepts.

If two components are set in parallel in the same side of a loop, the outlet node of the first component is the inlet node of the second component. For instance, if an air loop has a cooling and heating coils set in parallel, the outlet node of the cooling coil is the inlet node of the heating coil. Figure 4.27 illustrates the given example.

Figure 4.27: An illustration of two components sharing the same node in a loop.

Branches and Connectors

Loops, in EnergyPlus, consist of branches. Each one of the branches must have a component, at least, and the branches are connected with each other through connectors, such as splitters and mixers [32]. For instance, a supply side of a heating loop has one inlet that would deliver the hot water through to several heating coils. Hence, there would be a splitter splitting the incoming hot water to deliver it to the coils, and there would be a mixer mixing the incoming hot water out of the coils to deliver it to the outlet node of the supply side of the heating loop. Moreover, there would be a main branch, “branchlist”, containing the branches in the demand side of the loop. Figure 4.28 illustrates the example.

Figure 4.28: An illustration of the branch and connector concepts.

Control

In EnergyPlus, an HVAC system could be controlled through various objects, such as a setpoint manager and a controller; the mentioned objects were employed to control the HVAC systems in this study. A setpoint manager is a high-level controller that can sense any nodes in the systems then use the sensed data to calculate for a setpoint. Then, a controller would call the data, which

the setpoint manager obtained, to adjust the controlled parameters to meet the desired conditions. For instance, a chilled-water coil has two loops: the chilled water loop and the air loop. Controlling the coil requires sensing the conditions of the air leaving the coil and modifying the flow of the chilled water. Therefore, the setpoint manager will sense the conditions of the air and will calculate for the adjustment requiring to reach the setpoint; the controller will use the data obtained by the setpoint manager to determine the chilled water flow rate at any time step through the simulation.

Figure 4.29 shows a controller, “Controller:WaterCoil,” screen, Figure 4.30 and 4.31 show setpoint managers, “SetpointManager:OutdoorAirReset” and “SetpointManager:MixedAir,” screens. The setpoint manager in Figure 4.31 references the node in the setpoint manager in Figure 4.30. In addition, the setpoint manager in the Figure 4.31, “SetpointManager:MixedAir,” considers the heat added by the supply fan, so the Supply Air Temperature (SAT) will be adjusted accordingly.

Field	Units	Obj1
Name		DOAS_Pod_1_Cool C_Controller
Control Variable		TemperatureAndHu midityRatio
Action		Reverse
Actuator Variable		Flow
Sensor Node Name		DOAS_Pod_1_2nd Heat Recovery-HeatC Node
Actuator Node Name		DOAS_Pod_1_Cool C Demand Inlet Node
Controller Convergence Tolerance	deltaC	
Maximum Actuated Flow	m3/s	autosize
Minimum Actuated Flow	m3/s	0

Figure 4.29: The “Controller:WaterCoil” screen.

EnergyPlus has various methods to set a setpoint manager, such as schedules and outside conditions, which are obtained through the weather file.

Equipment Sizing

Assessing the impact of implementing DOAS economically requires determining the sizes of the HVAC equipment. The size of the HVAC equipment varies depending on many factors, but the most important are the supplied air quantity and conditions. In DOAS, the outdoor requirements in ASHRAE 62.1, or similar regulations, regulate the quantity of supplied air. Moreover, to define the

Field	Units	Obj1
Name		DOAS SAT Setpoint
Control Variable		Temperature
Setpoint at Outdoor Low Temperature	C	15.6
Outdoor Low Temperature	C	10
Setpoint at Outdoor High Temperature	C	12.8
Outdoor High Temperature	C	21.1
Setpoint Node or NodeList Name		DOAS Supply Equipment Outlet Nodes
Schedule Name		
Setpoint at Outdoor Low Temperature 2	C	
Outdoor Low Temperature 2	C	
Setpoint at Outdoor High Temperature 2	C	
Outdoor High Temperature 2	C	

Figure 4.30: The “SetpointManager:OutdoorAirReset” screen.

Field	Units	Obj1
Name		VAV_Pod_1_Fan Upstream SAT Manager
Control Variable		Temperature
Reference Setpoint Node Name		VAV_Pod_1 Supply Equipment Outlet Node
Fan Inlet Node Name		VAV_Pod_1_HeatC-VAV_Pod_1 FanNode
Fan Outlet Node Name		VAV_Pod_1 Supply Equipment Outlet Node
Setpoint Node or NodeList Name		VAV_Pod_1 Fan Upstream Nodes
Cooling Coil Inlet Node Name		
Cooling coil Outlet Node Name		
Minimum Temperature at Cooling Coil Outlet Node	C	

Figure 4.31: The “SetpointManager:MixedAir” screen.

Table 4.11: HVAC equipment design conditions.

Climate Zone	Winter Design Day (99.6% DBT)			Summer Design Day (0.4% DBT, MWB)			
	DBT [$^{\circ}$ C]	V [m/s]	Wind Dir.	DBT [$^{\circ}$ C]	MWB [$^{\circ}$ C]	V [m/s]	Wind Dir.
1A	8.7	3.8	340	33.2	25.3	4.5	140
1B	5.9	1.6	320	44.2	18.7	4.5	0
2A	-1.6	2.8	0	36	24.8	3.5	170
2B	3.7	1.7	100	43.4	21.1	4.1	260
3A	-8.3	4.1	0	35.6	25.2	3.4	240
3B	-5.2	2.2	20	38.1	18.1	3.9	280
3C	3.8	2.2	150	28.3	17.2	5.9	310
4A	-10.6	3.9	290	34.4	23.9	4.6	280
4B	-7.9	3.2	0	35.1	15.7	4.4	220
4C	-5.6	2.1	0	33.3	19.4	4.3	0
5A	-20	4.9	270	33.3	23.7	5.2	230
5B	-16.3	2.3	120	36.7	17.9	4.2	330
5C	-7	2.9	100	25	18.2	3.6	300
6A	-22.4	3	60	31.3	21.7	4.5	170
6B	-26.3	1.6	300	33.7	16.4	4.9	290
7	-28.6	4.7	310	29.2	21	5.2	220
8	-41.9	-0.3	20	27.4	16.1	3.1	180

conditions of the outdoor air to size HVAC equipment, EnergyPlus offers options, such as Design Day, Weather File Days, and Weather File Condition Type. In this study, the design day method was selected to ensure the equipment would meet the loads in extreme conditions. For the winter design day, DBT that would be the minimum in 99.6% of the time in the corresponding location was selected. For the summer design day, DBT that would be exceeded in 0.4% of the time in the corresponding location was selected besides the coincident mean wet bulb temperature (MWB), for the latent load. Table 4.11 and Figure 4.32 map the design conditions to the considered climate zones, in accordance to ASHRAE's Handbook of Fundamentals-2009 [33].

Figure 4.32: The Conditions of Winter and Summer design days in the considered climate zones.

4.3 Climate Zones

Outdoor conditions play a significant role in determining the effectiveness of implementing DOAS. Therefore, considering various climate zones was essential to assess the effect of implementing DOAS.

Mainly, there are two parameters determining the main conditions of a climate zone: the ambient humidity and temperature. In terms of humidity, the considered humidity levels, for this study, are moist (A), dry (B), and marine (C). Moreover, in terms of dry bulb temperature, 8 levels were considered: 1 is the hottest and 8 is the coldest. Figure 4.33 shows the climate classifications in the United States, and Figure 4.34 shows the climate classifications at the world level through the Köppen-Geiger climate classification [24], [34].

CRB were modeled in 17 climate zones representing all climate zones in the United States, in addition to two zones, 1B, Riyadh, Saudi Arabia, and 5C, Vancouver, Canada [29]. Therefore, these 17 climate zones were considered for this study since they represented a wide range of climate zones. Table 4.12 maps the climate zones to the cities representing them.

The climate zones in EnergyPlus is represented through weather files, TMY3 files. TMY3 files are the most recent Typical Meteorological Year files that was utilized data from National Solar Radiation Database (NSRDB) in hourly bases for a span of one year. Records of many years are the source of the utilized data, so the “most usual conditions” are selected to represent each hour in the year.

Figure 4.33: The climate classifications in the United States.

World Map of Köppen-Geiger Climate Classification

updated with CRU TS 2.1 temperature and VASCLimO v1.1 precipitation data 1951 to 2000

Main climates

A: equatorial
B: arid
C: warm temperate
D: snow
E: polar

Precipitation

W: desert
S: steppe
f: fully humid
s: summer dry
w: winter dry
m: monsoonal

Temperature

h: hot arid
k: cold arid
a: hot summer
b: warm summer
c: cool summer
d: extremely continental
F: polar frost
T: polar tundra

Figure 4.34: The world map of the Köppen-Geiger climate classification.

Table 4.12: Mapping of climate zones to the cities representing them.

Climate Zone	Conditions	City
1A	Very hot, humid	Miami, FL
2A	Hot, humid	Houston, TX
3A	Warm, humid	Memphis, TN
4A	Mild, humid	Baltimore, MD
5A	Cold, humid	Chicago, IL
6A	Cold, humid	Burlington, VT
1B	Very hot, dry	Riyadh, SA
2B	Hot, dry	Phoenix, AZ
3B	Warm, dry	El Paso, TX
4B	Mild, dry	Albuquerque, NM
5B	Cold, dry	Boise, ID
6B	Cold, dry	Helena, MT
3C	Warm, marine	San Francisco, CA
4C	Mild, marine	Salem, OR
5C	Cold, marine	Vancouver, CN
7	Very cold	Duluth, MN
8	Subarctic	Fairbanks, AK

The files are not a reliable source for sizing HVAC equipment because the data in them represent the usual, not the extreme, conditions [35].

Chapter 5

Results and Discussions

To determine the impact of implementing DOAS in parallel with multi-zone VAV, the primary school model was simulated in the 17 climate zones in the 6 HVAC configurations, with total runs of 102. The assessments were observed from three aspects: energy consumption, thermal comfort, life cycle cost.

5.1 Energy Consumption

5.1.1 Alternative 1 Model Compared to Baseline Model

In the Alternative 1 model, where the air was supplied at 12.8-15.6° C DBT and 12.8° C DPT, the energy consumption by HVAC systems decreased in all climate zones compared to the Baseline model, as Figure 5.1 shows. The maximum change occurred in the climate zone 5B, the cooled-dry climate zone, by 40%, and the minimum change occurred in the climate zone 3A, the warm-humid climate zone, by 4%.

In addition, Figure 5.1 and Figure 5.2 show that the change in energy consumption was less in the moist climate zones compared to the dry and marine climate zones. Therefore, the latent load had a significant impact on the effectiveness of coupling DOAS in parallel with multi-zone VAV; as the load increases, the effectiveness decreases. However, exceptions occurred in the very hot zones, 1A and 2B, and the cold zones, 6A and 6B; the effectiveness increased as the humidity level increased.

For the main source of the change in energy consumption, Figure 5.3 shows that the main source was the cooling equipment in the very hot, hot, warm-humid, and mild-humid climate zones, while it was the heating equipment in the mild, warm, and cold climate zones. Hence, the main source

Figure 5.1: The change in HVAC energy consumption (climate zones order based on temperature): Alternative 1 model compared to Baseline model.

Figure 5.2: The change in HVAC energy consumption (climate zones order based on humidity level): Alternative 1 model compared to Baseline model.

of the change in energy consumption followed the equipment that handled the general dominating load, either cooling or heating, as Figure 5.4 emphases.

In addition, despite the total energy consumption by HVAC systems decreased in the Alternative 1 model compared to the Baseline model, energy consumption by the pumps increased in all climate zones. That would have been a result of the increase in the hydraulic equipment in the Alternative 1 model compared to the Baseline model. Nevertheless, the impact of the pump energy consumption on the total energy consumption was relatively low.

Figure 5.3: Breakdown of the change in HVAC energy consumption in GJ/Year (climate zones order based on temperature): Alternative 1 model compared to Baseline model.

Additionally, Figure 5.5 shows that although the increase in energy rate consumption by the heating equipment in very hot-humid and hot-humid climate zones was relatively low, it increased by 20% and 10%, respectively. Since the supply conditions did not change and the quantity of outdoor air was reduced in the Alternative 1 model compared to the Baseline model, the increase in energy consumption by the heating equipment would imply that the DOAS overcooled the zones, which enabled the VAV to heat the zones.

Figure 5.4: Breakdown of the change in HVAC energy consumption in GJ/Year (climate zones order based on humidity level): Alternative 1 model compared to Baseline model.

Figure 5.5: Breakdown of the change in HVAC energy consumption in percentage (climate zones order based on humidity level): Alternative 1 model compared to Baseline model.

5.1.2 Alternative 2 Model Compared to Baseline Model

In the Alternative 2 model, where the air was supplied at 12.8-15.6° C DBT and 6.9° C DPT, energy consumption by HVAC systems increased in all climate zones compared to the Baseline model, except in the climate zones 3-5B, and 8, as Figure 5.6 shows. The maximum increase occurred in the climate zone 3C, the warm-marine climate zone, by 50%, and the minimum increase occurred in the climate zone 1B, the very hot-dry climate zone, by 5%. While the maximum decrease occurred in the climate zone 5B, the cold-dry climate zone, by 30%, and the minimum decrease occurred in the climate zone 3B, the warm-dry climate zone, by less than 1%.

Figure 5.6: The change in HVAC energy consumption (climate zones order based on temperature): Alternative 2 model compared to Baseline model.

Figure 5.7 shows that the increase in energy consumption correlated with the humidity level; as the humidity level increased, the energy consumption increased. That because the dehumidifying process required cooling the outdoor to 6.9° C and reheat it to 12.8° C. In the climate zones with high humidity level the difference between the humidity ratios, preconditioned and post-conditioned, was high and occurred most the time. In addition, not only the load caused by the dehumidifying process increased, but also the load caused by the reheating process increased, as well.

Additionally, despite the DOAS in the Alternative 2 model might have offset the local latent load, the offset caused by the DOAS on the local sensible load would have been identical to the offset in the Alternative 1 model since the supply DBT in both models were identical. Hence, offsetting the local latent load through DOAS coupled in parallel with multi-zone VAV would not have a positive impact on decreasing the energy consumption, as the results showed. Offsetting the local latent load through DOAS might be a practical solution where the unit handling the local load cannot handle the local latent load, such as ceiling radiant beams, where the condensate water might drip into the zone.

Figure 5.7: The change in HVAC energy consumption (climate zones order based on humidity level): Alternative 2 model compared to Baseline model.

Figure 5.8 shows that the main source of the change in energy consumption in the Alternative 2 model was the heating equipment. In addition, it shows the energy consumed by cooling equipment increased in all climate zones, except in the climate zones 1B and 2B, the very hot-dry and hot-dry climate zones. That emphasizes that the dehumidification process had a significant impact on the increase in energy consumption since such climate zones have low humidity level.

Moreover, energy consumption by the pump increased in all climate zones, but the increase in

quantity was not significant compared to other equipment.

Figure 5.8: Breakdown of the change in HVAC energy consumption in GJ/Year (climate zones order based on temperature): Alternative 2 model compared to Baseline model.

Moreover, Figure 5.9 shows a sharp increase in the heating equipment consumption in the Alternative 2 model compared to the Baseline model in percentage. It exceeded 1500% in the climate zone 1A and exceeded 200% in the climate zone 2A, 1B, and 2B.

5.1.3 Alternative 3 Model Compared to Baseline Model

In the Alternative 3 model, where the air was supplied at 21-24° C DBT and 6.9° C DPT, energy consumption by HVAC systems increased in all climate zones compared to the Baseline model, as Figure 5.10 shows. The maximum increase occurred in the climate zone 3C, the warm-marine climate zone, by 157%, and the minimum increase occurred in the climate zone 8, the subarctic climate zone, by less than 1%.

Figure 5.11 shows that the increase in energy consumption in the moist climate zones was in the range of 70% to 100%, while it was in the range of 10% to 60% in the dry climate zones and from 80% to 160% in the marine climate zone. The high change in the marine climate zones could be

Figure 5.9: Breakdown of the change in HVAC energy consumption in percentage with different scales (climate zones order based on temperature): Alternative 2 model compared to Baseline model.

Figure 5.10: The change in HVAC energy consumption (climate zones order based on temperature): Alternative 3 model compared to Baseline model.

interpreted by that the difference between the humidity ratio of outdoor air and supply air was high in the Alternative 3 model, while it was low in the Baseline model. The same could be observed in the Alternative 2 model, where the supply DPT was low, but not in the Alternative 1 model, where the supply DPT was identical to the Baseline model. Therefore, the marine climate zones would be highly negatively affected by supplying the ventilation air at low DPT, in terms of energy consumption.

Figure 5.11: The change in HVAC energy consumption (climate zones order based on humidity level): Alternative 3 model compared to Baseline model.

Figure 5.12 and Figure 5.13 show that the main source of the increase in energy consumption in the Alternative 3 model was the heating equipment. That would have been a result of the reheating process to a neutral temperature to the zones. Moreover, the energy consumption by the cooling equipment increased in all climate zones due to the dehumidification process to low DPT. The energy consumption by the cooling equipment increased significantly in the marine climate zones, which would support the interpretation of the high change in the energy consumption in those climate zones, which was mentioned previously.

In addition, the fan energy consumption increased in all climate zones. That implies the quantity

of the conditioned air increased, and since the quantity of air supplied by the DOAS would not have been changed in the Alternative 3 models compared to the previous alternative models, which did not experience increase in the fan consumption, the increase could have been caused by the VAV systems handling the local loads. Hence, supplying ventilation air at a neutral temperature might have caused an increase in the local load.

Also, the pump energy consumption increased in all climate zones, but the increase in quantity was not significant compared to other equipment.

Figure 5.12: Breakdown of the change in HVAC energy consumption in GJ/Year (climate zones order based on humidity level): Alternative 3 model compare to Baseline model.

5.1.4 Alternative 4 Model Compared to Baseline Model

In the Alternative 4 model, the supply conditions, 12.8-15.8° C DBT and 6.9° C DPT, was identical to the supply conditions in the Alternative 2 models. Yet, the difference was in the configuration of the DOAS equipment; the Alternative 4 model had a sensible wheel to absorb the heat from incoming outdoor air upstream the cooling coil and to release the heat downstream the cooling coil, which would reduce the loads on the cooling and heating coils. Figure 5.14 illustrates that the

Figure 5.13: Breakdown of the change in HVAC energy consumption in percentage with different scales (climate zones order based on humidity level): Alternative 3 model compared to Baseline model.

sensible wheel affected positively the energy consumption in the Alternative 4 model compared to the Alternative 2 model. However, compared to the Baseline model, the energy consumption increased in five climate zones, 2-5A, 3C, and 5C, with the maximum increase occurred in the climate zone 3C, the warm-marine climate zone, by 20%. On the other hand, the consumption decreased in the other climate zones, and the maximum decrease occurred in the climate zone 5B, the cold-dry climate zone, by 36%.

Figure 5.14: The change in HVAC energy consumption (climate zones order based on temperature): Alternative 4 model compared to Baseline model.

Figure 5.15 shows that the increase in energy consumption was not high in the moist climate zones, while it was significant in the marine climate zones, the climate zones 3C and 5C. Dehumidification process to low DPT in the marine climate zones might have affected the energy consumption negatively in the Alternative 4 model compared to the Baseline model.

In addition, the decrease in energy consumption showed a pattern in the dry climate zones; except in the climate zone 6B, the change in energy consumption increased as the general outdoor temperature decreased. An explanation for that pattern would be that the humidity ratio in the dry climate zones is low, so the need for the dehumidification process might have been low, as well.

As a result, outdoor air would not require to be cooled to a low temperature and reheated.

Figure 5.15: The change in HVAC energy consumption (climate zones order based on on humidity level): Alternative 4 model compared to Baseline model.

Figure 5.16 shows that in the climate zones experienced a decrease in the total energy consumption in the Alternative 4 model, the main source of the decrease in energy consumption was the heating equipment. In addition, in the climate zone 3C, which experienced the highest increased in the energy consumption, the cooling and heating equipment energy consumption increased mostly equally.

Figure 5.17 shows that the increase in the cooling equipment energy consumption in the marine climate zones was significant; it exceeded 50% in the climate zone 4C. That emphasizes the increase in energy consumption was affected mainly by the dehumidification process. In addition, the pump energy consumption increased in all climate zones, yet its magnitude was not significant.

5.1.5 Alternative 5 Model Compared to Baseline Model

In the Alternative 5 model, the supply conditions, 21-24° C DBT and 6.9° C DPT, was identical to the supply conditions in the Alternative3 models. Yet, the difference was in the configuration of the

Figure 5.16: Breakdown of the change in HVAC energy consumption in GJ/year (climate zones order based on humidity level): Alternative 4 model compared to Baseline model.

Figure 5.17: Breakdown of the change in HVAC energy consumption in percentage (climate zones order based on humidity level): Alternative 4 model compared to Baseline model.

DOAS equipment; the Alternative 5 model had a sensible wheel to absorb the heat from incoming outdoor air upstream the cooling coil and release the heat downstream the cooling coil.

Figure 5.18 shows an increase in energy consumption in the Alternative 5 model compared to the Baseline model in all climate zones, except 4B, 5B, 8. The maximum increase occurred in the climate zone 3C, the warm-marine climate zone, by 35%, and the minimum increase occurred in the climate zone 3B, the warm-dry climate zone, by less than 1%. Additionally, the energy consumption decreased by 14% in the climate zone 5B, the hot-dry climate zone. In general, the sensible wheel in the Alternative 5 model decreased significantly the energy consumption compared to the Alternative 3 models in all climate zones.

Figure 5.18: The change in HVAC energy consumption (climate zones order based on temperature): Alternative 5 model compared to Baseline model.

Figure 5.19 shows two patterns in the moist and dry climate zones. In the moist climate zones, the energy consumption increased as the general outdoor temperature decreased, while in the dry climate zones, the energy consumption decreased as the outdoor temperature decreased, except in the climate zones 1A, 6A, and 6B. In the moist climate zones, the demand for reheat is relatively high as a result of the dehumidification process; so, as the temperature of outdoor air is high, the sensible

wheel could provide most of the required heat for reheating process. That would reduce significantly energy consumption. However, as the outdoor temperature decreases, the sensible wheel would not be able to provide the same ratio of the required heat as in the hot zones, so energy consumption would increase. Moreover, the opposite would occur in the dry climate zone because outdoor air in such climates would not require reheating as the moist climate zones. Hence, energy consumption would decrease as the outdoor temperature decreases. That can be supported by Figure 5.20; it shows that the heating equipment was the main source of the change in energy consumption.

Figure 5.19: The change in HVAC energy consumption (climate zones order based on humidity level): Alternative 5 model compared to Baseline model.

Figure 5.21 shows that the change in energy consumption by heating equipment when it occurred was significant in most climate zones. Moreover, in the marine climate zones, the cooling equipment consumption increased by the range of 30% to 70%. That implies the dehumidification process in the Alternative 5 model in the marine climate zones experienced a significant change compared to the Baseline model; the same observation occurred in models where the ventilation air was supplied at low DPT. In addition, the fan energy consumption increased in all climate zones. That implies that the quantity of the supply air increased, and since the quantity of air supplied by DOAS would

Figure 5.20: Breakdown of the change in HVAC energy consumption in GJ/year in different scales (climate zones order based on humidity level): Alternative 5 model compare to Baseline model.

Table 5.1: Summary of the change in energy consumption in the alternative models compared to the Baseline model.

Zone	Alternative 1		Alternative 2		Alternative 3		Alternative 4		Alternative 5	
	GJ	%	GJ	%	GJ	%	GJ	%	GJ	%
1A	-163.1	-10.3	349.9	22.1	1549.7	97.8	-100.8	-6.4	192.2	12.1
2A	-77.8	-5.8	357.5	26.9	1312	98.6	2.9	0.2	154.8	11.6
3A	-49.8	-4.1	289.8	23.7	1042.7	85.1	21.9	1.8	262.8	21.5
4A	-73	-7.2	227.1	22.3	896.3	87.9	22	2.2	315.6	31
5A	-72.9	-6.8	224.1	20.9	944.1	88.2	25	2.3	379.5	35.5
6A	-92.8	-8.9	131.1	12.5	741.3	70.8	-6.1	-0.6	347.8	33.2
1B	-81.1	-5.3	74.4	4.8	479.9	31.2	-47.8	-3.1	134.7	8.8
2B	-97.3	-7	164.1	11.8	674.2	48.5	-44.5	-3.2	64.1	4.6
3B	-137.6	-12.9	-1.5	-0.1	472.7	44.2	-149.5	-14	2.2	0.2
4B	-274.5	-25.5	-200.9	-18.6	223.3	20.7	-295.7	-27.4	-77.2	-7.2
5B	-497.4	-40.2	-366	-29.6	101.2	8.2	-450	-36.4	-169.8	-13.7
6B	-50.9	-5.9	44.5	5.2	507.5	59	-23.6	-2.7	295.6	34.4
3C	-99.4	-14.9	329	49.4	1045.5	157.1	141.9	21.3	411.2	61.8
4C	-367.9	-35.7	45.3	4.4	829.8	80.4	-143.7	-13.9	193.7	18.8
5C	-167.3	-22.5	216.8	29.1	1002.5	134.6	63.4	8.5	465.2	62.4
7	-154.1	-12.1	72.7	5.7	696.4	54.8	-55.6	-4.4	326.9	25.7
8	-476.6	-19.9	-384.8	-16.1	6.7	0.3	-433.9	-18.1	-121.3	-5.1

have not been changed compared to other alternative models, the increase might have been caused by VAV, which handled the local load. Hence, supplying ventilation air at a neutral temperature might have caused an increase in the local load; the same observation occurred in the Alternative 3 model, where the supply temperature was neutral to the zones.

Finally, the pump energy consumption increased in all climate zones, which occurred in all alternative models. However, its quantity was not significant compared to other equipment.

Table 5.1 summaries the change in energy consumption in the alternative models compared to the Baseline model.

Figure 5.21: Breakdown of the change in HVAC energy consumption in percentage in different scales (climate zones order based on humidity level): Alternative 5 model compared to Baseline model.

5.2 Thermal Comfort

The parameters considered to show the impact of DOAS implementation on the thermal comfort were the temperature and the relative humidity. Then the Fanger Comfort Model was utilized in order to predict the thermal comfort in the zones from the occupant perspectives. To facilitate the study of the thermal comfort, the thermal properties in the corner classroom in pod 1 was selected; the other zones would respond similarly, so selecting one zone would be sufficient for the study.

5.2.1 Indoor Average Temperature

Figure 5.22 shows the average temperature in the corner class during occupancy hours. Compared to the Baseline model, the temperature increased in the models where the ventilation air was supplied neutral, the Alternative 3 and 5 models, and decreased in the models where the ventilation air was supplied cold, the Alternative 1, 2, and 4 models, in most climate zones. However, the change in the alternative models compared to the Baseline model did not exceed $\pm 0.5^\circ \text{C}$.

Figure 5.22: Corner-class average temperature during occupancy hours in all models.

5.2.2 Indoor Average Relative Humidity

Figure 5.23 shows the average relative humidity in the corner class during the occupancy hours. Compared to the Baseline model, the relative humidity decreased in the models where the ventilation air was supplied at 6.9° C DPT, up to 5%, in the moist and marine climate zones, while it increased in the dry climate zones. Moreover, the change in the Alternative 1 model compared to the Baseline model was not significant in all climate zones except the climate zone 1B, the very hot-dry zone. Therefore, in terms of the relative humidity, the indoor condition in the Alternative 1 model would have been identical to the condition in the Baseline model

Figure 5.23: Corner-class average humidity ratio during occupancy hours in all models.

5.2.3 Fanger Comfort Model

In general, there are environmental, physiological, and personal variables that influence the thermal comfort of occupants in a zone. The environmental variables are the air dry-bulb temperature, the mean radiant temperature, the relative velocity of the air motion, and the water vapor pressure in the ambient air. In addition, the physiological variables are the skin temperature, the internal temperature of the body, the sweat rate, the skin wettedness, the thermal conductance between the

Table 5.2: The utilized thermal sensation scale.

-3	-2	-1	0	1	2	3
Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

internal body and skin, and the asymmetrical heating or cooling. Finally, the personal variables are the thermal resistance of the clothing and the metabolic rate of the occupants.

The variables could be obtained through direct measurements or statistically-obtained correlations. For instance, the clothing is measured by “clo” and equals 0.155 [m² K/W]. For a zone with many occupants, it is found by multiplying the sum of “clo” by 0.82. For the metabolic rate, it is a function of the body surface area and the body heat production, and it is measured by “mat” that equals 58.2 [W/m²]. The body surface area, A_{du} , could be measured by the DuBois equation, Equation 5.1. However, EnergyPlus assumes the surface area to be 1.8 m².

$$A_{du}[m^2] = 0.202(weight[kg])^{0.425}(height[m])^{0.725} \quad (5.1)$$

From the mentioned variables, mathematical models have been developed to predict and represent the occupant thermal comfort. In this study, the Fanger Comfort Model was utilized with the thermal sensation scale in Table 5.2.

The Fanger Comfort Model was developed by P. O. Fanger in 1967, and it is the first developed human comfort model. Fanger derived the model experimentally through applying an energy analysis on human-body subjects in various surrounding environmental conditions and correlating the results to the response of the subjects. The results from the model are represented in the form of Predicated Mean Vote (PMV), which represent the thermal comfort on the thermal sensation scale, and then the PMV is correlated to the Predicted Percent of Dissatisfied (PPD), which represents the predicated percentage of the people who would feel the zone uncomfortable thermally. Equation 5.2 calculates for PPD :

$$PPD = 100 - (95)(exp(-0.03353PMV^4 - 0.2179PMV^2)) \quad (5.2)$$

From the equation, even if PMV is zero, which is neutral in the thermal sensation scale, there would be 5% of the occupants feel uncomfortable thermally [36].

In EnergyPlus, the model requires providing some variables in the “People” object as schedules in the input file. The provided variables in the “People” object are the clothing insulation, the activity levels, the air velocity, and the work efficiency. As they were set in the primary school model in

CRB, the values of the clothing schedule were 1.1 [clo] from 1/1 to 4/30 and 9/30 to 12/31, while 0.6 [clo] for the period from 4/30 to 9/30. In addition, the activity level value was 120 [W/Person], the air velocity value was 0.2 [m/s], and the work efficiency value was zero, which means the energy produced by a body is converted totally to heat [37].

Figure 5.24 shows that the *PMV* in all climate zones was between slightly cool and slightly warm. The maximum *PMV* occurred in the climate zone 1A, the very hot-humid climate zone, with a value around 0.3, and the minimum *PMV* occurred in the climate zone 8, the subarctic climate zone, with a value of -0.4. In addition, the general condition of the outdoor temperature influenced *PMV*; *PMV* increased toward warm sensation in the hot climate zones and decreased toward cool sensation in the cool climate zones. Moreover, in the alternative models where the ventilation air was supplied neutral, *PMV* indicated hotter compared to the other models.

However, despite the *PMV* varied among the models, the difference did not exceed 0.2. Therefore, by applying Equation 5.2, the maximum percentage of the people who would have experienced a change in the thermal comfort was less than 0.4% in all models in all climate zones.

Figure 5.24: The Predicated Mean Vote on the thermal comfort in the corner class according to the Fanger Comfort Model.

5.3 Life Cycle Cost

In this study, the impact of implementing DOAS on the cost considered the potential saving through the energy consumption, the potential saving through downsizing the existing equipment, and the cost of owning DOAS units.

5.3.1 Change in Energy Cost

In order to determine the change in the energy cost in the alternative models compared to the Baseline model, the cost of natural gas and electricity costs were needed to be defined. Therefore, the cost data from the U.S. Energy Information Administration for the residential sector in 2017 was used. According to the U.S. Energy Information Administration, the average cost of the natural gas was \$10.91/1000 ft³ and the electricity was \$12.89/kWh [38], [39]. For the natural gas, the average heat content in 2017 was 1.037 MMBtu/ 1000 ft³ (1.0949 GJ/1000 ft³) [40]. Therefore, the economic impact of the change in electricity consumption is 3.6 times the impact of the change in natural gas consumption.

Among the alternative models, Figure 5.25 to Figure 5.29 show that the Alternative 1 model was the most economically efficient in terms of the saving in the annual energy cost of HVAC systems, compared to the Baseline model in all climate zones.

In the Alternative 1 model, as shown by Figure 5.25, the annual energy cost of HVAC systems decreased in all climate zones compared to the Baseline model. The maximum decrease occurred in the climate zone 1A, the very hot-humid climate zone, by around \$6,000/year, while the minimum decrease occurred in the climate zone 6B, cool-dry, by around \$500/year. In addition, despite the change in energy consumption in the climate zone 5B was less than 1A by around 60%, as Figure 5.1 shows, the change in the energy cost in the climate zone 1A was higher than 5B. That because the main source of the energy consumption change in the climate zone 1A was the cooling equipment, which used electricity, while it was the heating equipment, which used natural gas, in the climate zone 5B, as Figure 5.3 shows.

5.3.2 Initial Costs

Implementing DOAS would affect the initial cost through downsizing multi-zone VAV equipment, upsizing plant equipment, and owning new DOAS equipment. For the multi-zone VAV equipment, since the ventilation load in the alternative models was separated, the load on the multi-zone VAV equipment, which used to handle the local loads, reduced. Hence, the equipment would have been

Figure 5.25: The change in the annual energy cost of HVAC systems in the Alternative 1 model compared to the Baseline model.

Figure 5.26: The change in the annual energy cost of HVAC systems in the Alternative 2 model compared to the Baseline model.

Figure 5.27: The change in the annual energy cost for HVAC systems in the Alternative 3 model compared to the Baseline model.

Figure 5.28: The change in the annual energy cost of HVAC systems in the Alternative 4 model compared to the Baseline model.

Figure 5.29: The change in the annual energy cost of HVAC systems in the Alternative 5 model compared to the Baseline model.

downsized. Moreover, implementing DOAS increases the number of the equipment being served by the plant equipment, the chiller, the boiler, and the pump, so the capacity of the plant equipment require to be increased.

In this study, since the Alternative 1 model was the most efficient model in terms of energy cost, it was considered alone among the alternative models for the initial cost analysis. In addition, for the equipment cost, “Mechanical Costs with RSMeans data, 2018” was used.

Figure 5.30 to Figure 5.35 show respectively the change in the capacity and size of cooling coils, heating coils, and supply fans of the multi-zone VAV units in the Alternative 1 model compared to the Baseline model. The change derived from the change in the sizing calculated by EnergyPlus.

Figure 5.30: The change in the cooling coil capacities of the multi-zone VAV units in the Alternative 1 model compared to the Baseline model in a power unit [Watt].

From the RSMeans data, the packaged, outdoor, central-station VAV air-handling unit was selected for the initial cost analysis [41]. Table 5.3 shows the saving from downsizing the multi-zone VAV equipment, the net costs of DOAS after subtracting the saving from downsizing the VAV equipment, the saving in energy cost, and the payback period to recover the net costs of DOAS units through the saving from the energy costs.

Figure 5.31: The change in the cooling coil capacities of the multi-zone VAV units in the Alternative 1 model compared to the Baseline model in percentage.

Table 5.3: The change in the initial costs in the Alternative 1 model compared to the Baseline model, and the payback period to recover the cost of owning the DOAS units.

Zone	Saving in VAV [\$]	Net Costs of DOAS [\$]	Saving in Energy [\$]	Payback Period [year]
1A	-39,248	84,612	-5,947	14
1B	-81,790	42,070	-2,805	15
2A	-41,093	82,768	-3,026	27
2B	-67,604	56,257	-3,177	18
3A	-40,367	83,493	-1,957	43
3B	-64,719	59,142	-2,406	25
3C	-31,588	92,272	-1,521	61
4A	-43,925	79,935	-1,984	40
4B	-70,797	53,064	-3,453	15
4C	-55,562	68,299	-3,728	18
5A	-47,114	76,746	-1,427	54
5B	-65,788	58,072	-5,443	11
5C	-47,821	76,040	-1,844	41
6A	-42,850	81,011	-1,501	54
6B	-69,559	54,302	-502	108
7	-46,742	77,118	-1,903	41
8	-57,510	66,351	-4,826	14

Figure 5.32: The change in the Heating coil capacities of the multi-zone VAV units in the Alternative 1 model compared to the Baseline model in a power unit [Watt].

Figure 5.33: The change in the Heating coil capacities of the multi-zone VAV units in the Alternative 1 model compared to the Baseline model in percentage.

Figure 5.34: The change in the supply fan sizes of the multi-zone VAV units in the Alternative 1 model compared to the Baseline model in volumetric rate.

Figure 5.35: The change in the supply fan sizes of the multi-zone VAV units in the Alternative 1 model compared to the Baseline model in percentage.

As Table 5.3 shows, the shortest payback period to recover the only cost of owning the DOAS units was 11 years. However, implementing the DOAS would not only cost owning new air-handling units, but also it would require extra costs, such as ductwork and upsizing the plant.

5.4 Results Verification

Generally, input values play a significant role in determining how realistic the simulation results are. In this study, the input values, such as lighting, plug, process, occupancy, and infiltration loads, were adopted from the CRB models, which were developed by the DOE in conjunction with three national labs; that would make the values reliable since the development of the models were under the supervision of experts in the field. Also, the values were randomly compared to the values in various standards, such as ASHRAE 90.1 and ASHRAE 62.1, if applicable, and no discrepancies could have been found.

For the HVAC-related results, the flow rate, temperature, and humidity ratio values, which play a significant role in calculations, were reviewed randomly at several nodes in the system in order to examine how reasonable they are. As an illustration, Figure 5.36 shows the flow rate, temperature, and humidity ratio values throughout the multi-zone VAV cycle on the 7th day of each month at 10 am in Maimi, FL, for the Baseline model; Figure 5.37 illustrates the points on the HVAC plan. The figure, Figure 5.36, shows reasonable results matching the processes done by each equipment in the system, except in January, May, and October. In January and May, the corresponding days of the 7th day were weekends, so the system was not operated, which can be shown through the flow rate; the system had no load to handle, especially with the absence of the load sources in the weekends. In October, the corresponding day was a weekend, as well, and there was a thermal load starting at 10 am, so the system was at the starting stage in order to handle the load (see Table D.10).

Moreover, Figure 5.38 shows the results for the Alternative 1 model. The values that showed a potential of abnormality were similar to that in the Baseline model except Point 7 in the DOAS cycle in January, May, and October. In the output data file, no explanation could be found to justify the drop in the temperature and humidity ratio through the air terminal. However, the flow rate at the mentioned cases was zero, so the temperature and humidity ratio values would not have impacted the calculations. In addition, in order to guarantee such drop would not have occurred when the flow was not zero, the input and output nodes of the air terminal were observed; they did not show any change in the temperature and humidity ratio, which was expected since no process was supposed to occur in the air terminal.

(a) The multi-zone VAV-1 flow rate.

(b) The multi-zone VAV-1 flow temperature.

(c) The multi-zone VAV-1 flow humidity ratio.

Figure 5.36: The flow rate, temperature, and humidity ratio at each node in the multi-zone VAV-1 cycle in the Baseline model on the 7th day in each month at 10 am in Miami, FL (see Figure 5.37 to locate the nodes on the HVAC system plan and Table D.1-D.3 for the corresponding values).

Figure 5.37: The illustration of the nodes that are mentioned in Figure 5.36 on the HVAC system plan.

(a) The DOAS-1 flow rate.

(b) The multi-zone VAV-1 flow rate.

(c) The DOAS-1 flow temperature.

(d) The multi-zone VAV-1 flow temperature.

(e) The DOAS-1 flow humidity ratio.

(f) The multi-zone VAV-1 flow humidity ratio.

Figure 5.38: The flow rate, temperature, and humidity ratio at each node in the HVAC system in the Alternative 1 model on the 7th day in each month at 10 am in Miami, FL (see Figure 5.39 to locate the nodes on the HVAC system plan and Table D.4-D.9 for the corresponding values).

Figure 5.39: The illustration of the nodes that are mentioned in Figure 5.38 on the HVAC system plan.

Chapter 6

Conclusions

Aiming to assess the impact of implementing DOAS in parallel with multi-zone VAV, a primary school model was simulated in 17 climate zones and in 6 HVAC configurations. The simulations were conducted for conditions of 8,760 hours/year. The assessment considered the impact on energy consumption, thermal comfort, and life cycle cost.

For the energy consumption, if the DOAS supply conditions would offset part of the local sensible load, utilizing DOAS coupled in parallel with multi-zone VAV in a primary school would reduce the HVAC energy consumption compared to utilizing multi-zone VAV only. In percentage, the moist climate zones could experience less of the reduction compared to the dry and marine climate zones. In addition, the moist climate zones would experience an increase in the heating load, especially in the climate zones 1A and 2A.

If DOAS is utilized, supplying ventilation air at a neutral DBT would increase energy consumption due to the reheating process. In addition, such supply conditions would overlook the potential of offsetting part of the local sensible load through the ventilation air. Additionally, supplying ventilation air at a low DPT for offsetting the local latent load would increase the HVAC energy consumption by increasing the dehumidification and reheating loads on the DOAS without even significant impact on thermal comfort. Such an approach might be effective in the case where the equipment handling the local load cannot handle the latent load, but not the case of the coupled system is a multi-zone VAV system.

Moreover, introducing a sensible wheel to enhance the dehumidification process would positively affect energy saving if such configuration is utilized in hot-humid climates. For climate zones with high outdoor latent load, the effectiveness of the sensible wheel in saving energy decreases as outdoor

temperature decreases.

For the thermal comfort, the integration of DOAS would not affect significantly the thermal comfort regardless the supplying conditions. That would enhance a decision toward selecting a configuration similar to the Alternative 1 model, where the air was supplied at 12.5-15.6° C DBT and 12.8° C DPT, because such configuration was optimal in terms of energy saving among other configurations considered in this study.

Economically, integrating DOAS supplying ventilation air at 12.8-15.6° C DBT and 12.8° DPT in parallel with multi-zone VAV could reduce the annual energy cost and the cost of owning multi-zone VAV units compared to the case utilizing multi-zone VAV for the entire load, the local and ventilation loads. As this study showed, in applications requiring relatively high ventilation, such as schools, the reduction in the energy and VAV costs would result in minimizing the payback period of the DOAS implementation compared to applications with low ventilation requirements, as [17] showed for office buildings if the reduction has occurred. However, even with such improvement in reducing the energy and VAV costs in applications with high ventilation requirements, the payback period of owning only the DOAS units was 11 years, in the best case. With such a payback period, the implementation of the DOAS would not be a practical solution economically.

The DOAS implementation comes with additional operating costs besides various additional initial costs, such as upsizing the plant equipment, owning new DOAS units, and extra ductwork. For the ductwork, even if the DOAS had delivered the outdoor air to the multi-zone VAV in order to save the cost of new ductwork, there would be an increase in energy consumption due to the necessity to increase the quantity of outdoor air to meet the ventilation requirements and to operate the multi-zone VAV even if there is no local load, which would vanish the economic benefit of the DOAS entirely.

For the future work, DOAS could be assessed differently through considering various coupling systems, centralized and local, to obtain an optimal configuration and determine precisely the benefit of DOAS.

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Appendix A

Energy-Consumption Result Tables

Table A.1: Summary of HVAC energy consumption [GJ/year]: Climate zones 1A to 4C.

Zone	Equipment	Baseline	Alt1	Alt2	Alt3	Alt4	Alt5
1A	Heating	23.85	28.03	410.84	1354.74	25.97	195.47
	Cooling	1168.53	1036.18	1155.36	1334.21	1073.11	1119.29
	Fans	302.44	252.15	252.41	314.43	268.86	331.18
	Pumps	89.28	104.67	115.34	130.4	115.39	130.31
1B	Heating	44.01	40.16	163.76	460.69	46.14	163.76
	Cooling	1098.6	1018.22	1050.22	1117.97	1024.06	1043.72
	Fans	313.69	299.13	299.1	338.83	320.27	364.14
	Pumps	83.06	100.72	100.71	101.75	101.06	102.47
2A	Heating	122.33	131.67	447.92	1214.02	145.91	224.26
	Cooling	857.66	790.5	898.77	1033.39	834.44	847.88
	Fans	276.39	243.61	243.7	285.4	255.32	303.18
	Pumps	73.62	86.45	97.11	109.23	97.23	109.51
2B	Heating	69.76	57.88	247.64	639.1	65.38	126.11
	Cooling	945.53	868.15	933.93	1010.42	891.16	892.12
	Fans	301.63	280.45	280.45	321.41	296.05	342.11
	Pumps	73.61	86.75	92.56	93.82	93.46	94.26
3A	Heating	266.89	273.64	521.22	1131.89	288.87	454.74
	Cooling	627.74	587.08	670.02	769.58	626.88	651.03
	Fans	266.94	239.71	239.81	271.15	247.31	286.68
	Pumps	63.17	74.52	83.48	94.82	83.61	95.12
3B	Heating	214.94	117.32	217.95	592.76	88.36	185.39
	Cooling	534.54	502.82	535.63	591.58	505.36	509.16
	Fans	275.62	260.71	260.71	301.98	272.47	320.82
	Pumps	44.15	50.76	53.44	55.65	53.55	56.11
3C	Heating	196.22	117.36	435.72	1074.48	266.64	486.76
	Cooling	178.55	184.72	282.67	328.49	259.57	264.07
	Fans	264.87	232.65	232.44	261.99	237.5	279.53
	Pumps	25.99	31.5	43.76	46.17	43.85	46.46
4A	Heating	249.77	225.41	440.19	1000.85	262.45	490.56
	Cooling	457.86	425.39	500.84	565.41	467.28	477.84
	Fans	264.22	239.22	239.29	274.21	245.44	291.14
	Pumps	47.43	56.26	66.01	75.1	66.1	75.34
4B	Heating	378.74	132	189.51	522.29	101.68	252.44
	Cooling	373.26	359.69	375.29	412.05	356.6	362.48
	Fans	292	273.45	273.49	326.65	284.94	345.2
	Pumps	34.13	38.49	38.91	40.46	39.23	40.8
4C	Heating	527.71	162.18	457.82	1139.25	292.09	569.18
	Cooling	236.57	228.07	328.17	396.34	299.46	313.09
	Fans	238.68	238.23	238.28	267.05	243.62	284.27
	Pumps	28.47	35.02	52.49	58.55	52.55	58.63

Table A.2: Summary of HVAC energy consumption [GJ/year]: Climate zones 5A to 8.

Zone	Equipment	Baseline	Alt1	Alt2	Alt3	Alt4	Alt5
5A	Heating	405.56	359.77	573	1181.95	399.04	684.9
	Cooling	368.62	353.27	427.87	499.49	396.92	416.52
	Fans	255.17	235.79	235.87	265.63	241.63	280.81
	Pumps	40.64	48.27	57.38	67.04	57.39	67.25
5B	Heating	663.21	184.66	285.85	682.16	211.12	436.75
	Cooling	289.51	268.35	295.66	326.1	278.81	282.26
	Fans	253.41	250.45	250.47	288.69	257.88	306.67
	Pumps	30.48	35.75	38.62	40.83	38.81	41.1
5C	Heating	362.08	201.62	478.74	1158.61	342.45	668.64
	Cooling	119.4	117.83	208.72	273.35	187.09	209.34
	Fans	245.36	236.44	236.47	267.06	241.08	283.79
	Pumps	18.15	21.79	37.87	48.44	37.81	48.41
6A	Heating	523.62	453.12	611.62	1145.64	490.47	792.11
	Cooling	244.25	236.24	293.76	336.59	272.21	280.87
	Fans	251.72	231.87	231.91	259.38	237.41	274.93
	Pumps	27.98	33.53	41.34	47.24	41.34	47.44
6B	Heating	428.91	377.79	453.15	858.47	390.33	659.9
	Cooling	173.5	169.6	187.98	209.52	176.02	177.86
	Fans	235.63	236.31	236.33	270.9	242.94	288.94
	Pumps	21.56	24.99	26.62	28.24	26.73	28.46
7	Heating	817.19	677.38	839.15	1391.1	725.51	1056.61
	Cooling	174.86	176.22	231.81	271.76	212.58	220.66
	Fans	255.66	235.54	235.56	261.3	239.99	277.19
	Pumps	22.75	27.26	36.67	42.69	36.76	42.9
8	Heating	2049.87	1576.27	1644.2	2020.42	1597.81	1890.92
	Cooling	88.33	90.25	111.17	111.86	103.56	95.37
	Fans	242.45	235.05	235.05	250.52	239.81	268.39
	Pumps	14.59	17.09	20.05	19.14	20.13	19.29

Appendix B

Equipment-Size Result Tables

Table B.1: Summary of the boiler capacities [W].

Zone	Baseline	Alt1	Alt2	Alt3	Alt4	Alt5
1A	168914.34	270256.86	270256.86	330110.56	270256.86	330110.56
1B	195717.39	289840.64	289840.64	352762.27	289840.64	352762.27
2A	306344.96	407725.23	407725.23	457374.59	407725.23	457374.59
2B	221685.86	314841.9	314841.9	382811.88	314841.9	382811.88
3A	399319.94	503844.71	503844.71	544478.82	503844.71	544478.82
3B	313413.22	402405.34	402405.34	449598.4	402405.34	449598.4
3C	227792.6	321104.09	321104.09	397410.43	321104.09	397410.43
4A	409417.26	497241.28	497241.28	564042.24	497241.28	564042.24
4B	316333.11	400656.24	400656.24	441973.96	400656.24	441973.96
4C	336890.54	425056.04	425056.04	495543.62	425056.04	495543.62
5A	530713.09	617218.1	617218.1	674934.44	617218.1	674934.44
5B	447019.2	530655.15	530655.15	583785.79	530655.15	583785.79
5C	359406.3	449582.82	449582.82	505879.33	449582.82	505879.33
6A	556818.15	640187.68	640187.68	700476.66	640187.68	700476.66
6B	540682.26	620607.02	620607.02	661502.16	620607.02	661502.16
7	619583.86	701057.03	701057.03	752338	701057.03	752338
8	784184.53	847595.4	847595.4	904479.29	847595.4	904479.29

Table B.2: Summary of the chiller capacities [W].

Zone	Baseline	Alt1	Alt2	Alt3	Alt4	Alt5
1A	472619.64	536134.36	590624.71	663249.67	591226.22	665991.85
1B	413956.38	460208.53	460208.53	467126.37	460939.83	469933.47
2A	451770.19	514949.19	569319.91	642035.78	570116.08	644648.28
2B	396088.51	444458.82	467411.07	473982.2	468012.63	476724.43
3A	466495.31	531562.4	585598.67	659016.59	586200.23	661564.22
3B	312321.7	343341.54	356459.69	372955.02	357061.25	375697.25
3C	220685.96	261392.93	297478.69	303205.05	298145.12	306077.02
4A	429289.84	491601.22	545845.29	617350.67	546446.85	620092.9
4B	289889.77	315871.5	315871.5	333356.54	316602.8	336228.5
4C	305966.6	354325.14	408424.07	410912.25	409090.5	413719.35
5A	427107.74	489016.33	542259.68	616568.17	542861.24	619050.93
5B	324791.08	365782.19	367658	374937.19	368389.29	377809.15
5C	259092.93	295676.49	350202.71	384780.99	350934	387523.22
6A	355555.76	410543.88	464438.36	516863.56	465169.66	519411.18
6B	288992.1	320988.35	324501.36	336892.7	325297.53	339829.53
7	341524.17	395698.01	447500.56	504778.48	448102.12	507390.97
8	245971.48	311285.62	329739.31	308648.65	330470.61	311585.48

Table B.3: Summary of the cooling coil capacities [W]: Climate zones 1A to 3B.

Zone	Unit	Baseline	Alt1	Alt2	Alt3	Alt4	Alt5
1A	DOAS-1	N/A	104733.88	120469.23	113803.51	120642.78	114594.67
	DOAS-2	N/A	104754.2	120489.47	113803.51	120663.02	114594.67
	DOAS-3	N/A	92422.79	105995	98220.95	106144.78	98903.78
	DOAS-Other	N/A	72618.25	82066.66	68623.44	82171.31	69100.51
	VAV-1	128789.39	39452.68	39452.68	66615.14	39452.68	66615.14
	VAV-2	128641.77	39446.18	39446.18	66573.07	39446.18	66573.07
	VAV-3	113891.31	34525.8	34525.8	60297.79	34525.8	60297.79
	VAV-Other	101305.06	48189.52	48189.52	75323.32	48189.52	75323.32
1B	DOAS-1	N/A	82111.95	82111.95	63939.85	82322.94	64749.74
	DOAS-2	N/A	81905.83	81905.83	63939.85	82116.82	64749.74
	DOAS-3	N/A	73026.33	73026.33	55184.88	73208.43	55883.87
	DOAS-Other	N/A	51020.87	51020.87	38555.69	51148.1	39044.05
	VAV-1	108960.33	39767.39	39767.39	58981.35	39767.39	58981.35
	VAV-2	109084.06	39674.36	39674.36	58942.82	39674.36	58942.82
	VAV-3	97205.1	35387.16	35387.16	53900.56	35387.16	53900.56
	VAV-Other	98713.79	57322.31	57322.31	73689.17	57322.31	73689.17
2A	DOAS-1	N/A	99127.62	114828.41	107940.34	115058.12	108694.08
	DOAS-2	N/A	99187.41	114887.95	107940.34	115117.66	108694.08
	DOAS-3	N/A	87667.3	101209.33	93160.59	101407.58	93811.13
	DOAS-Other	N/A	69074.24	78502.51	65087.96	78641.02	65542.46
	VAV-1	122821.04	39193.08	39193.08	66683	39193.08	66683
	VAV-2	122844.36	39187.38	39187.38	66743.65	39187.38	66743.65
	VAV-3	108665.64	34224.79	34224.79	60370.41	34224.79	60370.41
	VAV-Other	97446.68	47295.96	47295.96	74120.2	47295.96	74120.2
2B	DOAS-1	N/A	78250.09	84875.81	70798.12	85049.37	71589.29
	DOAS-2	N/A	78322.74	84948.33	70798.12	85121.89	71589.29
	DOAS-3	N/A	70190.73	75904.29	61104.08	76054.08	61786.92
	DOAS-Other	N/A	51635.02	55622.79	42691.22	55727.45	43168.3
	VAV-1	104910.93	39177.31	39177.31	55075.14	39177.31	55075.14
	VAV-2	104998.94	39114.12	39114.12	55156.42	39114.12	55156.42
	VAV-3	93622.73	34652.31	34652.31	50556.64	34652.31	50556.64
	VAV-Other	92562.52	53123.9	53123.9	67810.38	53123.9	67810.38
3A	DOAS-1	N/A	103882.79	119487.26	112711.34	119660.82	113446.37
	DOAS-2	N/A	103909.5	119513.86	112711.34	119687.42	113446.37
	DOAS-3	N/A	91960.4	105418.49	97278.33	105568.28	97912.71
	DOAS-Other	N/A	71926.62	81296.87	67964.87	81401.52	68408.09
	VAV-1	127390.14	39239.13	39239.13	66958.87	39239.13	66958.87
	VAV-2	127451.73	39233.7	39233.7	67030.62	39233.7	67030.62
	VAV-3	112659.19	34242	34242	60756.69	34242	60756.69
	VAV-Other	99002.03	47177.12	47177.12	73615.52	47177.12	73615.52
3B	DOAS-1	N/A	54439.17	58227.05	49666.66	58400.61	50457.84
	DOAS-2	N/A	54533.63	58321.4	49666.66	58494.96	50457.84
	DOAS-3	N/A	49468.61	52734.91	42866.05	52884.7	43548.89
	DOAS-Other	N/A	39345.22	41621.65	29948.97	41726.3	30426.05
	VAV-1	80999.77	34514.3	34514.3	47941.16	34514.3	47941.16
	VAV-2	81140.89	34447.98	34447.98	48067.53	34447.98	48067.53
	VAV-3	72826.82	30388.86	30388.86	44229.64	30388.86	44229.64
	VAV-Other	77359.44	46209.5	46209.5	60574.56	46209.5	60574.56

Table B.4: Summary of the cooling coil capacities [W]: Climate zones 3C to 5B

Zone	Unit	Baseline	Alt1	Alt2	Alt3	Alt4	Alt5
3C	DOAS-1	N/A	28873.46	39295.95	35809.53	39488.22	36638.14
	DOAS-2	N/A	29015.51	39437.6	35809.53	39629.87	36638.14
	DOAS-3	N/A	27242.89	36231.78	30906.31	36397.72	31621.46
	DOAS-Other	N/A	28797.8	35050.7	21593.13	35166.64	22092.77
	VAV-1	55924.03	37273.61	37273.61	43715.54	37273.61	43715.54
	VAV-2	56061.77	37274.25	37274.25	43849.8	37274.25	43849.8
	VAV-3	50850.92	32531.43	32531.43	40251.14	32531.43	40251.14
	VAV-Other	57852.92	40388.35	40388.35	51275.13	40388.35	51275.13
4A	DOAS-1	N/A	91614.21	107276.36	98314.26	107449.92	99105.44
	DOAS-2	N/A	90732.37	106398.25	98314.26	106571.81	99105.44
	DOAS-3	N/A	81686.89	95193.44	84852.57	95343.23	85535.42
	DOAS-Other	N/A	63262.16	72672.55	59283.44	72777.2	59760.52
	VAV-1	116228.54	40141.43	40141.43	69477.97	40141.43	69477.97
	VAV-2	115171.28	40000.58	40000.58	68317.93	40000.58	68317.93
	VAV-3	103446.06	35198.13	35198.13	63401.54	35198.13	63401.54
	VAV-Other	94451.12	48973.64	48973.64	75398.97	48973.64	75398.97
4B	DOAS-1	N/A	46345.62	46345.62	36989.91	46556.62	37818.52
	DOAS-2	N/A	45982.4	45982.4	36989.91	46193.4	37818.52
	DOAS-3	N/A	42334.74	42334.74	31925.06	42516.84	32640.21
	DOAS-Other	N/A	33364.17	33364.17	22304.89	33491.39	22804.54
	VAV-1	74134.8	34955.08	34955.08	49125.12	34955.08	49125.12
	VAV-2	73701.77	34815.6	34815.6	48705.04	34815.6	48705.04
	VAV-3	67107.66	31031.89	31031.89	45429.86	31031.89	45429.86
	VAV-Other	74950.38	47047.25	47047.25	61892.29	47047.25	61892.29
4C	DOAS-1	N/A	51414.37	67033.51	54516.64	67225.78	55326.53
	DOAS-2	N/A	50928.64	66549.83	54516.64	66742.11	55326.53
	DOAS-3	N/A	47836.82	61302.68	47051.94	61468.63	47750.94
	DOAS-Other	N/A	36845.14	46238.79	32873.5	46354.73	33361.86
	VAV-1	79186.38	40614.6	40614.6	54438.52	40614.6	54438.52
	VAV-2	78525.51	40514.39	40514.39	53806.03	40514.39	53806.03
	VAV-3	72445.35	35625.82	35625.82	50927.49	35625.82	50927.49
	VAV-Other	75814.46	50551.27	50551.27	62788.35	50551.27	62788.35
5A	DOAS-1	N/A	90526.32	105900.25	97005.4	106073.81	97721.72
	DOAS-2	N/A	90114.16	105489.83	97005.4	105663.39	97721.72
	DOAS-3	N/A	80896.55	94153.72	83722.93	94303.51	84341.16
	DOAS-Other	N/A	62399.81	71637.27	58494.2	71741.92	58926.14
	VAV-1	115579.43	40422.61	40422.61	70558.17	40422.61	70558.17
	VAV-2	114897.51	40316.92	40316.92	69788.26	40316.92	69788.26
	VAV-3	102980.68	35407.96	35407.96	64435.15	35407.96	64435.15
	VAV-Other	93657.24	48940.15	48940.15	75568.94	48940.15	75568.94
5B	DOAS-1	N/A	57586.54	58128.06	45308.8	58339.05	46137.41
	DOAS-2	N/A	56934.48	57476.1	45308.8	57687.09	46137.41
	DOAS-3	N/A	52527.18	52994.1	39104.89	53176.2	39820.04
	DOAS-Other	N/A	39374.42	39700.21	27321.18	39827.44	27820.83
	VAV-1	84533.58	37854.14	37854.14	52883.43	37854.14	52883.43
	VAV-2	83938.02	37744.96	37744.96	52242.34	37744.96	52242.34
	VAV-3	76410.62	33503.24	33503.24	48964.63	33503.24	48964.63
	VAV-Other	79914.27	50263.33	50263.33	63809.37	50263.33	63809.37

Table B.5: Summary of the cooling coil capacities [W]: Climate zones 5C to 8

Zone	Unit	Baseline	Alt1	Alt2	Alt3	Alt4	Alt5
5C	DOAS-1	N/A	36898.89	52644.2	44358.33	52855.19	45149.51
	DOAS-2	N/A	36277.75	52025.68	44358.33	52236.68	45149.51
	DOAS-3	N/A	35164.01	48739.37	38284.56	48921.47	38967.41
	DOAS-Other	N/A	30747.12	40205.62	26748.05	40332.85	27225.13
	VAV-1	66799.97	38490.3	38490.3	58411.88	38490.3	58411.88
	VAV-2	66033.35	38368.79	38368.79	57653.18	38368.79	57653.18
	VAV-3	61089.84	33747.47	33747.47	53791.63	33747.47	53791.63
	VAV-Other	65174.09	45987.1	45987.1	61181.43	45987.1	61181.43
6A	DOAS-1	N/A	68745.75	84308	76327.51	84519	77062.55
	DOAS-2	N/A	68110.7	83675.64	76327.51	83886.63	77062.55
	DOAS-3	N/A	61986.78	75406.95	65876.36	75589.05	66510.75
	DOAS-Other	N/A	49977.79	59325.8	46025.45	59453.03	46468.67
	VAV-1	94653.06	39874.84	39874.84	63127.76	39874.84	63127.76
	VAV-2	93756.4	39727.07	39727.07	62185.7	39727.07	62185.7
	VAV-3	84916.6	34782.15	34782.15	57895.83	34782.15	57895.83
	VAV-Other	82235.63	47345.65	47345.65	69106.05	47345.65	69106.05
6B	DOAS-1	N/A	46923.48	47937.69	36530.84	48167.4	37378.16
	DOAS-2	N/A	46322.12	47336.52	36530.84	47566.23	37378.16
	DOAS-3	N/A	43407.12	44281.54	31528.85	44479.8	32260.15
	DOAS-Other	N/A	33117.74	33727.79	22028.07	33866.3	22539.01
	VAV-1	74378.32	35881.34	35881.34	51140.84	35881.34	51140.84
	VAV-2	73661.39	35779.72	35779.72	50444.11	35779.72	50444.11
	VAV-3	67661.23	31743.5	31743.5	47508.32	31743.5	47508.32
	VAV-Other	73295.98	47818.67	47818.67	61186.45	47818.67	61186.45
7	DOAS-1	N/A	64051.41	79010.16	71512.54	79183.72	72266.29
	DOAS-2	N/A	63315.49	78277.35	71512.54	78450.91	72266.29
	DOAS-3	N/A	58303.7	71201.45	61720.68	71351.24	62371.21
	DOAS-Other	N/A	46920.91	55905.96	43122.02	56010.62	43576.52
	VAV-1	91107.91	40670.23	40670.23	65140.51	40670.23	65140.51
	VAV-2	90215.68	40547.16	40547.16	64191.31	40547.16	64191.31
	VAV-3	81949.33	35383.17	35383.17	59684.69	35383.17	59684.69
	VAV-Other	78256.94	46512.54	46512.54	67902.62	46512.54	67902.62
8	DOAS-1	N/A	44633.65	49957.83	27984.58	50168.83	28831.9
	DOAS-2	N/A	44633.65	49957.83	27984.58	50168.83	28831.9
	DOAS-3	N/A	38522.19	43117.35	24152.79	43299.45	24884.09
	DOAS-Other	N/A	26914.07	30124.54	16874.68	30251.77	17385.62
	VAV-1	63515.15	38611.25	38611.25	53489.35	38611.25	53489.35
	VAV-2	62457.41	38441.86	38441.86	52458.18	38441.86	52458.18
	VAV-3	58576.69	34200.66	34200.66	49830.16	34200.66	49830.16
	VAV-Other	61426.34	45333.48	45333.48	55879.47	45333.48	55879.47

Table B.6: Summary of the heating coil capacities [W]: Climate zones 1A to 3B

Zone	Unit	Baseline	Alt1	Alt2	Alt3	Alt4	Alt5
1A	DOAS-1	N/A	11021.16	11021.16	41127.75	11021.16	41127.75
	DOAS-2	N/A	11021.16	11021.16	41127.75	11021.16	41127.75
	DOAS-3	N/A	9512.09	9512.09	35496.33	9512.09	35496.33
	DOAS-Other	N/A	6645.75	6645.75	24800.01	6645.75	24800.01
	VAV-1	11453.76	15843.11	15843.11	34400.03	15843.11	34400.03
	VAV-2	11453.76	15843.11	15843.11	34400.03	15843.11	34400.03
	VAV-3	9945.02	13933.45	13933.45	29689.83	13933.45	29689.83
	VAV-Other	9257.44	25473.93	25473.93	25473.93	25473.93	25473.93
1B	DOAS-1	N/A	24268.9	24268.9	45285.27	24268.9	45285.27
	DOAS-2	N/A	24268.9	24268.9	45285.27	24268.9	45285.27
	DOAS-3	N/A	20941.33	20941.33	39076.09	20941.33	39076.09
	DOAS-Other	N/A	14634.13	14634.13	27306.99	14634.13	27306.99
	VAV-1	25221.48	17971.73	17971.73	39021.89	17971.73	39021.89
	VAV-2	25221.48	17971.73	17971.73	39021.89	17971.73	39021.89
	VAV-3	21899.2	15805.5	15805.5	33678.84	15805.5	33678.84
	VAV-Other	20385.13	28896.51	28896.51	28896.51	28896.51	28896.51
2A	DOAS-1	N/A	38625.92	38625.92	68668.3	38625.92	68668.3
	DOAS-2	N/A	38625.92	38625.92	68668.3	38625.92	68668.3
	DOAS-3	N/A	33337.06	33337.06	59265.88	33337.06	59265.88
	DOAS-Other	N/A	23291.4	23291.4	41406.94	23291.4	41406.94
	VAV-1	40142.03	15809.32	15809.32	34326.66	15809.32	34326.66
	VAV-2	40142.03	15809.32	15809.32	34326.66	15809.32	34326.66
	VAV-3	34854.35	13903.74	13903.74	29626.51	13903.74	29626.51
	VAV-Other	32444.58	25419.6	25419.6	25419.6	25419.6	25419.6
2B	DOAS-1	N/A	30770.77	30770.77	52491.32	30770.77	52491.32
	DOAS-2	N/A	30770.77	30770.77	52491.32	30770.77	52491.32
	DOAS-3	N/A	26557.48	26557.48	45303.94	26557.48	45303.94
	DOAS-Other	N/A	18554.76	18554.76	31652.23	18554.76	31652.23
	VAV-1	31978.56	18573.9	18573.9	40329.36	18573.9	40329.36
	VAV-2	31978.56	18573.9	18573.9	40329.36	18573.9	40329.36
	VAV-3	27766.21	16335.08	16335.08	34807.29	16335.08	34807.29
	VAV-Other	25846.5	29864.73	29864.73	29864.73	29864.73	29864.73
3A	DOAS-1	N/A	56249.41	56249.41	86106.91	56249.41	86106.91
	DOAS-2	N/A	56249.41	56249.41	86106.91	56249.41	86106.91
	DOAS-3	N/A	48547.45	48547.45	74300.57	48547.45	74300.57
	DOAS-Other	N/A	33918.36	33918.36	51922.41	33918.36	51922.41
	VAV-1	58457.26	15712.04	15712.04	34115.42	15712.04	34115.42
	VAV-2	58457.26	15712.04	15712.04	34115.42	15712.04	34115.42
	VAV-3	50757.03	13818.17	13818.17	29444.19	13818.17	29444.19
	VAV-Other	47247.76	25263.18	25263.18	25263.18	25263.18	25263.18
3B	DOAS-1	N/A	48548.3	48548.3	68154.34	48548.3	68154.34
	DOAS-2	N/A	48548.3	48548.3	68154.34	48548.3	68154.34
	DOAS-3	N/A	41900.81	41900.81	58822.3	41900.81	58822.3
	DOAS-Other	N/A	29274.59	29274.59	41097.02	29274.59	41097.02
	VAV-1	50453.87	16765.72	16765.72	36403.28	16765.72	36403.28
	VAV-2	50453.87	16765.72	16765.72	36403.28	16765.72	36403.28
	VAV-3	43807.88	14744.85	14744.85	31418.79	14744.85	31418.79
	VAV-Other	40779.07	26957.38	26957.38	26957.38	26957.38	26957.38

Table B.7: Summary of the heating coil capacities [W]: Climate zones 3C to 5B

Zone	Unit	Baseline	Alt1	Alt2	Alt3	Alt4	Alt5
3C	DOAS-1	N/A	31753.31	31753.31	54357.37	31753.31	54357.37
	DOAS-2	N/A	31753.31	31753.31	54357.37	31753.31	54357.37
	DOAS-3	N/A	27405.49	27405.49	46914.48	27405.49	46914.48
	DOAS-Other	N/A	19147.23	19147.23	32777.46	19147.23	32777.46
	VAV-1	33558.98	19577.22	19577.22	42507.88	19577.22	42507.88
	VAV-2	33558.98	19577.22	19577.22	42507.88	19577.22	42507.88
	VAV-3	29138.45	17217.47	17217.47	36687.51	17217.47	36687.51
	VAV-Other	27123.87	30658.87	30658.87	31477.96	30658.87	31477.96
4A	DOAS-1	N/A	70144.41	70144.41	92633.46	70144.41	92633.46
	DOAS-2	N/A	70144.41	70144.41	92633.46	70144.41	92633.46
	DOAS-3	N/A	60539.88	60539.88	79949.61	60539.88	79949.61
	DOAS-Other	N/A	42297.03	42297.03	55857.92	42297.03	55857.92
	VAV-1	72897.66	19231.07	19231.07	41756.27	19231.07	41756.27
	VAV-2	72897.66	19231.07	19231.07	41756.27	19231.07	41756.27
	VAV-3	63295.28	16913.04	16913.04	36038.82	16913.04	36038.82
	VAV-Other	58919.14	30921.38	30921.38	30921.38	30921.38	30921.38
4B	DOAS-1	N/A	52018.11	52018.11	70611.82	52018.11	70611.82
	DOAS-2	N/A	52018.11	52018.11	70611.82	52018.11	70611.82
	DOAS-3	N/A	44895.52	44895.52	60930.05	44895.52	60930.05
	DOAS-Other	N/A	31366.89	31366.89	42578.88	31366.89	42578.88
	VAV-1	54059.88	15900.04	15900.04	34523.64	15900.04	34523.64
	VAV-2	54059.88	15900.04	15900.04	34523.64	15900.04	34523.64
	VAV-3	46938.89	13983.52	13983.52	29796.52	13983.52	29796.52
	VAV-Other	43693.61	25565.47	25565.47	25565.47	25565.47	25565.47
4C	DOAS-1	N/A	56657.1	56657.1	79106.14	56657.1	79106.14
	DOAS-2	N/A	56657.1	56657.1	79106.14	56657.1	79106.14
	DOAS-3	N/A	48899.32	48899.32	68274.52	48899.32	68274.52
	DOAS-Other	N/A	34164.2	34164.2	47700.95	34164.2	47700.95
	VAV-1	58880.96	19196.86	19196.86	41681.99	19196.86	41681.99
	VAV-2	58880.96	19196.86	19196.86	41681.99	19196.86	41681.99
	VAV-3	51124.91	16882.95	16882.95	35974.71	16882.95	35974.71
	VAV-Other	47590.22	30866.37	30866.37	30866.37	30866.37	30866.37
5A	DOAS-1	N/A	93559.29	93559.29	115635.08	93559.29	115635.08
	DOAS-2	N/A	93559.29	93559.29	115635.08	93559.29	115635.08
	DOAS-3	N/A	80748.67	80748.67	99780.06	80748.67	99780.06
	DOAS-Other	N/A	56416.19	56416.19	69727.88	56416.19	69727.88
	VAV-1	97231.6	18877.68	18877.68	40988.95	18877.68	40988.95
	VAV-2	97231.6	18877.68	18877.68	40988.95	18877.68	40988.95
	VAV-3	84423.85	16602.24	16602.24	35376.57	16602.24	35376.57
	VAV-Other	78586.91	30353.17	30353.17	30353.17	30353.17	30353.17
5B	DOAS-1	N/A	78961.89	78961.89	99754.36	78961.89	99754.36
	DOAS-2	N/A	78961.89	78961.89	99754.36	78961.89	99754.36
	DOAS-3	N/A	68150.02	68150.02	86095.48	68150.02	86095.48
	DOAS-Other	N/A	47613.97	47613.97	60151.81	47613.97	60151.81
	VAV-1	82061.23	17780.27	17780.27	38606.17	17780.27	38606.17
	VAV-2	82061.23	17780.27	17780.27	38606.17	17780.27	38606.17
	VAV-3	71251.78	15637.12	15637.12	33320.05	15637.12	33320.05
	VAV-Other	66325.55	28588.67	28588.67	28588.67	28588.67	28588.67

Table B.8: Summary of the heating coil capacities [W]: Climate zones 5C to 8

Zone	Unit	Baseline	Alt1	Alt2	Alt3	Alt4	Alt5
5C	DOAS-1	N/A	60815.67	60815.67	83419.72	60815.67	83419.72
	DOAS-2	N/A	60815.67	60815.67	83419.72	60815.67	83419.72
	DOAS-3	N/A	52488.47	52488.47	71997.46	52488.47	71997.46
	DOAS-Other	N/A	36671.81	36671.81	50302.04	36671.81	50302.04
	VAV-1	55372.32	15860.03	15860.03	34436.76	15860.03	34436.76
	VAV-2	55372.32	15860.03	15860.03	34436.76	15860.03	34436.76
	VAV-3	48078.45	13948.33	13948.33	29721.53	13948.33	29721.53
	VAV-Other	44754.38	25325.24	25325.24	25501.13	25325.24	25501.13
6A	DOAS-1	N/A	101061.83	101061.83	123401.81	101061.83	123401.81
	DOAS-2	N/A	101061.83	101061.83	123401.81	101061.83	123401.81
	DOAS-3	N/A	87223.92	87223.92	106505	87223.92	106505
	DOAS-Other	N/A	60940.22	60940.22	74411.21	60940.22	74411.21
	VAV-1	105028.62	19103.6	19103.6	41479.49	19103.6	41479.49
	VAV-2	105028.62	19103.6	19103.6	41479.49	19103.6	41479.49
	VAV-3	91193.81	16800.93	16800.93	35799.94	16800.93	35799.94
	VAV-Other	84888.82	30716.42	30716.42	30716.42	30716.42	30716.42
6B	DOAS-1	N/A	98023.38	98023.38	117674.84	98023.38	117674.84
	DOAS-2	N/A	98023.38	98023.38	117674.84	98023.38	117674.84
	DOAS-3	N/A	84601.51	84601.51	101540.15	84601.51	101540.15
	DOAS-Other	N/A	59108.04	59108.04	70957.86	59108.04	70957.86
	VAV-1	101870.91	16804.56	16804.56	36487.62	16804.56	36487.62
	VAV-2	101870.91	16804.56	16804.56	36487.62	16804.56	36487.62
	VAV-3	88452.05	14779.01	14779.01	31491.58	14779.01	31491.58
	VAV-Other	82336.61	27019.84	27019.84	27019.84	27019.84	27019.84
7	DOAS-1	N/A	112986.71	112986.71	134459.29	112986.71	134459.29
	DOAS-2	N/A	112986.71	112986.71	134459.29	112986.71	134459.29
	DOAS-3	N/A	97515.99	97515.99	116048.43	97515.99	116048.43
	DOAS-Other	N/A	68130.91	68130.91	81078.87	68130.91	81078.87
	VAV-1	117421.56	18361.86	18361.86	39868.97	18361.86	39868.97
	VAV-2	117421.56	18361.86	18361.86	39868.97	18361.86	39868.97
	VAV-3	101954.31	16148.6	16148.6	34409.93	16148.6	34409.93
	VAV-Other	95259.15	29523.79	29523.79	29523.79	29523.79	29523.79
8	DOAS-1	N/A	152341.89	152341.89	174597.06	152341.89	174597.06
	DOAS-2	N/A	152341.89	152341.89	174597.06	152341.89	174597.06
	DOAS-3	N/A	131482.46	131482.46	150690.33	131482.46	150690.33
	DOAS-Other	N/A	91862.07	91862.07	105281.91	91862.07	105281.91
	VAV-1	158321.49	19031.07	19031.07	41322.01	19031.07	41322.01
	VAV-2	158321.49	19031.07	19031.07	41322.01	19031.07	41322.01
	VAV-3	137466.72	16737.14	16737.14	35664.02	16737.14	35664.02
	VAV-Other	133703.96	29997.47	29997.47	30599.8	29997.47	30599.8

Table B.9: Summary of the fan sizes [m³/s]: Climate zones 1A to 3B

Zone	Unit	Baseline	Alt1	Alt2	Alt3	Alt4	Alt5
1A	DOAS-1	N/A	2.22	2.22	2.22	2.22	2.22
	DOAS-2	N/A	2.22	2.22	2.22	2.22	2.22
	DOAS-3	N/A	1.92	1.92	1.92	1.92	1.92
	DOAS-Other	N/A	1.34	1.34	1.34	1.34	1.34
	VAV-1	2.93	2.41	2.41	2.92	2.41	2.92
	VAV-2	2.93	2.41	2.41	2.92	2.41	2.92
	VAV-3	2.68	2.11	2.11	2.68	2.11	2.68
	VAV-Other	3.79	2.97	2.97	3.79	2.97	3.79
1B	DOAS-1	N/A	2.22	2.22	2.22	2.22	2.22
	DOAS-2	N/A	2.22	2.22	2.22	2.22	2.22
	DOAS-3	N/A	1.92	1.92	1.92	1.92	1.92
	DOAS-Other	N/A	1.34	1.34	1.34	1.34	1.34
	VAV-1	3.98	2.69	2.69	3.99	2.69	3.99
	VAV-2	3.98	2.68	2.68	3.98	2.68	3.98
	VAV-3	3.64	2.39	2.39	3.64	2.39	3.64
	VAV-Other	4.97	3.87	3.87	4.98	3.87	4.98
2A	DOAS-1	N/A	2.22	2.22	2.22	2.22	2.22
	DOAS-2	N/A	2.22	2.22	2.22	2.22	2.22
	DOAS-3	N/A	1.92	1.92	1.92	1.92	1.92
	DOAS-Other	N/A	1.34	1.34	1.34	1.34	1.34
	VAV-1	2.94	2.4	2.4	2.93	2.4	2.93
	VAV-2	2.94	2.4	2.4	2.93	2.4	2.93
	VAV-3	2.69	2.1	2.1	2.68	2.1	2.68
	VAV-Other	3.73	2.92	2.92	3.73	2.92	3.73
2B	DOAS-1	N/A	2.22	2.22	2.22	2.22	2.22
	DOAS-2	N/A	2.22	2.22	2.22	2.22	2.22
	DOAS-3	N/A	1.92	1.92	1.92	1.92	1.92
	DOAS-Other	N/A	1.34	1.34	1.34	1.34	1.34
	VAV-1	3.6	2.57	2.57	3.61	2.57	3.61
	VAV-2	3.61	2.56	2.56	3.61	2.56	3.61
	VAV-3	3.31	2.27	2.27	3.31	2.27	3.31
	VAV-Other	4.44	3.48	3.48	4.44	3.48	4.44
3A	DOAS-1	N/A	2.22	2.22	2.22	2.22	2.22
	DOAS-2	N/A	2.22	2.22	2.22	2.22	2.22
	DOAS-3	N/A	1.92	1.92	1.92	1.92	1.92
	DOAS-Other	N/A	1.34	1.34	1.34	1.34	1.34
	VAV-1	2.95	2.4	2.4	2.94	2.4	2.94
	VAV-2	2.95	2.4	2.4	2.94	2.4	2.94
	VAV-3	2.71	2.1	2.1	2.7	2.1	2.7
	VAV-Other	3.71	2.92	2.92	3.7	2.92	3.7
3B	DOAS-1	N/A	2.22	2.22	2.22	2.22	2.22
	DOAS-2	N/A	2.22	2.22	2.22	2.22	2.22
	DOAS-3	N/A	1.92	1.92	1.92	1.92	1.92
	DOAS-Other	N/A	1.34	1.34	1.34	1.34	1.34
	VAV-1	3.43	2.47	2.47	3.43	2.47	3.43
	VAV-2	3.44	2.47	2.47	3.44	2.47	3.44
	VAV-3	3.17	2.18	2.18	3.17	2.18	3.17
	VAV-Other	4.34	3.31	3.31	4.34	3.31	4.34

Table B.10: Summary of the fan sizes [m³/s]: Climate zones 3C to 5B

Zone	Unit	Baseline	Alt1	Alt2	Alt3	Alt4	Alt5
3C	DOAS-1	N/A	2.22	2.22	2.22	2.22	2.22
	DOAS-2	N/A	2.22	2.22	2.22	2.22	2.22
	DOAS-3	N/A	1.92	1.92	1.92	1.92	1.92
	DOAS-Other	N/A	1.34	1.34	1.34	1.34	1.34
	VAV-1	2.76	2.36	2.36	2.76	2.36	2.76
	VAV-2	2.77	2.36	2.36	2.77	2.36	2.77
	VAV-3	2.54	2.06	2.06	2.55	2.06	2.55
	VAV-Other	3.24	2.55	2.55	3.24	2.55	3.24
4A	DOAS-1	N/A	2.22	2.22	2.22	2.22	2.22
	DOAS-2	N/A	2.22	2.22	2.22	2.22	2.22
	DOAS-3	N/A	1.92	1.92	1.92	1.92	1.92
	DOAS-Other	N/A	1.34	1.34	1.34	1.34	1.34
	VAV-1	3.09	2.46	2.46	3.08	2.46	3.08
	VAV-2	3.03	2.45	2.45	3.02	2.45	3.02
	VAV-3	2.86	2.16	2.16	2.85	2.16	2.85
	VAV-Other	3.82	3.03	3.03	3.81	3.03	3.81
4B	DOAS-1	N/A	2.22	2.22	2.22	2.22	2.22
	DOAS-2	N/A	2.22	2.22	2.22	2.22	2.22
	DOAS-3	N/A	1.92	1.92	1.92	1.92	1.92
	DOAS-Other	N/A	1.34	1.34	1.34	1.34	1.34
	VAV-1	3.68	2.62	2.62	3.68	2.62	3.68
	VAV-2	3.65	2.61	2.61	3.65	2.61	3.65
	VAV-3	3.4	2.33	2.33	3.41	2.33	3.41
	VAV-Other	4.64	3.53	3.53	4.64	3.53	4.64
4C	DOAS-1	N/A	2.22	2.22	2.22	2.22	2.22
	DOAS-2	N/A	2.22	2.22	2.22	2.22	2.22
	DOAS-3	N/A	1.92	1.92	1.92	1.92	1.92
	DOAS-Other	N/A	1.34	1.34	1.34	1.34	1.34
	VAV-1	3.37	2.51	2.51	3.37	2.51	3.37
	VAV-2	3.33	2.5	2.5	3.33	2.5	3.33
	VAV-3	3.16	2.21	2.21	3.16	2.21	3.16
	VAV-Other	3.9	3.15	3.15	3.9	3.15	3.9
5A	DOAS-1	N/A	2.22	2.22	2.22	2.22	2.22
	DOAS-2	N/A	2.22	2.22	2.22	2.22	2.22
	DOAS-3	N/A	1.92	1.92	1.92	1.92	1.92
	DOAS-Other	N/A	1.34	1.34	1.34	1.34	1.34
	VAV-1	3.15	2.46	2.46	3.14	2.46	3.14
	VAV-2	3.11	2.46	2.46	3.1	2.46	3.1
	VAV-3	2.91	2.17	2.17	2.91	2.17	2.91
	VAV-Other	3.85	3.04	3.04	3.84	3.04	3.84
5B	DOAS-1	N/A	2.22	2.22	2.22	2.22	2.22
	DOAS-2	N/A	2.22	2.22	2.22	2.22	2.22
	DOAS-3	N/A	1.92	1.92	1.92	1.92	1.92
	DOAS-Other	N/A	1.34	1.34	1.34	1.34	1.34
	VAV-1	3.6	2.58	2.58	3.6	2.58	3.6
	VAV-2	3.56	2.57	2.57	3.56	2.57	3.56
	VAV-3	3.33	2.28	2.28	3.34	2.28	3.34
	VAV-Other	4.35	3.42	3.42	4.35	3.42	4.35

Table B.11: Summary of the fan sizes [m³/s]: Climate zones 5C to 8

Zone	Unit	Baseline	Alt1	Alt2	Alt3	Alt4	Alt5
5C	DOAS-1	N/A	2.22	2.22	2.22	2.22	2.22
	DOAS-2	N/A	2.22	2.22	2.22	2.22	2.22
	DOAS-3	N/A	1.92	1.92	1.92	1.92	1.92
	DOAS-Other	N/A	1.34	1.34	1.34	1.34	1.34
	VAV-1	3.19	2.45	2.45	3.19	2.45	3.19
	VAV-2	3.15	2.44	2.44	3.14	2.44	3.14
	VAV-3	2.96	2.14	2.14	2.96	2.14	2.96
	VAV-Other	3.51	2.84	2.84	3.51	2.84	3.51
6A	DOAS-1	N/A	2.22	2.22	2.22	2.22	2.22
	DOAS-2	N/A	2.22	2.22	2.22	2.22	2.22
	DOAS-3	N/A	1.92	1.92	1.92	1.92	1.92
	DOAS-Other	N/A	1.34	1.34	1.34	1.34	1.34
	VAV-1	3.06	2.44	2.44	3.05	2.44	3.05
	VAV-2	3	2.43	2.43	3	2.43	3
	VAV-3	2.83	2.14	2.14	2.83	2.14	2.83
	VAV-Other	3.7	2.94	2.94	3.69	2.94	3.69
6B	DOAS-1	N/A	2.22	2.22	2.22	2.22	2.22
	DOAS-2	N/A	2.22	2.22	2.22	2.22	2.22
	DOAS-3	N/A	1.92	1.92	1.92	1.92	1.92
	DOAS-Other	N/A	1.34	1.34	1.34	1.34	1.34
	VAV-1	3.66	2.57	2.57	3.66	2.57	3.66
	VAV-2	3.61	2.56	2.56	3.61	2.56	3.61
	VAV-3	3.4	2.27	2.27	3.4	2.27	3.4
	VAV-Other	4.37	3.42	3.42	4.37	3.42	4.37
7	DOAS-1	N/A	2.22	2.22	2.22	2.22	2.22
	DOAS-2	N/A	2.22	2.22	2.22	2.22	2.22
	DOAS-3	N/A	1.92	1.92	1.92	1.92	1.92
	DOAS-Other	N/A	1.34	1.34	1.34	1.34	1.34
	VAV-1	3.16	2.47	2.47	3.16	2.47	3.16
	VAV-2	3.11	2.46	2.46	3.11	2.46	3.11
	VAV-3	2.94	2.16	2.16	2.93	2.16	2.93
	VAV-Other	3.67	2.92	2.92	3.67	2.92	3.67
8	DOAS-1	N/A	2.22	2.22	2.22	2.22	2.22
	DOAS-2	N/A	2.22	2.22	2.22	2.22	2.22
	DOAS-3	N/A	1.92	1.92	1.92	1.92	1.92
	DOAS-Other	N/A	1.34	1.34	1.34	1.34	1.34
	VAV-1	3.43	2.49	2.49	3.44	2.49	3.44
	VAV-2	3.37	2.48	2.48	3.37	2.48	3.37
	VAV-3	3.2	2.2	2.2	3.2	2.2	3.2
	VAV-Other	3.59	2.91	2.91	3.59	2.91	3.59

Table B.12: Summary of the fan sizes, pressure rise [Pa]: Climate zones 1A to 3B

Zone	Unit	Baseline	Alt1	Alt2	Alt3	Alt4	Alt5
1A	DOAS-1	N/A	1461	1461	1461	1508	1673
	DOAS-2	N/A	1461	1461	1461	1508	1673
	DOAS-3	N/A	1426	1426	1426	1472	1633
	DOAS-Other	N/A	1426	1426	1426	1472	1633
	VAV-1	1461	1224	1224	1224	1224	1224
	VAV-2	1461	1224	1224	1224	1224	1224
	VAV-3	1461	1195	1195	1224	1195	1195
	VAV-Other	1482	1224	1224	1242	1224	1242
1B	DOAS-1	N/A	1461	1461	1461	1518	1678
	DOAS-2	N/A	1461	1461	1461	1518	1678
	DOAS-3	N/A	1426	1426	1426	1482	1638
	DOAS-Other	N/A	1426	1426	1426	1482	1638
	VAV-1	1482	1224	1224	1242	1224	1242
	VAV-2	1482	1224	1224	1242	1224	1242
	VAV-3	1482	1224	1224	1242	1224	1242
	VAV-Other	1482	1242	1242	1242	1224	1242
2A	DOAS-1	N/A	1461	1461	1461	1523	1663
	DOAS-2	N/A	1461	1461	1461	1523	1663
	DOAS-3	N/A	1426	1426	1426	1486	1624
	DOAS-Other	N/A	1426	1426	1426	1486	1624
	VAV-1	1461	1224	1224	1224	1224	1224
	VAV-2	1461	1224	1224	1224	1224	1224
	VAV-3	1461	1195	1195	1224	1195	1224
	VAV-Other	1482	1224	1224	1242	1224	1242
2B	DOAS-1	N/A	1461	1461	1461	1508	1673
	DOAS-2	N/A	1461	1461	1461	1508	1673
	DOAS-3	N/A	1426	1426	1426	1472	1633
	DOAS-Other	N/A	1426	1426	1426	1472	1633
	VAV-1	1482	1224	1224	1242	1224	1242
	VAV-2	1482	1224	1224	1242	1224	1242
	VAV-3	1482	1224	1224	1242	1224	1242
	VAV-Other	1482	1242	1242	1242	1242	1242
3A	DOAS-1	N/A	1461	1461	1461	1508	1658
	DOAS-2	N/A	1461	1461	1461	1508	1658
	DOAS-3	N/A	1426	1426	1426	1472	1619
	DOAS-Other	N/A	1426	1426	1426	1472	1619
	VAV-1	1461	1224	1224	1224	1224	1224
	VAV-2	1461	1224	1224	1224	1224	1224
	VAV-3	1482	1195	1195	1224	1195	1224
	VAV-Other	1482	1224	1224	1242	1224	1242
3B	DOAS-1	N/A	1461	1461	1461	1508	1673
	DOAS-2	N/A	1461	1461	1461	1508	1673
	DOAS-3	N/A	1426	1426	1426	1472	1633
	DOAS-Other	N/A	1426	1426	1426	1472	1633
	VAV-1	1482	1224	1224	1242	1224	1242
	VAV-2	1482	1224	1224	1242	1224	1242
	VAV-3	1482	1195	1195	1242	1224	1242
	VAV-Other	1482	1224	1242	1242	1242	1242

Table B.13: Summary of the fan sizes, pressure rise [Pa]: Climate zones 3C to 5B

Zone	Unit	Baseline	Alt1	Alt2	Alt3	Alt4	Alt5
3C	DOAS-1	N/A	1461	1461	1461	1513	1683
	DOAS-2	N/A	1461	1461	1461	1513	1683
	DOAS-3	N/A	1426	1426	1426	1477	1643
	DOAS-Other	N/A	1426	1426	1426	1477	1643
	VAV-1	1461	1224	1224	1224	1224	1224
	VAV-2	1461	1224	1224	1224	1224	1224
	VAV-3	1461	1195	1195	1224	1195	1224
	VAV-Other	1482	1224	1224	1242	1224	1242
4A	DOAS-1	N/A	1461	1461	1461	1508	1673
	DOAS-2	N/A	1461	1461	1461	1508	1673
	DOAS-3	N/A	1426	1426	1426	1472	1633
	DOAS-Other	N/A	1426	1426	1426	1472	1633
	VAV-1	1482	1224	1224	1242	1224	1242
	VAV-2	1482	1224	1224	1242	1224	1242
	VAV-3	1461	1195	1195	1224	1195	1224
	VAV-Other	1482	1242	1242	1242	1242	1242
4B	DOAS-1	N/A	1461	1461	1461	1518	1683
	DOAS-2	N/A	1461	1461	1461	1518	1683
	DOAS-3	N/A	1426	1426	1426	1482	1643
	DOAS-Other	N/A	1426	1426	1426	1482	1643
	VAV-1	1482	1224	1224	1242	1224	1242
	VAV-2	1482	1224	1224	1242	1224	1242
	VAV-3	1482	1224	1224	1242	1224	1242
	VAV-Other	1482	1242	1242	1242	1242	1242
4C	DOAS-1	N/A	1461	1461	1461	1513	1678
	DOAS-2	N/A	1461	1461	1461	1513	1678
	DOAS-3	N/A	1426	1426	1426	1477	1638
	DOAS-Other	N/A	1426	1426	1426	1477	1638
	VAV-1	1482	1224	1224	1242	1224	1242
	VAV-2	1482	1224	1224	1242	1224	1242
	VAV-3	1482	1224	1224	1242	1224	1242
	VAV-Other	1482	1242	1242	1242	1242	1242
5A	DOAS-1	N/A	1461	1461	1461	1508	1653
	DOAS-2	N/A	1461	1461	1461	1508	1653
	DOAS-3	N/A	1426	1426	1426	1472	1614
	DOAS-Other	N/A	1426	1426	1426	1472	1614
	VAV-1	1482	1224	1224	1242	1224	1242
	VAV-2	1482	1224	1224	1242	1224	1242
	VAV-3	1461	1195	1195	1224	1195	1224
	VAV-Other	1482	1242	1242	1242	1242	1242
5B	DOAS-1	N/A	1461	1461	1461	1518	1683
	DOAS-2	N/A	1461	1461	1461	1518	1683
	DOAS-3	N/A	1426	1426	1426	1482	1643
	DOAS-Other	N/A	1426	1426	1426	1482	1643
	VAV-1	1482	1224	1224	1242	1224	1242
	VAV-2	1482	1224	1224	1242	1224	1242
	VAV-3	1482	1224	1224	1242	1224	1242
	VAV-Other	1482	1242	1242	1242	1242	1242

Table B.14: Summary of the fan sizes, pressure rise [Pa]: Climate zones 5C to 8

Zone	Unit	Baseline	Alt1	Alt2	Alt3	Alt4	Alt5
5C	DOAS-1	N/A	1461	1461	1461	1518	1673
	DOAS-2	N/A	1461	1461	1461	1518	1673
	DOAS-3	N/A	1426	1426	1426	1482	1633
	DOAS-Other	N/A	1426	1426	1426	1482	1633
	VAV-1	1482	1224	1224	1242	1224	1242
	VAV-2	1482	1224	1224	1242	1224	1242
	VAV-3	1482	1195	1195	1242	1195	1242
	VAV-Other	1482	1224	1224	1242	1224	1242
6A	DOAS-1	N/A	1461	1461	1461	1518	1658
	DOAS-2	N/A	1461	1461	1461	1518	1658
	DOAS-3	N/A	1426	1426	1426	1482	1619
	DOAS-Other	N/A	1426	1426	1426	1482	1619
	VAV-1	1482	1224	1224	1242	1224	1242
	VAV-2	1482	1224	1224	1242	1224	1242
	VAV-3	1461	1195	1195	1224	1224	1224
	VAV-Other	1482	1224	1224	1242	1224	1242
6B	DOAS-1	N/A	1461	1461	1461	1523	1688
	DOAS-2	N/A	1461	1461	1461	1523	1688
	DOAS-3	N/A	1426	1426	1426	1486	1648
	DOAS-Other	N/A	1426	1426	1426	1486	1648
	VAV-1	1482	1224	1224	1242	1224	1242
	VAV-2	1482	1224	1224	1242	1224	1242
	VAV-3	1482	1224	1224	1242	1224	1242
	VAV-Other	1482	1242	1242	1242	1242	1242
7	DOAS-1	N/A	1461	1461	1461	1508	1663
	DOAS-2	N/A	1461	1461	1461	1508	1663
	DOAS-3	N/A	1426	1426	1426	1472	1624
	DOAS-Other	N/A	1426	1426	1426	1472	1624
	VAV-1	1482	1224	1224	1242	1224	1242
	VAV-2	1482	1224	1224	1242	1224	1242
	VAV-3	1461	1195	1195	1224	1195	1224
	VAV-Other	1482	1224	1224	1242	1224	1242
8	DOAS-1	N/A	1461	1461	1461	1518	1688
	DOAS-2	N/A	1461	1461	1461	1518	1688
	DOAS-3	N/A	1426	1426	1426	1482	1648
	DOAS-Other	N/A	1426	1426	1426	1482	1648
	VAV-1	1482	1224	1224	1242	1224	1242
	VAV-2	1482	1224	1224	1242	1224	1242
	VAV-3	1482	1224	1224	1242	1224	1242
	VAV-Other	1482	1224	1224	1242	1224	1242

Table B.15: Summary of the pump sizes, water flow rate [m³/s]: Cooling system

Zone	Baseline	Alt1	Alt2	Alt3	Alt4	Alt5
1A	0.0169	0.0191	0.0211	0.0237	0.0211	0.0238
1B	0.0148	0.0164	0.0164	0.0167	0.0165	0.0168
2A	0.0161	0.0184	0.0203	0.0229	0.0204	0.0230
2B	0.0141	0.0159	0.0167	0.0169	0.0167	0.0170
3A	0.0167	0.0190	0.0209	0.0235	0.0209	0.0236
3B	0.0112	0.0123	0.0127	0.0133	0.0128	0.0134
3C	0.0079	0.0093	0.0106	0.0108	0.0106	0.0109
4A	0.0153	0.0176	0.0195	0.0221	0.0195	0.0221
4B	0.0104	0.0113	0.0113	0.0119	0.0113	0.0120
4C	0.0109	0.0127	0.0146	0.0147	0.0146	0.0148
5A	0.0153	0.0175	0.0194	0.0220	0.0194	0.0221
5B	0.0116	0.0131	0.0131	0.0134	0.0132	0.0135
5C	0.0093	0.0106	0.0125	0.0137	0.0125	0.0138
6A	0.0127	0.0147	0.0166	0.0185	0.0166	0.0186
6B	0.0103	0.0115	0.0116	0.0120	0.0116	0.0121
7	0.0122	0.0141	0.0160	0.0180	0.0160	0.0181
8	0.0088	0.0111	0.0118	0.0110	0.0118	0.0111

Table B.16: Summary of the pump sizes, water flow rate [m³/s]: Heating system

Zone	Baseline	Alt1	Alt2	Alt3	Alt4	Alt5
1A	0.0037	0.0058	0.0058	0.0071	0.0058	0.0071
1B	0.0042	0.0063	0.0063	0.0076	0.0063	0.0076
2A	0.0066	0.0088	0.0088	0.0099	0.0088	0.0099
2B	0.0048	0.0068	0.0068	0.0083	0.0068	0.0083
3A	0.0086	0.0109	0.0109	0.0118	0.0109	0.0118
3B	0.0068	0.0087	0.0087	0.0097	0.0087	0.0097
3C	0.0049	0.0070	0.0070	0.0086	0.0070	0.0086
4A	0.0089	0.0108	0.0108	0.0122	0.0108	0.0122
4B	0.0068	0.0087	0.0087	0.0096	0.0087	0.0096
4C	0.0073	0.0092	0.0092	0.0107	0.0092	0.0107
5A	0.0115	0.0134	0.0134	0.0146	0.0134	0.0146
5B	0.0097	0.0115	0.0115	0.0126	0.0115	0.0126
5C	0.0078	0.0097	0.0097	0.0109	0.0097	0.0109
6A	0.0121	0.0139	0.0139	0.0152	0.0139	0.0152
6B	0.0117	0.0134	0.0134	0.0143	0.0134	0.0143
7	0.0134	0.0152	0.0152	0.0163	0.0152	0.0163
8	0.0170	0.0183	0.0183	0.0196	0.0183	0.0196

Appendix C

Indoor-Condition Result Tables

Table C.1: Summary of the average temperature [$^{\circ}$ C] in the corner classroom-Pod 1 during occupancy

Zone	Baseline	Alt1	Alt2	Alt3	Alt4	Alt5
1A	23.6	23.6	23.6	24.0	23.8	24.0
1B	23.7	23.7	23.7	23.9	23.8	24.0
2A	23.2	23.1	23.1	23.8	23.2	23.8
2B	23.6	23.6	23.6	23.9	23.7	23.9
3A	22.9	22.7	22.7	23.5	22.8	23.5
3B	23.5	23.5	23.5	23.9	23.6	23.9
3C	22.8	22.7	22.7	23.7	22.7	23.7
4A	23.1	23.0	23.0	23.7	23.1	23.7
4B	23.6	23.7	23.7	23.9	23.7	23.9
4C	22.9	22.8	22.8	23.7	22.8	23.7
5A	22.9	22.8	22.8	23.6	22.8	23.6
5B	23.2	23.1	23.1	23.7	23.1	23.7
5C	22.7	22.6	22.6	23.5	22.6	23.5
6A	22.8	22.7	22.7	23.5	22.7	23.5
6B	23.1	23.0	23.0	23.6	23.0	23.6
7	22.7	22.6	22.6	23.4	22.6	23.4
8	22.4	22.3	22.3	23.0	22.3	23.0

Table C.2: Summary of the average relative humidity [%] in the corner classroom-Pod 1 during occupancy

Zone	Baseline	Alt1	Alt2	Alt3	Alt4	Alt5
1A	50.0	51.0	44.1	43.0	42.8	42.1
1B	29.8	35.6	34.6	35.3	34.3	35.0
2A	47.3	47.4	41.7	40.2	40.8	39.6
2B	35.9	38.0	35.6	34.7	35.2	34.4
3A	43.2	43.0	38.5	37.6	38.0	37.2
3B	32.4	33.7	32.2	31.6	31.8	31.2
3C	47.0	47.2	44.8	43.0	44.4	42.0
4A	39.6	39.4	35.7	34.5	35.3	34.1
4B	27.4	28.9	28.2	27.7	28.0	27.4
4C	42.4	43.4	40.8	39.5	40.6	38.9
5A	40.1	39.7	36.7	35.5	36.5	35.4
5B	29.6	31.7	31.3	30.2	31.1	30.1
5C	43.9	43.4	41.6	40.4	41.4	39.9
6A	36.6	36.2	34.1	33.1	34.0	32.9
6B	30.0	29.9	29.6	28.6	29.5	28.4
7	35.0	34.6	33.0	31.9	32.9	31.7
8	27.8	27.6	27.1	26.7	27.0	26.5

Table C.3: Summary of PMV in the corner classroom-Pod 1 during occupancy

Zone	Baseline	Alt1	Alt2	Alt3	Alt4	Alt5
1A	0.24	0.24	0.20	0.27	0.23	0.27
1B	0.17	0.21	0.21	0.25	0.23	0.25
2A	0.07	0.05	0.02	0.15	0.04	0.15
2B	0.16	0.18	0.17	0.22	0.18	0.22
3A	-0.06	-0.08	-0.11	0.04	-0.10	0.04
3B	0.03	0.05	0.04	0.11	0.06	0.11
3C	-0.11	-0.13	-0.14	0.05	-0.14	0.05
4A	-0.02	-0.03	-0.05	0.08	-0.05	0.08
4B	0.06	0.09	0.08	0.13	0.10	0.13
4C	-0.08	-0.09	-0.11	0.07	-0.11	0.06
5A	-0.09	-0.10	-0.12	0.02	-0.12	0.02
5B	-0.07	-0.06	-0.06	0.05	-0.06	0.05
5C	-0.14	-0.17	-0.18	0.01	-0.18	0.01
6A	-0.16	-0.18	-0.19	-0.04	-0.19	-0.04
6B	-0.13	-0.14	-0.14	-0.03	-0.14	-0.03
7	-0.20	-0.21	-0.22	-0.08	-0.22	-0.08
8	-0.38	-0.39	-0.39	-0.25	-0.39	-0.25

Appendix D

Results-Verification Tables

Table D.1: The flow rate [kg/s] at each node in the multi-zone VAV-1 cycle in the Baseline model on the 7th day in each month at 10 am in Miami, FL (see Figure 5.37 to locate the nodes on the HVAC system plan)

Month	Node Number										
	1	2	3	4	5	6	7	8	9	10	11
Jan	0	0	0	0	0	0	0	0	0	0	0
Feb	2.83	2.83	2.83	2.83	2.83	2.83	0.23	0.23	0.23	2.83	2.83
Mar	2.78	2.78	2.78	2.78	2.78	2.78	0.22	0.22	0.22	2.78	2.78
Apr	2.90	2.90	2.90	2.90	2.90	2.90	0.26	0.26	0.26	2.90	2.90
May	0	0	0	0	0	0	0	0	0	0	0
Jun	3.41	3.41	3.41	3.41	3.41	3.41	0.36	0.36	0.36	3.41	3.41
Jul	2.78	2.78	2.78	2.78	2.78	2.78	0.22	0.22	0.22	2.78	2.78
Aug	2.78	2.78	2.78	2.78	2.78	2.78	0.22	0.22	0.22	2.78	2.78
Sep	2.80	2.80	2.80	2.80	2.80	2.80	0.24	0.24	0.24	2.80	2.80
Oct	1.02	1.02	1.02	1.02	1.02	1.02	0.09	0.09	0.09	1.02	1.02
Nov	3.01	3.01	3.01	3.01	3.01	3.01	0.30	0.30	0.30	3.01	3.01
Dec	2.89	2.89	2.89	2.89	2.89	2.89	0.25	0.25	0.25	2.89	2.89

Table D.2: The temperature [$^{\circ}\text{C}$] at each node in the multi-zone VAV-1 cycle in the Baseline model on the 7th day in each month at 10 am in Miami, FL (see Figure 5.37 to locate the nodes on the HVAC system plan)

Month	Node Number										
	1	2	3	4	5	6	7	8	9	10	11
Jan	24.9	24.9	24.3	24.3	24.3	24.3	24.3	24.3	24.4	24.3	24.3
Feb	23.4	23.3	23.3	11.4	11.4	12.8	12.8	12.8	23.8	23.3	23.4
Mar	21.7	21.7	21.7	11.5	11.5	12.8	12.8	12.8	23.4	23.1	23.1
Apr	25.3	24.2	24.2	11.4	11.4	12.8	12.8	12.8	24.0	23.8	25.0
May	27.6	27.6	25.5	25.5	25.5	25.5	25.5	25.5	25.6	25.5	25.5
Jun	29.5	25.8	25.8	10.9	10.9	12.8	12.8	12.8	24.0	24.5	28.3
Jul	30.2	24.6	24.6	11.5	11.5	12.8	12.8	12.8	23.0	22.6	28.3
Aug	29.4	24.6	24.6	11.5	11.5	12.8	12.8	12.8	23.5	22.9	27.8
Sep	27.4	24.6	24.6	11.5	11.5	12.8	12.8	12.8	23.9	23.5	26.4
Oct	29.5	28.1	26.4	21.2	21.2	21.7	21.7	21.7	26.2	25.9	27.4
Nov	24.9	24.0	24.0	11.3	11.3	12.8	12.8	12.8	24.0	23.8	24.6
Dec	25.6	24.1	24.1	11.4	11.4	12.8	12.8	12.8	24.0	23.6	25.1

Table D.3: The humidity ratio [kg/kg] at each node in the multi-zone VAV-1 cycle in the Baseline model on the 7th day in each month at 10 am in Miami, FL (see Figure 5.37 to locate the nodes on the HVAC system plan)

Month	Node Number										
	1	2	3	4	5	6	7	8	9	10	11
Jan	0.0167	0.0167	0.0130	0.0130	0.0130	0.0130	0.0130	0.0130	0.0130	0.0130	0.0130
Feb	0.0129	0.0113	0.0113	0.0084	0.0084	0.0084	0.0084	0.0084	0.0102	0.0100	0.0116
Mar	0.0131	0.0131	0.0131	0.0084	0.0084	0.0084	0.0084	0.0084	0.0103	0.0101	0.0101
Apr	0.0134	0.0116	0.0116	0.0084	0.0084	0.0084	0.0084	0.0084	0.0104	0.0103	0.0122
May	0.0140	0.0140	0.0120	0.0120	0.0120	0.0120	0.0120	0.0120	0.0121	0.0120	0.0120
Jun	0.0176	0.0131	0.0131	0.0081	0.0081	0.0081	0.0081	0.0081	0.0097	0.0100	0.0145
Jul	0.0168	0.0120	0.0120	0.0084	0.0084	0.0084	0.0084	0.0084	0.0088	0.0088	0.0135
Aug	0.0181	0.0126	0.0126	0.0084	0.0084	0.0084	0.0084	0.0084	0.0088	0.0087	0.0142
Sep	0.0180	0.0126	0.0126	0.0084	0.0084	0.0084	0.0084	0.0084	0.0088	0.0088	0.0142
Oct	0.0168	0.0155	0.0123	0.0107	0.0107	0.0107	0.0107	0.0107	0.0116	0.0113	0.0127
Nov	0.0144	0.0117	0.0117	0.0083	0.0083	0.0083	0.0083	0.0083	0.0099	0.0099	0.0126
Dec	0.0163	0.0126	0.0126	0.0084	0.0084	0.0084	0.0084	0.0084	0.0104	0.0101	0.0138

Table D.4: The flow rate [kg/s] at each node in the DOAS-1 cycle in the Alternative 1 model on the 7th day in each month at 10 am in Miami, FL (see Figure 5.39 to locate the nodes on the HVAC system plan)

Month	Node Number									
	1	2	3	4	5	6	7	8	9	10
Jan	0	0	0	0	0	0	0	0	0	0
Feb	2.59	2.59	2.59	2.59	2.59	0.22	0.22	0.31	2.59	2.59
Mar	2.59	2.59	2.59	2.59	2.59	0.22	0.22	0.31	2.59	2.59
Apr	2.59	2.59	2.59	2.59	2.59	0.22	0.22	0.31	2.59	2.59
May	0	0	0	0	0	0	0	0	0	0
Jun	2.59	2.59	2.59	2.59	2.59	0.22	0.22	0.36	2.59	2.59
Jul	1.18	1.18	1.18	1.18	1.18	0.10	0.10	0.19	1.18	1.18
Aug	1.18	1.18	1.18	1.18	1.18	0.10	0.10	0.20	1.18	1.18
Sep	1.18	1.18	1.18	1.18	1.18	0.10	0.10	0.25	1.18	1.18
Oct	0	0	0	0	0	0	0	0	0	0
Nov	2.59	2.59	2.59	2.59	2.59	0.22	0.22	0.31	2.59	2.59
Dec	2.59	2.59	2.59	2.59	2.59	0.22	0.22	0.31	2.59	2.59

Table D.5: The flow rate [kg/s] at each node in the multi-zone VAV-1 cycle in the Alternative 1 model on the 7th day in each month at 10 am in Miami, FL (see Figure 5.39 to locate the nodes on the HVAC system plan)

Month	Node Number					
	11	12	13	14	15	16
Jan	0	0	0	0	0	0
Feb	1.23	1.23	1.23	1.23	0.09	0.09
Mar	1.23	1.23	1.23	1.23	0.09	0.09
Apr	1.23	1.23	1.23	1.23	0.09	0.09
May	0	0	0	0	0	0
Jun	1.46	1.46	1.46	1.46	0.15	0.15
Jul	1.23	1.23	1.23	1.23	0.09	0.09
Aug	1.26	1.26	1.26	1.26	0.11	0.11
Sep	1.52	1.52	1.52	1.52	0.16	0.16
Oct	0.56	0.56	0.56	0.56	0.04	0.04
Nov	1.26	1.26	1.26	1.26	0.10	0.10
Dec	1.23	1.23	1.23	1.23	0.09	0.09

Table D.6: The temperature [$^{\circ}\text{C}$] at each node in the DOAS-1 cycle in the Alternative 1 model on the 7th day in each month at 10 am in Miami, FL (see Figure 5.39 to locate the nodes on the HVAC system plan)

Month	Node Number									
	1	2	3	4	5	6	7	8	9	10
Jan	24.9	24.9	24.3	24.3	24.3	24.3	12.3	24.4	24.3	24.3
Feb	23.4	22.6	10.9	10.9	12.8	12.8	12.8	22.8	22.3	23.2
Mar	21.7	21.7	10.9	10.9	12.8	12.8	12.8	22.4	22.2	22.2
Apr	25.3	23.5	10.9	10.9	12.8	12.8	12.8	23.3	22.9	24.7
May	27.6	27.6	25.6	25.6	25.6	25.6	13.0	25.7	25.6	25.6
Jun	29.5	25.4	10.9	10.9	12.8	12.8	12.8	24.0	24.0	28.2
Jul	30.2	25.0	12.0	12.1	12.8	12.8	12.8	23.6	23.1	28.4
Aug	29.4	25.1	12.0	12.1	12.8	12.8	12.8	24.0	23.5	28.0
Sep	27.4	24.8	12.0	12.1	12.8	12.8	12.8	24.0	23.9	26.5
Oct	29.5	29.5	26.6	26.6	26.6	26.6	13.5	26.6	26.6	26.6
Nov	24.9	23.4	10.9	10.9	12.8	12.8	12.8	23.7	23.0	24.4
Dec	25.6	23.5	10.9	10.9	12.8	12.8	12.8	23.3	22.8	24.9

Table D.7: The temperature [$^{\circ}\text{C}$] at each node in the multi-zone VAV-1 cycle in the Alternative 1 model on the 7th day in each month at 10 am in Miami, FL (see Figure 5.39 to locate the nodes on the HVAC system plan)

Month	Node Number					
	11	12	13	14	15	16
Jan	24.3	24.3	24.3	24.3	24.3	24.3
Feb	22.2	12.3	12.3	12.8	12.8	12.8
Mar	22.2	12.3	12.3	12.8	12.8	12.8
Apr	22.8	12.3	12.3	12.8	12.8	12.8
May	25.6	25.6	25.6	25.6	25.6	25.6
Jun	24.0	12.2	12.2	12.8	12.8	12.8
Jul	23.1	12.3	12.3	12.8	12.8	12.8
Aug	23.5	12.3	12.3	12.8	12.8	12.8
Sep	23.9	12.2	12.2	12.8	12.8	12.8
Oct	26.1	20.3	20.3	20.5	20.5	20.5
Nov	22.8	12.3	12.3	12.8	12.8	12.8
Dec	22.7	12.3	12.3	12.8	12.8	12.8

Table D.8: The humidity ratio [kg/kg] at each node in the DOAS-1 cycle in the Alternative 1 model on the 7th day in each month at 10 am in Miami, FL (see Figure 5.39 to locate the nodes on the HVAC system plan)

Month	Node Number									
	1	2	3	4	5	6	7	8	9	10
Jan	0.0167	0.0167	0.0132	0.0132	0.0132	0.0132	0.0066	0.0132	0.0132	0.0132
Feb	0.0129	0.0109	0.0081	0.0081	0.0081	0.0081	0.0081	0.0097	0.0096	0.0116
Mar	0.0131	0.0131	0.0081	0.0081	0.0081	0.0081	0.0081	0.0097	0.0096	0.0096
Apr	0.0134	0.0112	0.0081	0.0081	0.0081	0.0081	0.0081	0.0098	0.0097	0.0119
May	0.0140	0.0140	0.0125	0.0125	0.0125	0.0125	0.0062	0.0125	0.0125	0.0125
Jun	0.0176	0.0131	0.0081	0.0081	0.0081	0.0081	0.0081	0.0099	0.0099	0.0145
Jul	0.0168	0.0122	0.0087	0.0087	0.0087	0.0087	0.0087	0.0092	0.0091	0.0136
Aug	0.0181	0.0128	0.0087	0.0087	0.0087	0.0087	0.0087	0.0091	0.0091	0.0144
Sep	0.0180	0.0128	0.0087	0.0087	0.0087	0.0087	0.0087	0.0091	0.0091	0.0144
Oct	0.0168	0.0168	0.0121	0.0121	0.0121	0.0121	0.0061	0.0121	0.0121	0.0121
Nov	0.0144	0.0115	0.0081	0.0081	0.0081	0.0081	0.0081	0.0097	0.0096	0.0125
Dec	0.0163	0.0124	0.0081	0.0081	0.0081	0.0081	0.0081	0.0099	0.0098	0.0136

Table D.9: The humidity ratio [kg/kg] at each node in the multi-zone VAV-1 cycle in the Alternative 1 model on the 7th day in each month at 10 am in Miami, FL (see Figure 5.39 to locate the nodes on the HVAC system plan)

Month	Node Number					
	11	12	13	14	15	16
Jan	0.0132	0.0132	0.0132	0.0132	0.0132	0.0132
Feb	0.0095	0.0087	0.0087	0.0087	0.0087	0.0087
Mar	0.0095	0.0087	0.0087	0.0087	0.0087	0.0087
Apr	0.0096	0.0087	0.0087	0.0087	0.0087	0.0087
May	0.0125	0.0125	0.0125	0.0125	0.0125	0.0125
Jun	0.0098	0.0087	0.0087	0.0087	0.0087	0.0087
Jul	0.0091	0.0086	0.0086	0.0086	0.0086	0.0086
Aug	0.0091	0.0086	0.0086	0.0086	0.0086	0.0086
Sep	0.0091	0.0085	0.0085	0.0085	0.0085	0.0085
Oct	0.0116	0.0107	0.0107	0.0107	0.0107	0.0107
Nov	0.0095	0.0087	0.0087	0.0087	0.0087	0.0087
Dec	0.0096	0.0087	0.0087	0.0087	0.0087	0.0087

Table D.10: The flow rate, temperature, and humidity ratio at nodes 1 and 6 in the multi-zone VAV-1 cycle in the Baseline model on the 7th day in October in Miami, FL (see Figure 5.37 to locate the nodes on the HVAC system plan)

Time	Flow Rate [kg/s]		Temperature [°C]		Humidity Ratio [kg/kg]	
	1	6	1	6	1	6
1:00 am	0	0	25.6	25.3	0.0176	0.0103
2:00 am	0	0	25.3	25.2	0.0176	0.0105
3:00 am	0	0	25.0	25.0	0.0178	0.0108
4:00 am	0	0	25.0	24.9	0.0180	0.0110
5:00 am	0	0	25.0	24.8	0.0180	0.0112
6:00 am	0	0	24.7	24.7	0.0177	0.0112
7:00 am	0	0	24.8	24.6	0.0178	0.0114
8:00 am	0	0	26.6	24.9	0.0177	0.0115
9:00 am	0	0	28.4	25.8	0.0175	0.0117
10:00 am	1.02	1.02	29.5	21.7	0.0168	0.0107
11:00 am	1.40	1.40	31.0	19.3	0.0160	0.0093
12:00 pm	1.50	1.50	30.7	19.2	0.0164	0.0090
1:00 pm	2.32	2.32	30.0	15.0	0.0165	0.0086
2:00 pm	1.85	1.85	30.0	17.4	0.0160	0.0086
3:00 pm	2.32	2.32	29.6	15.1	0.0160	0.0085
4:00 pm	1.85	1.85	29.1	17.4	0.0163	0.0086
5:00 pm	2.32	2.32	28.5	15.1	0.0162	0.0085
6:00 pm	1.30	1.30	28.0	20.0	0.0162	0.0088
7:00 pm	0	0	27.5	25.7	0.0166	0.0092
8:00 pm	0	0	27.6	26.4	0.0169	0.0096
9:00 pm	0	0	27.5	26.4	0.0166	0.0100
10:00 pm	0	0	26.9	26.2	0.0166	0.0104
11:00 pm	0	0	26.7	26.0	0.0167	0.0107
12:00 am	0	0	26.7	25.8	0.0171	0.0109

Table D.11: The flow rate, temperature, and humidity ratio at nodes 11 and 14 in the multi-zone VAV-1 cycle in the Alternative 1 model on the 7th day in October in Miami, FL (see Figure 5.39 to locate the nodes on the HVAC system plan)

Time	Flow Rate [kg/s]		Temperature [$^{\circ}$ C]		Humidity Ratio [kg/kg]	
	11	14	11	14	11	14
1:00 am	0	0	25.3	25.3	0.0107	0.0107
2:00 am	0	0	25.1	25.1	0.0109	0.0109
3:00 am	0	0	25	25	0.0111	0.0111
4:00 am	0	0	24.9	24.9	0.0113	0.0113
5:00 am	0	0	24.8	24.8	0.0115	0.0115
6:00 am	0	0	24.7	24.7	0.0115	0.0115
7:00 am	0	0	24.6	24.6	0.0117	0.0117
8:00 am	0	0	24.9	24.9	0.0118	0.0118
9:00 am	0	0	25.7	25.7	0.012	0.012
10:00 am	0.56	0.56	26.1	20.5	0.0116	0.0107
11:00 am	0.83	0.83	25.8	17.5	0.0108	0.0097
12:00 pm	1.09	1.09	25.8	15.2	0.0102	0.0091
1:00 pm	0.98	0.98	26.4	17.6	0.01	0.0092
2:00 pm	1.25	1.25	26.2	15.3	0.0097	0.0088
3:00 pm	1	1	26.6	17.7	0.0096	0.0089
4:00 pm	1.17	1.17	26.2	15.3	0.0095	0.0088
5:00 pm	0.9	0.9	26.3	17.7	0.0095	0.0089
6:00 pm	1.03	1.03	25.3	15.2	0.0094	0.0088
7:00 pm	0	0	26.8	26.8	0.0097	0.0097
8:00 pm	0	0	27	27	0.01	0.01
9:00 pm	0	0	26.8	26.8	0.0104	0.0104
10:00 pm	0	0	26.5	26.5	0.0107	0.0107
11:00 pm	0	0	26.3	26.3	0.011	0.011
12:00 am	0	0	26.1	26.1	0.0113	0.0113